The Development of a Robotic Coarse-to-Fine Positioning System

by

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the degree of Master of Engineering Management at
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Declaration

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Abstract

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Thesis: MScEng (Man)

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There is a need for a coarse-to-fine positioning system as per a case study presented by the project collaboration partner, the Technical University of Chemnitz. The case study involves the picking and placing of piezo-ceramic micro parts into milled micro cavities. The focus of the project is the creation and development of a systematic approach for the design and the implementation of a coarse-to-fine positioning system for micro material handling. A second focus is to determine the applicability of the system for highly accurate and repeatable micro drilling and micro-milling. A systematic approach entails combining innovation management (assists in overall project structure), systems engineering (assists in specific design steps and tools) and research questions. Micro-milling was achieved, however the system proved unsuitable for highly accurate and repeatable micro drilling. The coarse-to-fine positioning system was successfully designed, built, and tested for accurate micro material handling.

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Uittreksel

Die Ontwikkeling van ’n Robotmatige Grof-tot-Fyn-Posisioneringstelsel

(“The Development of a Robotic Coarse-to-Fine Positioning System”)

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Desember 2012

Daar bestaan ’n behoefte aan ’n grof-tot-fyn-posisioneringstelsel - soos blyk uit die gevallestudie uiteengesit deur die samewerkende projekvennoot, die Tegniese Universiteit van Chemnitz. Die gevallestudie behels die uitsoek en plasing van piezo-keramiek partikels in gefreesde mikroholtes. Hierdie projek het gefokus op die skepping en ontwikkeling van ’n stelselmatige benadering tot die ontwerp en implementering van ’n grof-tot-fyn-posisioneringstelsel vir mikromateriaalhantering en mikromasjienering. ’n Stelselmatige benadering behels dat innovasiebestuur (hulp met die algehele projekstruktuur), stelselingenieurswese (hulp met spesifieke ontwerpstappe en -hulpmiddels) en navorsingsdoelwitte gekombineer word. Die geïmplementeerde stelsel is eksperimenteel getoets en daar is bevind dat dit aan die spesifikasies en vereistes voldoen.

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Dedication

This thesis is dedicated to the Lord God Almighty, His son Jesus Christ and the Holy Spirit.

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Nomenclature

Abreviations

MEMS	Micro-electromechanical System
CNC	Computer Numerical Control
CMM	Coordinate Measuring Machine
GUI	Graphical User Interface
SEM	Scanning Electron Microscope

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Chapter 1

Introduction

The manufacturing of adaptronic materials is being used as a case study for the project. Two processes essential to the creation of these materials are the handling of micro-materials and the machining of micro cavities. Piezo-ceramic micro parts (250 μm × 250 μm × 10 mm) are currently being manually manipulated into the micro cavities using tweezers and a microscope. This process is highly inefficient, time-consuming and expensive. There is also no manner in which the current methods can facilitate large-scale production.

1.1 Technical Purpose of the Project

The University of Stellenbosch is collaborating with Chemnitz University in Germany, which is closely affiliated with the Fraunhofer IWU in Germany in order to create a coarse-to-fine positioning system. This system is designed to achieve highly accurate and repeatable micro-material handling. A secondary focus is to determine the feasibility of using the system for micro-machining. The primary aim of this project is thus to design, build and test the afore mentioned system. In order to do this, the system is divided into the following subsystems: coarse positioning subsystem, fine positioning subsystem, gripper subsystem, micro-machining subsystem, vision subsystem, control subsystem and a user robot interface subsystem.

1.2 Innovation and Systems Management Approach

In this approach, innovation management, systems engineering and research questions were combined. To this end, specific innovation management and systems engineering models were selected. This combination was then success-

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fully used to guide and structure the design and development process.

1.3 Conferences and Journals

In addition to performing a number of experiments, another source of validation in this project is that of conference papers and journals. Two conferences papers were written by the author of this thesis in the role of lead author and then accepted. An additional two conference papers were co-authored. A journal is currently being written. The detail and nature of the afore-mentioned can be seen in table 1.1.

Table 1.1: Conferences and a Journal

Detail	**Title**	**Role**	**Status**	**Chapters Covered**
CIE42 Conference	Development of a MicroMaterial Handling System	Main author	accepted	5,8,17
COMA 13 Conference	Polyurethane Micro Gripper Utilising Van der Waals Forces in Micro Assembly	First co-author	Submitted and accepted	5,8,11,15,16,17
COMA 13 Conference	Handling Robots for High Volume Micro-assembly: An Economic and Technological Comparison of Different Kinematic Principles	First co-author	Submitted and accepted	5,10
RobMech 2012 Conference	An Intuitive, Teachable Micro Material Handling	Main author	Submitted and accepted	5,8,9,10,11,13,14,15
Precision Engineering Journal Elsevier	An Intuitive Teachable Micro Material Handling	Main author	Being written	16,17

1.4 Document Approach

In order to create a coarse-to-fine positioning system, this document can be thought of as having two themes that are in line with the innovation and systems management and technical purposes. The first theme deals with creating and proving a project methodology. The second theme solves a technical problem.

Because of the complex nature of the system, it has been decided to employ both an innovation model and a systems engineering model. The innovation model will be used to structure the overall project and promote product

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commercialisation, while the systems engineering model will be used in the technical design.

In order to ensure flow of the document, it is first necessary to discuss and then select an innovation management model. It is then necessary to select a systems engineering model. A design methodology is then defined in the chapter titled Design Methodology. This approach will ensure that a thorough knowledge of both innovation management and systems engineering is in place before a design methodology is created.

After the methodology has been created, only then can the various steps of the design and project begin. It is, therefore, logical only to include the research methodology chapter after the chapters titled Innovation Models and Systems Engineering Models.

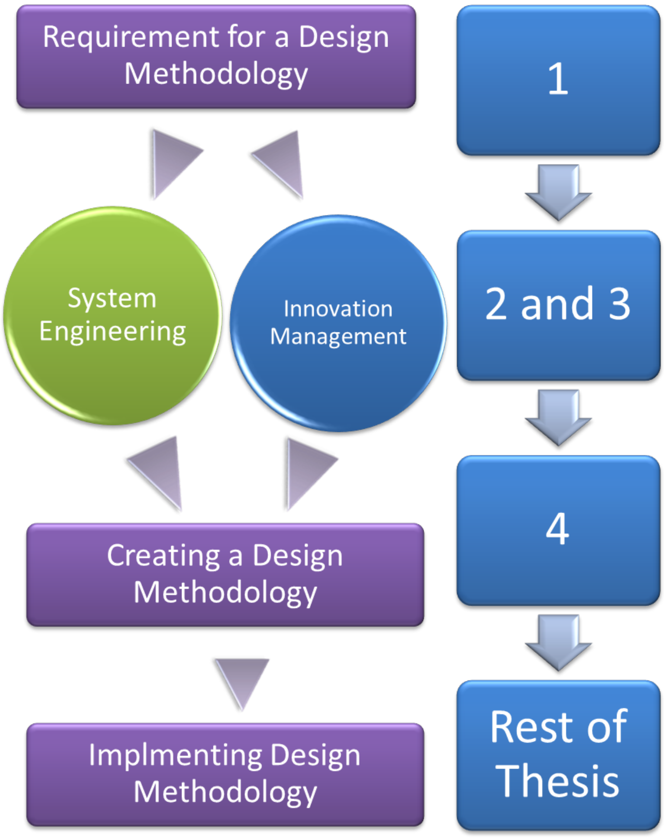

Figure 1.1: Document Approach of Initial Chapters Relating to the Formation of the Design Methodology

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Chapter 2

Innovation Models

The purpose of this chapter is to provide an understanding of innovation management and then to select an applicable innovation model. By applying applying and exploiting an innovation management model, the chances of the successful development of a coarse-to-fine positioning system are greatly improved. Innovation management controls and structures the 'bigger picture'. In order to ensure compliance with innovation and systems engineering terminology, the words project and thesis will be used interchangeably.

In order to select an appropriate innovation model, a number of characteristics were considered. Firstly, it is necessary to consider the number and nature of the life-cycle phases covered by each of the models. It is also necessary to examine the focus of each of the relevant models. This helps to determine their applicability to the project. It is then necessary to examine both the detail and complexity of the models themselves. An ideal model would be one that has a relatively large amount of detail but is not too complex.

2.1 Innovation Background

Marais (2010) states the following definition of innovation management:
"The successful generation, development and implementation of new and novel ideas, which introduce new products, processes and/or strategies to a company or enhance current products, processes and/or strategies leading to commercial success and possible market leadership and creating value for stakeholders, driving economic growth and improving standards of living."

Another definition as per Salvendy (1992) is: "Innovation is not just one simple act. It is not just a new understanding or the discovery of a new phenomenon, not just a flash of creative invention, not just the development of a new product or manufacturing process; nor is it simply the creation of new

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capital and markets. Rather innovation involves related creative activity in all these areas. It is a connected process in which many and sufficient creative acts, from research through service, are coupled together in an integrated way for a common goal."

Van Zyl (2006) states that it is important to differentiate between invention and innovation. Invention is simply a solution to a problem. Innovation, on the other hand, is the commercially successful use of an invention. Invention can thus be thought of as the first step in the innovation process. Innovation is a process that encompasses the development and commercialisation of products, services or processes, (Van Zyl, 2006). Innovation can be the combination or improvement of existing products, services and processes, (Van Zyl, 2006). When considered in terms of an enterprise, Marais (2010) states that innovation helps to increase an organisation's success by increasing competitiveness.

Tidd and Bessant (2009) does not provide a single concise definition of innovation or innovation management, but instead stresses the idea that innovation turns ideas into reality and captures value from them. The following definitions adds further clarity. "Definitions of innovation may vary in their wording, but they all stress the need to complete the development and exploitation aspects of new knowledge, not just its invention. "

For the purposes of this project, innovation management is defined as a process that can be implemented through the use of various models. In this process a product or service is created, developed and managed with the end goal of its successful commercialisation.

2.2 The Need for an Innovation Framework

Rothberg (1981) states the need for a structured framework as follows: "... There is a great deal of wasted time and effort in new product development. What is required are good strategic planning, proper management controls, and healthy organisational attitudes."

The need for a framework or map in order to implement the process of innovation is best explained in the following quotation by Mahdjoubi (1997): "Our perception and understanding of the process of innovation depends largely on the paradigms and models that we implement. In understanding the process of innovation, models may have the same role as that of maps and atlases in determining our perception of the world. Map-making has always been a useful analogy to help us understand the interconnectedness of human life, and

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mapping is an active metaphor to study the process of innovation. ”

As per Van Zyl *et al.* (2007), a key manner in which uncertainty, in an innovation, can be reduced is by making use of a structured model. A structured model helps to guide innovation. It also ensures that experience is gained and knowledge is captured from the innovation experience.

The function of a framework is to guide the processes of collecting and analysing information. This helps to establish the relationships between inputs, strategy, operations, market needs and outputs. These frameworks can be constructed at a number of different levels. These range from individual company projects to an industry sector, and even to national or global levels, (Van Zyl, 2006).

2.3 Innovation Life Cycles

The innovation life cycle is summarised by Marais (2010) in the following diagram, figure 2.1. The figure 2.1 shows how different stages of the innovation life cycle occur. Every innovation project goes through the same five phases from invention to disposal, (Van Zyl *et al.*, 2007). It should be noted that each of these phases requires input and activities to be performed. Once performed, these are converted into usable outputs, (Du Preez, 2009).

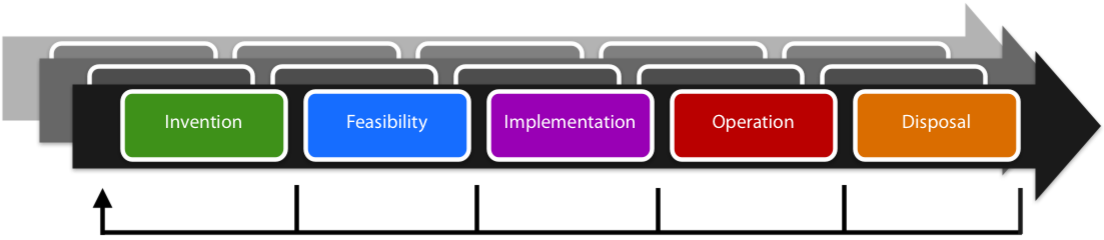

Figure 2.1: Innovation Life Cycle, Marais (2010) adapted from Rothberg (1981)

The five phases as illustrated in figure 2.1 are described as per Van Zyl *et al.* (2007):

1. Invention. This phase is where ideas are generated
2. Feasibility. Here the feasibility of the specification, design, functional analysis and the concepts is analysed

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3. Innovation (Implementation). This is the detailed design and manifestation of the concepts
4. Operation. This phase entails the production and maintenance activities.
5. Disposal. This phase is conducted at the end of the product's useful life and deals with system termination

Essmann (2009) states that a large part of the innovation life cycle is learning. After each phase has been completed, an opportunity arises to learn from the successes and failures of that phase. At the conclusion of a project, successes and failures must be examined. In addition to successes and failures, it is also necessary to determine how the initial set goals match those achieved. The differences should be noted and improved upon in future projects, (Essmann, 2009).

2.4 Sources of Innovation

Rothberg (1981) created three key questions to ask when in the early stages of innovation. Firstly, it is necessary to ask which customers and specific needs will the innovation address. Secondly, it is necessary to assess the benefits associated with alternative technology sets. Thirdly, how do the technology alternatives satisfy the customer needs.

There are seven sources of innovation, (Van Zyl, 2006). All of these seven sources of innovation create opportunities for market pull and technology push activities. These sources of innovation are summarised in the table 2.1.

2.5 Product Innovation

As per Du Preez (2009), there are many different types of innovation. These include product, process, strategy and marketing innovation. Accordingly, each type requires a different approach. The focus in this project will be on product innovation.

Product innovation can be defined differently, depending on whether it is perceived from the side of the innovator or from that of the market, (Van Zyl, 2006). Some characteristics of product innovations can be seen in figure 2.2. Rothberg (1981) states the following about product innovation: "From a business perspective a product innovation can be said to represent change in, or an addition to, the physical entities that comprise its product line. From a market perspective, however, the term refers to a new or revised set of customer

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Table 2.1: Seven Sources of Innovation, (Drucker, 1985)

Sources	**Description**
The Unexpected	Unexpected success (e.g. products selling in an unanticipated way) Unexpected failures (e.g. products or services that "should" succeed but fail miserably) Unexpected outside events (such as the explosion in book-buying in the US)
Incongruities	A discrepancy between what "is" and what "ought" to be: Incongruities with the economic realities of the industry Incongruities between the reality of the industry and the assumptions about it Incongruities between the efforts of an industry and the values and expectation of its customers Incongruities within a process
Process Needs	A clearly understood need for which a process solution does not yet exist
Changes in the Industry or Market Structure	Shifts in the relationships and dynamics between players in an industry or market (often brought on by rapid growth, technology convergence, or rapid changes in practice)
Demographics	Changes in population (size, age, employment, education status, income, and ethnicity)
Changes in Perception, Mood and Meaning	Changes in how people think about problems or issues (for example, the obsession with health and fitness)
New Knowledge	Advances in scientific and technical knowledge and know-how

perceptions concerning a particular benefits cluster."

Du Preez (2009) and Essmann (2009) both state that the requirement for a product innovation is that both parties, customer as well as client, gain value from the transfer of the innovation. In the course of this transfer, product innovation may create a competitive advantage. If the created products are differentiated enough from the currently available products, they may claim a portion of an undefined or untapped market, (Essmann, 2009).

Johne and Snelson (1988) define product innovations according to three types. The first is that of the development or improvement of an existing product. The second is that of the development of a new product with technology that is existing in the organisation. The third is the development of a new product with technology that is not currently existent in the organisation.

As per Van Zyl *et al.* (2007) a product has two key dimensions. The first is that of technology. Technology allows the product to be produced economically. The second dimension is that of markets. Markets enable profit generation. Innovation is thus the creation of a product in line with the needs of a customer. Johne and Snelson (1988) concur with this by stating that product development is the parallel set of activities in which technical and marketing disciplines interact.

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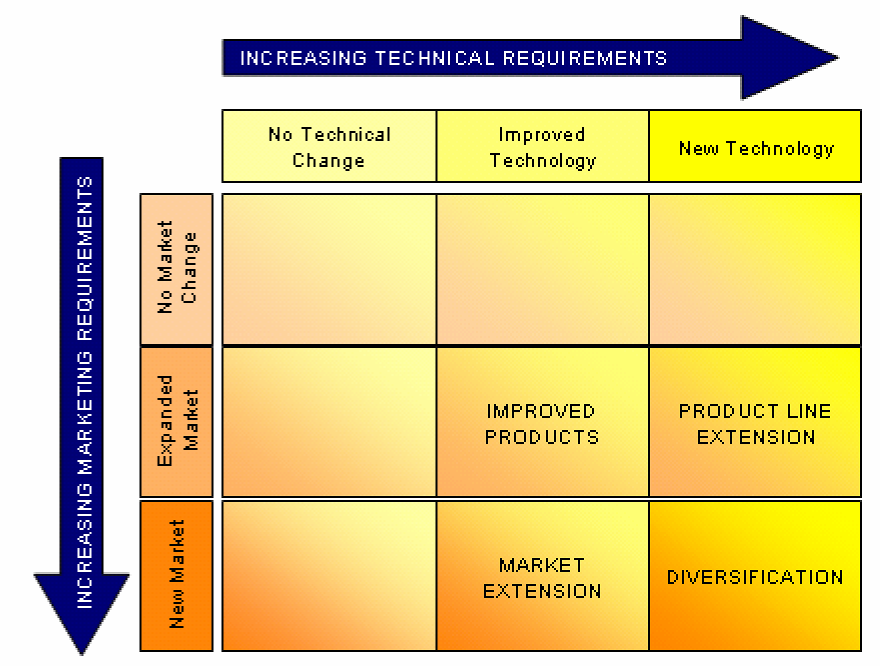

Figure 2.2: Two-Dimensional Characteristics of Products, Rothberg (1981) adapted by Van Zyl *et al.* (2007)

Johne and Snelson (1988) state that six generic tasks for product development are as follows:

1. New Product Planning
2. Idea Generation
3. Screening and Evaluation
4. Technical Development
5. Market Appraisal
6. Launch

2.6 Innovation Models

The term 'architecture' is defined by Williams *et al.* (1998) as a drawing, a model or a description that shows the interrelationship of the parts and functions of a device, system or an enterprise. Innovation process models consist of a number of the following steps: idea generation and identification, concept

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development, concept evaluation and selection, development and implementation. Of paramount importance to the innovation process is the manner in which these different functions or steps are integrated, (Du Preez, 2008).

Van Zyl (2006) states that a model that represents the structure of an entity, be it physical or conceptual, is called an architecture. Architectures can be divided into two groups. The first is the structural arrangement of a physical system. The second is the structural arrangement of the development and implementation of a project programme, such as a manufacturing or enterprise integration or enterprise development program, (Van Zyl, 2006).

2.6.1 Innovation Model Comparison

In order to compare different innovation frameworks or models a common standard is needed. Both Van Zyl (2006) and Nieberding (2010) followed a method presented by Williams *et al.* (1998), where different models are mapped and compared according to the life cycle phases they encompass. As per Van Zyl (2006), the five life cycle phases of invention, feasibility, innovation, operation and disposal describe the progress of an innovation from beginning to end.

Nieberding (2010) states that, in general, while all the authors agree on the sequence of the life cycle events, there is great discrepancy about where the product development phase begins. In order to illustrate this, Nieberding (2010) adapted the work of Cavallucci and Lutz (2000). There is also a large amount of variation about what is included in the product development models. Ullman, for instance, incorporates project planning into his model. This is not the case in other product innovation models, (Nieberding, 2010).

Having extensively examined all the models from both Van Zyl (2006), Nieberding (2010) and Cross (2000), as well as examining the original sources of models (where applicable), an adapted innovation landscape has been created. This illustration of the various models and their life cycles can be seen in figure 2.3.

2.6.2 General Models of Innovation

The product innovation models were all designed with a specific application or need in mind. Van Zyl (2006) goes on to describe general innovation models: Utterback's Model, and the Improved Chiesa Framework. Mahdjoubi (1997) mentions the two generals models of the Linear Model of Innovation and Stephen Kline's Chain-linked Model. These general models need to be adapted in order to fit the needs of a particular project. Because of the nature

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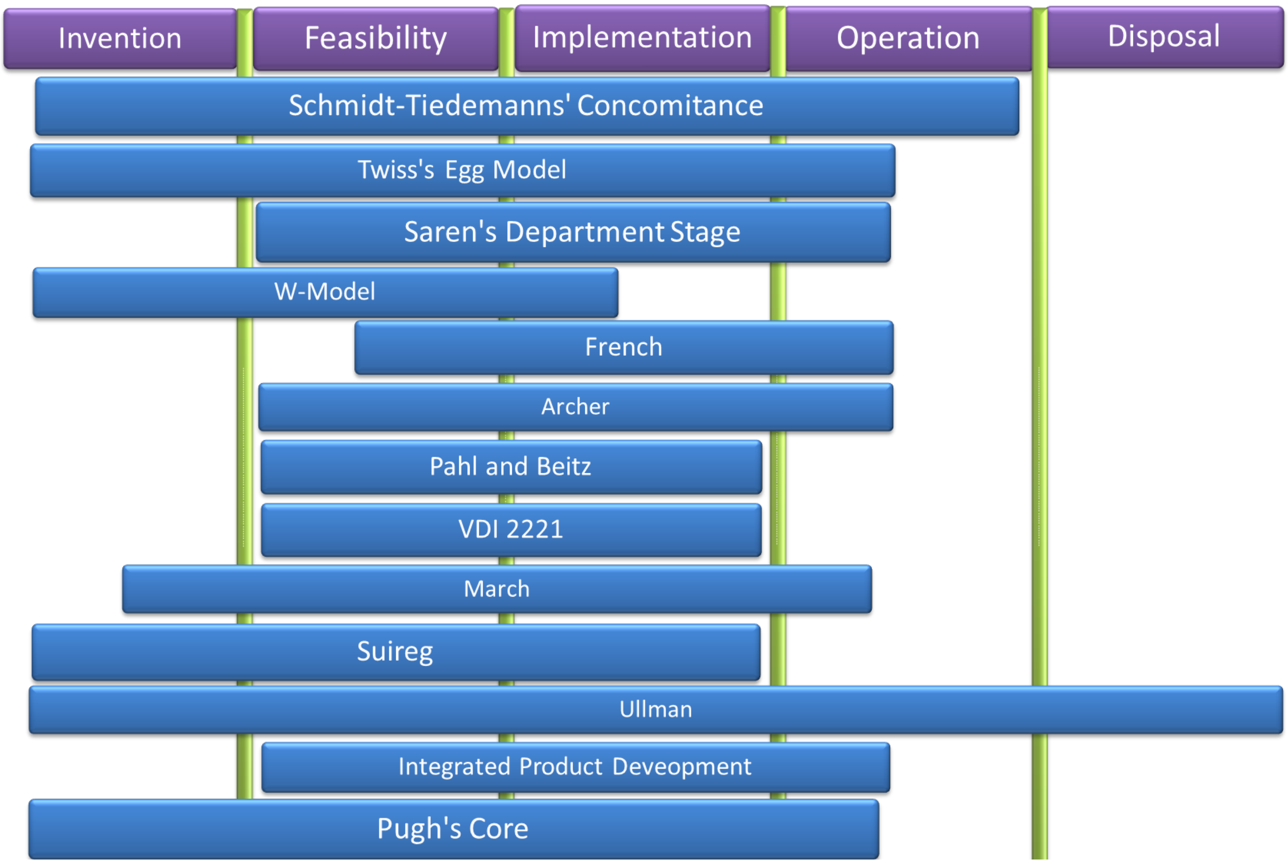

Figure 2.3: Innovation Product Models and Their Life Cycle Stages adapted from Van Zyl *et al.* (2007),Nieberding (2010) and Cross (2000)

of these general models, they can be applied to both product and innovation projects.

Utterback's Three-stage Model

As per Van Zyl (2006), the Utterback model has three stages in its process see figure 2.4. These stages include generation of an idea, problem development, and implementation and diffusion. The latter are in line with the first of the innovation life cycle phases: invention, feasibility and innovation. Despite the fact that model is linear, there are a number of sequential activities performed in each stage. Even though external influences are included, the model is a basic one. More thorough models can be built onto this model, (Van Zyl, 2006).

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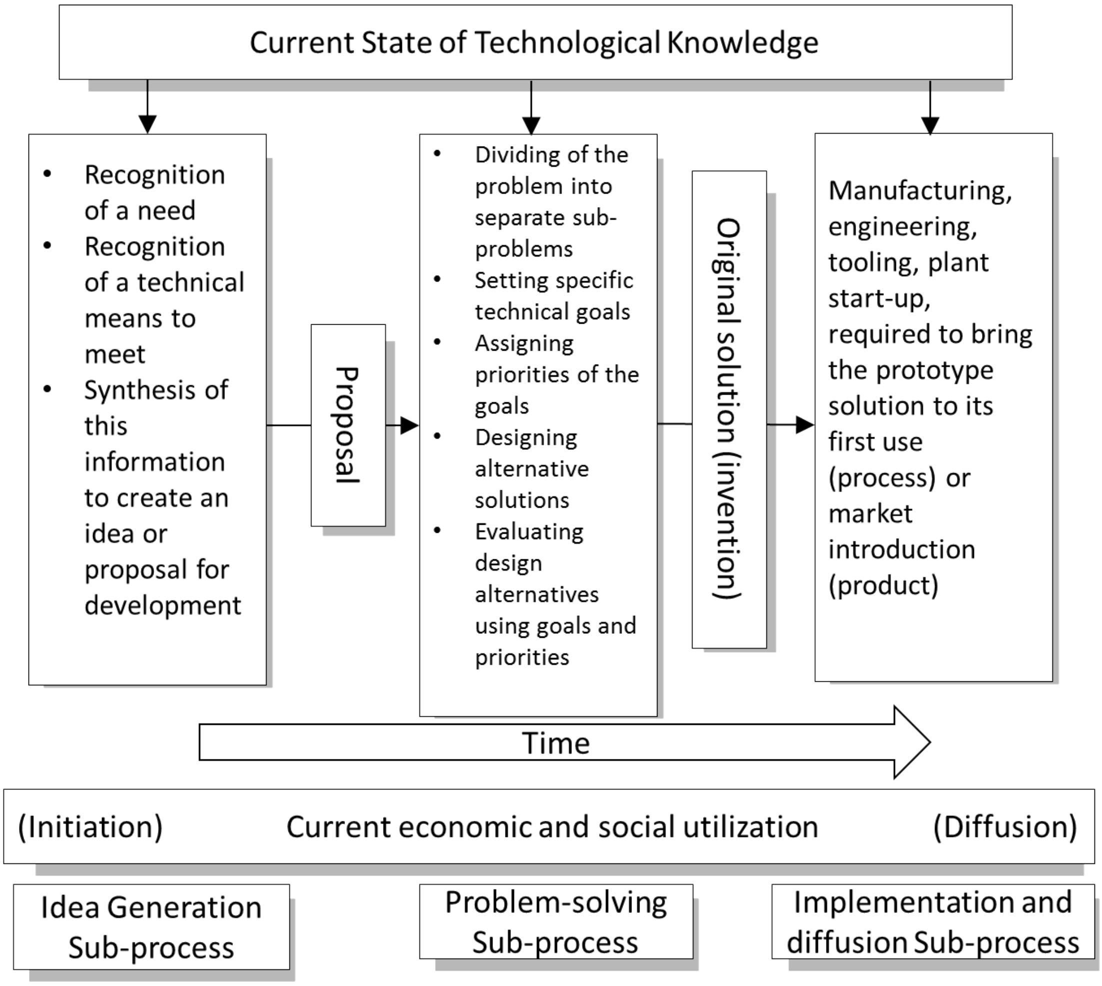

Figure 2.4: Utterback's Three-stage Model for Innovation, (Van Zyl, 2006)

Improved Chiesa Framework

Verhaeghe and Kfir (2002) state that the Chiesa model was developed using a number of interviews conducted with a group of managers. The main aim of these interviews was to determine the points that influence innovation management. These points were then combined into a framework. Three central elements identified by the framework are inputs of innovation, core process of innovation and outputs of innovation.

Verhaeghe and Kfir (2002) continue on to state that the central elements as described above are further subdivided as follows. The input element is divided into leadership, resourcing innovation, and market focus. The core process element is divided into offer innovation, offering development, technology transfer, technology acquisition, networking, systems and tools. Lastly, the output element has the sub-element of innovation performance. After a

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number of improvements the Chiesa model was created as seen in figure 2.5.

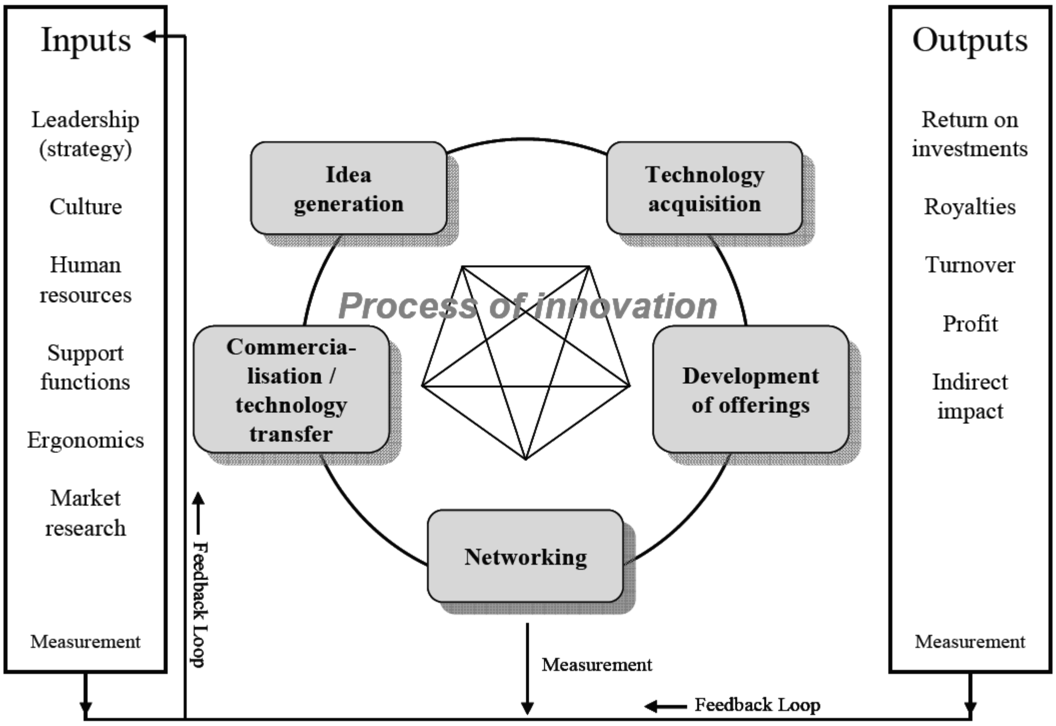

Figure 2.5: A Holistic Systems Framework of Innovation, (Verhaeghe and Kfir, 2002)

The improved Chiesa framework is used in holistic innovation management. This model clearly shows the interconnection of elements. It does not, however, distinctly show life cycle phases. Despite this, it can be tailored to develop more specific models. The Chiesa model covers the innovation life cycle phases from invention to operation, (Van Zyl, 2006).

Linear Model of Innovation

One of the most basic innovation models is that of the Linear Model of innovation as presented by Mahdjoubi (1997). The model is comprised of four steps as can be seen in figure 2.6. Basic research is conducted without the specific product or process in mind. Applied research is conducted in order to develop a specific product or process, (Mahdjoubi, 1997). The Linear Model is limited in its flexibility, detail and applicability.

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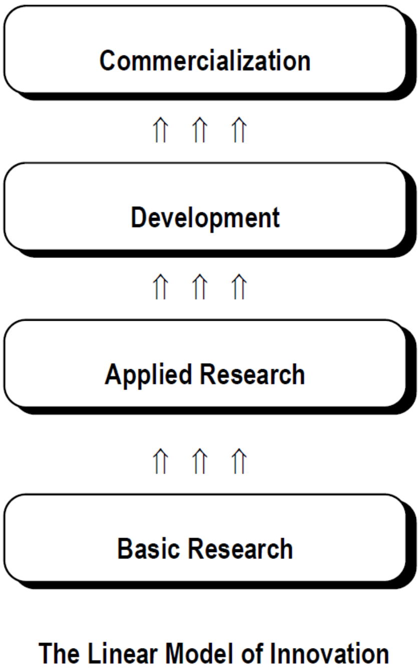

Figure 2.6: The Linear Model of Innovation, (Mahdjoubi, 1997)

Stephen Kline's Chain-linked Model

This model was developed to replace the Linear Innovation Model. This more complex model better helps to explain the nature of Innovation in general. The model covers the steps from design to marketing. This model does not begin with research; however, research is an integral part. This model also incorporates a large amount of feedback between the technical phases and the currently available knowledge, (Mahdjoubi, 1997). This relationship can be seen in figure 2.7.

2.6.3 Product Innovation Models

Product development processes generally have two main features, (Holmes and Campbell, 2004). The first is the organisation of the process into a number of phases. The second is that these phases are usually separated by a number of gates. These gates serve as review points, where work of the relevant phase is assessed. Plans for the future are also assessed. Holmes and Campbell (2004) continue on to state that, generally, product development processes deal with technical matters and are functionally separated from the business performance.

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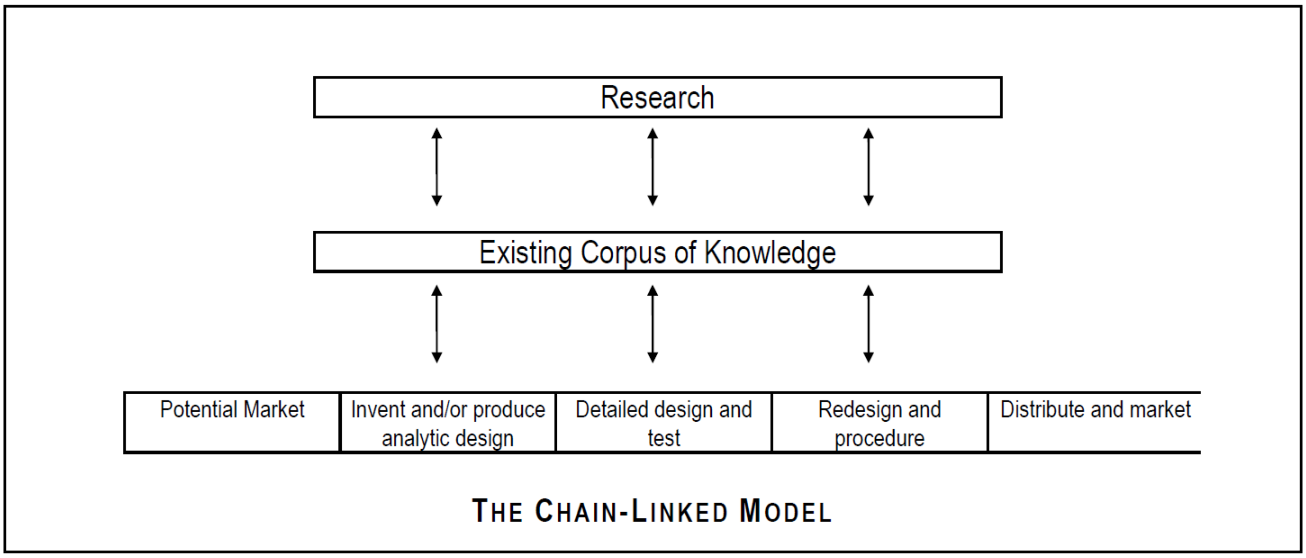

Figure 2.7: The Chain-linked Model, (Mahdjoubi, 1997)

Nieberding (2010) states that a reason for the wide number of innovation models is that each model was developed by its author in a specific context. The various authors have different perceptions of the development process. These perceptions can thus be seen in the different models created, (Nieberding, 2010).

Schmidt-Tiedemann's Concomitance Model

As per Van Zyl (2006), Schmidt-Tiedemann created this Concomitance model for the managerial planning process of an innovation project. The model or architecture is divided into three areas: the research function, the technical function and the commercial function. The model can be seen in figure 2.8.

As can be seen in figure 2.8, this model divides the process into the phases of exploitation, innovation and diffusion. A key element of this model is that there are a large number of milestones and decision points. These decision points can be used to terminate the project throughout the project life cycle. Another key feature of this model is that there are a number of feedback loops. The research, tehcnical and commercial functions are thus linked, (Van Zyl, 2006).

Van Zyl (2006) states that the Schmidt-Tiedemann's Model does not take environment considerations into account. These include suppliers, customers, etc. This model focuses on invention, feasibility, innovation and operation. It

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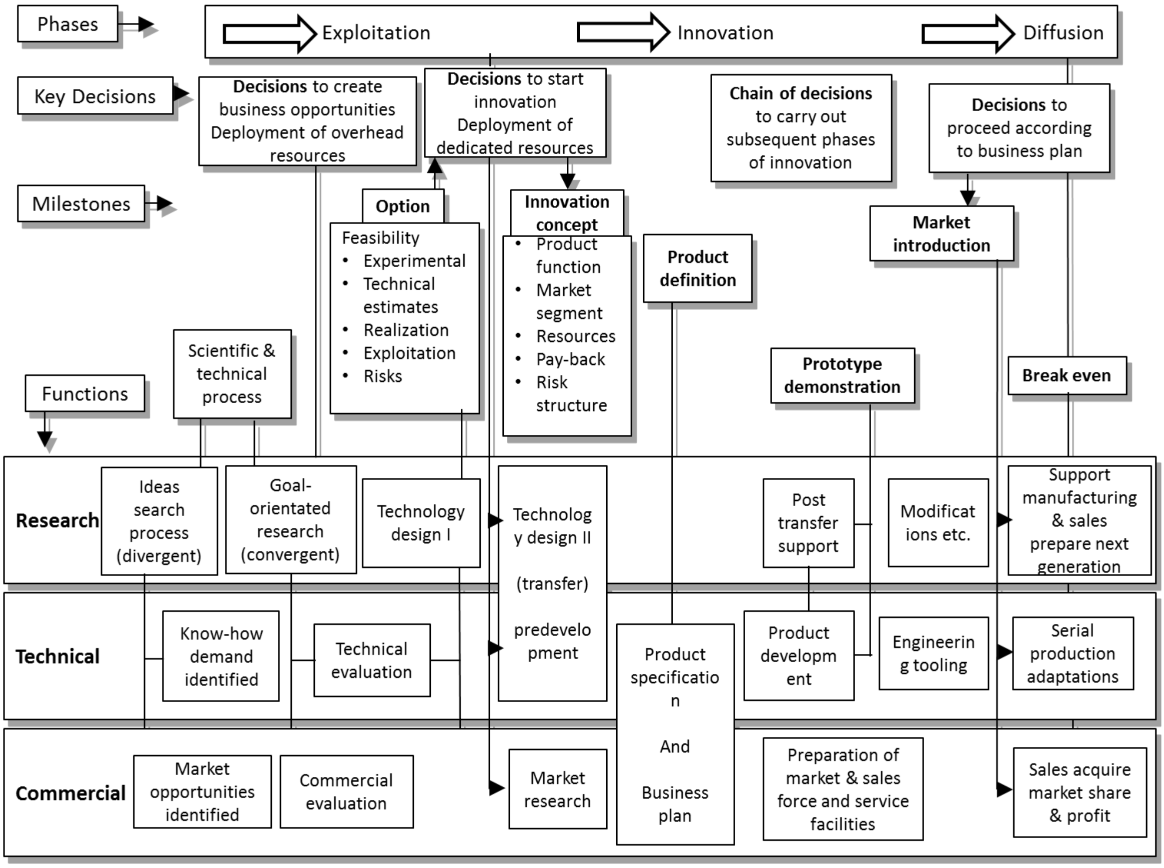

Figure 2.8: The Schmidt-Tiedemann's Concomitance Model, (Van Zyl, 2006)

does, however, neglect the life cycle phase of disposal, (Van Zyl, 2006).

Twiss's Activity Stage Model

Twiss developed a model based on an evaluation of numerous studies. Twiss's Activity Stage Model, unlike the Schmidt-Tiedemann's Model, has clear internal and external environmental interactions. In this model, knowledge from both the market and research are fed into the innovation process, (Van Zyl, 2006). The model can be seen in figure 2.9.

Van Zyl (2006) states that the Activity Stage Model is purposefully made to not be highly detailed. This allows more flexibility when applying it. This model focuses on the life cycle stages of invention, feasibility and innovation. There is a passing reference to the operation life cycle phase. The project management phase touches on production and marketing. There is, however, no mention of maintenance. The Twiss model also does not touch on the dis-

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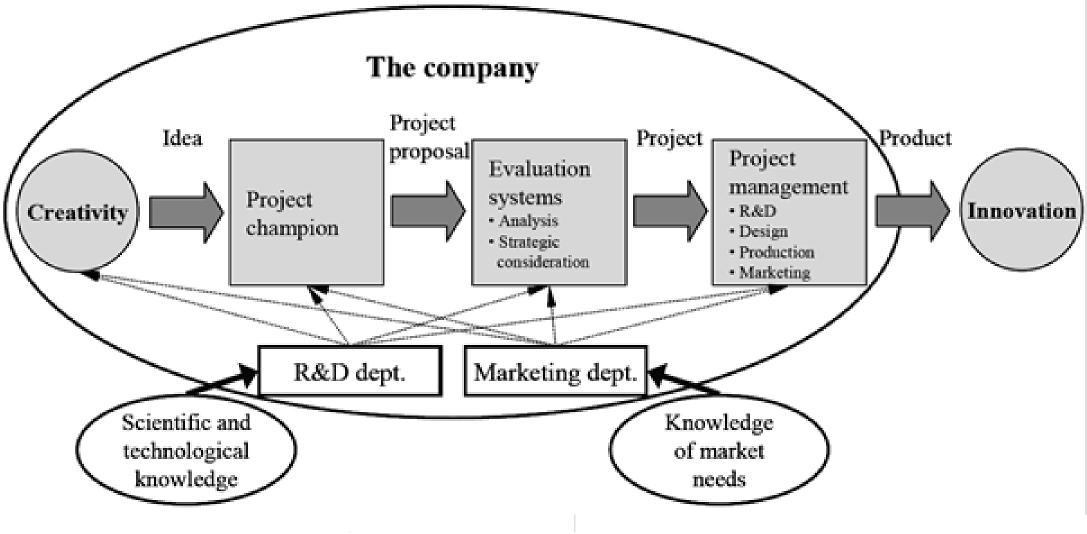

Figure 2.9: Twiss's Activity Stage Model, (Van Zyl, 2006)

posal model of the innovation life cycle.

Saren's Department Stage Model

Saren's Stage Model describes the innovation process in terms of the departments that are involved at each successive phase of the project, (Van Zyl, 2006). This linear model can be seen in figure 2.10.

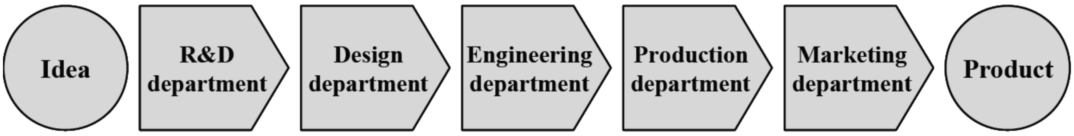

Figure 2.10: The Department Stage Model, (Van Zyl, 2006)

The W-Model

Van Zyl (2006) states that the W-Model was created by Fraunhofer IPT for technical product innovations. This model is divided into seven steps: designing objectives, analysing future, generating ideas, valuing ideas, detailing ideas, valuing concepts and transfer. There are a large number of models, tools and techniques for use in completing sub steps. Information from each of these sub steps is needed in order to allow for progression from one step to another,

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see figure 2.11 (Van Zyl, 2006).

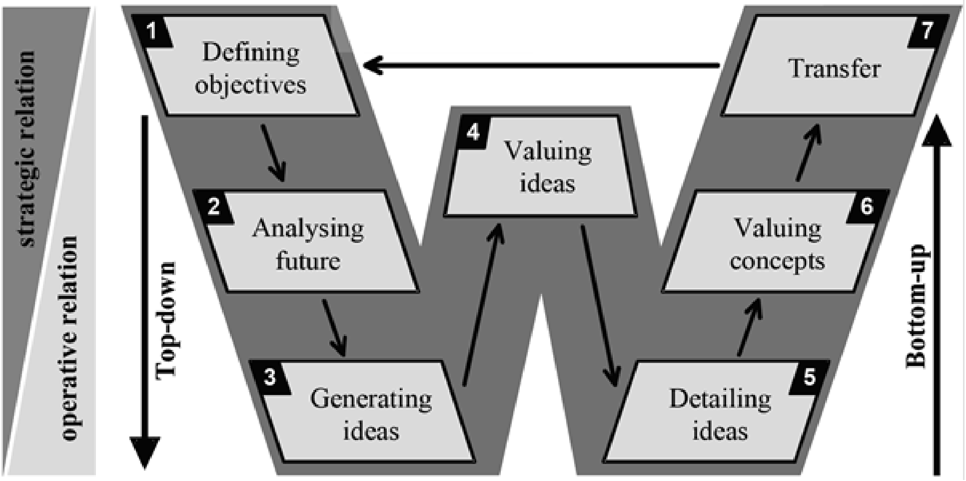

Figure 2.11: The W-Model, (Van Zyl, 2006) Adapted from (Baessler *et al.*, 2002)

Two central concepts to this model are that of the strategic relation and that of the operative relation. This ensures the project is in line with the overall strategy, yet within the operational capability, (Van Zyl, 2006). The W-Model guides the user through the life cycle phases of invention, feasibility and innovation. What differentiates the W-Model from other models, is that it does this on a practical level with activities and tool kits, (Van Zyl, 2006).

French's Model

In a similar manner to Saren's model, French's model describes a linear development process. A major difference between the two is that French's model incorporates feedback loops, as can be seen in figure 2.12. The circles in the figure represent stages achieved, while the rectangles represent work in progress, (Cross, 2000).

Cross (2000) states that French's model consists of four phases. This model is triggered by a specific need. The four phases are analysis of problem, conceptual design, embodiment of schemes, and detailing. There are a number of decision gates in this model. This prevents progression onto the next stage unless all the conditions of the gate have been satisfied. The life cycle phases supported by this model are the feasibility, innovation and, to some extent, the operation phase. French's model assumes that the need has already been

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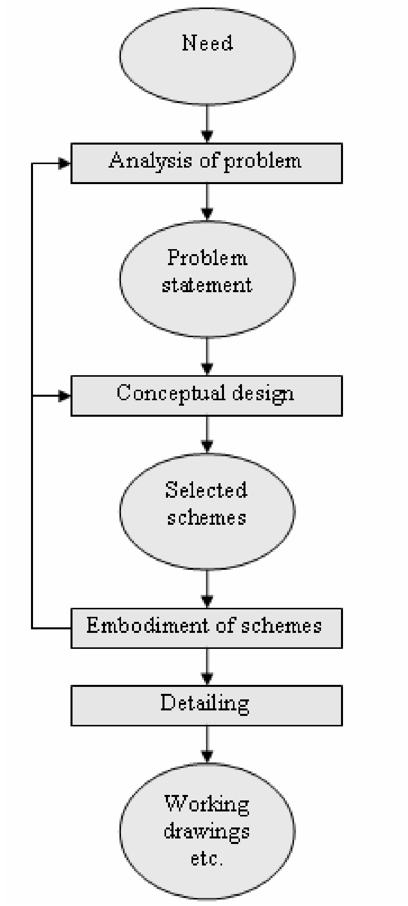

Figure 2.12: French's Model of the Design Process, (Cross, 2000)

identified, (Cross, 2000).

Archer's Model

Archer's model includes interactions with items outside of the design process, (Cross, 2000). These items include client inputs, designers experience, etc. The Archer's Model consists of the analytical phase, the creative phase, and the executive phase. Each of these phases is subdivided into activities as per figure 2.13. Van Zyl (2006) states that the feedback loops in Archer's model provide a more realistic interpretation of the iterative nature of the design process when compared to French's model. Archer's model focuses on the feasibility, innovation and operation life cycle phases.

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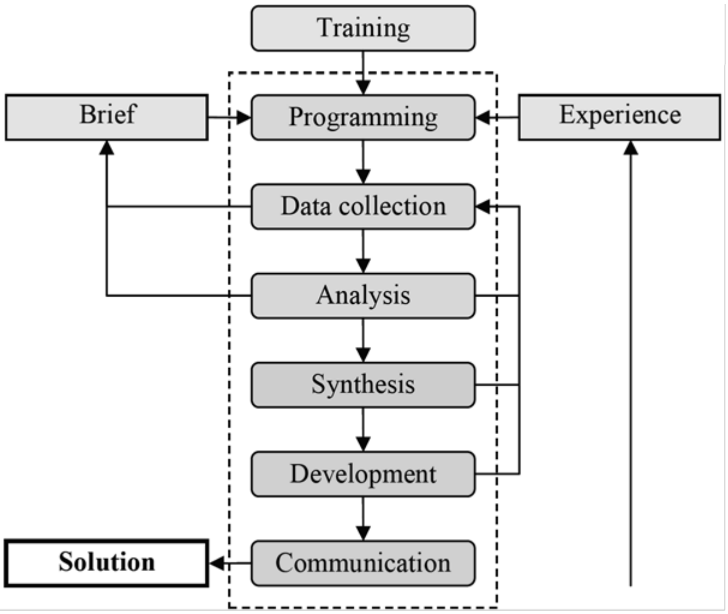

Figure 2.13: Archer's Model of the Design Process, (Cross, 2000)

Pahl and Beitz's Model

The design process according to Pahl and Beitz provides an extensive description of the flow of work during the product design process. A large amount of emphasis is placed on increasing the effectiveness of the development process and on reducing unnecessary procedures. The model is comprised of the following steps: clarification of the task, conceptual design, embodiment design, and detail design, (Cross, 2000).

Nieberding (2010) states that both the Pahl and Beitz's model and the Model of Development Process as Defined by VDI 2221 are very similar. They share the following characteristics. When compared to the other product innovation models, the two approaches are both very structured and very detailed as can be seen in figure 2.14. Both models have roots in the mechanical design process. They both emphasise the decomposition of system products into modules. The bulk of the focus is thus on the design phase, (Nieberding, 2010).

The Model of the Development Process as Defined by VDI 2221

VDI stands for Verein Deutscher Ingenieure or the Association of German Engineers, (Cross, 2000). This model is very similar to the previously described model as per Pahl and Beitz. The model can be seen in figure 2.15. Cross (2000) states that it is important to note that the stages in the figure do not

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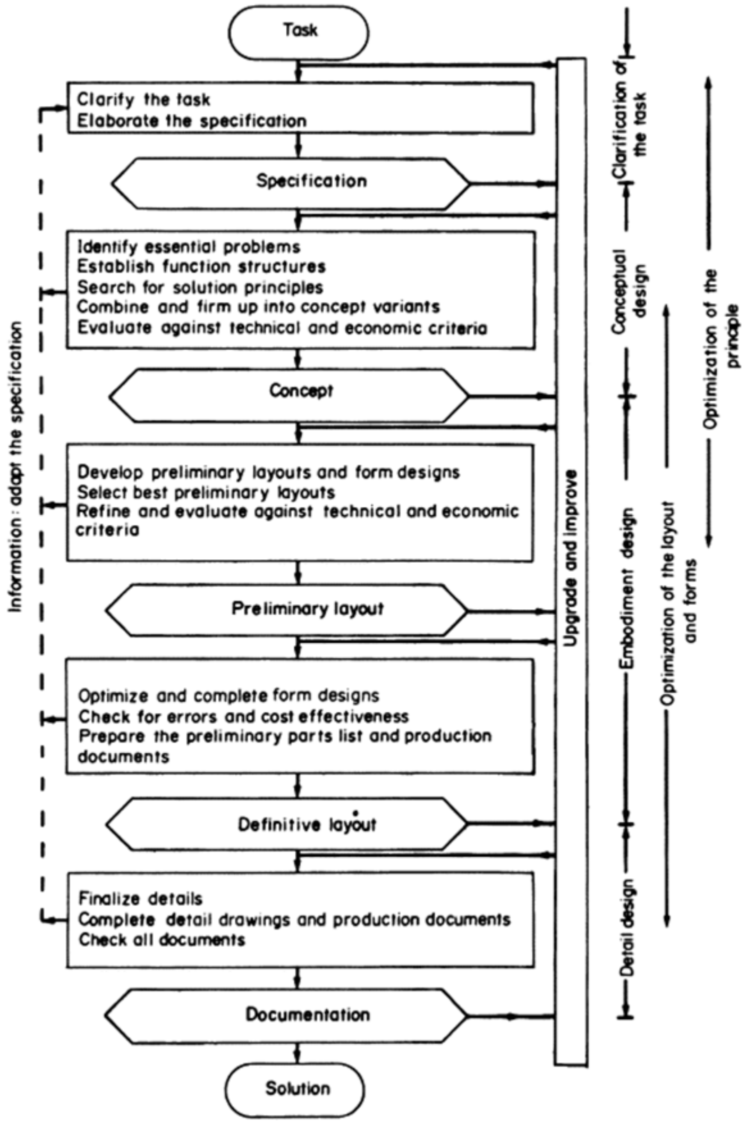

Figure 2.14: Pahl and Beitz Model of the Design Process, (Cross, 2000)

have to be followed in exact sequence but can be performed iteratively.

The first step in this process is to clarify the intended task. In this initial step the context and purpose of the project is established. The output of this clarification is a system specification. This specification is later frozen during the course of the project. Freezing of the specification prevents scope creep. The next step of the project is to determine the principle solution. This is done by analysing the needed functions and how they relate to one another, (Cross, 2000).

As per Cross (2000), after the principle solution has been established, the

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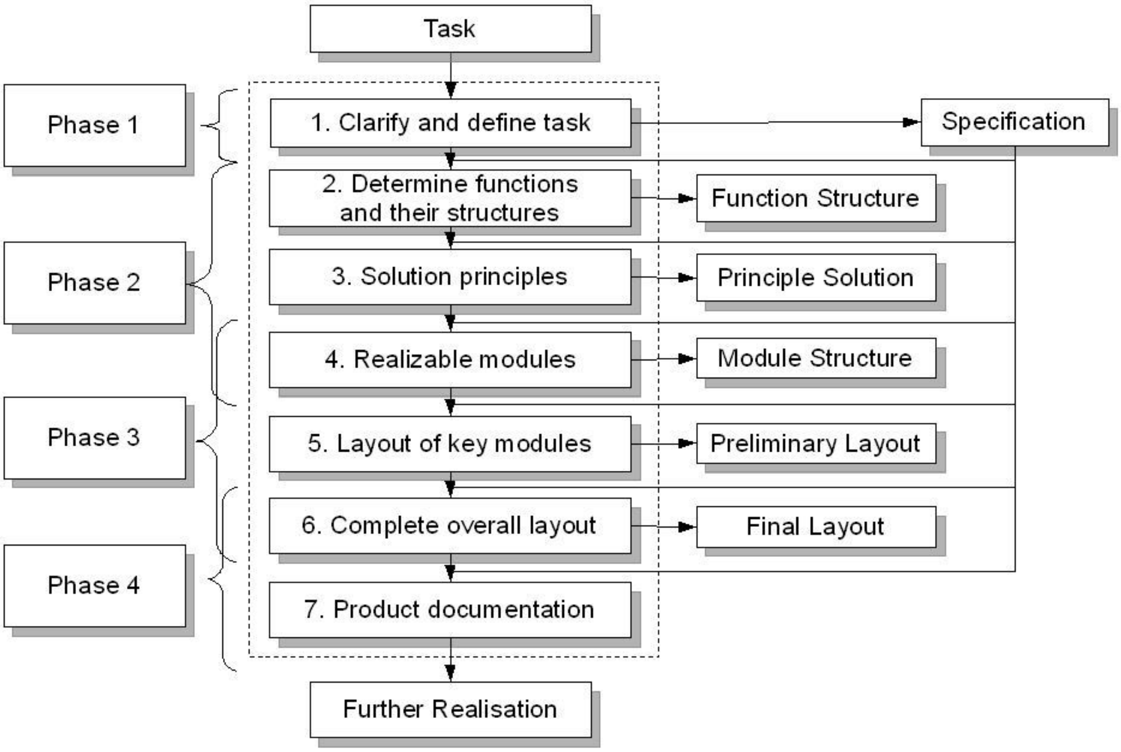

Figure 2.15: The Product Development Process According to the VDI, Nieberding (2010) adapted from Cross (2000)

design can begin. It is here that the concept is modularised. This decomposition into modules assists in designing complex systems. Solutions to these modules can then be found. Once this has occurred, the various sub-solutions are combined into an overall solution.

March's Model

As per Cross (2000), March's Model is based on abductive reasoning, deductive reasoning and inductive reasoning. Deduction works to derive the consequences of what is known, i.e. it proves something is. Abduction works in an opposite manner and explains what is known, i.e. it suggests that something may be. Induction deals with something that actually is. This model can be seen in figure 2.16.

Cross (2000) continues by stating that during the design process, abductive reasoning is used to create a design proposal. Performance characteristics are determined by analysing the proposal using deductive reasoning. Inductive evaluation is then conducted to refine the system. The cycle is then repeated.

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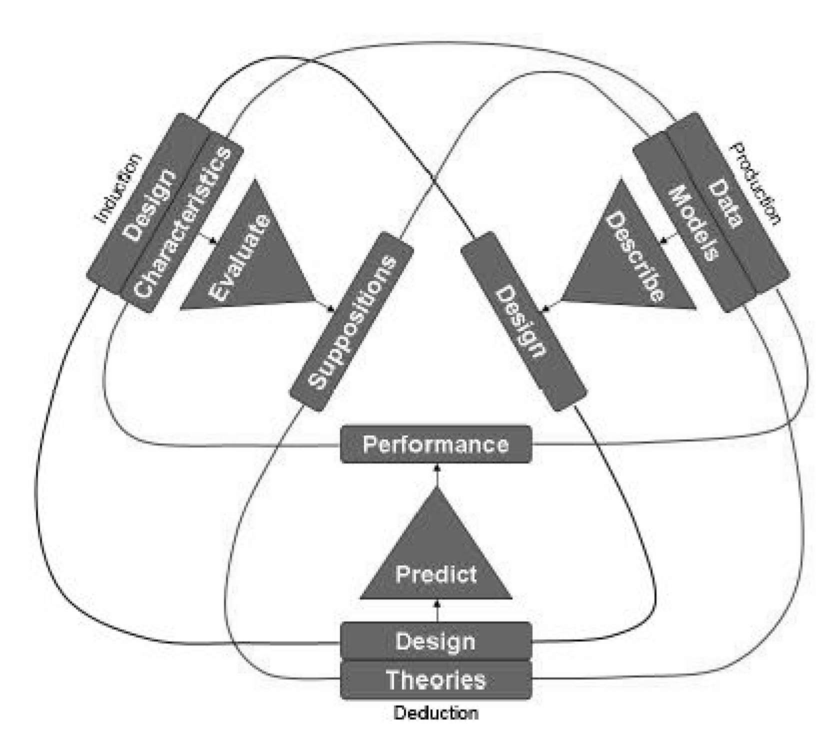

Figure 2.16: March's Model of the Design Process, (Cross, 2000)

The model focuses on the feasibility and innovation life cycle phases. Passing reference is also given to the invention and operation phase. The disposal phase is, however, not included, (Van Zyl, 2006).

Suireg's Model

Suireg's Model makes use of the philosophy that there are general guidelines and a basic structure to the design activity. The model itself focuses on the design of the product, (Van Zyl, 2006). The model can be seen in figure 2.17.

This model does not take external factors into account. Instead of activities taking place simultaneously, the Suireg's model makes use of feedback loops. This allows information to be fed back into the process. The model focuses on the feasibility phase until the end of the development phase, i.e. invention, feasibility and innovation life cycle phases (Van Zyl, 2006).

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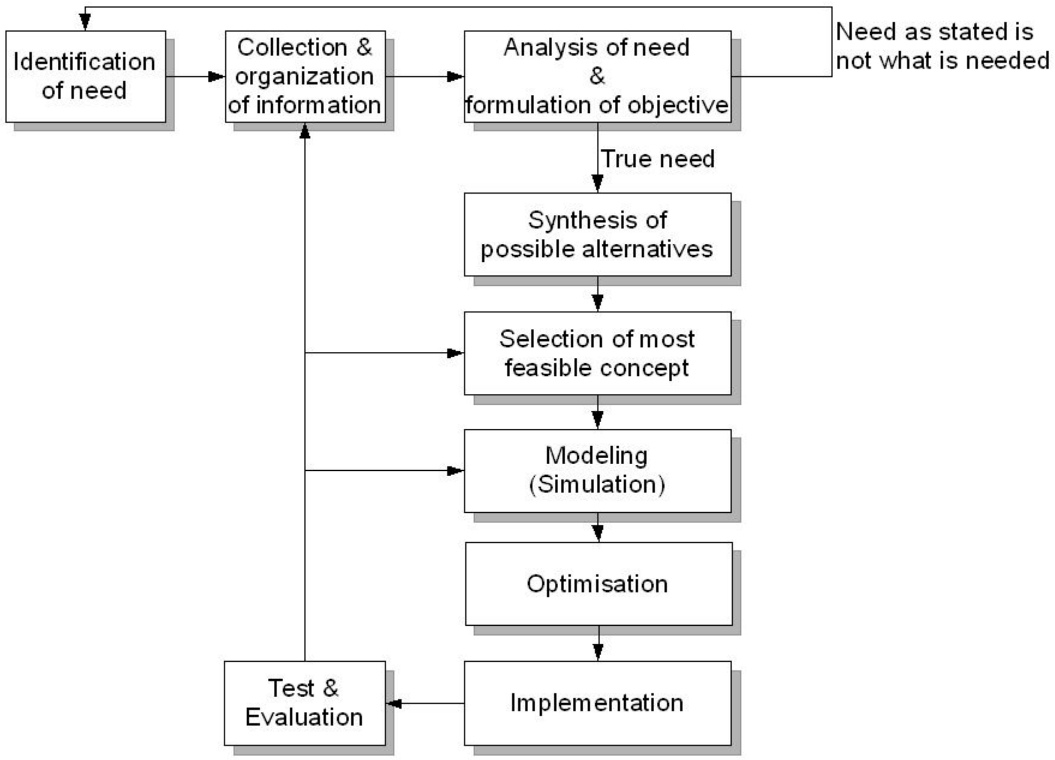

Figure 2.17: Suireg's Model of the Product Development Process, (Nieberding, 2010)

Ullman's Model

As per Ullman (2003), Ullman's Model consists of five phases of engineering product development as can be seen in figure 2.18. The output of the first phase is a flow chart. This chart documents the project's activities. In the second phase new product customers and their requirements are identified. In addition to this performance, targets are generated. The third phase is a conceptual design phase. Here the most valid concepts are selected. Lastly, the product development phase is to be executed. This phase is comparable to the detail design phases of other product innovation models. In addition to design, the material to be used in manufacturing is decided upon. All of these activities are executed in an iterative manner whilst considering the customer needs. The final phase focuses on product support and production, (Ullman, 2003).

Ullman makes use of design reviews as a means to ensure the success of the previous phase. In addition to these decision gates, Ullman proposes the use of a hierarchical problem structure. This drives the solution process, (Nieberding, 2010). Decomposition is also used to allow focus on sub-problems. Sub-

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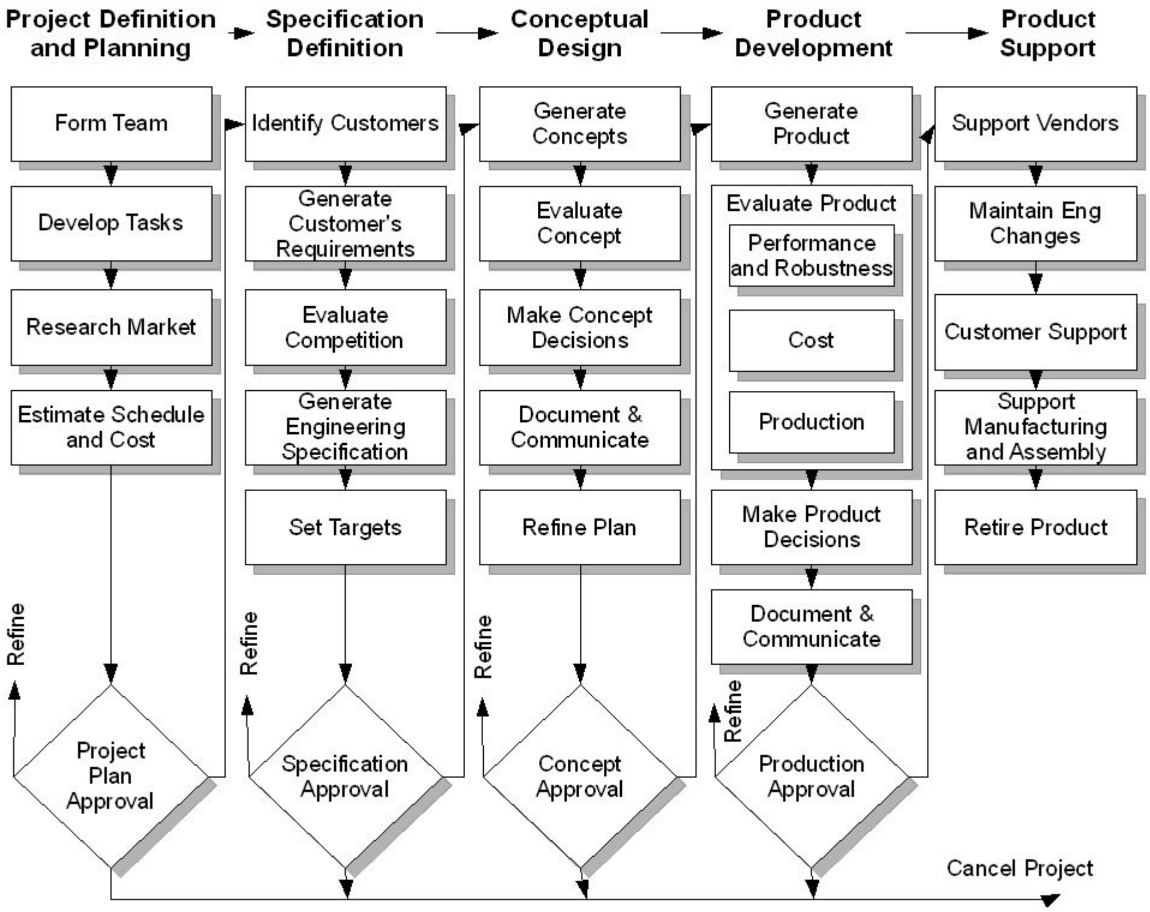

Figure 2.18: The Mechanical Design Process According to Ullman, (Ullman, 2003)

components are then defined to address each sub-problem. The solution to the problem as a whole is thus addressed by assembling all of the sub-components, (Nieberding, 2010).

Nieberding (2010) states that Ullman's model focuses on the design of a mechanical system. An emphasis is placed on the product creation portion of the product life cycle, with the focus being on the design phase. In light of this, Ullman describes a number of different types of design processes, (Nieberding, 2010). They are listed below.

- Selection Design. This deals with the selection of items from a list of similar items.
- Configuration Design. This requires existing components to be assembled into a complete product.

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- Parametric Design. This involves finding values for a particular object.
- Original Design. This is the development of a process, assembly or component that has not previously been in existence.
- Redesign. This is the modification of an existing product to meet new requirements.

Integrated Product Development

The Integrated Product Development model views the market, the product and the production as being paramount to an organisation's success, (Andreasen and Hein, 1987). The three elements thus need to be managed harmoniously in an inter-related manner. This relationship can be seen in figure 2.19. A large part of the focus of this model is on executing phases of the product life cycle from strategy to distribution. A large emphasis is on placed on concurrency, (Andreasen and Hein, 1987).

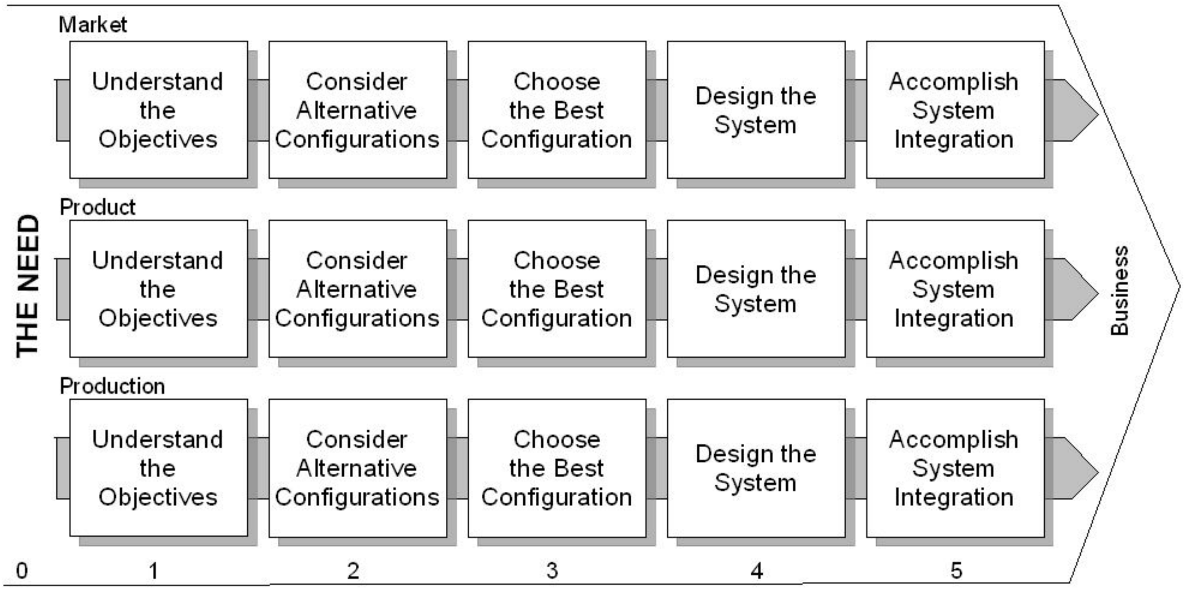

Figure 2.19: Process of Integrated Product Development by Andreasen and Hein, (Andreasen and Hein, 1987)

Integrated Product Development is divided into six phases. Phase 0 signifies the need that is to be satisfied by a new product. In phase 1 the needed product is briefly described. The potential market for this product is also investigated. During phase 2 the product is further explored. Under the market strand the product's potential uses are examined. Under the product strand,

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functions are defined. Under the production strand, an initial product structure is defined. In phase 3 preliminary designs are conducted for the product, and production strands and sales channels are identified for the market strand. Phase 4 is where the three strands are geared towards production. Phase 5 is the execution of the sales and distribution. In the product and production strands, errors are corrected and support is offered, (Nieberding, 2010).

Pugh's Core-based Model

Nieberding (2010) states that Pugh's model focuses on the phases of strategy to distribution. An emphasis is also placed on iteration. The model was proposed as a process of iteration, testing and evaluation. These activities surround a design core made up of activities for design, regardless of the design nature. Pugh makes use of a concept called total design. Total design incorporates everything from identification of a market to selling of a product to meet the need. The model can be seen in figure 2.20.

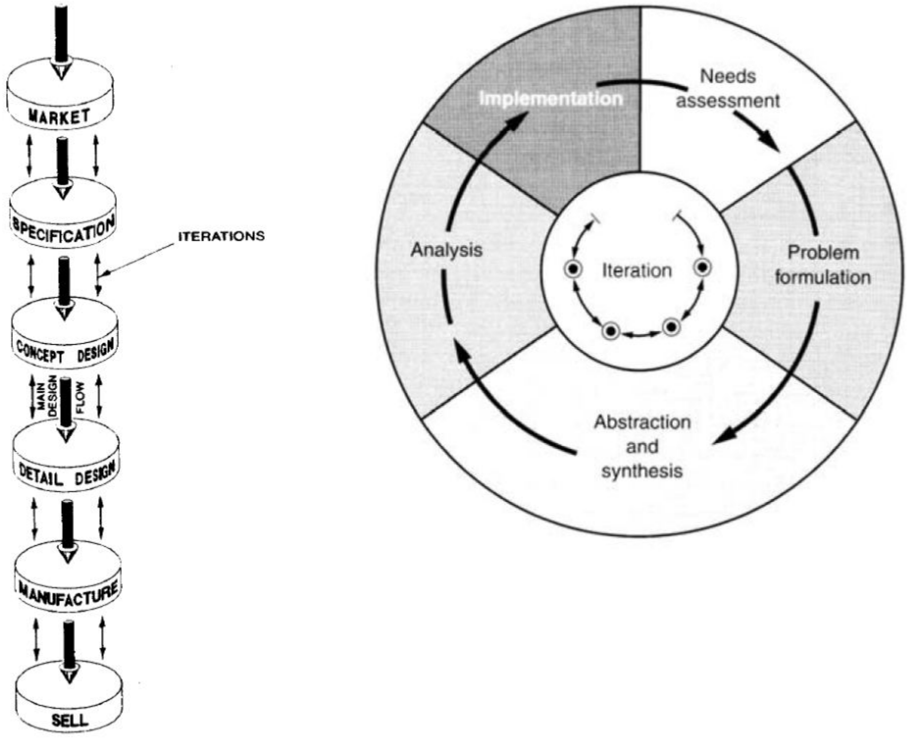

Figure 2.20: Pugh's Core-based Model, (Nieberding, 2010)

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2.7 Model Selection

One of the main characteristics used to a select a product innovation model is that it covers the majority of the life cycle phases. This will allow for the bigger picture control and guidance as stated in the introduction. The purpose of the overall innovation model is to ensure a well-rounded project. The project in this instance is the technical development of a coarse-to-fine positioning system. The selected model should, therefore, not have a significant focus on enterprise considerations, but should have a technical/design focus. The results of these criteria are listed in the figure 2.21.

Despite the fact that the Concomitance Model covers the majority of the life cycle phases needed, there is a large amount of focus on enterprise activities. These enterprise activities include market introduction, sales, acquiring market share and profit, development of a business plan, and preparation of the market and the sales force, etc. These aspects are important but are not applicable to the scope of this thesis.

The Integrated Product Development approach has the desired detail and concurrent execution. The model is also thorough in its considerations. In a similar manner to the Concomitance Model, this model has a significant focus on enterprise considerations. A third of the model is devoted to sales and market considerations. The final model to be selected should, in no way, neglect this aspect of innovation; however, it should be more aligned with shaping the product design.

The W-Model has the necessary design-oriented philosophy. It is also a well-known and widely used technical product innovation model. It does, however, not take the operation and disposal aspects of the system life cycle into consideration. Furthermore, the model has a significant focus on the decomposition and analysis of the problem. In this project the bulk of the problem has already been defined.

Ullman's Model of the Development Process has the necessary broad scope, covering all the system's life cycle phases. This model is also focused on technical aspects of product innovation. It incorporates design gates in order to ensure success of a phase before the next phase is begun. In addition to this, Ullman's Model does not have a large number of in-depth tools and processes that need to be implemented. This means that the model can be tailored as needed. The latter is desirable when using the model as an overall guide for the project. Ullman's Model of the Development Process is thus selected as the innovation model to guide the project.

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	No. of Life Cycle Stages	Focus	Detail Level	Complexity Level
Concomitance	4	Innovation Project Management	High	Medium
Twiss	3.5	Incorporating External Input	Medium	High
Saren	2.5	Department Interaction	Low	Low
W-Model	2.5	Bottom-up and Top-down Product Design	Medium	High
French	2	Stage Gates and Feedback	Low	Low
Archer	2.5	External Input and Feedback	Low	Medium
Pahl and Beitz	2	Structured, Effective Design	High	Medium
VDI 2221	2	Decomposition and Module Combination	Medium	Medium
March	3	Abduction, Deduction and Induction	Medium	High
Suireg	3	Structure and Feedback Loops	Low	Medium
Ullman	5	Thorough Product Design	High	Medium
IPD	2.5	Concurrency of Market, Product and Product Development	High	Medium
Pugh	3.5	Activities around a Design Core	Low	High

Figure 2.21: Criteria Used in the Selection of an Innovation Model

2.8 Chapter Conclusion

Having extensively considered definitions of innovation management, the innovation landscape, and the nature of innovation, a single innovation model has been selected. The wide scope and favourable characteristics of Ullman's Model of the Development Process are in line with the needs of this project. Ullman's model will thus assist in the successful development of a coarse-to-fine positioning system.

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Chapter 3

Systems Engineering Models

The purpose of this chapter is to provide a thorough understanding of what systems engineering is and what systems engineering does. To this end, a number of models and approaches are analysed. The end goal is to identify a specific model. This model is to be used as a basis for the technical design process. This basis is then to be added to by using elements from the different methodologies and approaches identified.

INCOSE (2007) states that a complete step-by-step guide to systems engineering should not be followed. Rather, stepwise approaches should be adapted to specific projects. This incremental and iterative development is ideal for situations where exact requirements are not known. A main goal of this chapter is to make use of extensive tailoring when applying the identified technical methodology.

With the main goal of selecting a model and then applying various levels of tailoring, it becomes necessary to employ a number of selection criteria. In addition to tailoring, it has been decided to incorporate elements of other models that assist design. To this end, the first criterion used when assessing the models is Useful Elements. The next selection element is that of Focus. This is defined as the differentiating concept behind the model. It is important that this differentiating concept be in line with focus of the project, i.e. creation of a technical system from a list of specifications. In addition to this the level of detail and the complexity of the model itself is considered. When dealing with technical systems engineering, it is important to have a model that is highly detailed and relatively complex.

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3.1 Systems Engineering Background

One definition of systems engineering in the INCOSE Systems Engineering Handbook v 3.1 is as follows:
"Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs." (INCOSE, 2007).

3.1.1 History

INCOSE (2007) states that the origin of systems engineering can be traced back to the 1930s. The most important date in the development of systems engineering was in 2002 when the international standard ISO/IEC 15288 was introduced. It was at this time that systems engineering was formally recognised as the preferred mechanism for the creation of products and services, (INCOSE, 2007).

Systems engineering was already in use during World War II where a number of enterprises used it while collaborating with the Department of Defence. A unifying factor of the early systems engineers is their ability to see the 'bigger picture' despite their differing technical backgrounds. They were also unified in their capacity to solve complex problems, conduct trade-off studies, and utilise requirements analyses, (Lake, 1996).

Gorod *et al.* (2008) states that around World War II there was a paradigm shift in dealing with complex projects. This shift incorporated the introduction of new engineering techniques that focused on complex systems as opposed to separate individual components. This new focus was the beginning of systems engineering.

In 1981 the concept of the system engineering life cycle was presented, (Blanchard, 2008). The focus was on including all the aspects of the system throughout its life cycle. In 1995, Sage suggested that systems engineering was a management technology that controlled a total life cycle process. The result of this management technology would be a high quality, effective system that satisfied the user's needs, (Gorod *et al.*, 2008).

One notable step for systems engineering was the formation of the International Council on Systems Engineering (INCOSE) in 1990, as per (Lake, 1996)

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and (Gorod *et al.*, 2008). In August of that year, 35 individuals met to discuss the need for an organisation that would foster understanding of systems engineering. From the outset there were varied opinions on a definition for systems engineering. The group decided that a single definition would be counter productive to the organisation's aims. The prominent vision of INCOSE was that a system could be developed at low cost, within deadline, and would fulfil technical and qualitative requirements, (Lake, 1996).

3.1.2 Systems Engineering Definition

One informal definition supplied on the INCOSE website as per Lake (1996) is as follows:
"Systems engineering is the discipline of managing the development of complex systems. It focuses on defining required functionality early in the development cycle, documenting these requirements, then proceeding with design synthesis while considering the complex problem: performance, manufacturing, cost and schedule, quality, training, and disposal. Systems engineering integrates all disciplines and speciality groups under one umbrella, employing a structured design process that facilitates the transition from concept to production to operation in an orderly fashion. Systems engineering considers both the business and technical needs of all customers - both users and suppliers." (Lake, 1996).

Systems engineering is comprised of two sub-processes; the technical management process and the technical process, (INCOSE, 2010). The technical management process is more closely aligned with project management. It includes project planning, review, change management, etc. As defined by INCOSE, INCOSE (2010), systems engineering is an interdisciplinary approach and a means of enabling the realisation of systems. Systems engineering focuses on defining customer requirements at an early stage. Once the requirements have been documented then design can begin. Design is then followed by validation.

The systems life cycle can be divided into three aspects: business aspects, budget aspects and technical aspects. The systems life cycle establishes a framework for meeting customer requirements. It should be noted that the role played by systems engineering changes as the engineering effort moves through the system life cycle, (INCOSE, 2010).

Lake (1996) created the following definition for systems engineering as per Lake (1996):
"Systems engineering is an interdisciplinary, comprehensive approach to solving complex system problems and satisfying stakeholder requirements," (INCOSE, 2007). In order to better understand this definition a number of words have

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to be expanded upon. According to Lake (1996), a system is comprehensive if it is well defined, well managed, scalable (able to be tailored to different size systems) and disciplined (has innate mechanisms to ensure different activities are followed). Another needed definition is that of complex system problems. These are new system/product developments, incremental product developments, family of product developments, and modifications. Solving the problem entails creating the system solution, (Lake, 1996).

According to INCOSE (2007) systems engineering is a profession, a process, and a perspective. The three different definitions are supported by various authors:
"Systems engineering is a discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspects." (Ramo, 2002).

"Systems engineering is an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for the system." (Eisner, 2011).

"Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. " (INCOSE, 2007).

Another aspect of systems engineering as per INCOSE (2007) is the inclusion of both technical and management processes. An integral part of both these processes is that decisions made early in the life cycle of a system, when not properly understood, can have severe implications later in the life cycle.

Nicholas and Steyn (2003) begin a definition of systems engineering by defining a system as follows:
"An organised or complex whole; an assembly of parts interacting in a coordinated way, " (Nicholas and Steyn, 2003).
The definition also states that systems engineering includes three main features. Firstly, parts of the system both affect the system and are affected by it. Secondly, all the parts, when combined, execute a certain function. Lastly, the system is something being examined. Systems engineering also deals largely with the approach of wholism, which means viewing items as more than the sum of their parts.

Aslaksen and Belcher (1992) state that a system consists of three sets. These include a set of elements, a set of element interactions, and a set of boundary conditions. Boundary conditions are defined per Aslaksen and Belcher (1992) as the way in which elements of a system interact with other objects.

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Systems thinking is a core value of systems engineering. It is so central to systems engineering that it is worth mentioning when considering a systems engineering definition. Systems thinking is a perspective on reality. Its focus is on how parts within a whole relate to each other and to the whole. Another aspect of this concept is circular causation. This is the idea that a single variable can be both the cause and the effect of the variation of another variable. Again, the concept deals with interrelationships and the primacy of the whole, (INCOSE, 2007).

For the purposes of this project systems engineering is defined as a process that can be implemented through the use of various models. Systems engineering is used to ensure a structured technical approach to solving an engineering problem.

3.1.3 Systems Engineering Purpose

Lake (1996), in accordance with the various systems engineering requirements, created an operational definition of what systems engineering does:
"Systems engineering evolves the definition of a product item through distinct life-cycle development activities-need or opportunity analysis, concept definition, system definition, preliminary design, detailed design, and evaluation. Upon completion of these primary development activities, there are post-development activities for systems engineering to perform. During the post-development period of a product, the systems engineering primary development activities of opportunity analysis, concept definition, system definition, preliminary design, detailed design, and evaluation are accomplished to:

a correct product design deficiencies discovered during production, production test, deployment/installation, training, operation, support and disposition;

b improve deployed products to make them more competitive, secure, safe, and/or marketable; and

c make modifications to the product or its related life-cycle processes such as production,test, deployment, installation, training, support or disposition.

Systems engineering also encompasses the planning, organising control, and implementation activities of the systems engineering process defined in EIA/IS-632 and IEEE 1220-1994. The activities include:

a analysis of the development problem (analysis of functional and performance requirements);

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b synthesizing design solutions for the development problem;

c assessment of alternative solutions and selection of the best set of balanced requirements, functions, and product and process solutions;

d verifying that the selected physical solution meets requirements derived from the analysis of the development problem;

e capturing all design results and rationale and data on supporting models, tools, assessments and trade studies, and plans for the management and implementation of systems engineering activities;

f information, data, and configuration management;

g requirements, interface, and change management;

h risk management;

i performance-based measurements such as technical performance measurement, earned value, and design reviews and audits; and

j planning and organizing to accomplish the activities of a. through i."

Systems engineering is used to manage complexity and change. Nicholas and Steyn (2003) state that in order to create an appropriate system, it is necessary to define subsystems and elements that will comprise the system. Aslaksen and Belcher (1992) state that complexity in dealing with a system can be reduced by considering individual elements of the system. This is particularly relevant to modern complex projects, i.e. projects containing multiple electronic systems that interact.

A study conducted by the INCOSE Systems Engineering Center of Excellence found an inverse correlation between cost and schedule overruns and the amount of systems engineering used. The study went further in explaining that systems engineering effort has a proactive role in controlling cost overruns and reducing project execution uncertainty, (INCOSE, 2007). Honour (2004) concurs with this by stating that the major contribution of systems engineering is to reduce risk early on in the system life cycle. Early risk prevention lowers the probability of risk occurring later in the project where it could lead to greater costs.

Blanchard (2008) states systems engineering is an "orderly process of bringing a system into being". The system is comprised of a wide range of resources in combination. These resources include equipment, software, facilities, etc. This description of what systems engineering does goes a step further by noting that requirements are continuously changing.

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University (2001) states that three major activities are performed in systems engineering. The first activity is development phasing. This controls the system design process and defines a baseline. Another activity is defining a structure. This design structure assists in tracking the flow of requirements throughout the systems engineering design effort. A final activity is life cycle integration. This gets both stakeholders and customers involved in the design process. This helps to ensure viability of the developed system for an effective life cycle.

A large part of what systems engineering does involves working with stakeholders. The system requirements are defined by listening to stakeholders' needs. This is done in order to discover potential problems that might occur in manufacturing and operations, and, in so doing, potential problems can be avoided. Systems engineering also addresses the systems structural and functional design. This is done with a focus on how the system must meet the stakeholder requirements. Lastly, the entire systems life cycle is taken into account, (Nicholas and Steyn, 2003).

Aslaksen and Belcher (1992) state that systems engineering starts at the top and works its way down. It is thus known as a top-down design. The beginning point for this top-down design is a set of objectives and boundary conditions. This is also know as the purpose of the system.

The Systems Design Process as per Blanchard (2008) involves an initial conceptual design, a preliminary design, detail design and, finally, some form of testing. It is this design approach that best incorporates the system life cycle, whereby all aspects of a system's life, from production to operation and disposal, are considered.

3.2 Systems Engineering Processes and Tools, etc.

It is important to recognise the difference between a process, a method and a tool, Estefan (2007). A process is a sequence of tasks that describes 'what' is to be down without specifying 'how'. A method, on the other hand, addresses 'how' a task is to be performed. In this instance a process is performed by using methods. Finally, tools are used to help execute methods. Tools usually consist of an assisting software package, Estefan (2007).

The purpose of the International Council on Systems Engineering (INCOSE) Systems Engineering Handbook Version 3.1 is to provide a description

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of key process activities performed by systems engineers. The descriptions in the book illustrate what each systems engineering process activity entails, bearing in mind the main aims of achieving affordability and performance in a project. The book sets out these considerations in a manner consistent with the international standard for systems engineering, ISO/IED 15288: 2002(E) - Systems engineering - System life cycle processes (referred to as ISO/IEC 15288), (INCOSE, 2007).

The ISO 15288 divides systems engineering into four process groups as can be seen in figure 3.1, (INCOSE, 2007). Owing to the fact that this project is to take place in a university research environment, emphasis is to be placed on the technical, project and agreement processes.

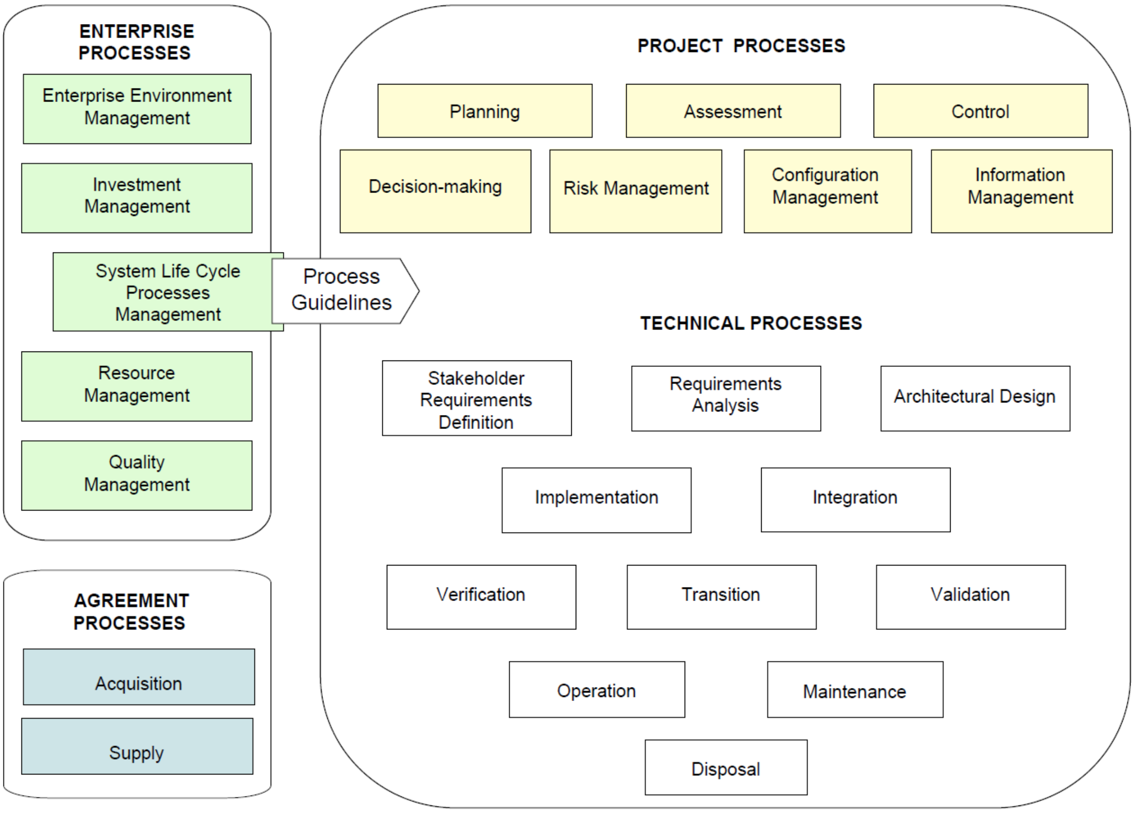

Figure 3.1: System Life Cycle Processes Overview as per ISO/IED 15288, (INCOSE, 2007)

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3.2.1 Technical Processes

Technical processes are used throughout the system's life cycle. These processes have a number of functions. They establish requirements in order to set the base for creation of product and they help to sustain the system through its different life cycles, (INCOSE, 2007).

Stakeholder Requirements Definition Process

The purpose of this process is to acquire, analyse, document and maintain the stakeholders' requirements. A stakeholder is any person or organisation that has a vested interest in the system, i.e. users, decision-makers, etc.

According to INCOSE (2007), the requirements definition process entails a number of activities. The foremost activity is to identify the stakeholders. The next step is to obtain requirements. After the requirements have been obtained, it is necessary to determine what constraints are in place. It is then necessary to differentiate between critical performance objectives and desired performance objectives. A final group of activities is to validate, record, and maintain the stakeholder requirements throughout the system life cycle.

One visual method of illustrating the above is through the use of a Quality Function Deployment, see figure 3.2. This tool is used to translate customer requirements into specifications. This is needed when defining user requirements that are unclear, (INCOSE, 2007).

Requirements Analysis Process

Once the requirements have been defined as per the previous process, it is necessary to review, assess, prioritise and balance them. The requirements also need to be converted into functional and technical requirements. This process can be thought of as an interim process between the requirements definition and the architectural design process. It should be noted that the desired output of this process is not a single solution but a description of characteristics that the system must possess, (INCOSE, 2007).

In analysing the requirements it is necessary to identify all environmental factors that will affect the system. The effects of the system on potential users and the environment should also be taken into consideration. It is at this stage that verification criteria should also be defined, (INCOSE, 2007).

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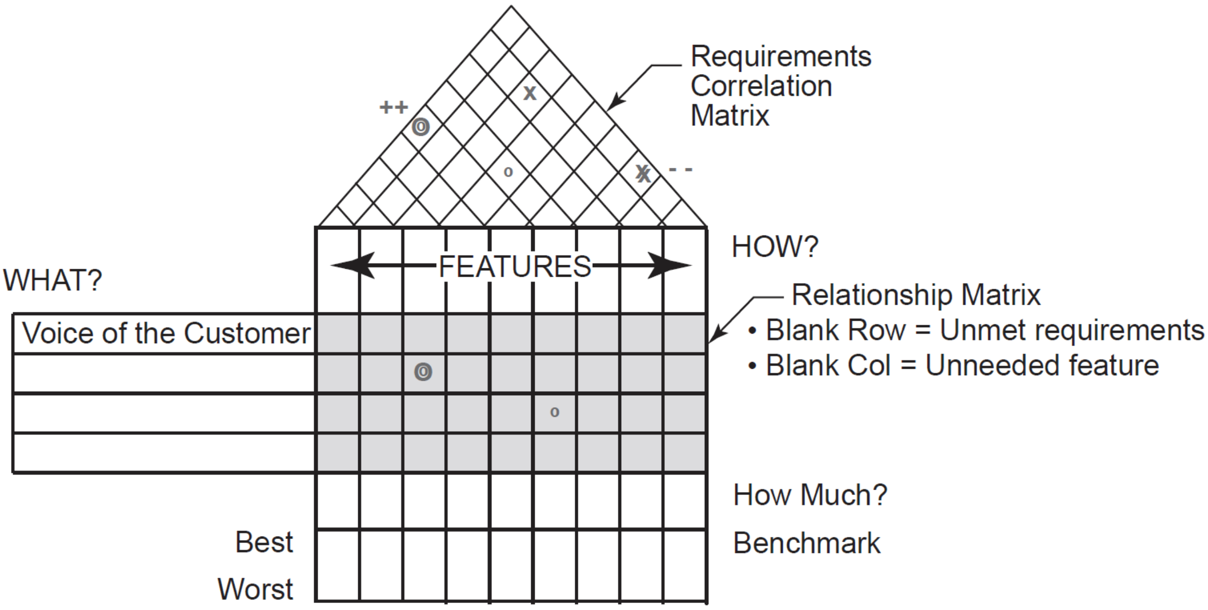

Figure 3.2: Quality Function Deployment,(INCOSE, 2007)

Architectural Design Process

According to INCOSE (2007) the purpose of the architectural design process is to synthesise a system architecture baseline such that the original requirements are satisfied. A major activity in this process is dividing the system requirements between the appropriate system elements and subsystems. Existing off the shelf solutions should be evaluated in this regard. Criteria for selection of the correct alternative are as follows: systems ability to fulfil objectives, ability to operate within constraints, accommodation of interfaces, costs within budget, and effects associated with selected option.

Figure 3.3, shows the flow of the architectural design process. Although the approach appears linear and sequential, it is usually executed in an iterative fashion. In addition to the figure, a number of tools are available in order to assist the architectural design process. The QFD previously mentioned provides a framework for organisation and testing. Other tools include system hierarchies, functional flow block diagrams, etc., (INCOSE, 2007).

Implementation Process

INCOSE (2007) states that this process is between the development and the production stages. Its purpose is to design and create a system element according to the detailed description. In conjunction with this requirements are

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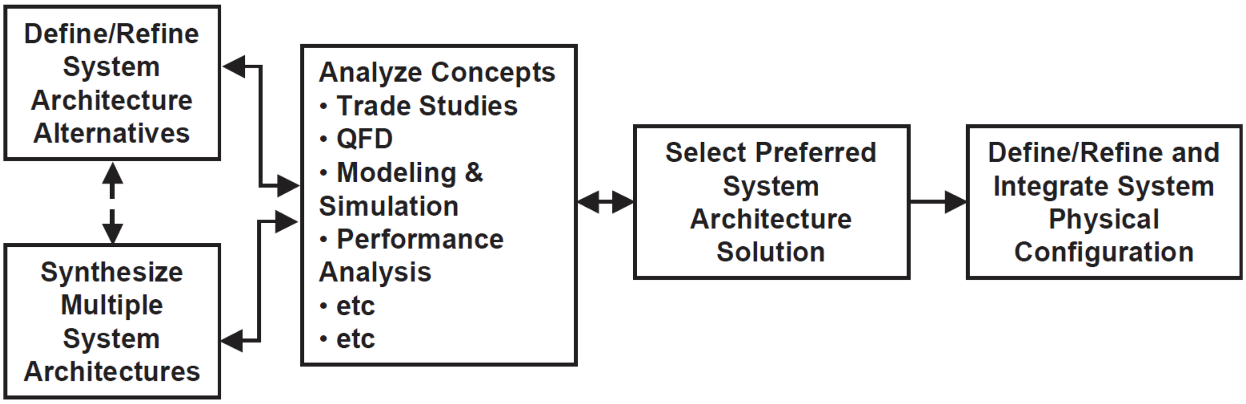

QFD = Quality Function Deployment

Figure 3.3: System Architecture Synthesis Process Flow,(INCOSE, 2007)

verified and stakeholder requirements are validated. The process begins with a detailed design. It also includes a development and implementation strategy defining fabrication procedure, tools, etc.

Integration Process

Here system elements are combined in accordance with the architectural activities. In order to facilitate this combination, enabling or support systems may have to be designed and built. The majority of activities in this process deal with assembling system elements. Interfaces also have to be validated and verified, (INCOSE, 2007).

Verification/Validation Phases

The verification process confirms that all elements perform in accordance with in accordance with the appropriate requirements. Methods for verification include test, inspection, analysis and demonstration. Activities for verification include: developing verification procedures, scheduling and installing enabling systems, and executing and documenting verification procedures, (INCOSE, 2007).

INCOSE (2007) states that validation confirms that the realised system is in line with stakeholder requirements. Validation is also executed on a continuous basis. One of the major activities in this process is the development of validation procedures that demonstrate the aptness of the system. During

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this stage anomalies are detected and can be analysed for corrective action.

Operation, Maintenance and Disposal Processes

As the name suggests, the purpose of the operation process is to use the system to deliver its services. Similarly, the process of maintenance is to sustain the created system throughout its life cycle. The maintenance also involves a level of monitoring on the side of the user. Feedback from the user is used to identify and correct problems. Finally, that process of disposal entails removing the system elements from the operational environment, (INCOSE, 2007).

3.2.2 Project Processes

As can be seen in figure 3.4, systems engineering and project management activities and processes overlap. It is important to consider this overlapping when executing a systems engineering approach. Project processes are divided into project specific processes and life cycle processes. Life cycle processes apply both in and out of the boundary of a specific project; they include decision-making, risk, configuration and information management. (INCOSE, 2007).

Project Planning Process

INCOSE (2007) states that the project planning begins with a statement of need. An initial embodiment of this is a project proposal. This process works to create project milestones, a project description, a risk assessment and a methodology, an identification of other technical plans and documentation.

Project Assessment Process

It is during this process that the status of the project is evaluated against the original plan. This helps to assess the project maturity, availability of resources and compliance with project performance measures. These assessments can take place at milestones and decision gates, (INCOSE, 2007).

Project Control Process

The assessments made in the project assessment process are used here, if necessary, to alter the course of the project. If the project is not achieving the desired maturity and is deviating from the project plan, a decision should be

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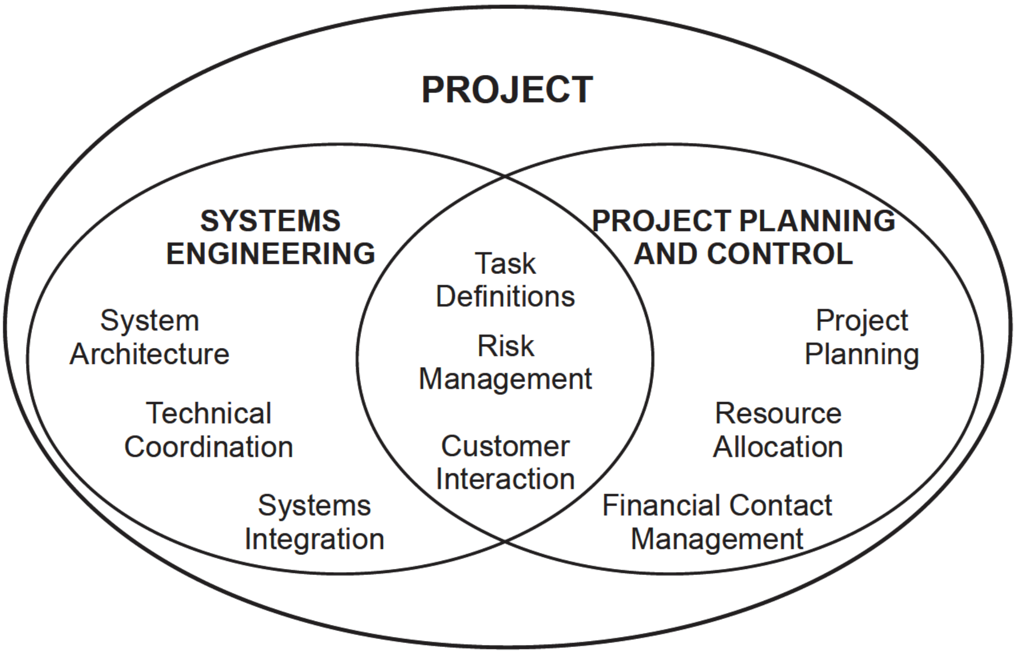

Figure 3.4: Project Management and Systems Engineering Overlap,(INCOSE, 2007)

taken whether or not to proceed passed the decision gate, (INCOSE, 2007).

Decision Making Process

Milestones are essential to the systems engineering life cycle models. These milestones correspond to decision ‘gates’, which signify major decisions during the gate review process, (Estefan, 2007). The need for a decision should be clear. The strategy for making decisions should also be decided upon before making the decision. It is important to note that acquisition models include both lifecycle phases and decision milestones, as well as gate reviews. The NASA project life cycle epitomises this combination as seen in figure 3.5.

For performing specific trade-off studies, as with selecting an off the shelf product, INCOSE (2007) suggests the following key components: a list of alternatives, screening criteria, selection criteria, selection criteria metrics, and weighting values.

Risk and Opportunity Management Process

INCOSE (2007) states that this process is used to avoid extra cost, sched-

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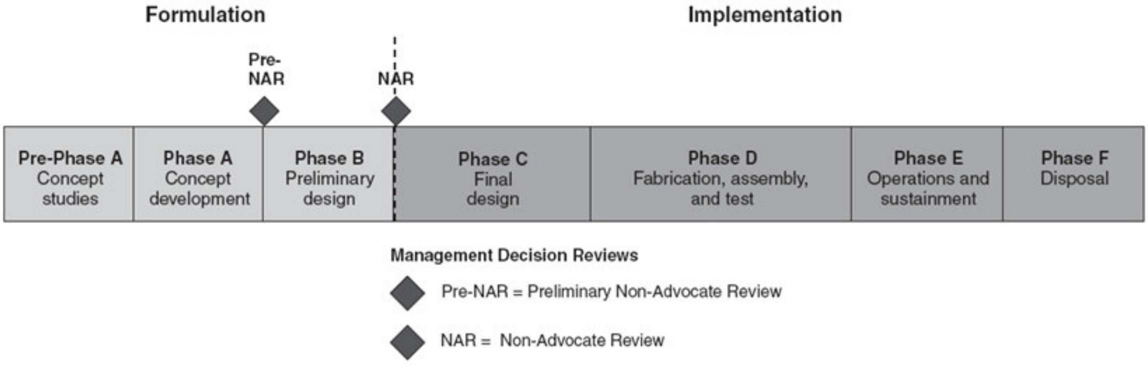

Figure 3.5: NASA Project Lifecycle,(Estefan, 2007)

ule overruns and technical problems. The process takes a proactive approach seeking to diminish risk and identify possible opportunities. A major risk applicable to this project is that of rushing the system development. This may lead to schedule risk. It is necessary to identify risks early in order to mitigate damage.

Configuration Management Process

This process ensures that a system that is continually changing is managed accordingly. At the core of this configuration management process is the concept of baselines. Baselines are reference points for maintaining development and control of a system. They often coincide with milestones and decision gates. The configuration management process ensures that changes to product characteristics are identified, approved and documented, (INCOSE, 2007).

Information Management Process

This process ensures that all the project information is properly stored and maintained. An information management plan can be created. This plan identifies information to be collected, retained, and secured.

3.2.3 Enabling Systems Engineering Process Activities

INCOSE (2007) identified a number of different process activities that occur repeatedly throughout systems engineering literature. These common enabling processes include decision management, requirements management, and risk and opportunity management. Said tasks are essential when tailoring activi-

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ties to every system life cycle.

Decision Management

This section deals with decision gates, trade-off studies and methods for making difficult decisions. Decision gates have already been mentioned above and ensure that new activities are not started until previous activities have been completed or an acceptable level of risk has been mitigated. This reduces expensive changes further on in the project life cycle. INCOSE (2007) defines the options at each decision gate as follows: acceptable (proceed); acceptable with reservations (proceed but respond to problems); unacceptable (repeat review); unacceptable (go to proceeding stage); unacceptable (activity on hold); and unsalvageable (terminate the project).

Difficult decision-making requires information, experience and sound judgement. There are a number of tools available in this regard. Clear decision-making should be preceded by a clear understanding of the decision ramifications and the decision environment. One illustration of a decision-making process is a decision-making tree. A decision tree begins on the left with an initial decision point and moves to the right. This helps to map decisions and their ramifications, see figure 3.6. Other techniques are as follows: sensitivity analysis, value of information methods, and multi-attribute utility analysis, (INCOSE, 2007).

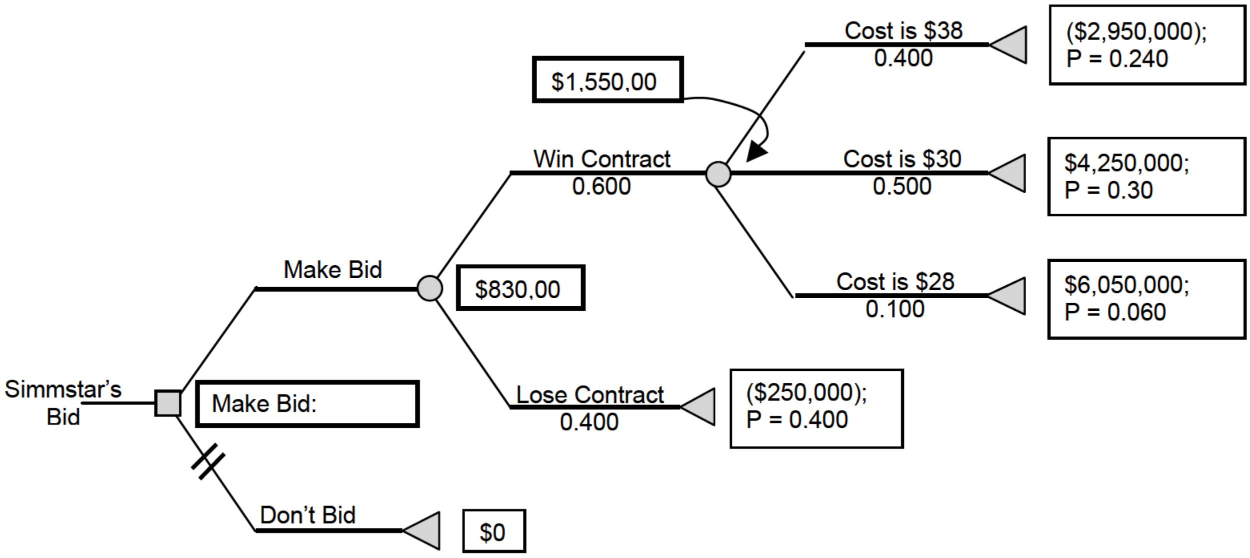

Figure 3.6: Decision Tree for a 'Bid-No Bid' Decision,(INCOSE, 2007)

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Trade studies is a method for comparing different technical solutions. It does this by comparing option characteristics. Trade studies justify why a certain alternative was selected. They often include different weightings according to the alternatives. The studies are often accompanied by a sensitivity analysis. This analysis determines how sensitive the recommendation is to the altering of different criteria, (INCOSE, 2007).

Requirements Management

Requirements management deals with the collection, analysis and validation of the system requirements. INCOSE (2007) states that requirements actually serve as drivers for the system life-cycle processes. Capturing these requirements may be done at the beginning of the project, or may be done continually throughout the project.

The required capabilities, performance objectives and constraints serve as driving factors for the architecture design activities. If information is lacking in one of these areas, it should be noted and possibly placed within the category of risk management, (INCOSE, 2007).

Technical performance measures convey the necessary performance requirements. They serve as a means to view the status of technical objectives and, as such, can be used to measure the risk of the project. Technical performance measures are usually assessed at decision gate or milestone reviews, (INCOSE, 2007).

Risk and Opportunity Management

Risks are events that can have a negative impact on the successful completion of a project. They should also be analysed to determine the likelihood they will occur and the impact that they could have. A project is said to have technical risk if it is operating close to the state of the art. Schedule risk occurs when the project is executed with tight deadlines. The majority of projects have cost risk. Finally, programmatic risks are risks that are out of control of the project manager; delays in authorisation, reduced funding, etc, (INCOSE, 2007). The figure 3.7 illustrates these different risks and how they interact.

3.2.4 Systems Engineering Support Activities

This section highlights recommended activities for the systems engineering effort. According to INCOSE (2007), a large number of these activities will be

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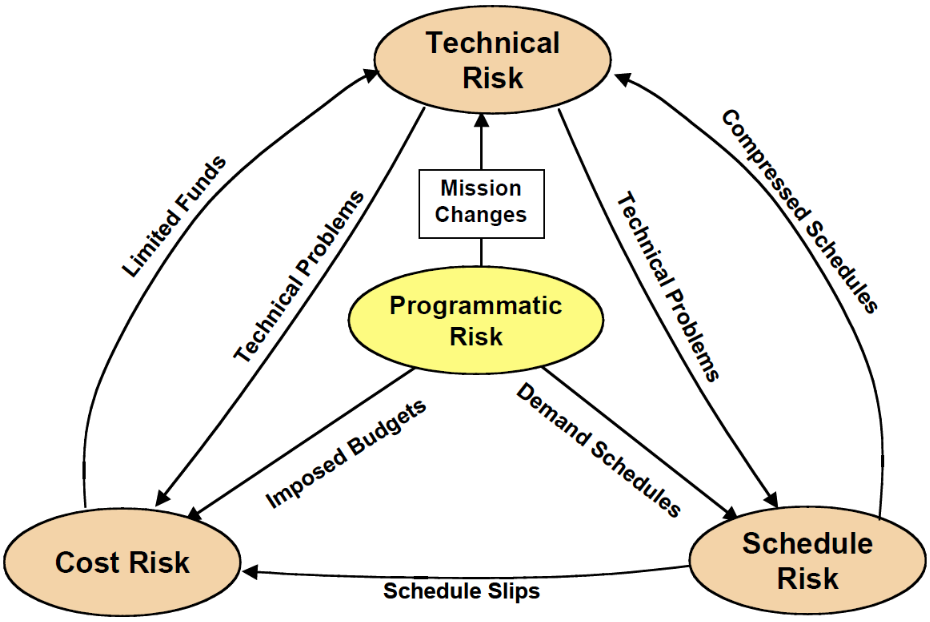

Figure 3.7: Typical Relationships Among the Risk Categories,(INCOSE, 2007)

included in the project execution.

Acquisition and Supply

Once a number of needs have been identified and resources committed to fulfilling these needs, it is possible to begin defining the parameters between the project entity (company, university, etc.) and suppliers, (INCOSE, 2007).

Architectural Design

The system architectural design process provides the framework for systems development. INCOSE (2007) refers to four methodologies that systems architecture builds on. Firstly, solutions-based methodologies such as building codes, etc. Secondly, systems architecture builds on method-based methodologies such as systems analysis and engineering. A third methodology used is that of stakeholder-based methodologies such as systems concurrent engineering. The fourth building block is that of a heuristic methodology.

Configuration Management

As previously stated configuration management establishes and maintains control of the requirements and documentation through the duration of the sys-

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tems life cycle. In summation it manages the changes to the system. Systems engineers ensure that the changes made are essential. The configuration management plan contains the scope of items contained within the plan, tasks that need to be performed and finally the methodologies and procedures that will be used, (INCOSE, 2007).

Information Management

As discussed in Project Processes, information management is used to archive project information in a structured manner. Similar to configuration management, the details of information management are defined in the information management plan. Items under information management include test documentation, analysis reports, etc., (INCOSE, 2007).

Investment Management

INCOSE (2007) states that a tool used in this instance is that of the life cycle cost analysis. This method evaluates all costs of the system over a given period of time. This method examines the following costs: research and development costs, utilization and support, and disposal costs.

Project Planning

Project planning estimates the budget and schedule for a project. These metrics are then used throughout the project to monitor progress. Activities include planning, scheduling and reviewing. Project planning is reflected in both the Systems Engineering Plan (SEP) and the Systems Engineering Master Schedule (SEMS). The Systems Engineering Plan is the top level plan for the systems engineering approach. It contains the necessary actions and structure to create a satisfying system. The Systems Engineering Master Schedule is part of the Engineering Plan and serves to identify the critical path of activities, (INCOSE, 2007).

Other Support Activities

Other support activities include Quality Management, Resource Management, Validation, and Verification.

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3.3 Systems Engineering Approaches

There are a number of different systems engineering approaches or guidelines. Two approaches of interest are those presented by Nicholas and Aslaksen. These approaches summarise steps that need to be taken when employing systems engineering in design.

3.3.1 Nicholas Approach

(Nicholas and Steyn, 2003) outlines a useful set of life cycle stages that facilitate clear understanding of the systems engineering process.

Needs Identification and Conceptual Design

It is essential that fuzzy stakeholder needs and ideas are converted into clear needs, problems and objectives. The requirements issued by the stakeholders are listed in the original language used in a document known as the stakeholder requirements document (SRD), (Nicholas and Steyn, 2003).

Nicholas and Steyn (2003) state that once the SRD has been approved, it is then necessary to specify what the system must be able to do in order to satisfy the requirements. This systems requirement phase translates needs into performance and physical characteristics.

As per Nicholas and Steyn (2003), the functions that the system must perform are specified in the functional requirements. These functions include all those needed to satisfy requirements, as well as functions needed to support, operate, and maintain the system. One tool used to better illustrate this process is the use of functional flow block diagrams. Each block of this diagram represents a function that the system must perform.

Functional parameters specify what a system must do. Performance parameters, on the other hand, specify how well a system must do it. These include metrics such as speed, acceleration, weight, etc., (Nicholas and Steyn, 2003).

Another step in the needs identification and conceptual design phase is that of synthesis. Synthesis examines the relationship among the system level requirements and the ways of satisfying them. The result of this is a comprehensive list of all the functions the system must satisfy as well as solutions for each. This document is known as the systems specification, (Nicholas and Steyn, 2003).

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Preliminary Design

Here the functional flow block diagrams are decomposed. This is done to define performance and testing requirements for each block. The detail of each block should be such that it is enough to completely define it. This detail should permit decisions about how to meet functions. The focus in this instance is not what the system will do, but more how the system will do it, (Nicholas and Steyn, 2003).

As per Nicholas and Steyn (2003), configuration management is the purpose of documenting and tracking design changes. This form of management is put in place to ensure that changes do not detract from the system's ability to satisfy functional requirements. Traceability is used to prevent failures.

Subsystems that satisfy a function are known as configuration items. In the step of requirement allocation, responsibility for each requirement is assigned to a configuration item. This ensures that every functional requirement is satisfied by at least one subsystem. An allocation matrix can be used to illustrate this. Configuration items embody the conversion from a 'what' to a 'how', (Nicholas and Steyn, 2003).

Detailed Design and System Development

Nicholas and Steyn (2003) state that detail design involves converting thought-out designs to designs that can be fabricated or manufactured. This involves checking how subsystems integrate into the system as a whole; the checking of the validity of design assumptions as well as the needed interfaces.

Construction and Operation

As soon as the design is approved, the construction phase begins. Here materials are acquired, inventory is managed, etc. Under the operation phase the end user operates the finished system, (Nicholas and Steyn, 2003).

3.3.2 Aslaksen Approach

In engineering a system, there are five distinct approaches. These include definition, analysis, design, implementation and verification. The level of work to be conducted in each phase varies, Aslaksen and Belcher (1992).

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Definition

Aslaksen and Belcher (1992) state that the project objectives can only be properly defined by close interaction between the user, or client, and engineer. In this interaction, the engineer helps the user, or client, to formulate clear objectives. In doing so a scope of work is formed. Boundary conditions are also decided upon.

Analysis

The end goal of the analysis phase is to produce a systems specification that can be used for the system design. Inputs are transformed into outputs. The functionality of the system is broken down into system functions or elements. A number of high-level choices can be made in this phase. These include the overall structure, technology, etc. The result of this phase is the system specification, (Aslaksen and Belcher, 1992).

According to Aslaksen and Belcher (1992), the specification must fulfil the following two conditions. Firstly, it must cover all areas of concern expressed by the client. Secondly, is must be relatively easy to understand. A structure of a system specification is outlined as follows, (Aslaksen and Belcher, 1992):

1. Title Page
2. Purpose
3. Supporting Information
4. System Level Requirements
5. Functional Elements
6. Quality Assurance provisions
7. Appendix

Design

In this phase the system specification is divided into subsystems. This decomposition continues until the result is a production unit or a design is formed. It is essential that the whole design activity is carried out along the shortest route towards the requirement of the system specification. The approach described by Aslaksen and Belcher (1992) also advocates a high level of documentation.

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Implementation

The main activities in this phase are design, purchasing, etc., (Aslaksen and Belcher, 1992).

Verification

Aslaksen and Belcher (1992) state that verification can either be taken on a single day or carried out over the entire operation of the system. This phase is carried out in order to determine if the system requirements have been satisfied.

Aslaksen and Belcher (1992) state that system verification is planned top down but is executed bottom up. The lowest level of the system is thus tested. There are a number of methods of verification. Experimentation involves direct measurement. Inspection and analysis can be used when testing would otherwise damage the system.

3.4 Systems Engineering Models

Estefan (2007) conducted a survey on a number of "Model-Based Systems Engineering (MBSE) Methodologies". These are collections of processes, methods, and tools used to assist with the implementation of systems engineering.

3.4.1 Models

Estefan (2007) states that the majority of systems engineering models are rooted in either the Royce Waterfall Model, Boehm's Spiral Model or Forsberg and Moog's V-model as per (Forsberg and Mooz, 1995). Blanchard and Fabrycky (2006) mention the Waterfall model, the Spiral model and the V-model as well established systems engineering models. The waterfall and spiral models have been used predominantly in software development. The V-model, on the other hand, has been applied more extensively in the area of systems development, (Estefan, 2007).

V-systems Model

Greeff (2011) states that a typical guide to system engineering can be found in the V-systems approach. This approach is often tailored and applied by systems engineering implementers. The approach can be seen in figure 3.8. The V-systems approach illustrates how a problem is dissected into a functional

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solution and how this solution is integrated and tested collectively, (Forsberg and Mooz, 1995). This approach also clearly displays the relationship between the different systems engineering life-cycle stages, (Greeff, 2011) and (Nicholas and Steyn, 2003).

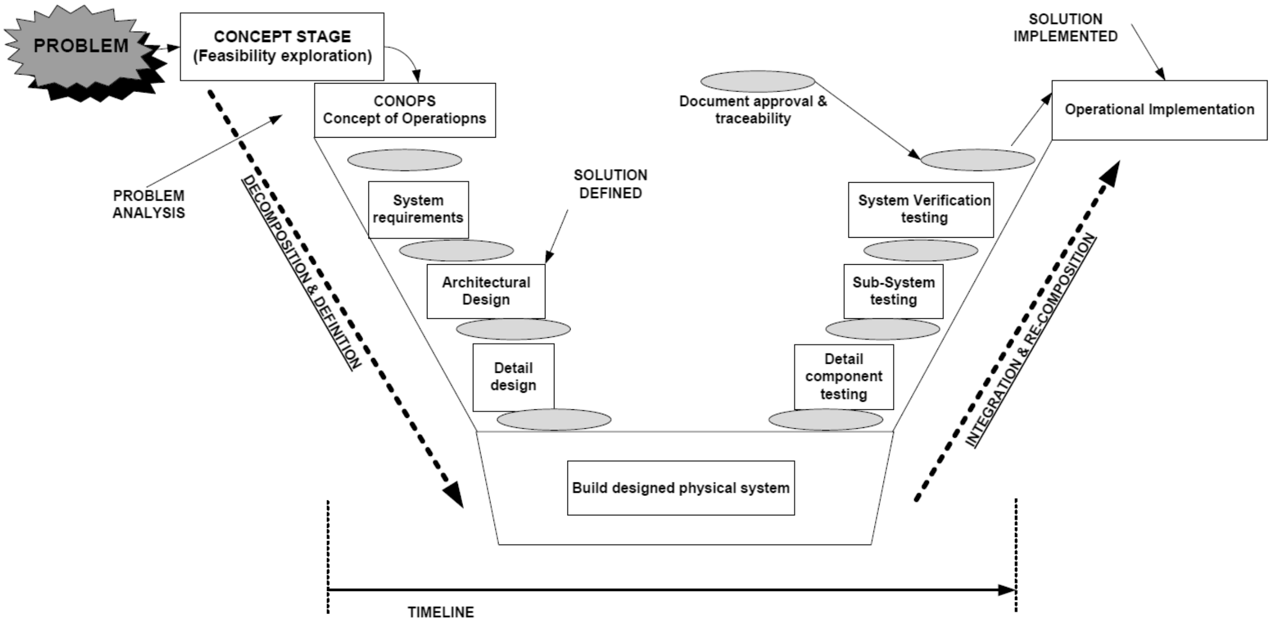

Figure 3.8: The V-Systems Approach, a Practical Way to Implement Systems Engineering,Greeff (2011) adapted from Forsberg and Mooz (1995)

Nicholas and Steyn (2003) state that the structure of systems integration is described in the systems engineering life cycle as being part of the ‘up’ slope of the afore mentioned V-model. This upward slope begins with implementation and ends with validation of the completed system. Sauser *et al.* (2008) continue by stating that integration is the process of assembling components into a system. Despite this simple definition, integration is often a complex process. It can contain multiple overlapping and iterative tasks. These tasks ensure that the system is designed according to user and environmental requirements.

INCOSE Object-Orientated Systems Engineering Method

Estefan (2007) states that this top-down model aims to create systems that are flexible and can adapt to evolving technology and changing requirements. The model has its roots in software development, but is designed to integrate hardware, software, and manual procedure components. Core elements of this

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approach include integrated product development with a view to improving communication and a recursive "Vee" life-cycle process model applied in each level, (Estefan, 2007). The model can be seen in figure 3.9.

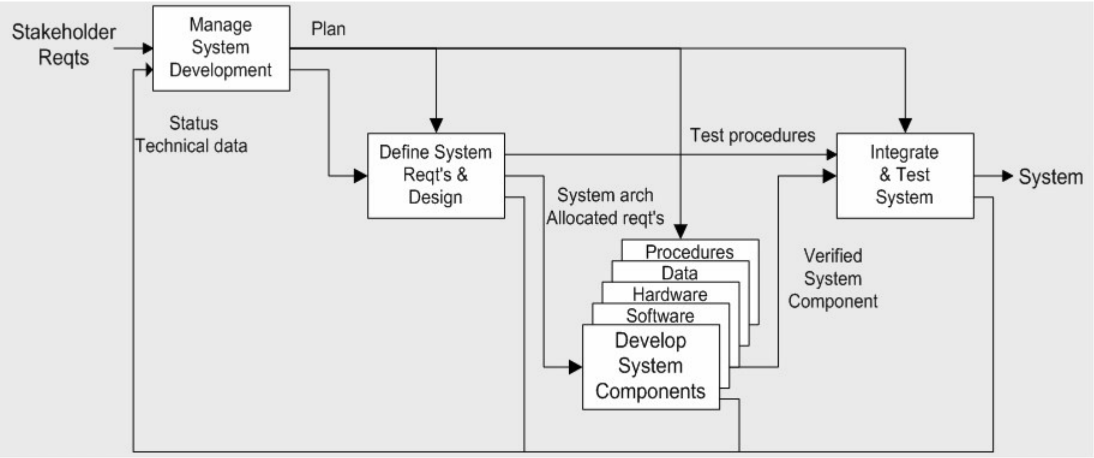

Figure 3.9: OOSEM Activities in the Context of the System Development Process,(Estefan, 2007)

The “Define System Requirements” makes mention of modelling the system as a black box interacting with external systems and users. Scenarios are then to describe how the intended black box is used to support users and other systems, (Estefan, 2007). Extensive trade-off studies are conducted, in the “Optimize and Evaluate Alternatives” phase, with criteria and weighting factors that are derived from the system requirements. It is here that technical performance measures are monitored. Finally, during the “Validate and Verify System” phase, scenarios and requirements are used to develop verification procedures, (Estefan, 2007).

Vitech Model-Based System Engineering (MBSE) Methodology

The company Vitech developed a model-based systems engineering methodology. The activities of this methodology can be seen in the figure 3.10. A defining feature of this methodology is that is stresses the use of System Definition Language (SDL). This SDL acts as a structured common language for technical communication. Other key aspects of this methodology include the use of semantically meaningful graphics to be consistent and explicit, an engineer system in complete converging layers (illustrated in the Onion model), and the use of tools for use of basic and repetitive tasks, (Estefan, 2007).

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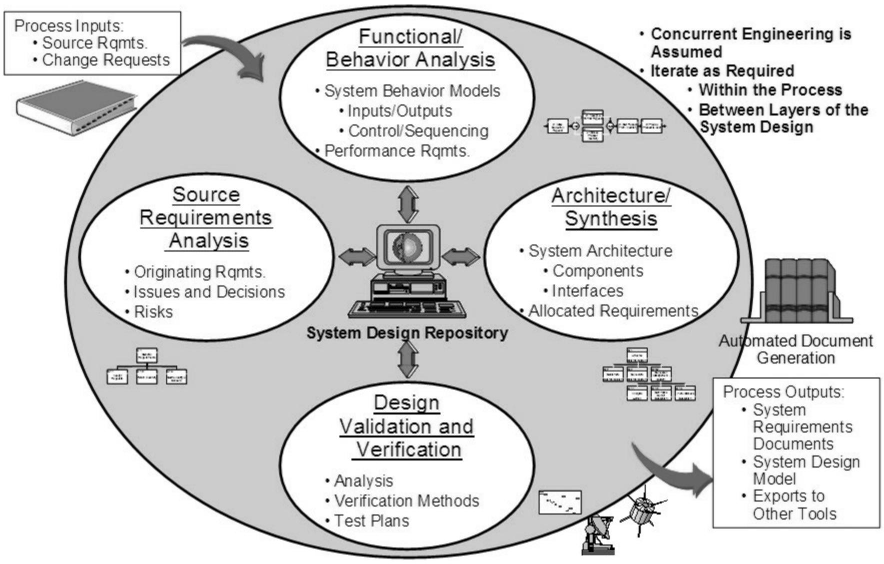

Figure 3.10: Vitech MBSE Primary SE Activities,(Estefan, 2007)

The Onion model concept, according to Estefan (2007), completes systems engineering activities at different layers concurrently. When one level of system design has been completed the next layer is explored. This is iterated until the desired level of detail is realised. This approach is more beneficial than a Waterfall systems engineering approach as risk is reduced by having completed solutions at increasing levels of detail. If no solution to a layer can be found, it is necessary to re-evaluate constraints or modifications in a previous layer, (Estefan, 2007).

Dori Object-Process Methodology (OPM)

This approach is based on the combination of formal models known as Object-Process Diagrams (OPDs) and constrained natural languages sentences known as Object-Process Language (OPL), (Dori, 2002). The combination is used to express the function, structure, and behaviour in a single model, (Estefan, 2007).

Dori (2002) states that OPM handles system complexity through three particular refinement tools. The first is folding and unfolding. This tool is used to determine the structure of the system. The second is zooming in and zooming out. This deals with viewing the details of the system, whilst keeping a view on the whole. The last tool is state expressing and suppressing. This focuses on better understanding the state of an object, (Dori, 2002).

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In addition to the above, the main idea behind OPM is that everything is either an object or a process. OPM models are built up of objects, processes and states. An 'object' can be something physical or something mentally conceived. A 'process' is the transformation an object undergoes and a 'state' is the characteristics of an object at a set point in time, (Estefan, 2007).

As can be seen in figure 3.11 there are a number of sequential states of system developing process: requirement specification, analysing and designing, implementation, and using and maintaining. The figure also displays the client, system architecture, user and implementer as being inputs into system developing. These inputs are orientated around requirement specification. As can be seen in figure 3.11 the client and system architect both serve as inputs to the requirement specification. This produces a requirement document through system development. Once the specification of requirements has been completed, the analysis and design phases are begun, (Estefan, 2007).

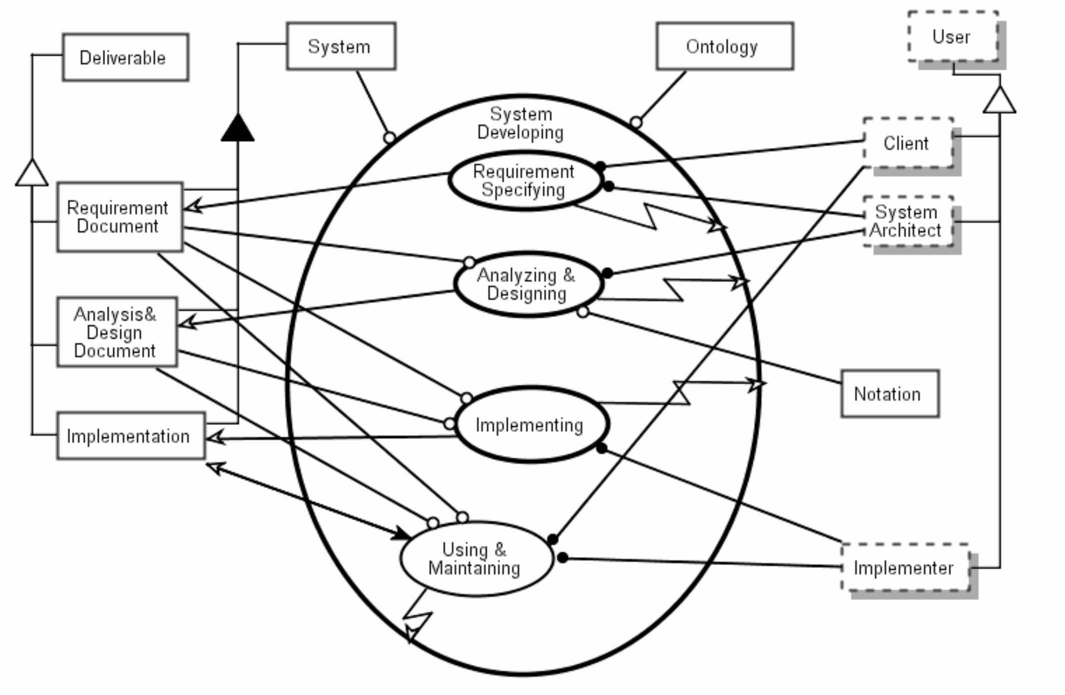

Figure 3.11: Zooming into System Developing,(Estefan, 2007)

Estefan (2007) states that OPM also advocates re-use. Items such as analogous systems, products or existing artefacts can be re-used in this regard. This approach helps to increase the quality of a system as well as to reduce

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development and debugging time.

Systems Engineering and Analysis

Blanchard and Fabrycky (2006) state that system design should convert a customer need into a system configuration. In addition to this, this form of design should ensure the design's compatibility with related physical and functional requirements. System's design also considers operational outcomes. These operational outcomes consist of producibility, reliability, maintainability, usability and supportability, etc. (Blanchard and Fabrycky, 2006).

The systems engineering and analysis approach presented by Blanchard and Fabrycky (2006) emphasises detailed application of life-cycle thinking throughout the project. The life-cycle processes and phases can be see in figure 3.12. This model serves to highlight the approach taken by Blanchard and Fabrycky (2006).

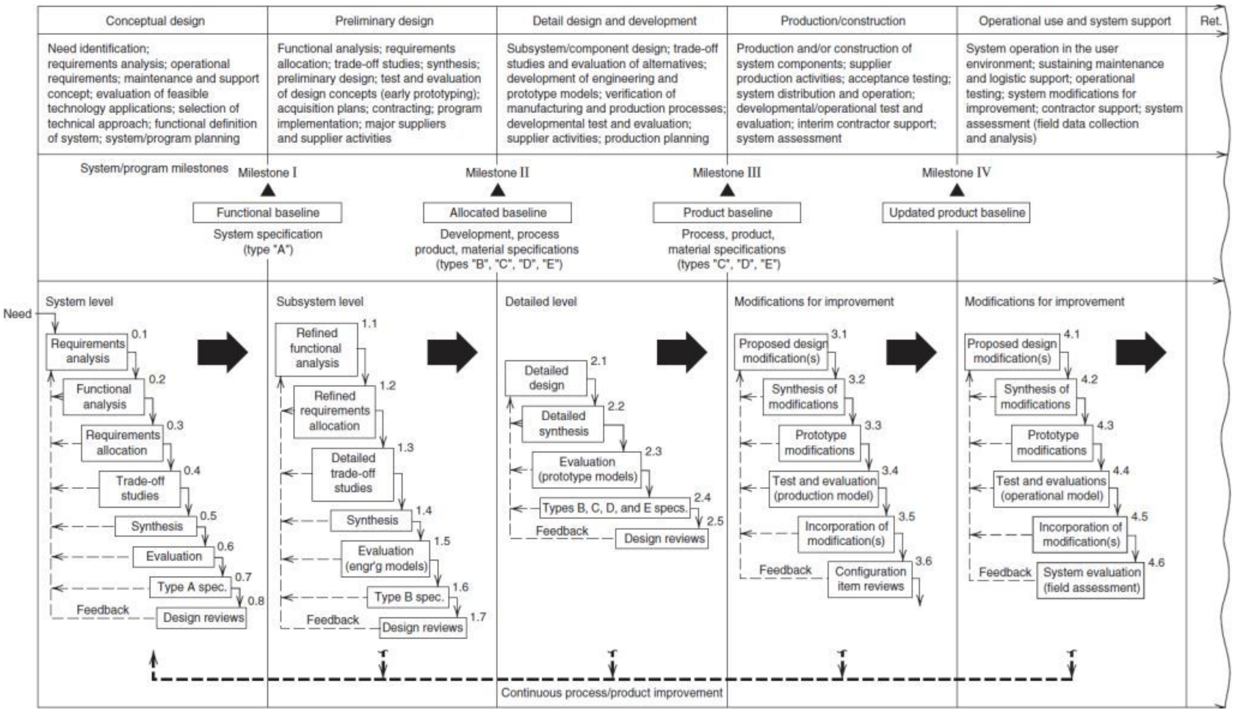

Figure 3.12: System Process Activities and Interactions Over the Life Cycle,(Blanchard and Fabrycky, 2006)

The figure 3.12 emphasises the iterative and top-down nature of this approach. The process is one of an evolutionary design and development process.

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By making use of feedback and design refinement, this approach gives rise to a successful design, (Blanchard and Fabrycky, 2006).

3.5 Tailoring

Activities concerning the systems engineering process can be applied with varying degrees of formality, (INCOSE, 2007). Aslaksen and Belcher (1992) state that a large part of systems engineering is the adaptation and modification of tools and techniques. These are often adapted from use in other areas to suit the needs of the project. Blanchard and Fabrycky (2006) concur with this by stating that the actual implementation of systems engineering will vary from system to system.

An example of tailoring as per INCOSE (2007) is the more stringent application of control and assessment earlier in the project. When executing a tailoring process, it is essential to balance the amount of tailoring, i.e. high rigidity means higher cost and schedule overruns, while insufficient rigidity means high risk. This can be seen in figure 3.13.

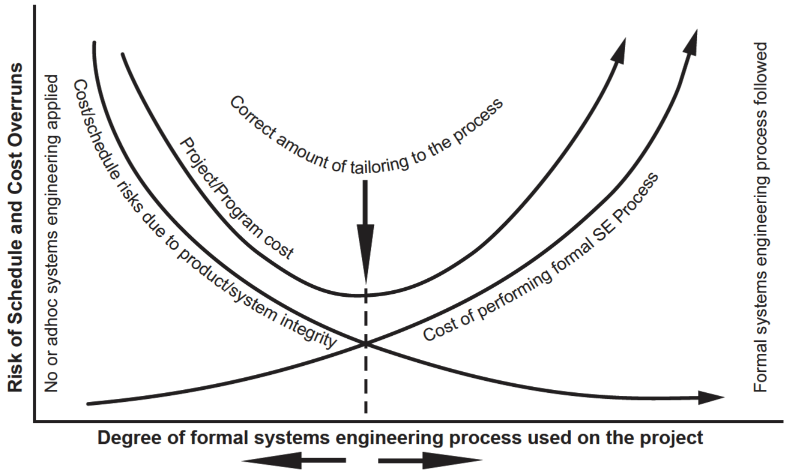

Figure 3.13: Tailoring Requires Balance Between Risk and Process,(INCOSE, 2007)

A list of tailoring activities is as follows: identify tailoring for each stage; determine process relevance to cost/schedule/risk; determine process relevance to system integrity; determine quality of documentation, and finally determine extent of review and decision methods. One major trap to be avoided when tailoring is that of using all the process to err on the side of caution. This

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leads to redundant activities and wasted time, (INCOSE, 2007).

3.5.1 Elements Incorporated

A wide variety of elements of the INCOSE methodology is to be incorporated in the systems engineering baseline. A large number of the concepts presented by INCOSE (2007) are already fully developed in the approach as per Blanchard and Fabrycky (2006).

Specific items that are highlighted in the INCOSE methodology and are not emphasised in the methodology by Blanchard and Fabrycky (2006) are mentioned as follows. The INCOSE system places high emphasis on the Stakeholder Identification and Stakeholder Requirements Definition. This point is addressed in the Specification Definition chapter. The Architectural Design Process, as per INCOSE (2007), is integrated into the Preliminary Design. Similarly, the Verification is integrated into the Verification Method chapter.

INCOSE (2007) also incorporates a number of useful project processes. The Project Planning Process is incorporated into the Project Planning chapter. This includes the Risk and Configuration Management Processes as described in the INCOSE standard. Requirement Management is to be incorporated again in the Specification Definition chapter.

Elements from other models and approaches included in this project include the following. The tool of functional flow block diagrams as per Nicholas and Steyn (2003) is included in the Preliminary Design chapter. The elements of Preliminary Design and the Detailed Design presented by Nicholas and Steyn (2003) are consistent with the elements as described by Blanchard and Fabrycky (2006).

Aslaksen and Belcher (1992) provide a particularly relevant description of the structure and content of the system specification. This information has been incorporated into the Specification Definition chapter.

3.6 Systems Engineering Model Selection

Owing to the complex nature of the project, a table has been created to assist in model selection, see figure 3.14. There are a number of systems engineering models that, as a whole, are not directly applicable to the project. Despite this, elements of these modules are used in the systems engineering of the

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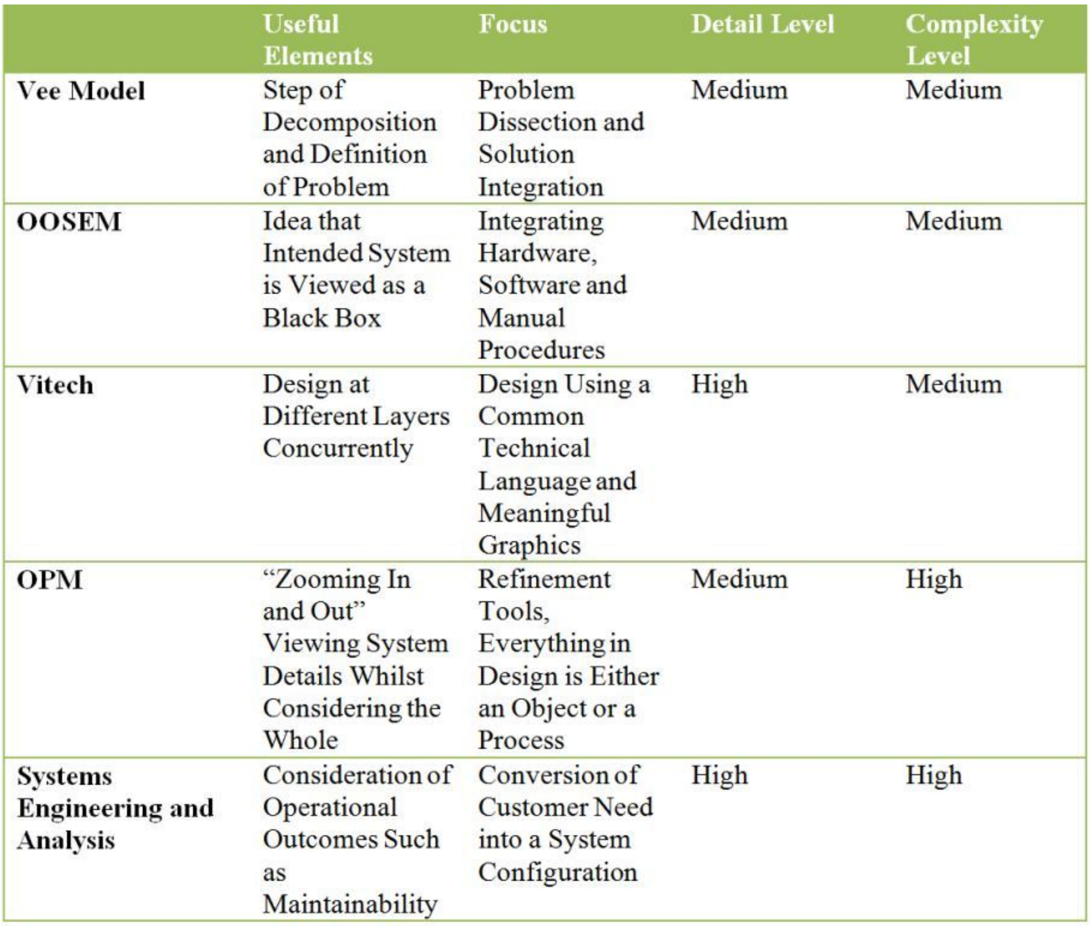
project.



	Useful Elements	Focus	Detail Level	Complexity Level
Vee Model	Step of Decomposition and Definition of Problem	Problem Dissection and Solution Integration	Medium	Medium
OOSEM	Idea that Intended System is Viewed as a Black Box	Integrating Hardware, Software and Manual Procedures	Medium	Medium
Vitech	Design at Different Layers Concurrently	Design Using a Common Technical Language and Meaningful Graphics	High	Medium
OPM	"Zooming In and Out" Viewing System Details Whilst Considering the Whole	Refinement Tools, Everything in Design is Either an Object or a Process	Medium	High
Systems Engineering and Analysis	Consideration of Operational Outcomes Such as Maintainability	Conversion of Customer Need into a System Configuration	High	High

Figure 3.14: Criteria Used in the Selection of a Systems Engineering Model and Additional Elements to be Incorporated into the Project

In order to implement systems engineering in this highly technical project a model is sought with focus on guiding the design process through problem dissection, and converting a need into a product. Three models in particular have the needed focus: the V-model, Vitech Model, and the Systems Engineering Analysis Model.

The problem to be addressed by this project has already been largely identified. Research still needs to be conducted. However, the main technical focus has been established. A major fault associated with the V-model is that half of the model is focused on the decomposition of the problem. This level of decomposition are simply not need in this project. It is therefore excluded.

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The Vitech model has the high level of detail needed for the project as well as a medium complexity level. In addition to this, this model considers a large range of product development issues such as risks and change requests. It also advocates clear communication and documentation. This model is, however, only second in nature when compared to high-detail level, complexity and the number of tools associated with the Systems Engineering and Analysis model of Blanchard.

The Systems Engineering and Analysis model considers the application of overall systems thinking to each aspect of the life-cycle stage. It also makes extensive use of specific tools to complete the technical design processes. The selected base model is that of the systems engineering and analysis model as presented by Blanchard and Fabrycky (2006).

3.6.1 Model Elements Incorporated

Although none of the other models identified is used directly in systems engineering, various concepts and elements associated with these elements are incorporated into the chosen methodology.

The concept of initially viewing the system as a black box interacting with its environment is one of the main aspects incorporated from the Object Orientated Systems Engineering model. This is particularly relevant in the Conceptual Design chapter. In this chapter the system is seen as performing a specific function. Details of the system are later enhanced in the Preliminary Design chapter.

The Vitech Model-based System Engineering (MBSE) Methodology mentions the Onion concept. In this concept, different systems engineering activities or layers are completed concurrently. The onion-type systems engineering approach ensures that each subsystem should be fully tested and implemented before combining it into the entire system. This was done in the Preliminary Design chapter where various elements are selected and tested independently of one another. This greatly reduces the system risk.

A generic concept associated with the Dori Object-Process Methodology is that of explaining concepts through the use of figures and punchy sentences. This concept was used in illustrating the functioning in the Detail Design Control chapter and the Detail Design Interface chapter.

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3.7 Chapter Conclusion

Having clearly examined the concept of systems engineering and numerous systems engineering models, the systems engineering and analysis model as presented by Blanchard and Fabrycky (2006) has been selected. This model forms the skeleton of the technical design process. Elements of all the different methodologies and models analysed are to be incorporated into this skeleton. The result is a well-rounded approach to the technical systems engineering aspect of this project.

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Chapter 4

Design Methodology

In this chapter a design methodology for the project is established. Now that a thorough knowledge of both innovation management and systems engineering has been achieved, it is possible to create an applicable design methodology. This methodology is a combination of innovation management, systems engineering and research objectives. The project was set out purposely such that only once the methodology had been created could the various phases of the two models be applied.

4.1 Models

Owing to the design-focused nature of both the selected innovation and the systems engineering models, they could easily be combined. In order to polarise this, each model was distilled into its basic steps. The Ullman model can be seen in figure 4.1. The basic phases of the model can be seen in figure 4.2.

The reason the two models are used in the first place is as a result of their differences. These stem from their different focuses. This is reflected in their definitions where innovation management is interpreted as the creation and development of a product or service with the final goal of its commercialisation. Despite the fact that the Ullman model is essentially one ‘phase’ shorter than the Blanchard model, it has a far broader reach. This point is emphasised by the inclusion of tasks such as Research Market and Evaluating Competition.

What becomes clear from this distillation is just how design-focused the systems engineering approach is. Systems engineering is also very structured. Many tools and methods are provided to assist with the technical design. Blanchard’s model can be seen in figure 4.3, while the basic phases of this model can be seen in figure 4.4.

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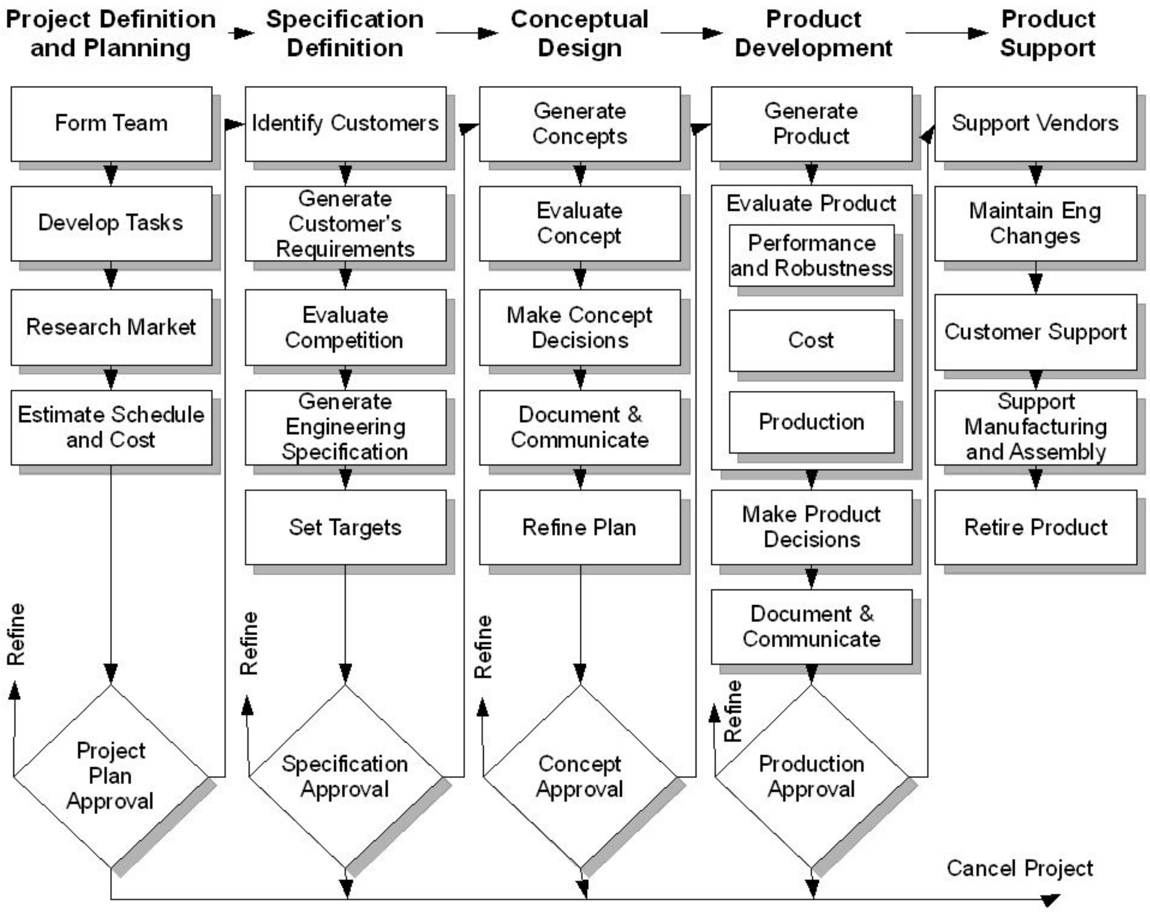

Figure 4.1: The Mechanical Design Process According to Ullman, (Nieberding, 2010)

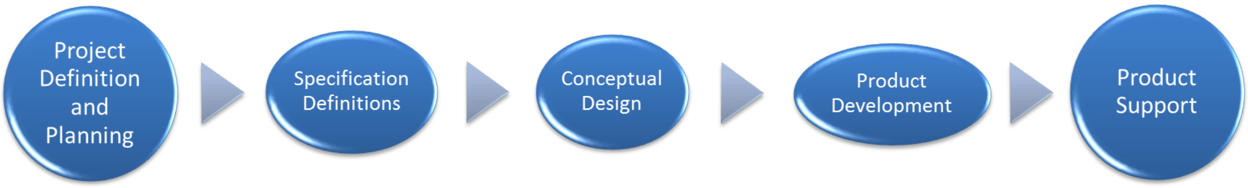

Figure 4.2: Ullman's Model of the Development Process

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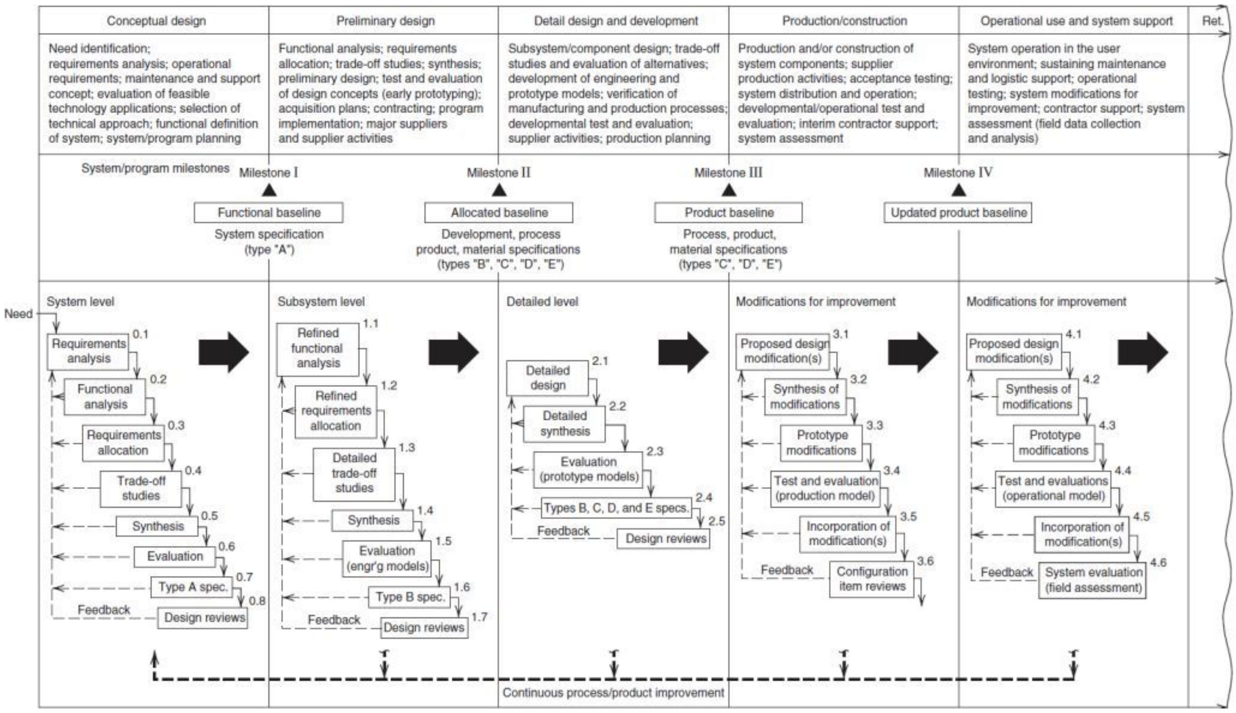

Figure 4.3: System Process Activities and Interactions Over the Life Cycle,(Blanchard and Fabrycky, 2006)

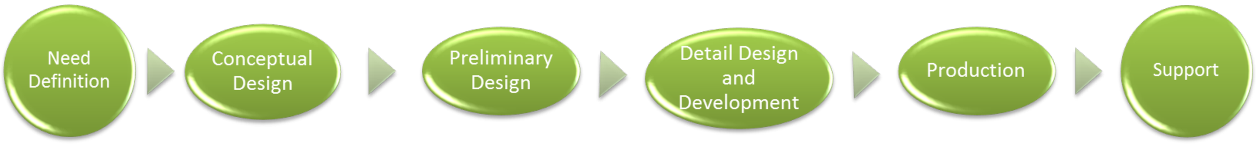

Figure 4.4: Blanchard's System Process Activities and Interactions Over the Life Cycle

4.2 Research Objectives

There are two main research objectives. The first is to create a methodology that will increase the chances of commercial and technical success of the product. The second is to design, build, and test the created system in accordance with the methodology. The second objective is made up of: creating a micro material handling system and secondly determining if the system is able to accuracy perform micro-machining.

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4.3 Research Questions

The research questions reflect the purpose of the project. They also provide a level of structure when implementing innovation management and systems engineering. The research questions are divided into design methods and technical design.

4.3.1 Design Methods

The design methods deal with innovation management, systems engineering and the design methodology.

Innovation Management

1. What is innovation management?
   It is important to ensure that there is a thorough understanding of innovation management before decisions can be made about innovation models.

2. What are some innovation models?
   In this objective, product innovation models are identified and explored. Each model is then compared to the selection criteria.

3. Which model is most appropriate?
   After examining how the various models fulfil the necessary selection criteria, one innovation model is selected.

Systems Engineering

1. What is systems engineering?
   As with innovation management, a thorough understanding of systems engineering is needed before model selection can begin.

2. What are some systems engineering models?
   This objective involves listing and describing systems engineering models.

3. What is the most appropriate model?
   Selection criteria are used to determine the most appropriate systems engineering model. At the same time important concepts from each model are noted.

4. What are applicable concepts from other models?
   The important concepts from each model are then discussed. In this objective, it is determined how both the important concepts and the selected model are applied to the project.

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Design Methodology

1. Show how innovation management and systems engineering models and research objectives are combined.

4.3.2 Technical Design

The technical design deals with steps for the creation of a coarse-to-fine positioning system for micro-material handling and micro-machining.

Main Objective: Robotic Coarse-to-Fine Positioning System for Micro-Material Handling and Micro-Machining

1. What is the background of the project (technically and commercially)?
   The project definition objective could be compared to a literature study. In this objective the background to the various project needs, concepts and problems is thoroughly examined.

2. What are the specifications?
   In addition to the project need there are a number of specifications. These include technical performance measure, for how the system should perform.

3. What are the subsystems?
   This objective involves determining what subsystems are needed for the system to function such that it satisfies the afore mentioned specifications.

4. What is the functioning concept for each subsystem?
   This objective is similar to that of a conceptual design. Here the overall concept for each subsystem is selected.

5. What are the components for each subsystem?
   Once the concept has been decided upon it is necessary to choose off the shelf components (where applicable).

6. What is the nature of the detail design?
   Certain subsystems require the objective of detail design which entails technical work at a low and technical level. An example of this would be programming.

7. What is the nature of component integration?
   The objective of systems integration deals with designing components that ensure the various subsystems combine into a functioning whole. An example of this would be designing a mounting plate.

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8. How is the system validated?
   Validation is used as a means to determine if the system achieves the specifications and objectives originally set out. The system concept can be proved by ensuring that the system can successfully perform micro-material handling and micro-machining according to the case study.
   a) Micro-material handling
   b) Micro-machining

4.4 Combination

As previously stated innovation management and systems engineering were combined in order to obtain and apply their different focuses to the designed system. Innovation focuses around the development and implementation of ideas of products leading to commercial success, (Marais, 2010). Systems engineering on the other hand is comprised of technical management and a technical process, (INCOSE, 2010).

Innovation management provides a structure that will increase the chances of future commercial success. In addition to this, systems engineering ensures a level of technical competency. The research questions help to shape the flow of this combination. The elements to be included can be seen in figure 4.5.

4.5 Resulting Structure

The phases of Conceptual Design and Product Development occur with similar content in each model. As such they were combined. The Project Definition and Planning phase (Ullman), and the Need Definition phase (Blanchard), occur simultaneously at the beginning of the project. Project Definition and Planning as per Ullman (2003) includes more project orientated tasks: market research, etc. As such, these phases cannot be combined. A similar situation is in place with the last two phases, Product Support (Ullman) and Utilisation and Support (Blanchard). The model as per Blanchard and Fabrycky (2006) focuses on the execution and testing of modifications. The model as per Ullman (2003) focuses more on supporting the customer and vendors. Given this, these four steps are said to occur simultaneously, but are not combined.

The created methodology can be seen in in figure 4.6. The blue path shows the traditional sequential phases of the Ullman's model approach. The green path shows the path of Blanchard's systems engineering. The numbers on each of the phases indicate the phases of the combined methodology. The sequence

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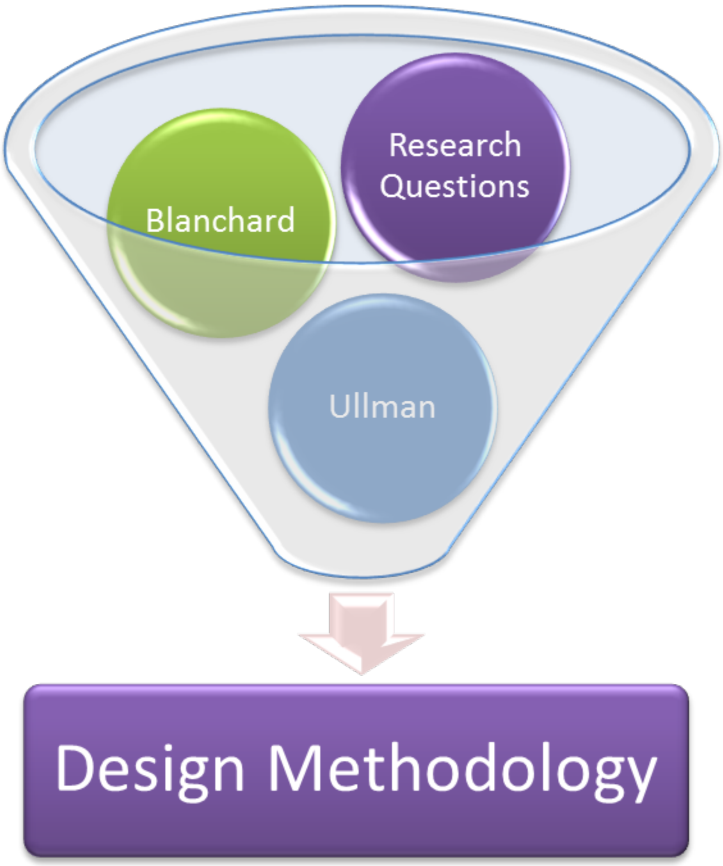

Figure 4.5: The Project Methodology is Achieved by Combining the Innovation Model, the Systems Engineering Model and the Research objectives

of the project thus follows the numbers in the figure. This was done purposefully to display how the contents of the methodologies were kept as original as possible, whilst still being adjusted so as to fit together.

4.6 Chapter Outline

The overall system framework as seen above can be simplified to a chapter outline matrix. It should be noted that this outline begins after the design methodology has been created. It reflects all of the steps of innovation management and systems engineering as per the combination above. This chapter outline can be seen in figure 4.7.

The project comprises various steps of design as per innovation manage-

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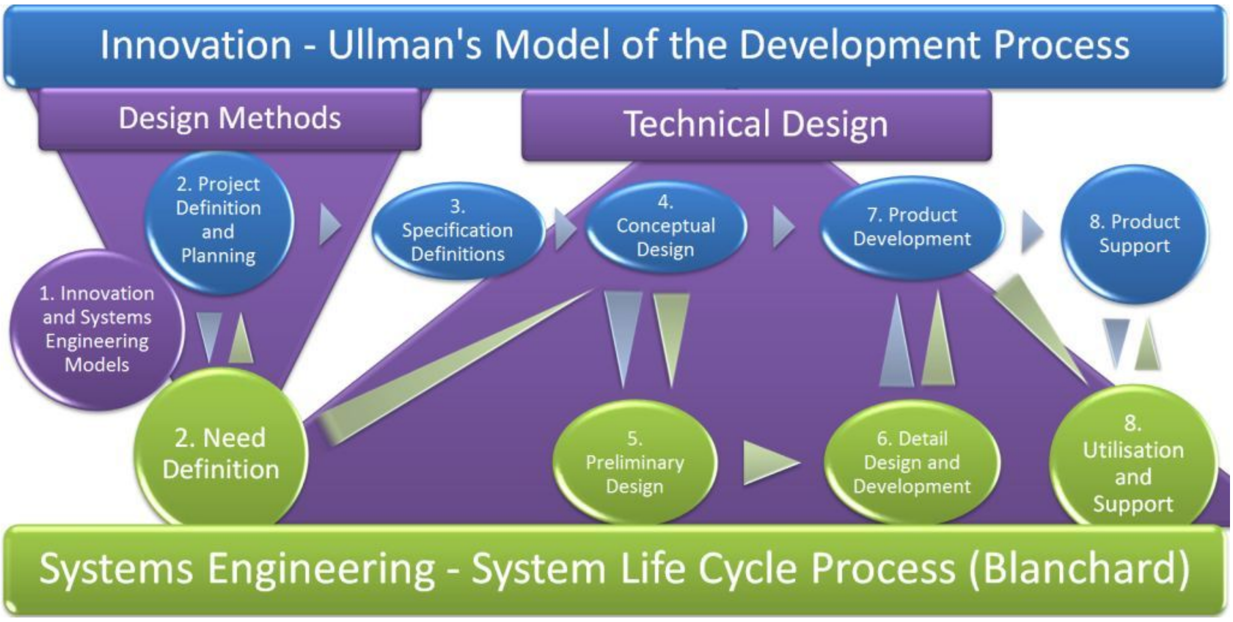

Figure 4.6: The Relationships Between the Innovation (Blue) Process and the Systems Engineering Process (Green) to be Followed. The Research objectives (Purple) are Addressed in this Project

ment and systems engineering: preliminary design, conceptual design, etc. In addition to this, there are a number of various different subsystems that are included, for instance, a vision subsystem and a gripper subsystem. It is important to note that not all of the design steps are applied to all of the subsystems. This is simply due to the nature of the subsystems. The control subsystem, for example, is simply a product of the detailed design step. Marker dots are thus used to indicate the design steps applied to the appropriate subsystem.

It should be noted that the design step of product development is applied to the various subsystems. Product development is redefined as the integration design step. Integration is taken to mean the creation of various parts to ensure that the system integrates into a functioning whole. This process can be thought of as being a precursor to large-scale production.

4.7 Chapter Conclusion

The steps laid out in this chapter show how an innovation and a systems engineering methodology can be combined with research objectives in order to create an overall design methodology for this project. The developed methodology assists with commercial, project and technical aspects of the project.

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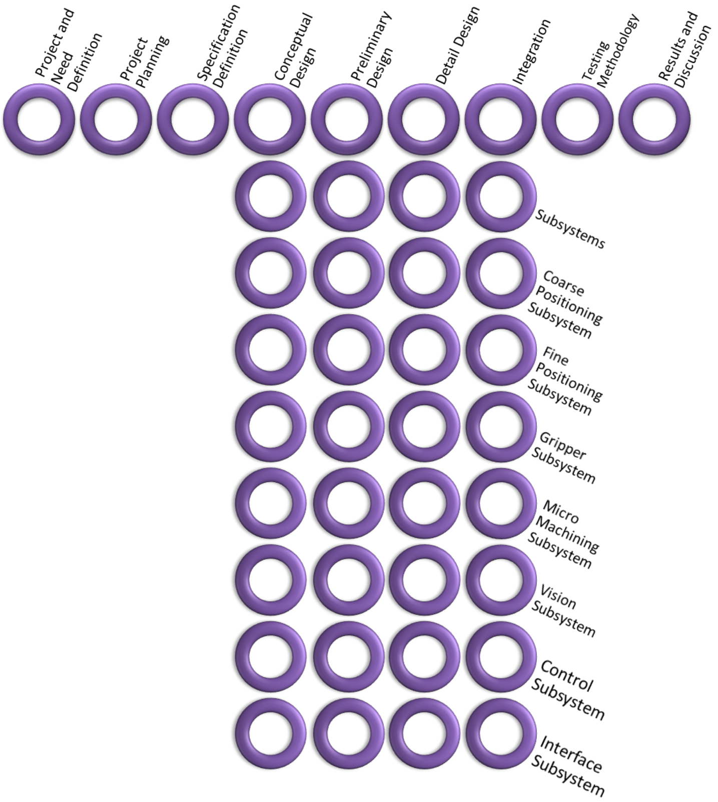

Figure 4.7: Chapter Outline

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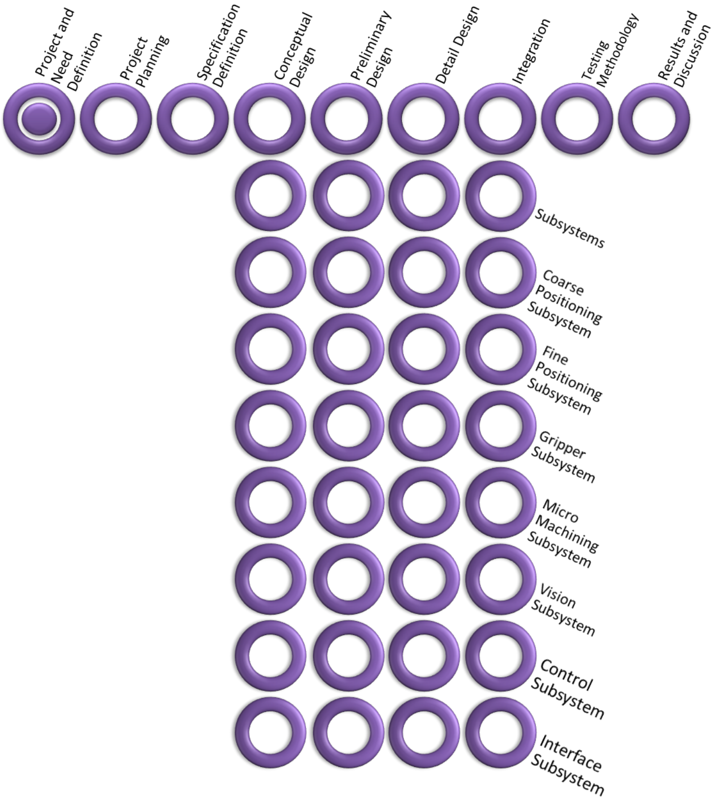
Chapter 5

Project Definition



This chapter sets out the technical definition and the commercial definition of the project. In order to shape the technical definition it is necessary to take an in depth look at the project motivation. It is also necessary to explain the nature of the micro parts used and the processes they are involved in. In

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addition to this the need for and the concept of a coarse-to-fine positioning system is explored. Finally the sequence of tasks needed to be performed by the system and the system's size and cost considerations are examined. When considering commercialisation, it is necessary to develop an understanding of system to be designed in the context of innovation i.e. the type of innovation. A market analysis is also conducted to determine a potential market strategy.

5.1 Technical Definition

Control of the dynamic behaviour of materials can be achieved by integrating materials with piezo-ceramic components,(Drossel *et al.*, 2009). Material integration with piezo-ceramic components also aids in vibration, acoustic and structural health monitoring. This topic has large safety, ergonomic and economic benefits when implemented in the context of the automotive industry. Under the German Research Foundation research has begun on commercialising these “smart" or adaptronic materials, (Drossel *et al.*, 2007). Current manufacturing techniques, involving the insertion of micro-sized piezo-ceramic elements into metals, are preventing the realisation of real economic benefits. New production techniques have, therefore, to be created, (Drossel *et al.*, 2009). This case study allows a platform on which a flexible and reconfigurable coarse-to-fine positioning system for handling and machining can be designed, built, and tested. It also forms part of a collaboration between the Chemnitz Technical University (Germany) and the University of Stellenbosch (South Africa).

5.1.1 Terminology

Owing to the technical nature of the project and the complexity of this chapter, it is necessary to ensure that a number of technical terms are fully understood. The terminology used in this project revolves largely around that of resolution, accuracy and repeatability. In addition to this, it is important to understand what is meant by the terms “micro-material handling” and “micro-machining”.

Resolution, Accuracy, and Repeatability

Accuracy can be defined as the difference between the actual position achieved and the instructed position, (Aerotech, 2012). The accuracy of a linear stage is affected by the sensor, drive mechanism, and the straightness of the bearings. Greenway (2000) states that accuracy is the maximum position or orientation error when moving to a point in Cartesian space.

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Repeatability is the ability of the system to move to a specific point again and again, (Greenway, 2000). Repeatability also need not be defined in Cartesian coordinates but in joint or encoder counts. Aerotech (2012) states that it is the range of positions attained when the system is commanded to one location numerous times.

Aerotech (2012) defines resolution as the smallest possible movement of the system. Resolution is also often referred to as "step size". It is determined by the resolution of the sensor system and the physical limitations of the system, (Aerotech, 2012). Figure 5.1 illustrates the difference between resolution, accuracy and repeatability.

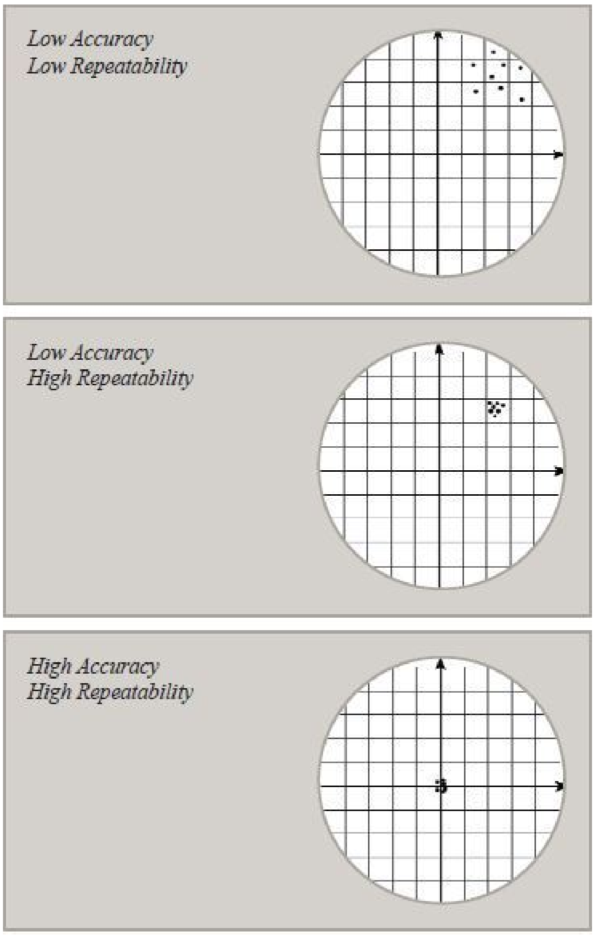

Figure 5.1: Resolution, Accuracy, and Repeatability, (Aerotech, 2012)

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Macro, Micro, Nano-Handling

According to Freundt *et al.* (2008*a*), a micro-assembly process cannot be executed under conditions used for macro-assembly, due to micro forces, and scaling considerations. The source goes on to state that it becomes difficult to integrate micro-assembly operations into production processes associated with macroscopic products. Table 5.1 illustrates the units of measurement associated with the terms “macro”, “micro” and “nano”.

Table 5.1: Robot Technologies, (Tarazon, 2010)

Type	**Size**	**Interaction with Environment**	**Main Application**
Macro-robot	Centimetres to metres	Mechanical	Industrial
Micro-robot	Micrometres to centimetres	Mechanical, chemical and electromagnetic	Micro-assembly
Nano-robot	Nanometres to micrometres	Chemical	Surgery (future)

As can be seen in figure 5.2, there are a number of different assembly technologies. Mueller *et al.* (2012) states that these technologies are associated with different robots. These robots can handle parts with dimensions from 10 μm to 1 m and assembly tolerances from 0.1 μm to 0.2 mm. Standard assembly covers the range from a few tenths of a millimetre to part sizes up to the metre range. This standard assembly is usually performed by articulated robot arms, because of their high flexibility, (Mueller *et al.*, 2012).

Mueller *et al.* (2012) states that Precision assembly can be defined as the assembly of millimetre sized parts with assembly tolerances around 0.05 mm. Transfer lines for surface-mount technology in PCB assembly are a typical example of precision assembly. For this type of application Cartesian or SCARA robots are most applicable.

Micro-assembly describes all the techniques for picking, positioning, placing and bonding of parts with dimensions of less than a few millimetres and assembly tolerances below 0.05 mm. When performing assembly at the micro level, it becomes imperative to use automation in order to achieve technical feasibility, (Koelemeijer Chollet *et al.*, 2003*a*). Automation as the micro-assembly level is limited to reliable pick and place operations with assembly tolerances higher than 0.1 μm. This is due to the fact that sensors have a finite resolution, (Mueller *et al.*, 2012).

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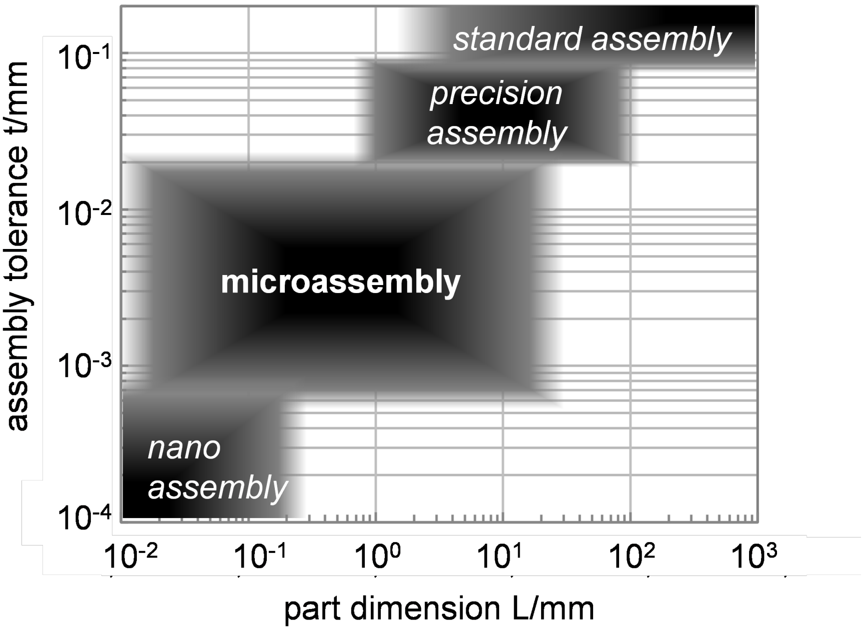

Figure 5.2: Classification of State of the Art Assembly Technologies, (Mueller *et al.*, 2012)

Macro and Micro-Machining

Both micro-handling and micro-machining experience similar forces and considerations. The definition for micro-milling should thus be considered in light of the definition for micro-handling. Chae *et al.* (2006) states that micro-mechanical machining is a fabrication method that creates components ranging from tens of micrometres to millimetres. This form of machining can produce parts relatively inexpensively when compared to other processes, (Jin *et al.*, 2009). This definition is illustrated figure 5.3.

5.1.2 Micro Part Dimensions

The piezo-ceramic components to be inserted into the material are rod-shaped. Schubert *et al.* (2010) states dimensions of the components as follows. The piezo-ceramic rods are 250 μm by 250 μm by 10 mm, see figure 5.4. The micro-cavities are 300 μm by 300 μm by 10 mm and are to be formed by micro-impact extrusion, as can be seen in figure 5.5. Once in place, the rods and cavities are joined by a forming process (Neugebauer *et al.*, 2010*a*). According to Schubert *et al.* (2010), it is during this forming process that a joining gap fill ratio of 1.8 becomes essential.

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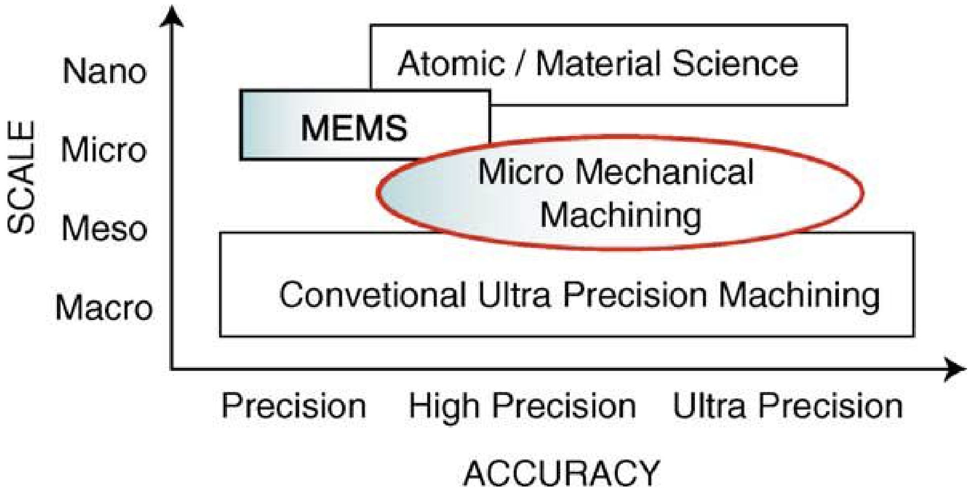

Figure 5.3: Scale Vs Precision of Machining, (Chae *et al.*, 2006)

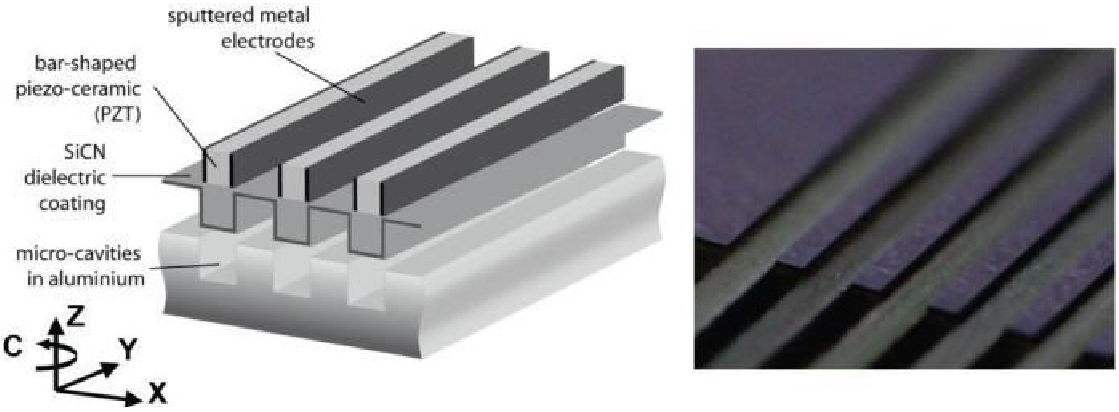

Figure 5.4: Schematic of Piezo-Metal Module and Photograph of Prototype, (Neugebauer *et al.*, 2010*a*)

As per Neugebauer *et al.* (2010*a*), the micro-structure is covered in a thin dielectric coating. This coating ensures correct functioning of the piezo-ceramic material. This coating is very delicate and should not be scratched. A high level of accuracy is thus needed for both the material handling and milling systems.

5.1.3 Micro Forces

In order to better grasp the concepts associated with micro-material handling and micro-machining, it is first necessary to examine micro forces. The conditions that affect macro assembly vary greatly from those that affect micro-

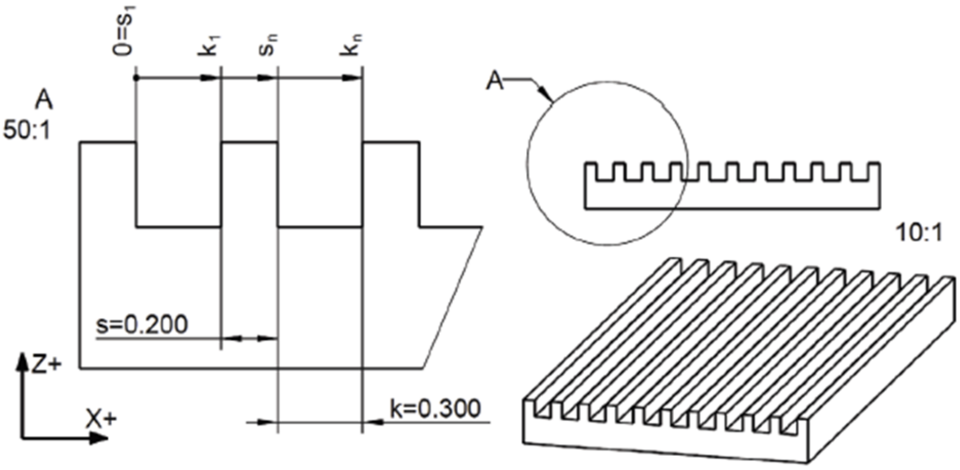

Figure 5.5: Dimensions of Micro-Cavities in Sheet Metal, (Neugebauer *et al.*, 2011*a*)

assembly, (Freundt *et al.*, 2008*a*). Intramolecular and intermolecular forces are the result of electrostatic attractions between opposite charges, (Silberberg, 2007). It is important to note that the effects of different forces change at the micro scale. The effects of forces such as surface tension, electrostatic forces, and viscosity are all increased at the micro scale, (Tanikawa and Arai, 1999). The effects of inertia are, however, decreased.

Types

Active adhesive forces at the micro level include: The Van der Waals forces, electrostatic forces, surface tension forces, and hydrogen bonding forces. At the micro level, adhesive forces are more influential than gravitational forces, (Fukuda and Arai, 1999) and (Cecil *et al.*, 2007). Fukuda and Arai (1999) continue on to state that these adhesive forces are highly dependent on conditions at the sight of contact such as temperature, humidity, surface condition, and motion. Cecil *et al.* (2007) state that forces at this level are a function of material properties.

Sanchez (2010) states that with objects that are lighter than $10^{-}6$ kg, gravity effects are less significant than adhesive forces. This idea is illustrated in figure 5.6. Both (Sanchez, 2010) and (Cecil *et al.*, 2007) classify molecular and surface forces into three categories. The first category is long-range attractive forces. Forces in this category include: Van der Waals, electrostatic, and magnetic forces. The second category of forces is that of adhesion forces: diffusion, condensation, diffusive mixing, mutual dissolution, liquid and solid bridges, and capillary forces. The final category of forces is that of short-range

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forces. These forces contribute to adhesion if an adhesion surface is in place. These short-range forces include chemical bonds, intermediate bonds and hydrogen bonds.

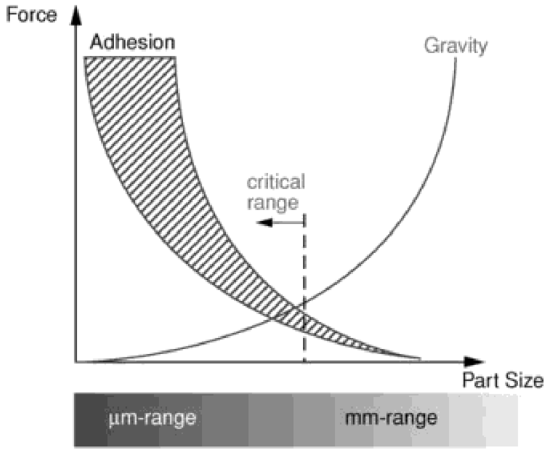

Figure 5.6: Significant forces depending on part size, (Sanchez, 2010)

Strength

Cecil *et al.* (2007) state that electrostatic forces are the strongest; the second strongest are capillary forces, then Van der Waals forces and finally magnetic forces. According to Ishihara *et al.* (1996) the typical forces that have a great influence in the air are Van der Waals, liquid bridge and electrostatic. The liquid bridge force is simply a result of surface tension. These forces are explained with the use of figure 5.7.

Size

When gripping a spherical object with a smooth surface, surface tension forces dominate when the sphere has a radius of 1 mm; Van der Waals forces dominate when the sphere's radius is in the region of 100 μm; and electric charge force dominates when the sphere has a radius of 10 μm, (Menciassi *et al.*, 2004). Arai *et al.* (1996*b*) concur with this by stating that adhesion forces only affect objects that are less than 100 μm. In general, the effects of different forces when considering size can be seen in the figure 5.8.

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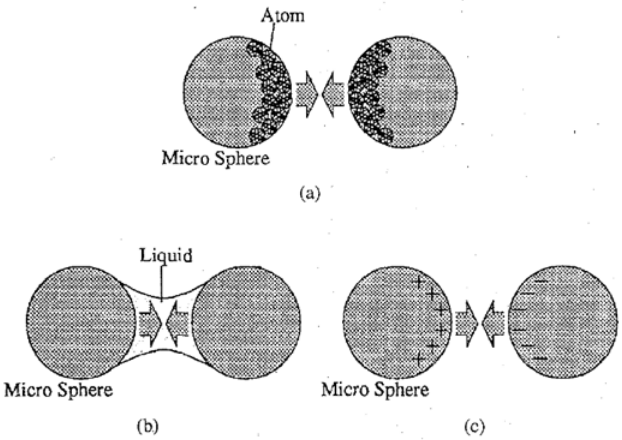
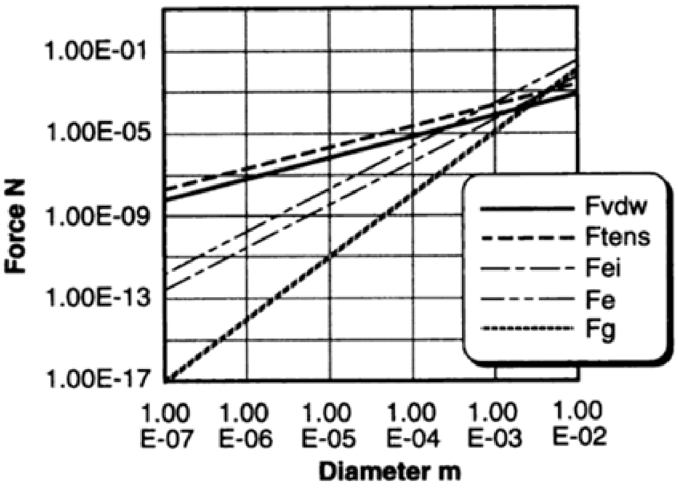


Figure 5.7: Attraction Force Between Micro Objects. a) Van der Waals. b) Liguid Bridge Force. c) Electrostatic Force. Ishihara *et al.* (1996)



F_{vdw}: van der Waals force; F_{tens}: surface tension force; F_{ei}: electrostatic force between charged body and uncharged body; F_e: electrostatic force between the charged bodies.

Figure 5.8: Gravitational and Adhesive Forces Compared Fukuda and Arai (1999)

Prevention Methods

An important consideration when executing micro-material handling is the occurrence of the “sticking” effect. The sticking effect occurs when adhesion forces $F_{adhesion}$ become greater than the force of gravity $F_{gravity}$, as per figure 5.9.

There is a wide vary of methods to decrease the affects of the above-

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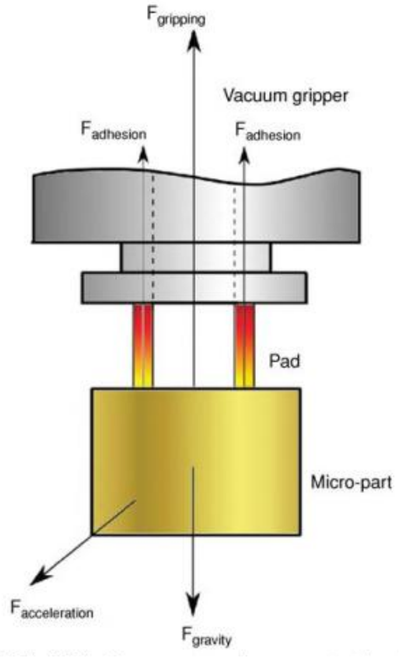

Figure 5.9: Force Vectors in Contact Handling, (Sanchez, 2010)

mentioned forces. Sanchez (2010) lists the following forces and methods of reducing them. Hydrophobic coatings can be used to decrease the effect of surface forces, conductive materials can be used to reduce electrostatic forces and Van der Waals forces can be reduced by increasing the surface roughness profile.

Owing to the fact that adhesive effects are increased at the micro scale, it is important to reduce the contact area of the end effector. Reducing the size of the contact area will ease the release of the gripped item, (Tanikawa and Arai, 1999). One manner of reducing the contact surface area is to make use of spherical grasping tips as opposed to planar grasping tips, (Fearing, 1995).

Deposition

Another issue affecting micro-material handling is that of deposition, (Cecil *et al.*, 2007). According to the source, deposition occurs when particles attach physically to the specified material. Deposition is determined by long-range forces whereas adhesion is determined by short-range forces, (Cecil *et al.*, 2007).

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5.1.4 Van der Waals

Arai *et al.* (1995) define the Van der Waals force as the force acting between atoms. This force is caused by orientation effect, excitation effect and dispersion effect. The dispersion effect results from instantaneous dipole generation when two atoms are in close proximity, Arai *et al.* (1995). Van der Merwe and Matope (2011) states that the effects of the Van der Waals forces are more active than those of surface tension, electrostatic and viscosity forces when considering a dry environment (humidity less than 9%). Van der Waals forces are highly dependent on the surface roughness of the contact areas, Arai *et al.* (1996*a*). The smoother the surfaces, the higher the Van der Waals forces exerted, (Van der Merwe and Matope, 2011).

In order to increase the surface roughness and thereby decrease the Van der Waals forces Arai *et al.* (1996*a*), coated a silicon plate with copper. In the source, experiments successfully proved that an increase in surface roughness effectively reduces adhesion forces. A similar approach was used in Arai *et al.* (1996*b*) where micro pyramids or sharp projections were etched into the surface of the gripper material. These micro pyramids, approximately 1.5 μm high, were then coated with a thin layer of Au (gold).

The above two adhesion forces were proven to be reduced by experimentation conducted by Arai *et al.* (1996*b*). A centrifugal force was applied to silicon dioxide spheres. The number of spheres that were not displaced gave an indication of the effectiveness of the applied adhesion reduction method. The graph below 5.10 indicates that Au-coated micro pyramids are far more effective at reducing adhesion affects than simply plating a material with Cu.

The micro pyramids used in Arai *et al.* (1996*b*) can also be used to reduced the electrostatic force. This is accomplished through self-discharge ion elimination, as explained in the previous sub-section. To further the reduction of this force, the contact plates were grounded.

5.1.5 Coarse-to-Fine System

The University of Stellenbosch currently has a Motoman SDA-10 dual robotic arm system. Each of these arms has 7 degrees of freedom, when combined with rotating torso results in 15 degrees of freedom. This system has a repeatability of 0.1 mm or 100 μm according to (RobotWorx, 2011). This is clearly insufficient when examined in relation to the components and cavities.

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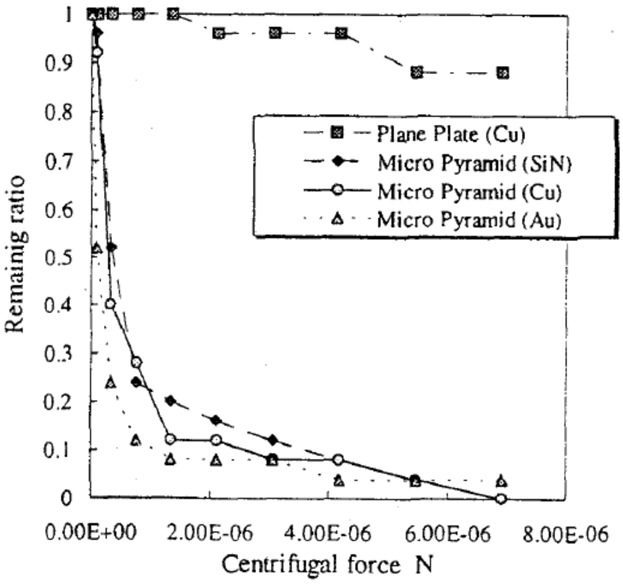

Figure 5.10: Experimental Results. Arai *et al.* (1996*b*)

Need for a Micro-Material Handling System

Brecher *et al.* (2005) and (Cecil *et al.*, 2007) state that a large component of micro-systems assembly is still being done manually. This strategy is time-consuming and inefficient. Despite this, the functionality used in manual micro-material handling still needs to be executed using robotic systems. Vision has to be performed by cameras instead of eyes; arms have to be replaced by micro-positioning stages and manual tweezers have to be replaced by automated grippers, (Cecil *et al.*, 2007).

A prime example of the need for the afore mentioned system is the handling of thin wires or micron diameter glass fibres. Another area to be considered is the production of flow sensors for medical engineering. The fundamental similarity between these applications and a wide variety of applications in industry is that assembly has to be executed manually as the necessary technology is either too expensive or does not exist, (Brecher *et al.*, 2005).

Ando *et al.* (2004) states that there is a high demand for micro-material handling systems. There are also few systems that have the ability to manipulate micro-materials with the accuracy of several micrometers. There are even fewer systems that incorporate force feedback for this micro-manipulation, (Ando *et al.*, 2004).

Again Freundt *et al.* (2008*a*) states that although many robotic systems exist for macroscopic assembly, there is no highly flexible and precise robotic

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system commercially available with a positioning accuracy of less than 1 μm. As per Sanchez (2010) the tele-operating micro-handling system that do exist are usually tailored to a specific task. There is also a lack of standard components for high precision micro-material handling, (Freundt *et al.*, 2008*a*).

There is a lack of highly flexible and yet precise micro-material handling systems, (Sanchez-Salmeron *et al.*, 2005). Sanchez-Salmeron *et al.* (2005) and Sanchez (2010) both state that one of the major challenges associated with micro-material handling is the fact that there is a need for high accuracy over a large range of distances. Micro-handling systems are precise; they are also very specialised and inflexible, i.e. they have been designed solely for one purpose, (Freundt *et al.*, 2008*b*). Freundt *et al.* (2008*a*) concur with Sanchez-Salmeron *et al.* (2005) by stating that high precision systems with more than 3 degrees of freedom, that could be used in automated micro-material handling applications, are not commercially available. This is the exact nature of the intended micro-material handling system.

The Coarse-to-Fine Solution

Freundt *et al.* (2008*b*) state that even the most precise macro-handling robot systems cannot be applied to a micro task with accuracies in the order of 1 μm, as only 20 μm is currently achievable. Despite this level of inaccuracy there are many advantages associated with macro or coarse material handling systems. The advantages of such systems are high flexibility, availability and a large working range. The accuracy of the coarse systems can be improved by combining them in series with a highly precise active assembly head. According to Freundt *et al.* (2008*b*), a coarse-to-fine hybrid system combines the large work space and dynamics associated with a coarse positioning system and the accuracy associated with a fine positioning system.

In agreement with Freundt *et al.* (2008*a*), Sanchez-Salmeron *et al.* (2005) and Brecher and Peschke (2006) proposed the solution of using a system incorporating a coarse-to-fine strategy. In this strategy, a large less-accurate robotic manipulator provides the large scale and less accurate movement. A smaller, and more accurate manipulation system, is then placed onto the 'large' system in order to achieve precise movements, (Sanchez-Salmeron *et al.*, 2005).

Sulzer and Kovac (2010) designed a macro to micro-material handling system. This system made use of an Epson Scara Robot type: E2C 351 and the Milasys Minirob fine positioning system. The Scara robot achieved the macro positioning while the fine positioning was achieved by the Milasys Minirob piezo system. The precision of the Minirob fine positioning system allowed nanometre accuracy to be achieved owing to its incorporation of piezo-actuated

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drivers, (Sulzer and Kovac, 2010).

Mueller *et al.* (2012) compared a gantry-type system and that of a coarse-to-fine system. Both approaches were considered in light of the piezo-ceramic case study. Cartesian or gantry-type robots are generally designed for a specific purpose. This approach is thus usually limited by a mechanical structure. Coarse-to-fine robots generally have a much higher degree of flexibility. An additional advantage to the coarse-to-fine system is that if the fine positioning system is treated as a tool, the system becomes highly reconfigurable. The control of a coarse-to-fine system can be separated according to the tool and to the coarse positioning system. Mueller *et al.* (2012) concludes this comparison by stating the following:
"For the integration of the micro-assembly in existing assembly lines of macro-size products, the coarse-to-fine positioning approach is favourable, " (Mueller *et al.*, 2012).

When short cycle times and small positioning distances are required, the best approach is that of Cartesian systems. Coarse positioning systems, on the other hand, perform well above 500 mm. They also have the advantage of incorporating reconfigurability, (Mueller *et al.*, 2012).

Coarse-to-Fine Components of A Micro-Material Handling System

The micro-material handling system can be considered a system composed of three parts. The first is the coarse positioning system. The coarse positioning robot provides the macro movements over large distances, as per the coarse-to-fine strategy in Sanchez-Salmeron *et al.* (2005). Brecher and Peschke (2006) concur with a system where a robot carriers out the pre-positioning for the micro-assembly. The Motoman SDA 10 system provides a highly reconfigurable yet rigid manipulation system. Therefore, it is feasible for use as the coarse positioning system. An example of this concept can be seen in figure 5.11.

As per Sanchez-Salmeron *et al.* (2005), the second part, or fine positioning system, provides the accuracy needed for micro manipulation. This system moves the end effector in the order of millimetres to micrometres. It is important to note that the fine positioning system will be mounted onto the coarse positioning system. The weight and size of the fine positioning system should thus be kept to a minimum. This will allow the system to be quickly and effectively manipulated.

According to Sulzer and Kovac (2010) and Freundt *et al.* (2008*a*), in order to construct the best possible micro-material handling system, it is necessary

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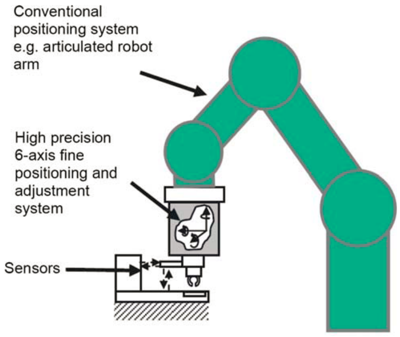

Figure 5.11: Hybrid System Concept Consists of a Coarse Positioning System and a Fine or Precise Positioning System, (Freundt *et al.*, 2008*a*)

to consider the manner in which the various feasible options for each stage interact with each other. This concept is highlighted in Sulzer and Kovac (2010) where the DIN ISO interface standards were used. These standard interfaces allow for fast and effective tool changes. This facilitates easier maintenance and reduces design time. Neugebauer *et al.* (2010*a*) made use of the Schunk MWS20 tool changing system. This system allows for the easy change of tools. It also complies with the German standard DIN 32565 interface, (Neugebauer *et al.*, 2010*a*).

Problems Affecting Coarse-to-Fine Systems

A major issue in a coarse-to-fine positioning system is that the fine positioning stages limit the flexibility of the assembly/handling system, (Freundt *et al.*, 2008*b*). This is due to the face that the fine positioning system has a small area of operation. Current fine positioning systems are not able to measure positioning errors, (Freundt *et al.*, 2008*a*). The source continues on to state that fine positioning systems can thus only be used in applications where sensor information can be used to control fine positioning. Brecher and Peschke (2006) states that the error associated with step size can be disregarded if the position of a micro component is determined relative to a reference point. In this case the gripper tips were used as a reference point. The combination of a reference point and a high resolution cameras provide the needed feedback.

Freundt *et al.* (2008*a*) states that fine positioning units can only be combined with positioning systems that have a high degree of inertia i.e. machine tools. This high degree of inertia greatly reduces vibrations and the need for drive deactivation however the dexterity associated with 6 axis robots is thus not achieved.

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Another problem stated by Brecher and Peschke (2006) is that fine positioning systems are highly sensitive to mechanical impact. Klocke (2011) goes so far as to say that some fine positioning system are so accurate that they are even susceptible to errors due to incorrect orientation. This kind of sensitivity has to be avoided if a dexterous system is to be implemented.

Thermal and Vibrational Problems

Both Freundt *et al.* (2008*b*) and Sanchez (2010) state that micro handling systems are greatly affected by thermal fluctuation and vibrations when compared to macro-material handling system. Macro robots are however more sensitive to vibrations and thermal fluctuations.

There is a lack of standardised components as well as the controlling software needed to implement micro-material handling. This lack of hardware and software means that in the majority of cases it is more feasible to manually assemble or handle the micro-materials, (Freundt *et al.*, 2008*b*).

A major problem associated with the coarse-to-fine approach is that of vibrations. These vibrations are caused by the active drive and need to be suppressed, (Freundt *et al.*, 2008*a*). In a 6 axis robotic system these vibrations can be several micrometres. Figure 5.12 shows the vibrations associated with a robot arm when responding to the force of gravity, (Freundt *et al.*, 2008*a*). These vibrations become detrimental to positioning accuracy when considered in the context of precise micro-material handling on the order of 1μm.

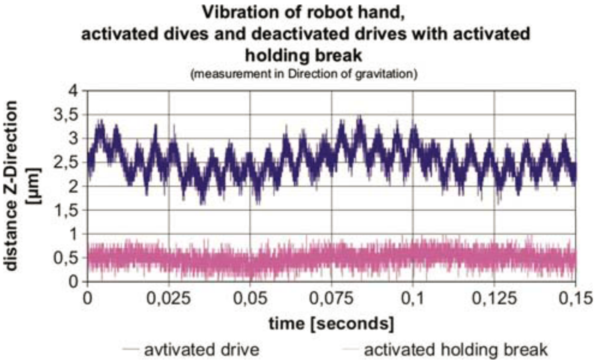

Figure 5.12: Robot Hand Position Deviation as a Result of Activating the Brakes and Deactivating the Drive, (Freundt *et al.*, 2008*a*)

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Solutions

The main advantage of using a dedicated system such as the micro factory used by Neugebauer *et al.* (2010*a*) is that due to the low inertia of its parts, very accurate high speed movement can be executed. There is thus potential for high speed production when compared to a high-inertia and slow-moving 6-axis robot. The parallel kinematics of this particular system also make it less susceptible to vibrational and thermal effects. Neugebauer *et al.* (2010*a*) also states that this micro factory concept allows for parallel assembly of different variations.

Freundt *et al.* (2008*a*) state that one solution to reduce these vibrations is to operate the robot with its brakes on and drives deactivated. This shifts the load from the drive train to the brakes. This change, however, causes the robot arm to sag. Experiments carried out by Freundt *et al.* (2008*a*) show that the robot hand moves approximately 300 μm away from the instructed position when the brakes are used. This is illustrated in figure 5.13. The measured deviation itself is subject to a deviation of ±100 μm as a result of friction, (Freundt *et al.*, 2008*a*).

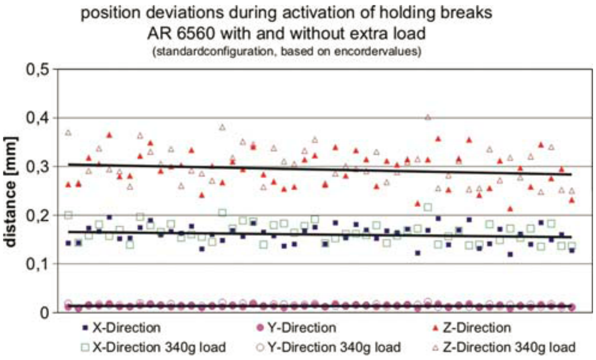

Figure 5.13: Vibrations of the AR6560 Arm Acting Against Gravity, (Freundt *et al.*, 2008*a*)

According to Freundt *et al.* (2008*a*), a coarse-to-fine positioning system can be used for precise micro-material handling, if the second stage or micro robot is designed to permit a travel of at least 1000 μm. This relatively large range of motion enables compensation for sagging.

In micro-material handling it is important to control structural set-point vibrations. Sanchez (2010) states that even with advanced controllers it is difficult to control machines without deflections and vibrations. The aforementioned source states that one solution to controlling set point vibrations

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is to implement input shaping. Input shaping eliminates decaying sinusoidal responses in a similar fashion to a notch filter, (Sanchez, 2010).

5.1.6 Fine-Positioning Actuators

The range of motion required from 1 micron to 100 microns is best satisfied by using DC and stepper motors, (Ouyang *et al.*, 2008). These conventional actuators are most appropriate where large motion ranges are required. When high accelerations are required, PZT actuators are more appropriate, (Ouyang *et al.*, 2008).

Ouyang *et al.* (2008) states that PZT actuators are more cost effective than conventional stepper and DC motors. PZT actuators also have high accuracy and accelerations. With the correct modelling and feedback, their non-linearity errors can be solved, (Ouyang *et al.*, 2008).

5.1.7 Sequence

According to Sanchez (2010) there are two main problems associated with automated micro-material handling. The first is inter-machine or inter-station transport. The second problem is the handling of the micro-material at current station or machine. When examining the problem of station/machine micro-material handling, it is also necessary to consider whether to handle individual components or handle a number of components in batches.

One of the aims of this project is to design a reconfigurable system that performs a pick-and-place task. According to the source serial pick-and-place processes are composed of the following subtasks, (Sanchez, 2010).

1. Picking sub-task
2. Hold and transport sub-task
3. Placing sub-task

Generic Tasks

In order to effectively perform complex micro-material handling tasks, the fine positioning system should be able to perform three separate process steps. The first step is picking up the micro part from the components holder. The second step is moving the part to the desired location and then aligning it. The final step is placing and positioning of the micro part, (Freundt *et al.*,

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2008*a*),(Neugebauer *et al.*, 2010*b*), and (Freundt *et al.*, 2008*b*). Sanchez (2010) describes the steps of micro-material pick and place in more detail, as can be seen in figure 5.14 and in table 5.2.

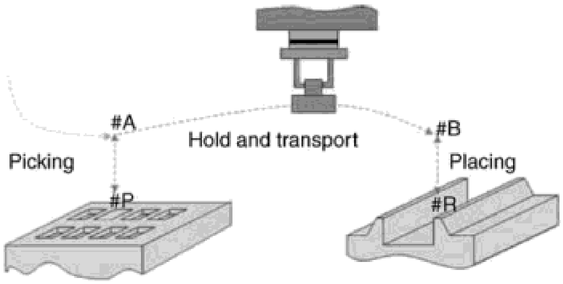

Figure 5.14: The Four Steps of a Pick and Place Task, (Sanchez, 2010)

Table 5.2: Sequence of Actions in Pick-and-Place Task, (Sanchez, 2010)

Sub-task	**Action**	**Velocity**	**Trajectory**
Picking	0. Move to # A	100%	Joint Space
	1. Approach to # P	30%	Cartesian Space
	2. Grasp	0%	Cartesian Space
	3. Depart to # A	70%	Cartesian Space
Hold and Transport	4. Transport # B	100%	Joint Space
Placing	5. Approach # R	30%	Cartesian Space
	6. Release	0%	Cartesian Space
	7. Depart to # B	70%	Cartesian Space

An example of a more complex and realistic pick-and-place sequence can be found in Tamadazte *et al.* (2008). The tasks completed are listed as follows: auto focusing, component detection, alignment of component, positioning of component under gripper, opening of gripper, descension of gripper, closing of gripper, grasping of component, ascension of gripper, positioning of component, decension of gripper with component, and opening of gripper. This sequence was able to achieve a positioning error of 1.4 μm with objects of a similar size to the intended case study or around 300 μm × 300 μm × 300 μm, (Tamadazte *et al.*, 2008). Freundt *et al.* (2008*b*) illustrates a similarly detailed and complex approach in the figure 5.15.

Task Sequence to be Executed by Coarse to Fine System

A micro-material handling robot should be able to move quickly and accurately in small increments, (Neugebauer *et al.*, 2010*a*). The aforementioned

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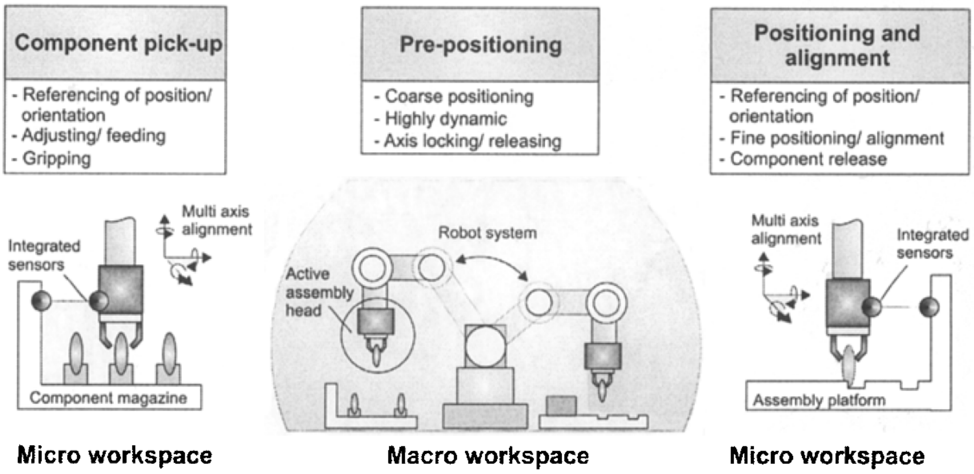

Figure 5.15: The Three Steps Needed in Micro-Assembly and Micro-Material Handling When Using a Coarse-to-Fine System, (Freundt *et al.*, 2008*b*)

increments should have high repeatability and dynamics. The system should also be able to quickly and effectively detect the appropriate micro-cavity. In order to further increase its effectiveness the material handling system should also be reconfigurable, (Neugebauer *et al.*, 2010*a*). If the system is reconfigurable, different materials can be handled using the same manipulator.

As is stated in the Introduction chapter the system is being designed with the piezo-ceramic element placement and slot machining case study in mind. The idea is to use a base coarse-to-fine positioning system with a micro-milling spindle to micro mill various cavities. The spindle is then detached and the gripper then attached. The gripped then picks and places piezo-ceramic components into the recently milled slots. In light of this, there are numerous different possibilities for different end effectors and operation sequences. The different options are illustrated in figure 5.16. One advantage over this approach is that slots can be dexterously machined into angled surfaces at different orientation (this is not possible to achieve when using a conventional cnc machine). Piezo-ceramic parts can then be placed in these obscure orientations.

5.1.8 Size and Cost Considerations

Prusi *et al.* (2011) examined a number of different factors affecting robots used for micro-manufacturing and handling. These factors should all be considered when designing any system operating on the micro level. These factors can be seen in figure 5.17.

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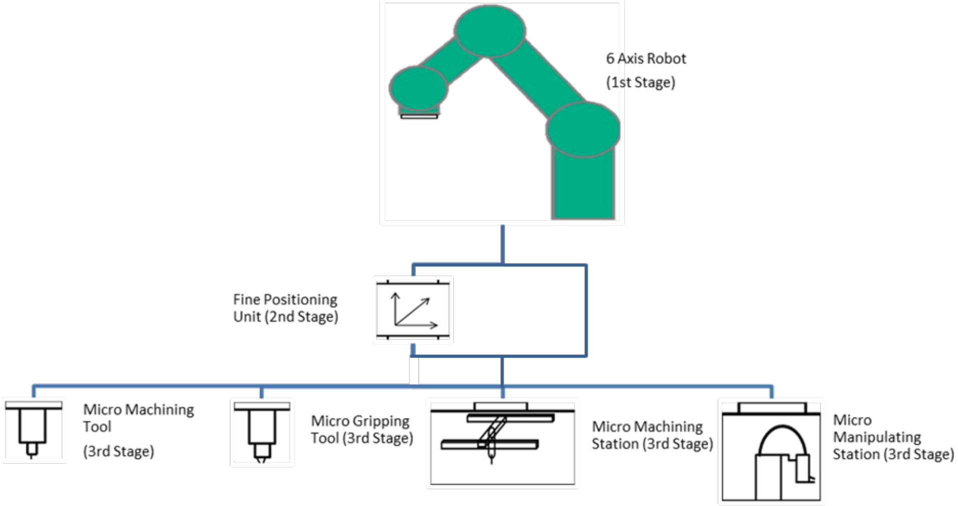

Figure 5.16: Options for Each Different Stage- 1st, 2nd, 3rd

Size

The size and weight of actuators becomes a dominant factor when compared to the other structures in a robot for micro-manufacture or handling, (Prusi *et al.*, 2011). This same issue applies to cabling and mountings. These issues are two of the factors preventing simple downscaling of existing macro solutions.

Prusi *et al.* (2011) states that size also negatively affects design when smaller components are needed. Smaller components are not as widely available. When small commercial components are available, they are usually very expensive. This price-size comparison has been plotted by Prusi *et al.* (2011) as can be seen in figure 5.18.

It also becomes difficult to implement sensors in the micro domain, because of size, weight, cabling, and proximity to measured surface, (Prusi *et al.*, 2011). Camera and vision systems are therefore, one of the most appropriate types of sensors.

An additional consideration is that of tolerances. A tolerance when viewed from a micro-level perspective appears far ‘larger’ than when viewed from a macro-level perspective. This difference in tolerances can result in backlash, misalignment, play and an overall performance decrease, (Prusi *et al.*, 2011).

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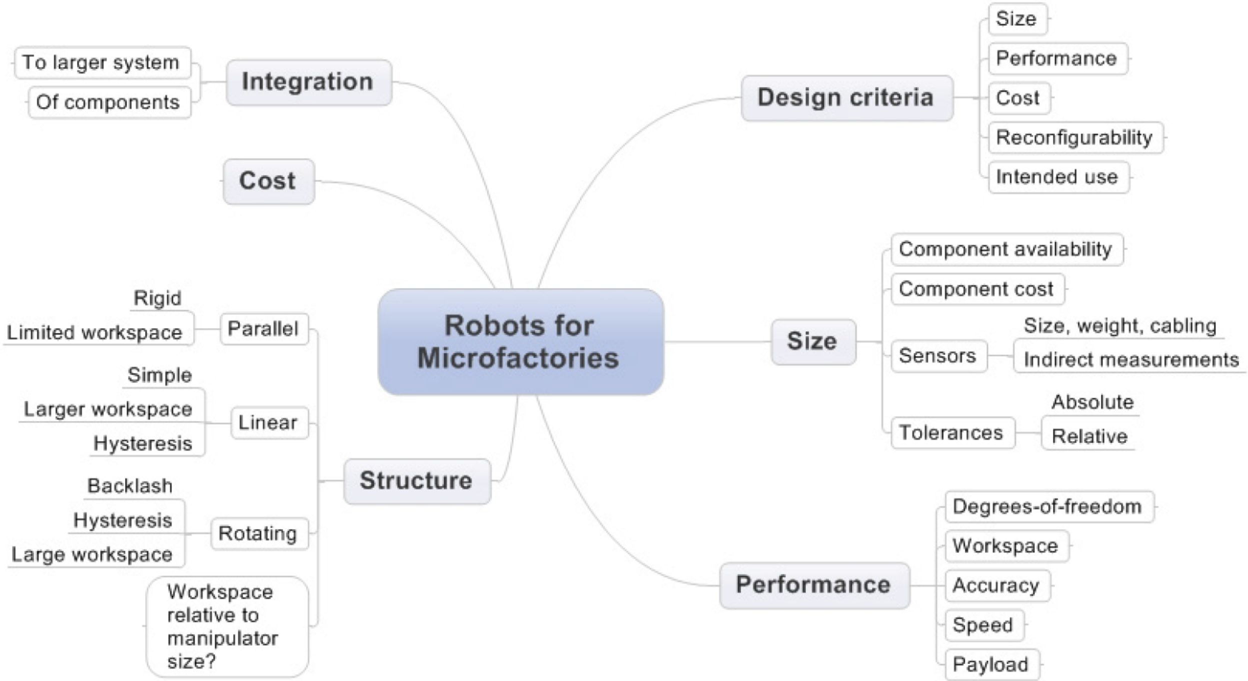

Figure 5.17: Different Factors Affecting the Design and Use of Robots in Micro and Desktop Factories, (Prusi *et al.*, 2011)

Cost

The industries of micro-systems technologies (MST) and electronics have been the main driving factor for an increase in the need for high accuracy equipment, (Koelemeijer Chollet *et al.*, 2003*b*). There is much emphasis on the idea that this increase in accuracy be combined with flexibility. The combination of these two attributes is essential when considering batch production, (Koelemeijer Chollet *et al.*, 2003*b*).

Koelemeijer Chollet *et al.* (2003*b*) state that the cost associated with micro-assembly is high because of the needed accuracy and relatively low yields. When performing assembly at the micro level, the limits of human performance are reached. Both Heilala *et al.* (2008) and Koelemeijer Chollet *et al.* (2003*b*) state that automation becomes imperative in order to achieve technical feasibility. Heilala *et al.* (2008) continue on to state that this is even the case in low-cost-labour countries.

In agreement with the above, Puik *et al.* (2011) state that micro-systems are usually manufactured for niche markets in batch sizes. When specialised equipment is used, a high product value is required in order to make the investment cost-effective. The use of workers, on the other hand, greatly reduces

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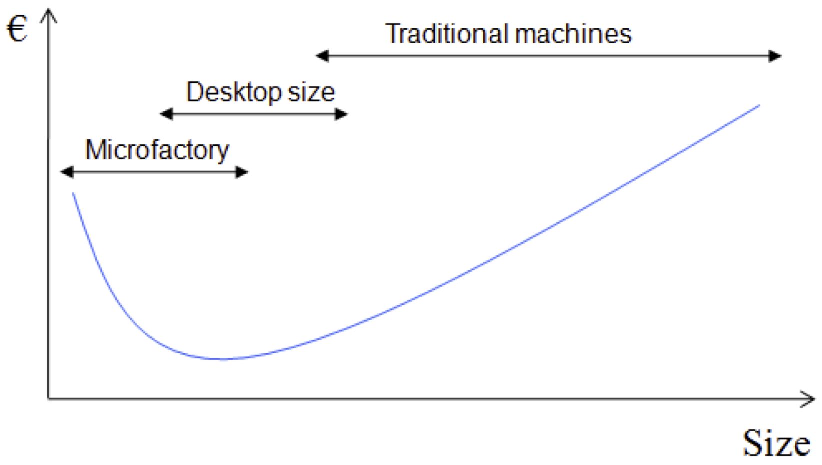

Figure 5.18: Component Size Versus Price, (Prusi *et al.*, 2011)

both quality and throughput. It is thus necessary to find a balance in the degree of automation in a dynamic market, (Heilala *et al.*, 2008).

Challenges

As per Dimov *et al.* (2012), there is a general need for the miniaturisation of products. There is a further need to predict product and or process performance. This helps to ensure that the amount of risk during production is reduced. A final need is to increase and improve production, (Dimov *et al.*, 2012).

Dimov *et al.* (2012) make mention of the fact that one of the major challenges associated with micro-manufacturing in general is the necessity of new standards. New standards and tolerance methods will address scaling issues, as well as process material interactions, (Dimov *et al.*, 2012).

Investing in automation equipment comes with the high risk of not being able to recoup the investment. Puik *et al.* (2011) state that the niche items have a short production life. This short life means that there is little time for errors to be corrected and thus the investment to be recouped, (Puik *et al.*, 2011).

Assembly Challenges

One of the major barriers to entry into micro production is that of assembly cost. The smaller the size of the components, the greater the cost associated

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with assembly. This increase in cost is due to an increase in cycle times and reduced accuracy, (Koelemeijer Chollet *et al.*, 2003*a*). In addition to this, Dewhurst and Boothroyd (1988) state that assembly is considered the most labour-intensive activity on a micro level.

Assembly cost represents approximately 50 percent of the total production cost, Koelemeijer Chollet *et al.* (2003*a*). In the majority of cases dedicated production lines are created for mass production. This serves to decry the original intention as micro-systems are used predominantly for specific applications and therefore small batches, (Koelemeijer Chollet *et al.*, 2003*a*).

Early Cost Estimating in Product Design

Dewhurst and Boothroyd (1988) state that there is a need to estimate manufacturing costs before component designs are fully detailed and without exact knowledge of the manufacturing process plans. These cost estimates are therefore based on assumed optimum manufacturing methods.

It is essential to analyse the issue of cost as early as possible during the design and implementation of a system. There are a number of factors affecting cost besides the initial purchase price of the system. A few of the afore mentioned factors include: operating cost, scrapping costs, throughput of system, and yield, (Heilala *et al.*, 2008).

5.1.9 Cost of Manual Micro-Material Handling

Precision micro parts are handled on numerous occasion both during manufacturing and assembly. Gillespie (2009) states that in one instance a micro part was handled a minimum of 25 times. In addition to this, groups of these parts were handled more than 26 times. Some common operations include machining, inspection, counting, cleaning, etc. Some micro parts are handled numerous times during single processes. This is due to the need for orientation, (Gillespie, 2009).

Gillespie (2009) sites the following example. In the example 10 machinists work to manufacture micro parts and these are paid R 120.00 an hour. If the handling time of each machinist was reduced by 15 minutes a day, the overall savings would be R 76 000.00.

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5.2 Commercial Definition

After conducting extensive research, as per the Coarse-to-Fine System section, it has been shown that there is currently no commercial system that offers the necessary high level of accuracy over a wide range of dexterous operations. Having established this, it is necessary to determine if there is an actual commercial need for a system being designed.

According to Tidd and Bessant (2009), there are very few new-to-world products. The majority of products take the form of extensions, variations and adaptations around core ideas. The designed system can be thought of as a recombinant innovation. The designed system is a combination of a fine positioning system and a macro or coarse positioning system. Both of these systems are currently separately commercially available. The newness of the system is illustrated by the fact that coarse and fine positioning systems are being taken out of their original context, combined and applied in a new context.

Kautt *et al.* (2007) defines the designed micro-material handling system as a sustaining technology. The system is a sustaining technology as it reinforces the current industry standard technology paradigms in that it uses available technology to enhance current production making it faster, and more effective.

Despite the designed system being a need pull innovation (potential market need), the fact that the project was initiated by the Fraunhofer research institute in Germany indicates that the project has elements of a technology push innovation. The relationship of technology push and market pull innovations is best surmised in the figure 5.19 from the source (Alting *et al.*, 2003).

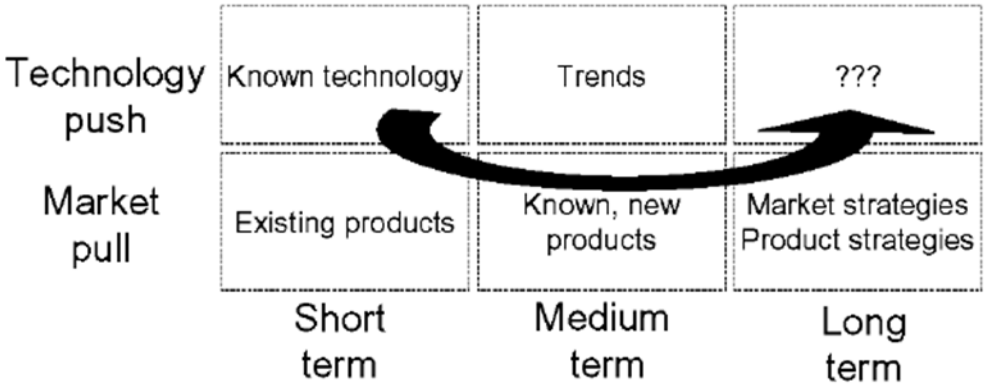

Figure 5.19: The Interaction Between Market Pull and Technology Push (Alting *et al.*, 2003)

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Alting *et al.* (2003) state that in order to secure market focus and ensure long term technology development, it is necessary to make use of a product-driven approach. The figure illustrates how technology pushed innovations are useful for short to medium-term development. Long term development can however only successfully be obtained from a market pull innovation or approach. The technology push provided by Fraunhofer will assist this innovation through to the medium term. Thereafter, the greater market pull will ensure that long-term development of this innovation is ensured.

5.2.1 Building the Innovation Case

In accordance with Tidd and Bessant (2009), one of the first steps in building the innovation case is to establish the details of the product. Tidd and Bessant (2009) analysed over 200 studies to determine which factors were essential for successful innovation. The four major factors identified were assessment of market opportunity, customer identification, potential barriers to entry and resources required.

Assessment of Market Opportunity

According to the source Exchange Micro-Electro-Mechanical Systems (MEMS) or Micro Systems Technology (MST) can be defined as a miniaturised mechanical and electro-mechanical element that is made using micro fabrication. Another definition as per Vigna (2006) is that MEMS are micron dimension devices that interact with the macro world. They are manufactured via micromachining and are typically described as a three-dimensional mechanical structure, usually on a silicon substrate.

Micro-assembly is widely used for the manufacturing of MEMS Gauthier and Régnier (2010) and hybrid microsystems. Schubert *et al.* (2010) state that due to a large number of developments in Micro-Systems-Technology (MST) it is now possible to launch industrial applications. Schubert *et al.* (2010) continues on to state that owing to these developments, metallic parts with sensor and actor properties are required.

Need for a Micro-Material Handling System

Hsu (2005) states that the majority of micro-assembly practices require human operators to pick and place micro parts manually. The human operators use tweezers and microscopes. The source states that the continual use of microscopes creates severe eye strain and makes it difficult for the users to achieve the necessary accuracy. The process is, therefore, not only inefficient but costly, (Hsu, 2005). Onori *et al.* (2005) state that human hands are also

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limited by their physical size and dexterity. According to Hsu (2005), one of the main reasons for the high cost of packaging and assembly of micro sized items is the lack of automation. In concurrence with this Qin *et al.* (2010) states major advance is needed in the handling and inspection of micro-scale manufacturing.

Hsu (2005) states that a fundamental requirement of an automated micro-assembly system is that the system has the ability to transport and precisely manipulate micro-materials. The micro-materials can thus be aligned and, if necessary, inserted with a high level of accuracy and speed. Qin *et al.* (2010) again concur with the aforementioned source and state that a key issue in MEMS manufacturing is the need for effective gripping and manipulation strategies when performing micro-assembly.

The source Zhou and Fatikow (2008) states that handling material at the micro scale is far more challenging than handling material at the macro scale, not only because of size restrictions but also because of variations in the strength of adhesion forces. The source goes on to say that innovative thinking and novel technology are needed to overcome the challenges presented. Despite these challenges, automating the micro handling process is essential for achieving high efficiency and reliability, (Zhou and Fatikow, 2008).

Sun (2009) states that current (2009) ultra-precision machine tools are expensive and too focused on specific applications. It is therefore necessary to develop equipment and solutions for micro-manufacturing that can perform mass customisation and fulfil dynamic requirements.

There is a lack of highly flexible and yet precise micro-material handling systems, (Sanchez-Salmeron *et al.*, 2005). One of the major challenges associated with micro-material handling is the fact that there is a need for high accuracy over a large range of distances. Freundt *et al.* (2008*b*) states macroscopic 6 axis robotic systems can only achieve a repeatability of 20 μm. An accuracy of 1-5 μm is needed for the intended application.

Nature of the Micro Technology Market
There has been little advancement in the field of micro-material systems in South Africa (SAinfo, 2008). It was thus decided to analyse the world micro technology market as a potential source of customers. The Nexus Market analysis for Microsystems has been the most recognised market data source for Microsystems worldwide since 1998, (Wicht and Bouchaud, 2005). According to the source the world market for MEMS and Microsystems grew from $ 12 billion in 2004, to $ 25 billion in 2009. The largest segment of the market is that of Read/Write disk heads, as those used in hard drives, etc. Wicht and Bouchaud (2005) state that RW heads make up 51 percent of the market

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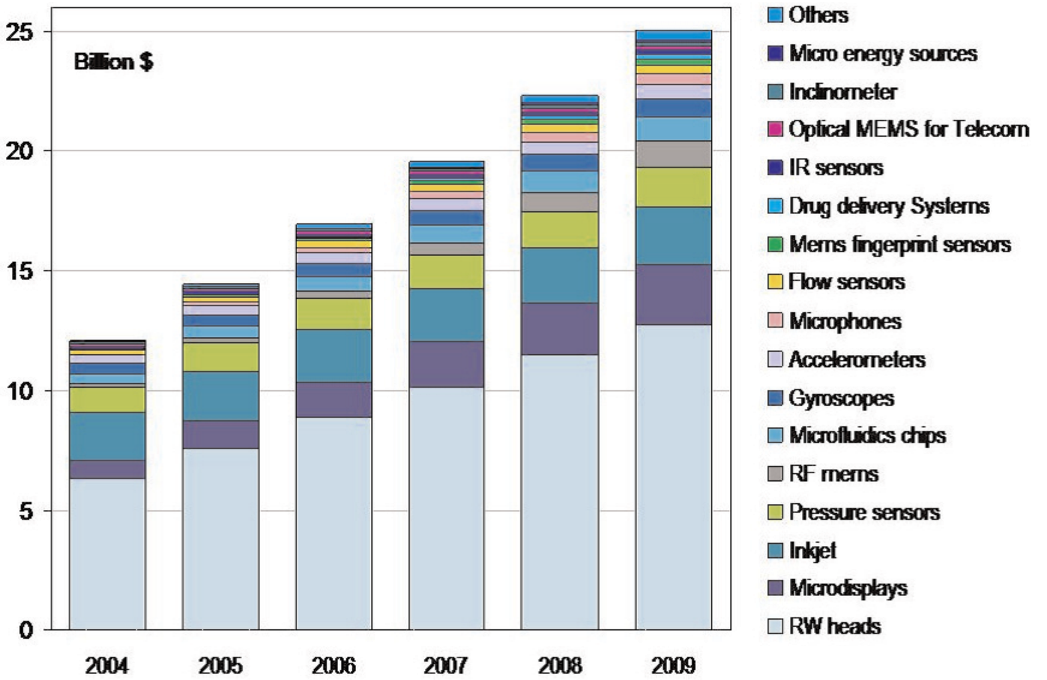
due to the inclusion of such devices in consumer electronics, i.e. iPods and smartphones.

Grace (2005) conducted a Delphi type research experiment to determine the progress of various aspects of a report card for the micro-material industry. This shows that Delphi-based research is feasible when determining the characteristics of the micro-material handling industry. The division of the MEMS market from 2004 to 2009 can be seen in figure 5.20.



* Other are: Microreaction, chip cooler, MEMS memories, liquid lenses, microspectrometer, wafer probes, micro-mirrors for optical processing, micro-pumps, micromotors, chemical analysis systems

Figure 5.20: The Division of the MEMS Market in Billions of Dollars as Predicted by (Wicht and Bouchaud, 2005)

Wicht and Bouchaud (2005) further divided the MEMS and micro systems market by application, as can be seen in figure 5.21. This division highlights the fact that IT peripherals, mainly due to RW heads, are dominant. Despite this dominance, IT peripherals face a decrease from 69 percent to 54 percent, (Wicht and Bouchaud, 2005). Consumer electronics, on the other hand, have grown rapidly from 6 percent in 2004 to 22 percent in 2009.

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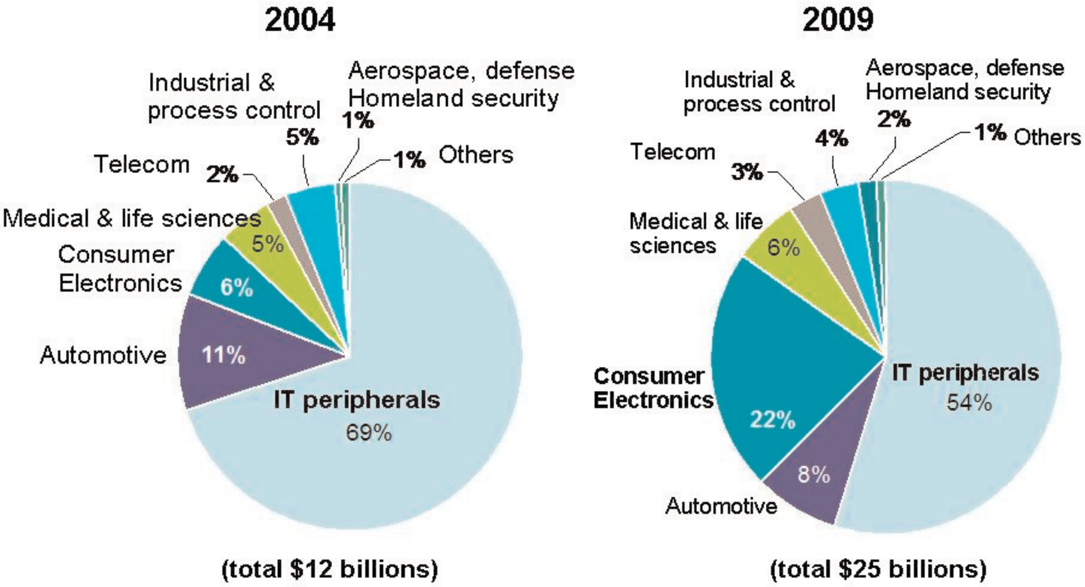

Figure 5.21: The Division of the MEMS Market in Billions of Dollars by Application Field as Predicted by (Wicht and Bouchaud, 2005)

Micro-assembly and micro-material handling are critical processes in micro-manufacturing, (Ehmann, 2007). The source Onori *et al.* (2005) states that this need for highly specialised micro-automation is a major factor in keeping micro-assembly knowledge within well-developed European companies. Micro technology is one of the key aspects aiding in the delivery of nanotechnology, (Dimov *et al.*, 2006). These elements are seen as an important contributor to Europe's economic future.

Dimov *et al.* (2006) conducted a road-mapping study for Multi-Material Micro-Manufacture. Attending a related workshop were 30 senior researchers, and 38 industrialists participated in a survey. The application areas included: micro-fluids, micro-sensors and actuators, and micro-optics. The diagram 5.22 helps to identify drivers, applications, micro technologies and challenges in the micro technology industry.

According to the panel assembled by Dimov *et al.* (2006), the major drivers for the Industry of Multi-Material Micro-Manufacture are lower cost, new markets/applications, improved product functionality, sensitivity and the volume production.

Dimov *et al.* (2006) also conducted a SWOT analysis to assess the barriers to successful manufacture of micro products, for Europe in the context of the

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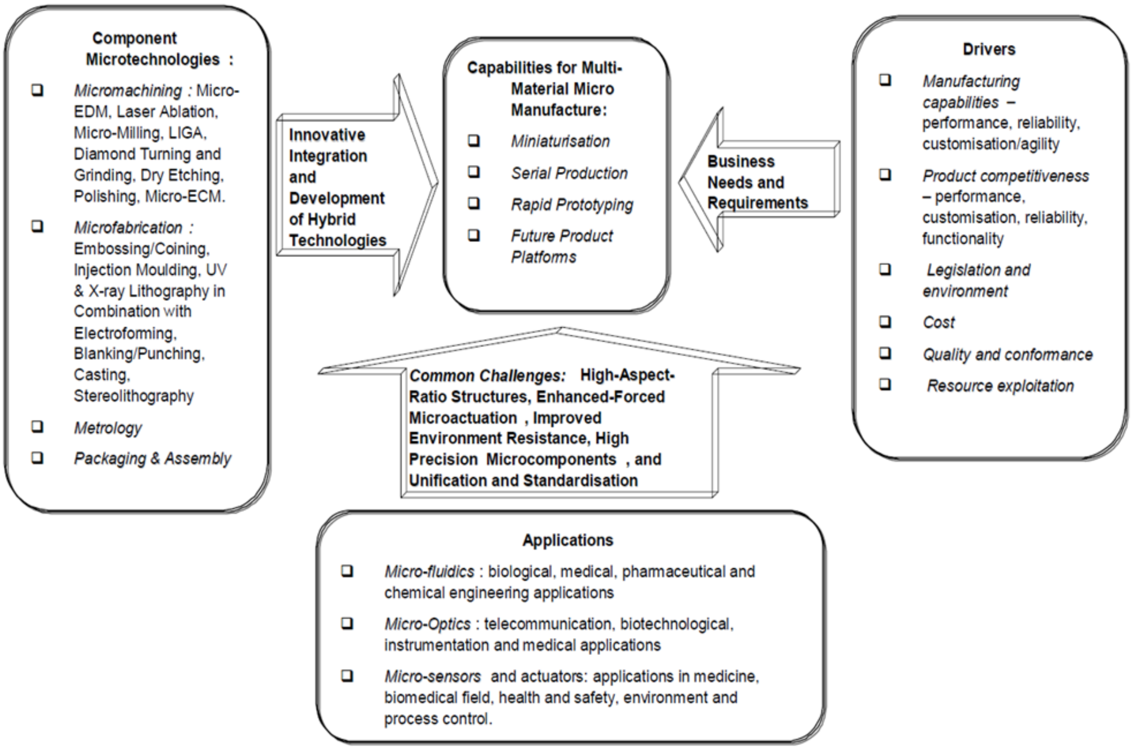

Figure 5.22: 4M Scope: Technologies, Business Drivers, and Technical Application Requirements Lead to Required or Provided Capabilities (Dimov *et al.*, 2006)

rest of the world. From the research a number of pertinent interpretations can be made. Firstly, Europe has a large number of highly trained people, particularly in multidisciplinary product development. Secondly, a major barrier to the adoption of micro technologies is cost. This barrier is compounded by the fact that a number of the micro technology industrial sectors are conservative. There is also a lack of knowledge-sharing between development centres and the industry.

Clarke (2011) states that according to IHS iSuppli research the global MEMS industry will grow 9.5 percent to \$ 7.73 billion in 2011. In 2010, 18.3 percent growth was recorded at \$ 7.06 billion. The research by IHS iSuppli states that the MEMS industry is then set to grow to \$10.81 billion from 2012 to 2014. One possible source of the difference in predictions between (Clarke, 2011), and the previously mentioned (Wicht and Bouchaud, 2005) (See figures 5.20 and 5.21) is (Wicht and Bouchaud, 2005) was written in 2004, whereas (Clarke, 2011) was written in 2011. Clarke (2011) is therefore assumed to be more accurate.

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As per Clarke (2011) a key contributor to this success was the inclusion of gyroscopes and MEMS microphones for noise suppression in handheld consumer electronics, such as the iPhone 4. A number of market followers soon after began inclusion of similar systems in their mobile phones. This can be seen from the fact that fewer than five cell phone models had MEMS gyroscopes in 2010, whereas in 2011 more than 45 phones and tablets had gyroscopes, (Clarke, 2011). MEMS are currently used in smartphones, netbooks, media tablets, gaming consoles, etc, (Clarke, 2011).

The source Martin (2011) states that Yole research group predicted 30 percent compound annual growth rate (CAGR) for multi-axis accelerometers from 2006 to 2011. Peter Cooney (practising director) states that smartphones provide the greatest boost to MEMS uptake. In agreement with this, Martin (2011) states that low g multi-axis accelerometers are prime examples of typical MEMS being employed in consumer electronics. A large number of suppliers are now active in this regard, with ADI and ST Microelectronics leading, (Martin, 2011).

Apple created the tablet market worth \$ 28 million in 2010 and \$200 million in 2015 for MEMS technology, (Lightman, 2011). Apple also pioneered the use of accelerometers and gyroscopes in cell phones with the iPhone (S). Another sector that is set for growth in this period is the automotive MEMS industry in China. This sector is set for large amounts of growth from 2009 to 2014. The Chinese government is also aiming to stimulate demand for optical MEMS components. This sector is thus set for a CAGR of 17 percent from 2009 to 2014, (Clarke, 2011). All of this growth means that, according to ABI research, 5 billion MEMS will be shipped during 2016, (Happich, 2011).

Identification of Target Customers

Kautt *et al.* (2007) states that companies are increasingly looking to external sources for obtaining new micro technology. Many governments are recognising micro and nano technology as a source of economic benefit. One expression of this can be seen in the international micro and nano technology centres being created in various countries. Companies are thus forming relationships with these “centres of excellence”, (Kautt *et al.*, 2007). These relationships clearly highlight how a product or system from a non-industry based institute, in this case a university, can be implemented by the appropriate firms.

A study conducted on the 2006 investment levels revealed that Europe (Germany and Switzerland) and Asia (Japan and Korea) will gain the most from developments in non-lithography based micro-manufacturing, (Ehmann, 2007). The study continues on to state that the U.S.A. places far less empha-

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sis on the government funding of micro-manufacturing and development of the micro-manufacturing industry. The MEMS industry is not yet structured in China, however China starts to play a role for labour-intensive process steps especially for assembly (Wicht and Bouchaud, 2008).

Ehmann (2007) states that research and development by the U.S.A in micro-manufacturing is behind the rest of the world . This is due to the fact that more emphasis has been placed on MEMS and nano technologies than on traditional micro-manufacturing methods. In direct contrast to this, countries such as Japan and Germany have invested heavily in micro-manufacturing research and development. It is essential that high levels of investment in research and development are executed as micro technology is an enabling technology for nano science, (Ehmann, 2007).

European (2009) states that according to the World Technology Evaluation Centre (WTEC) Europe is dominant in mechanically based micro-manufacturing. One of the major reasons for this dominance is the establishment of a large number of government-sponsored micro-manufacturing research projects and centres, as previously described. Schafer (2008) states that Europe has a commanding position in micro technology owing to its well-developed technical innovativeness and industrial exploitation of new technologies.

After conducting a workshop with 30 researchers in the micro industry, Dimov *et al.* (2006) went on to conduct a study involving 38 industrialists. After intensive interviews, the following table, see figure 5.23, was created about the perceived market sector importance for micro products. According to Tidd and Bessant (2009), it is essential when creating a new product or service that the customer perception be considered. The opinions considered are those of the leaders in the industry field. The fields where MEMS are considered more important will attract more focus in the form of research and resources than in other areas. These focus areas should thus be targeted when considering the potential market for the micro-material handling system.

Mokhoff (2011) summarises the market research conducted by Yole Development in 2010. According to the source, the four biggest MEMS manufacturers are Texas Instruments, Hewlett Packard, Robert Bosch and STMicroelectronics. 80 percent of MEMS sales are by the Top 30 MEMS companies, (Mokhoff, 2011). The sources go on to state that it now takes sales of \$ 52 million to make the Top 30 ranking, as opposed to \$ 31 million from 2009. Five of the Top 30 reached sales of \$ 100 million. It is therefore essential to consider the make-up of the Top 30 rankings when considering which companies to target, (Mokhoff, 2011). This is clearly illustrated in the figure 5.24.

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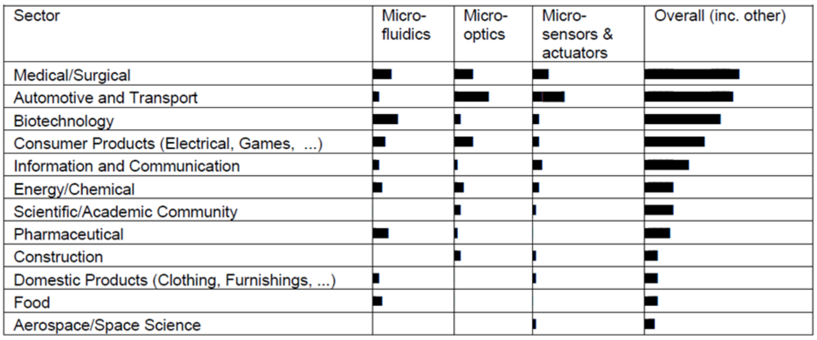

Figure 5.23: Perceived Market Sector Importance for Micro Products, (Dimov *et al.*, 2006)

As per the Mokhoff (2011) and in concurrence with the above-mentioned MEMS market leaders ABI research, Happich (2011), states that STMicroelectronics, Asahi Kasei, InvenSense, Bosch, Knowles, Kionix, Freescale Semiconductor are market leaders. Bosch and STMicroelectronics have diversified across a number of applications. This diversification is advantageous in a dynamic market.

According to Marek (2011), the MEMS automotive industry has a size of $ 1.7 billion (2010). The source continues by stating that the automotive sector also has a growth rate of 10 percent (2009-2014). The majority of this growth is in accelerometers, dynamic control systems (ESP), angular rate sensors (navigation and control) and pressure sensors.

The source iSuppli created the following graph illustrating the Top 10 automotive MEMS suppliers figure 5.25. The overall largest automotive MEMS Company is Robert Bosch, (Marek, 2011). This company has been an MEMS pioneer for 20 years. As per the source, in the year 2010 the company produced more than 400 million units.

Barriers to Entry

As stated in Dimov *et al.* (2006), the major barriers to multi-material micro-manufacture are as follows in order of importance: cost, conservative markets, knowledge about processes/technology, design knowledge, interdisciplinary knowledge, immaturity/lack of technology, packaging and assembly.

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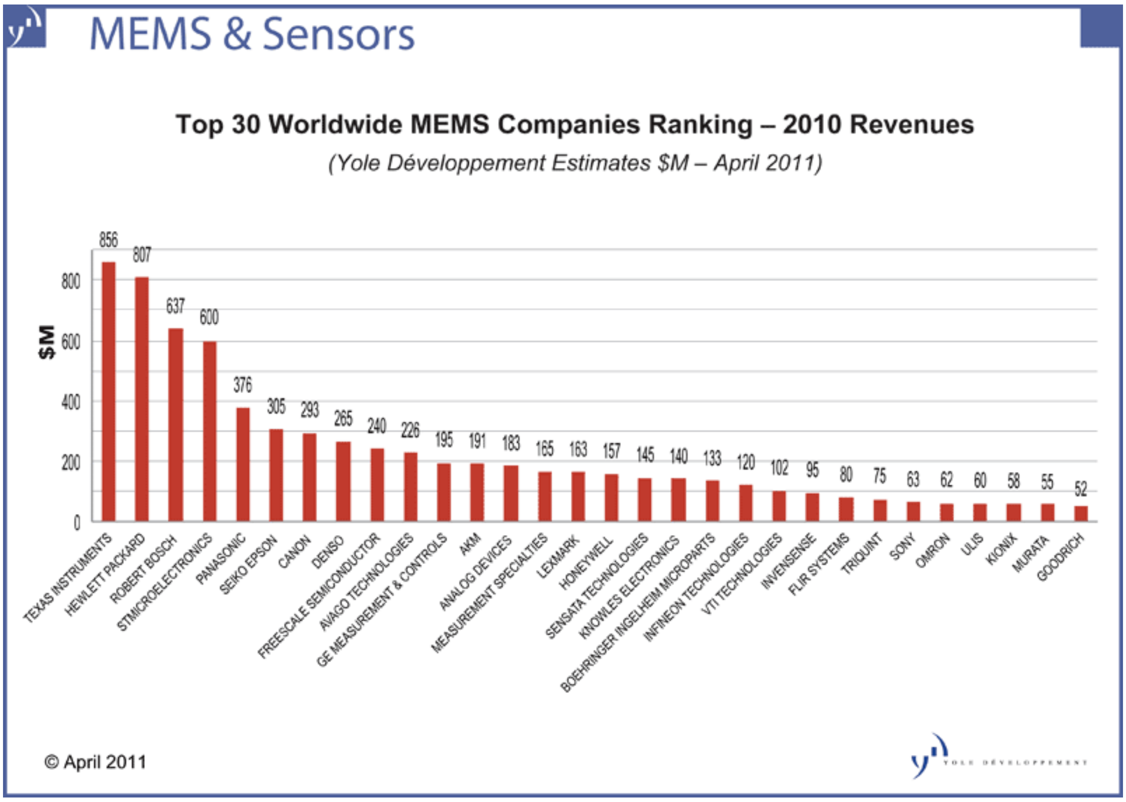

Figure 5.24: Top 30 Worldwide MEMS Companies Ranking-2010 Revenues (Mokhoff, 2011)

Financial and Resource Requirements

The resources required are to be explained in depth in the Project Planning chapter. It is in order to mention that a number of fine positioning systems are of similar price to the price of the entire project, around R 275 000.00. The MiniROB XSL positioning system is a prime example of this, (Milasys, 2006). The fact that these systems are commercially offered provides a clear indication of the need for these products.

5.2.2 Creating New Products and Services

According to Tidd and Bessant (2009), the process of product development is one whereby uncertainty is reduced through a series of problem stages. The scope of the product developed decreases due the increased knowledge of market and technology, as per the funnel model for new product development, figure 5.26. Currently, the project is in the detailed design phase. In order to increase the possible commercial success, it is necessary to develop a thorough

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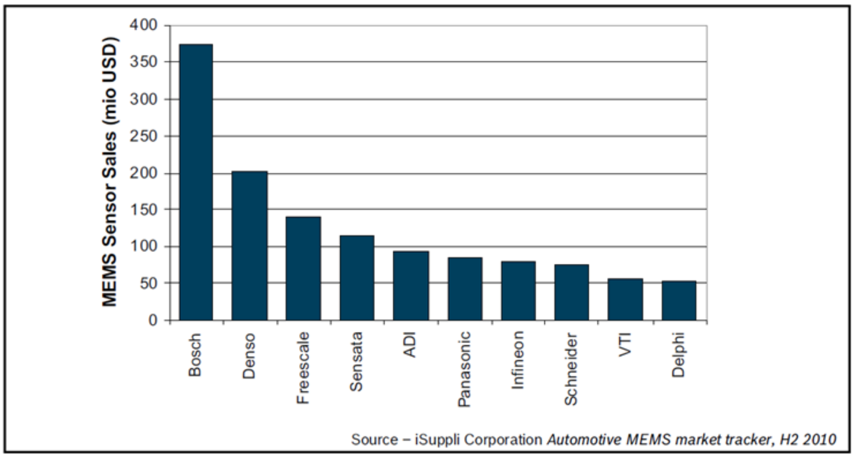

Figure 5.25: Top 10 Automotive MEMS Companies, (Marek, 2011)

understanding of the current market and technology.

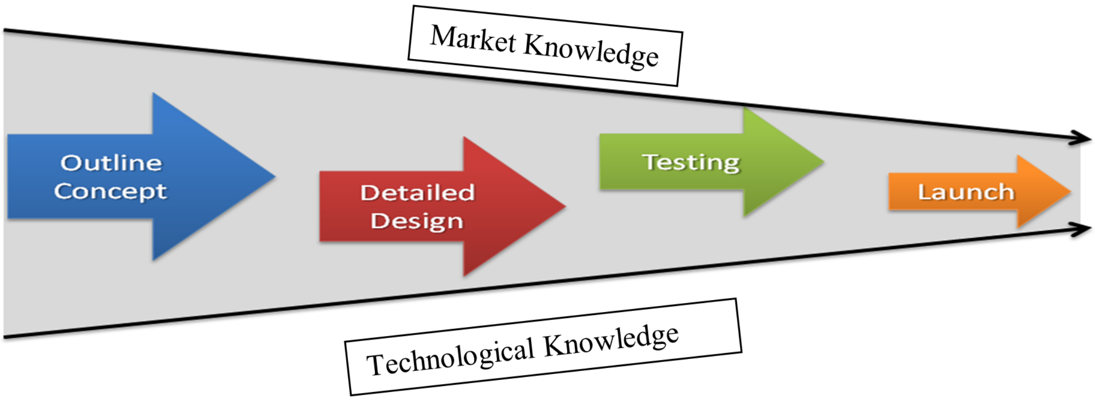

Figure 5.26: Development Funnel Model for New Product Development (Tidd and Bessant, 2009)

In order to simplify the number of processes in the life cycle of an innovation system project, Tidd and Bessant (2009) created a four-stage model for product development. The first stage is concept generation. The second stage is project assessment and selection. The third stage is product development and the final stage is product commercialisation.

The developed system involves micro-material handling with the Motoman SDA 10. The concept generation and selection phases of the four stages are thus not applicable. The two remaining stages of the product development

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model are product development and product commercialisation.

The phases of product development and commercialisation blur into each other, (Tidd and Bessant, 2009). This is one of the reasons this form of research is being conducted during the design phase of the project. In order to comply with the systems engineering approach it has been decided to perform the last two steps of this model concurrently. This will allow for a feedback system.

Factors Contributing to Success
Tidd and Bessant (2009) analysed over 200 different studies to determine the major factors that contribute to the success. Four major factors that contribute to successful innovation have already been discussed in the previous section: product advantage, market knowledge, barriers, and resources required. However, it is also essential to do a brief risk assessment and proficiency of execution analysis.

Assessing the risk of the system is constantly iterated throughout the system's design process. The initial risk of any project is that, because of lack of market pull or technology push, the project will lose momentum and ultimately come to a standstill. One safeguard in this project is that, as previously stated, the project has elements of both market pull and technology push. Even if it is found that there no need for the designed system, it will still be used extensively for research and thus further developed.

Influence of Technology and Markets

Tidd and Bessant (2009) state that detailed market studies and analyses are essential for commercial success. One aspect of these studies and analyses is determining the maturity or novelty of the potential market. Once the market and technological maturity have been assessed, it is possible to apply standard marketing procedures.

There are few existing systems for coarse-to-fine micro-material handling. Therefore, although there is a potential need for such a system, the market itself is highly novel. The technology used to fulfil this novel market, is of low novelty. According to figure 5.27 from (Tidd and Bessant, 2009) the project as an entirety takes the form of an architectural innovation.

According to Doorn (2006), Abernathy and Clark used the term 'architectural' to describe innovations that formed the basis of new industries, or the reform of old industries. As seen by figure 5.28, architectural innovations are comprised equally of technology push and market pull drivers. A main characteristic of the designed architectural innovations is, therefore, that it will lay

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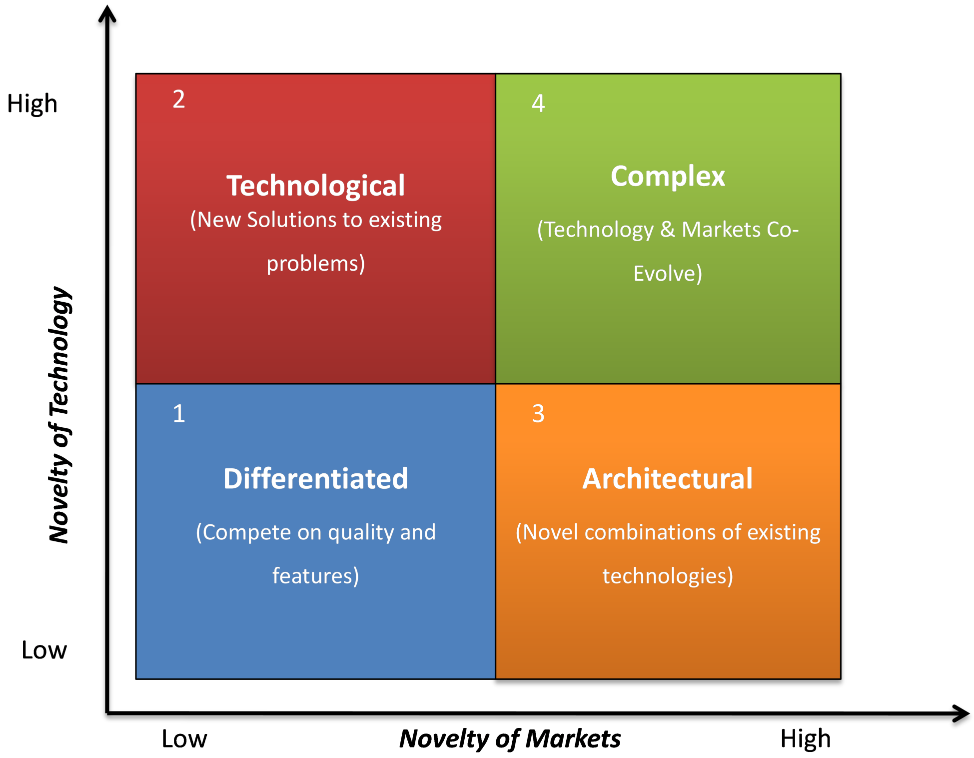

Figure 5.27: How Technological and Market Maturity Influence the Commercialisation Process (Tidd and Bessant, 2009)

the framework for the industry. It is upon this framework that competition will develop, (Doorn, 2006).

Differentiating Products

Walsh (2004) states that the technologies driving micro system production capability creation have a number of characteristics that help to differentiate the designed system from other micro production systems. The designed system will change current manufacturing paradigms due to the fact that a large portion of manual pick and place operations can now be automated in a reconfigurable manner. These advantages lead to strategic industrial competitiveness for the owner. Tidd and Bessant (2009) emphasise the fact that product differentiation is associated with profitability. Once designed, built and tested, the system is compared to other systems in the Results Chapter. It is here that the defining elements of the designed system are highlighted.

Tidd and Bessant (2009) state that, in order to obtain competitive advan-

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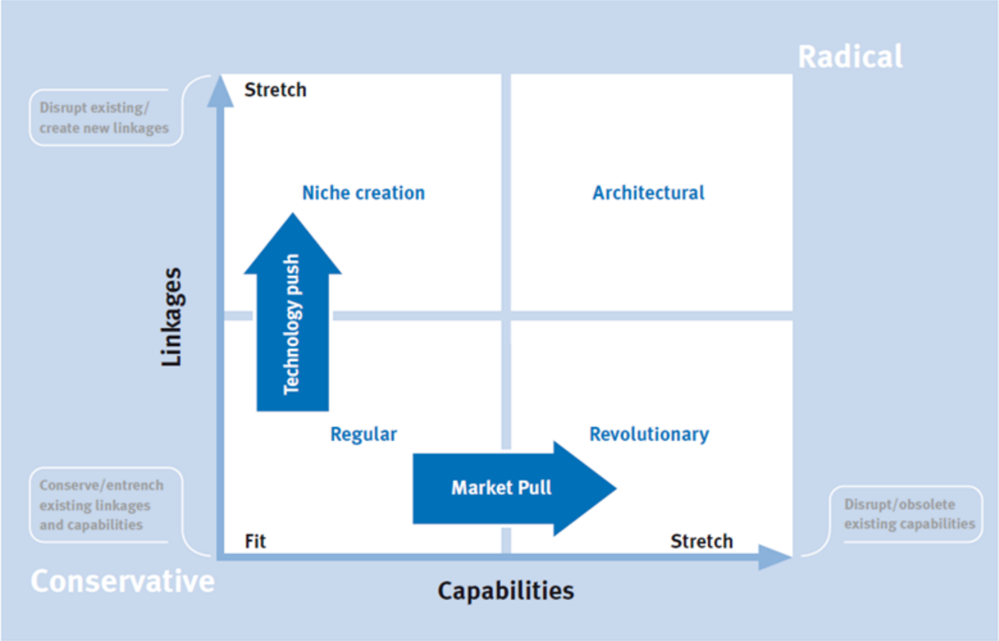

Figure 5.28: Four Types of Innovation, (Doorn, 2006)

tage, it is necessary to ensure the quality of the product offered. A product with a high level of quality is associated with a high return on sales, (Tidd and Bessant, 2009). This is due to the fact that the seller is able to demand a higher price. One of the key tools in achieving a high level of quality is the use of a Quality Function Deployment (QFD). This is a graphical technique for translating customer requirements into development needs. The aforementioned source states that this method is used to identify opportunities for product improvement or differentiation. This QFD for the designed system can be seen in the Results chapter. The Epson, Milasys system created by Sulzer and Kovac (2010) was used for comparison. The QFD analysis clearly highlights the relationship between different aspects of the system.

Building Architectural Products

Having successfully identified the market opportunities, potential customers, differentiated the product and established that it is an architectural innovation, it is necessary to identify or create new market segments, (Tidd and Bessant, 2009). Tidd and Bessant (2009) state that market share is associated with profitability. The source continues on to state that market leaders can earn three times the rate of return of businesses that are ranked four places below them. The goal is to segment the market into small and isolated segments which can be dominated and defended.

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The advantage that the designed system has is that the majority of the potential customers are businesses. Tidd and Bessant (2009) state that businesses are better informed than consumers. Businesses also make rational purchasing decisions. Because of the high cost of the system and the novelty of the market, it has been decided that the best approach is to segment the market by examining market position and potential buying power. The major focus is thus on the top micro systems technology companies. These companies, Texas Instruments, Hewlett Packard, Robert Bosch and STMicroelectronics, are all market leaders. Therefore, the latter will be far more willing to gain competitive advantage through new technologies or new combinations of technologies, than those companies that are struggling to get a market foothold.

In order to segment the market on the basis of the functionality of the technology, it is necessary to consider the nature of the different micro systems companies. The majority of these companies focus on semiconductors, micro and general IT technology. The origin of the project, as per Fraunhofer, is to pick and place micro-materials into the bodies of cars. It is, therefore, appropriate to focus on the automotive MEMS companies. Large amounts of dexterity and flexibility are needed by this segment in particular, as pick and place actions can be needed at many different orientations. The system has been designed to place micro components on non-flat car body surfaces. Again, it is only worth considering the top companies owing to the expense and novelty of the system. The top five automotive MEMS companies as per Marek (2011) are Bosch, Denso, Freescale, Sensata, and ADI.

From a combination of both functional and behavioural (market size) segmentation, it can be seen that one of the main target companies should be Bosch. According to Marek (2011), this company has been an MEMS pioneer for 20 years. In the year 2010 the company produced more than 400 million units, (Marek, 2011). Despite the fact that the focus of the marketing should be on this company, companies in the two different segments should also be considered as potential clients.

Implementing Complex Products

Owing to the nature of the niche market of micro-material handling and the relative complexity of product and customer, the innovation process has elements of both architectural and complex market maturity. According to Tidd and Bessant (2009), complex products have interacting components, their customers have a good technical knowledge, adoption takes over a long period of time and, finally, the purchasing process is lengthy. A highly technical company such as Robert Bosch is likely to have employees with a high level of

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technical knowledge. A company such as this would also have a lengthy bureaucratic purchasing system. By definition of potential customers, the system can be said to have elements of a complex innovation.

Another factor that helps to identify the designed system having elements of a complex innovation is that customers view price as being less important than performance, reputation and service. For a company such as Robert Bosch which sold 400 million units in 2010, Marek (2011), price is clearly less important that performance. From analysing the system's potential customers the system can be seen to have elements of a complex innovation.

5.3 Chapter Conclusion

Key issues regarding the motivation and details for the project have been thoroughly explained. Influencing factors, such as micro forces and size and cost considerations, have also been identified. In considering a commercial definition, it was possible to clearly define the system as an architectural innovation having elements of a complex innovation. Having identified the nature of the innovation, a market strategy was developed accordingly. Through market segmentation it has been shown that the marketing focus should be on Robert Bosch automotive MEMS. Having established a technical and commercial definition for the system, project planning can begin.

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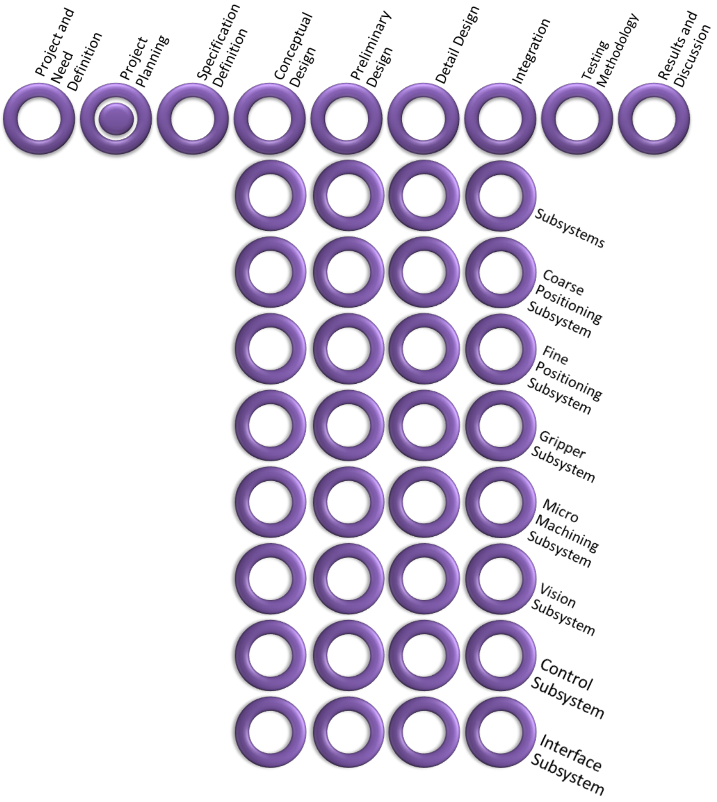
Chapter 6

Project Planning



There are a number of project planning topics that assist in ensuring that the project succeeds. This chapter aims to explore these topics and to describe how they are implemented in the context of the project. In addition to this, a number of potential problems and their solutions are highlighted. Ullman

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(2003) states that a project plan is used to keep a project under control.

6.1 Gantt Chart

Both Ullman (2003) and INCOSE (2007) stress the need for a project planning approach that estimates the budget and schedule for the project. Ullman (2003) provides a detailed explanation of how to create a Gantt chart. Before this process begins, it is necessary to define the type of project that this system falls under. As per Ullman (2003), the project takes the form of the Development of a New Product. In addition to this, there are elements of a Product Selection type project. The steps to create a Gantt chart are: Identifying Tasks, Objectives, Resources Needed, Task Sequences and Costs.

6.1.1 Identify the Tasks

The tasks to be executed mainly revolve around the soft topics of research methodologies, the literature, and the hard topics of system development. The tasks to be completed are as follows:

- Literature Review
- Innovation Management
- System Engineering
- Fine Positioning System
- End Effector System
- Vision System
- Product Structure
- Detailed Design Control
- Detailed Design Interface
- Micro-Machining
- Testing and Evaluation

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6.1.2 Objectives

The purpose of the Literature Review task is to develop a highly detailed picture of the system's functioning and interactions with itself and with the environment. Another objective of the Literature Review is to define the scope of the problems and their solutions. The objective of the Innovation Management task is to develop a thorough understanding of innovation and then select an applicable model. In addition to this, the potential commercial need of the system is evaluated. The objective of the Systems Engineering task is similar to that of the Innovation Management task.

The objectives of the tasks of Fine Positioning Subsystem, Gripper Subsystem, Micro-Machining Subsystem and Vision Subsystem are to research the applicable solutions. Once identified, the reasons for the selections need to be justified. One method to accomplish this is through a design trade-off analysis.

The Control and Interface Subsystems deal with the detailed design of programming the system. The objectives of these two tasks is to ensure that all the system components function together to produce the required result. The objective of the Micro-Machining Subsystem is to test the feasibility of performing micro-machining with a coarse-to-fine positioning system. In addition to this micro-machining is to be examined as a testing methodology. If successful it is then used to test the coarse-to-fine positioning system. The objective of the Testing and Evaluation task is to assess how well the systems function.

6.1.3 Time and Resources Needed

Due to the concurrent nature of the project, time estimates are not wholly meaningful. This is due to the fact that often tasks are begun at a certain period. Other tasks are then focused on. The task is then resumed again. Despite this, rough estimates of time are given for a form of comparison.

The literature review is one of the major soft topics. This task is perceived as continuous and ongoing. As such, the literature review will run the majority of the length of the project approximately 320 days. Another soft topic task that runs for the bulk of the project is that of research into the topic of innovation management: 240 days. Research in systems engineering similarly runs for a large amount of the project: 170 days. Apart from the obvious resources of computers, books, phones, there are no additional resources needed for these three tasks.

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The Fine Positioning Subsystem task, the End Effector Subsystem Task and the Vision Subsystem Task will all take approximately 200 days. The time taken to select and justify the various components will vary around 60 days or so. Most of the time will involve sorting out the necessary paper work, getting quotes for the parts and for transportation. In addition to this, the parts have to be shipped and then clear customs. The resources of the Industrial Engineering Department will be used in these tasks: this includes the services of the department's financial branch.

The task of the Product Structure or Integration will take approximately 80 days. This is largely due to the fact that nothing needs to be shipped from overseas. Again, the financial branch of the department will be used. Another resource used is that of the SMD Workshop of the University of Stellenbosch will be used extensively. The head of the workshop, Mr. Jakkie Blom, will not only facilitate the manufacturing of the needed parts, but will also play a consulting role.

The proposed time for the Detailed Design Control task is roughly 60 days. The proposed time for the Detailed Design Interface task is roughly 30 days. For the control phase two programmers are to be hired: one to develop a Graphical User Interface (GUI) and the other is to create a calibration system. The Micro-Milling task is to take around 40 days. For the Testing and Validation tasks the time proposed is around 60 days. Resources used in this task include testing equipment from the Industrial Department, including a micro-milling spindle. In addition to this, the CMM machines (Fixed and Portable) will be used.

6.1.4 Task Sequence

The tasks of Literature Review, Innovation Management and Systems Engineering models are to run in parallel to each other throughout the majority of the project. The Literature Review task is the first to begin, then Innovation Management, and finally the Systems Engineering models.

The tasks of Fine Positioning Subsystem, End Effector Subsystem, and Vision Subsystem also to be run concurrently. They are initiated at the start of the project at a time similar to that of the Literature Review task. The progression of subtasks will vary. The Product Structure or Integration task can be initiated slightly before the parts arrive; however, it is essential that the bulk of the designing is done only once the parts arrive.

The Detailed Design Control task can only be initiated once the parts arrive. The Detailed Design Interface is also only initiated after the parts have

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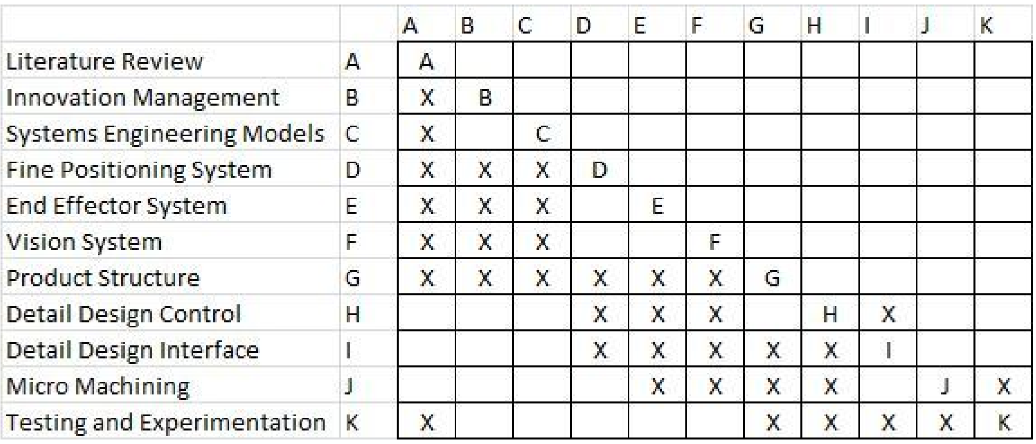
arrived, the structure has been manufactured and assembled, and once the control has been established. The Micro-Machining task can only be completed once the parts have arrived and the control structure has been developed. Testing can only begin once the proper methods have been researched and the structures and control have been developed. This information is summarised in figure 6.1.



		A	B	C	D	E	F	G	H	I	J	K
Literature Review	A	A										
Innovation Management	B	X	B									
Systems Engineering Models	C	X		C								
Fine Positioning System	D	X	X	X	D							
End Effector System	E	X	X	X		E						
Vision System	F	X	X	X			F					
Product Structure	G	X	X	X	X	X	X	G				
Detail Design Control	H				X	X	X		H	X		
Detail Design Interface	I				X	X	X	X	X	I		
Micro Machining	J					X	X	X	X		J	X
Testing and Experimentation	K	X						X	X	X	X	K

Figure 6.1: Design Structure Matrix as per Ullman (2003). This Figure Illustrates the Interdependencies of Various Tasks. Due to the Fact that Tasks A, B, and C Run for the Length of the Project, Any Task That is Dependent on Them Will Only Require Their Initiation

6.1.5 Costs

The costs of the soft topics are negligible. The cost of the Fine Positioning Subsystem is predicted to be around R 160 000.00. The Vision Subsystem is to cost around R 90 000.00. The End Effector on the other had is to cost around R 20 000.00. The cost for Detail Design Control and the Detail Design Interface is on the order of R 5 000.00. The total for the coarse-to-fine positioning system is to be R 275 000.00. The system developed is designed to be placed on existing 6 (or 7) degree of freedom robots. The cost of this is not included.

6.2 Management Topics

Now that a detailed structure of the tasks has been created, it is necessary to consider other project elements. These will help to ensure the success of the

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project. They include examining risk, information management, configuration management, and the decision-making process.

6.2.1 Risk

The major aspects of risk in this project, as per INCOSE (2007), are schedule risk and technical risk. These risks stem from the fact that the project has a relatively tight deadline and is highly technically orientated.

INCOSE (2007) The large risk of the project is that the parts do not arrive in time. Similar projects experience massive delays due to the length of time it takes the parts to clear customs, etc. Numerous steps are to be taken to ensure each part purchased is guaranteed to fulfil the necessary requirements and to integrate with other parts. The risk of customs and back order delays are thus hedged by ensuring the needed parts are procured as soon as possible without compromising their ability to fulfil system requirements at low cost.

Risk is to be averted in the Integration task by ensuring that the bulk of the designing is done only once the parts have arrived. This is done purposefully so that if parts are misrepresented in any manner in technical specification, then actual measurements can be taken and compared. This will remove the need for expensive reworking.

6.2.2 Information Management

In order to ensure that all information is correctly saved and catalogued, a filing system is created. INCOSE (2007) describes this as information management. A folder is created for research journals and papers. The rest are created according to various tasks that had to be performed. Another folder is created for components, and their appropriate quotations and payments. Finally a folder is created for the various conferences attended. Folders that required large amounts of space are placed on the c-drive of the computer. All information is to be backed up on regular occasions.

6.2.3 Decision Making Process

An important part of the decision making process is that of project milestones, (INCOSE, 2007). The major project milestones include the arrival of parts, the assembling of the system and final testing. The assembling of the system and the final testing both serve as decision making points. At these points a decision is made to continue or to go back and redo aspects of the work.

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The decision making process is assisted by various tools and techniques as mentioned in Blanchard and Fabrycky (2006) and INCOSE (2007). One example of this is the Trade-off Analysis process. Another tool to be used throughout the project is that of a functional analysis. The Preliminary Design Criteria also assist in the decision making process by helping to define what is needed. These criteria include: Functional Capability, Maintainability, Usability, Supportability and Serviceability and Affordability.

6.3 Chapter Conclusion

Ullman (2003) and INCOSE (2007) are followed in order to develop a project plan and Gantt chart. The steps identified and expanded upon are: Identifying Tasks, Objectives, Resources Needed, Task Sequences and Costs. In addition to these steps, issues such as project risk, decision making and information management are considered. This chapter has clearly illustrated how this project is to be carried out.

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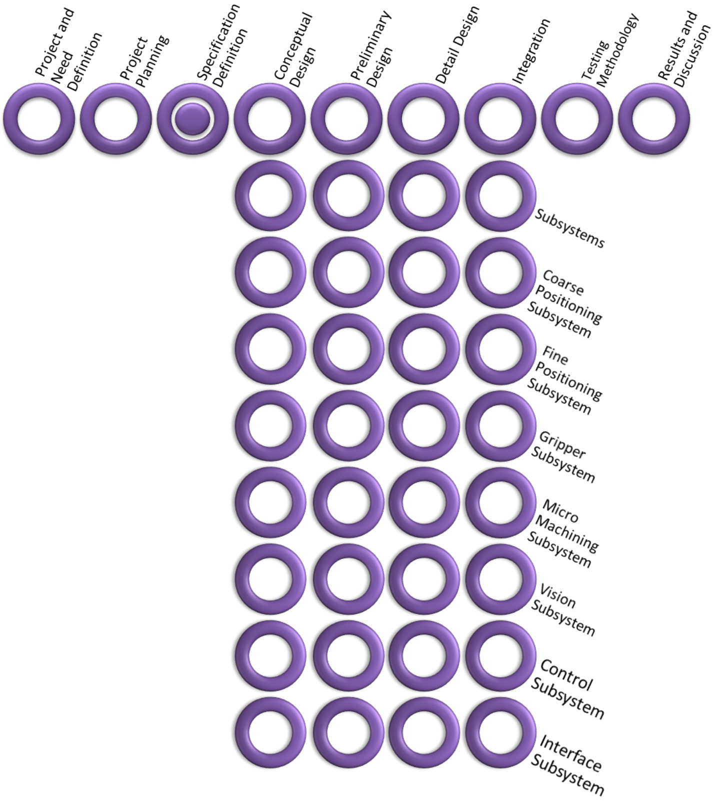
Chapter 7

Specification Definition



The specification definition is used to provide a thorough understanding of the users and their needs. It also provides a context in which the system is to operate. Once identified, each of the user's individual needs is examined. In addition to this, other factors influencing system development are explained.

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These include the utilisation and environmental requirements of the system.

7.1 Introduction

Aslaksen and Belcher (1992) state that the system specification or system definition must cover two areas. Firstly, it must cover all the areas of concern from the client. Secondly, it must be easy to understand. "This specification constitutes the top 'technical-requirements' document that provides overall guidance for system design from the beginning," (Blanchard and Fabrycky, 2006). The initial specifications are determined through the operational requirements. Further specifications are determined and presented in the preliminary design. This chapter determines the 'whats' of the system. Further chapters determine the 'hows'.

In creating the system specification, a large number of requirements are identified. Requirement management deals with collection, analysis and validation of the system requirements, (INCOSE, 2007). The required capabilities as defined in this section are used as driving factors for the architecture design activities, such as preliminary and detailed design.

7.2 Stakeholder Requirement Definition Process

INCOSE (2007) stresses the need to not only identify the important stakeholders but also to ensure that all of their needs are clearly defined.

A large number of the technical requirements were realised through the collaboration. The requirement for a micro-material handling system was made known. The issue of micro-machining was also mentioned. The created system should have a high accuracy and repeatability over a wide range of 500 mm. It should be able to pick and place the delicate 250 μm by 250 μm by 10 mm without damaging them. In order for the machining to be useful, it should also be accurate such that slots milled can successfully enclose the piezo elements. The milling should also not damage any of the system components in any manner. Not only this but is should be of good quality.

When considering the use of a Van der Waals gripper, additional requirements arise. Due to the needed pre-load of the Van der Waals gripper, it is necessary to incorporate a force sensor. The delicate nature of both the gripper and part dictates the need for an intuitive control system that has

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the ability to record and execute a series of actions. This intuitive control can be translated into the need for live-vision feedback and a force feedback control.

The system should have the ability to be operated from a remote location. This translates into the need for Ethernet communication. In addition to this, due to the discrepancy between the repeatability of the coarse positioning system and that of the fine positioning system, some form of calibration would be needed.

Should the system be used commercially, its stakeholders will include the car manufacturer Bosch as previously explained. This stakeholder will require a well-rounded combination of all of the above requirements. This includes a highly accurate and repeatable handling and machining capability. In addition to this an intuitive and force sensing control hardware and software should be in place. The system should also be able to record and perform various function. Lastly, it should have a calibration system and have the ability to be operated remotely.

7.3 Mission Definition

As stated in the Design Methodology chapter, the mission or objective of the project is the building, designing and testing of a coarse-to-fine positioning system. This coarse-to-fine positioning system should be able to perform micro-material handling and micro-machining.

7.4 Performance and Physical Parameters

The piezo-ceramic rods have a width of 264 μm, while the cavities have a width of 300 μm. According to Neugebauer *et al.* (2011*a*), this leaves an assembly clearance of 18 μm. In order to safely achieve this clearance, the system should be able to achieve the following parameters over the macro range of 500 mm.

1. 5 μm repeatability
2. 8 μm accuracy
3. 3 μm resolution

The system should be able to handle delicate 250 μm by 250 μm by 10 mm components without damaging them.

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It should be able to effectively mill a slot that is 300 μm wide, 300 μm deep and 10 mm long. The minimum width and depth achieved should be not smaller than 270 μm. The vibrations and forces generated should be less than the maximums of the components.

7.5 Utilisation Requirement

The system is to be designed, built and tested in order to perform the aforementioned task and to be used as a platform for further research. Should the system become commercially available, all of the parts available will be purchased such that 12-hours-a-day operation will be facilitated with a period of 1 month's maintenance at the end of the year.

7.6 Environmental Factors

If the system remains operational for research purposes, the environmental factors affecting operation will be at a minimum. The research environment is clean, and relatively risk-free when compared to an industrial environment. In addition to this, all academic users of the micro-material handling system are careful in their operation.

If the system is employed in car-manufacturing facility, additional environmental factors should be considered. Due to the sensitive nature of operating in the micro realm, the system will have to be re-calibrated with changes in temperature. Dust is also a major hamper to the functioning of the system and a sealant should be considered.

7.7 Other Considerations

In addition to being operated via Ethernet, the system should be created in such a manner that it is easy to integrate into an overall factory control system. Aspects such as reconfigurability and the use of off-the-shelf modular components should be considered.

It is important to remember that the picking and placing and machining relating to the piezo micro components is only used as a case study. It should thus be noted that the system specification should cover more than the characteristics needed to satisfy this case study. This will ensure that the developed

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system can be applied across a wide range of micro-material handling applications.

The Motoman SDA 10 is to be used as the base of the developed system. The project should thus ensure that all new elements integrate with the Motoman. As components of a system, the newly developed elements and the Motoman should work together to perform a function that is more than the result than the sum of two independent functions.

7.8 Chapter Conclusion

In this chapter the relevant stakeholders have been identified. In addition to this, the environment and various elements relating to the system usage have been examined. The context in which the system is to operate has been developed.

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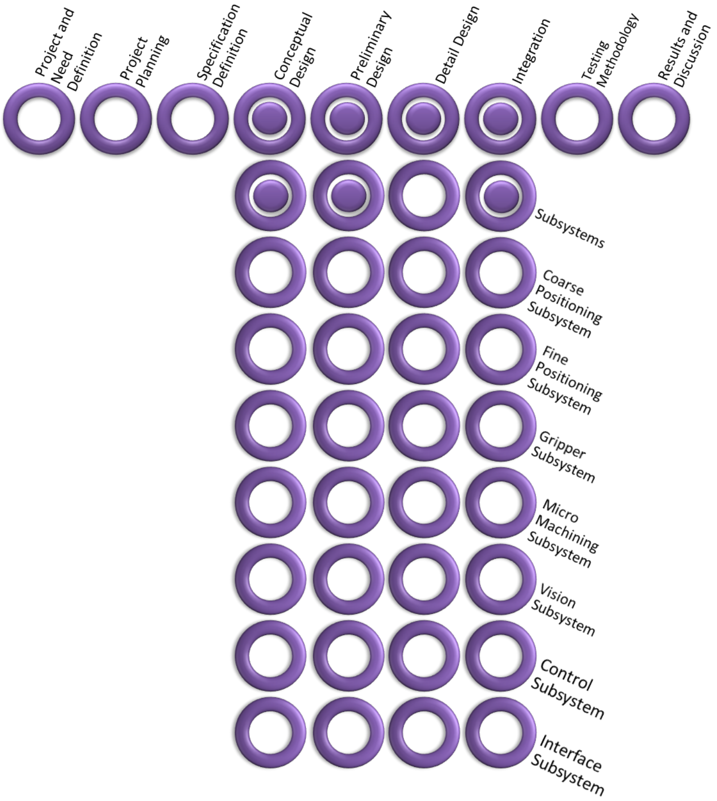
Chapter 8

Subsystems



The purpose of this chapter is to briefly discuss the chosen subsystems. In addition to this, concepts from conceptual design, preliminary design, integration and testing that are applicable to all subsystems are explained.

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8.1 Chosen Subsystems

Alting *et al.* (2003) state that the following subsystems are necessary for high-precision micro-assembly. The first is a vision feedback subsystem with a long working distance. A micro positioning subsystem is needed for precise manipulation and position and control. Finally a micro gripper subsystem is needed for the pick operation.

In order to implement a coarse-to-fine positioning system, a coarse positioning subsystem and a fine positioning subsystem are needed. In order to ease control and provide means of calibration, a vision subsystem is needed. For micro-material handling, a gripper is needed. For micro-machining a micro-machining subsystem is needed. In order to effect both micro-material handling and micro-machining with the various components, a control subsystem is needed. Lastly, in order to ease control, a human robot interface subsystem is needed. For the sake of clarity control deals with basic functioning of the system, while interface deals with a high-level intuitive means of effecting system movement.

8.2 Conceptual Design Subsystems

Nicholas and Steyn (2003) state that one tool used to illustrate the functional requirements of the system is that of functional flow block diagrams. Initially this functional-flow block diagram, derived from Specification Definition, is used to identify surface level solutions. In later chapters this form of diagram will include all functions needed to satisfy requirements, support, operate and maintain the system, (Nicholas and Steyn, 2003). The basic overall function of the system can be seen in figure 8.1.

8.3 Preliminary Design Subsystems

The purpose of the preliminary design is to identify the system subcomponents. INCOSE (2007) states that this is one of the major focuses of the architectural design process (Preliminary Design Process). The three major subcomponents of the system are the fine positioning system, the end effector and the vision system. The University of Stellenbosch already has a micro-machining spindle. After the components have been identified, a solution is sought that fulfils the function of that subcomponent.

In an effort to increase the modularity of the system, off-the-shelf solutions are preferred where applicable, (INCOSE, 2007). In determining the correct

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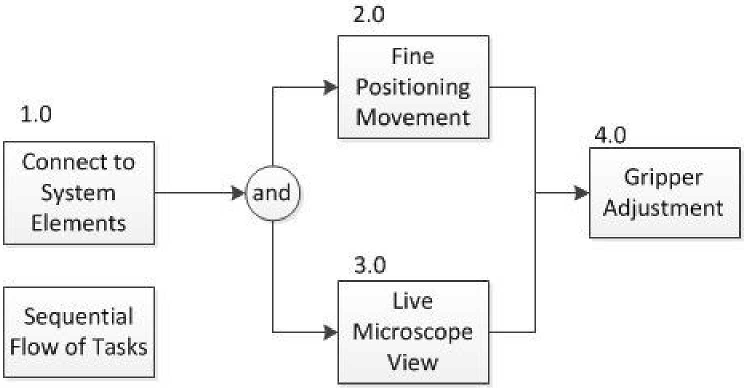

Figure 8.1: Basic Overall Functional Analysis

solutions, it is necessary to highlight a number of different existing products for the current problems, (Blanchard and Fabrycky, 2006). The trade-off analysis process is used as a means of assisting in this selection process, as mentioned in the Project Planning chapter. This trade-off analysis process can be seen in figure 8.2.

8.4 Integration Subsystems

The maximum weight allowed per arm of the Motoman SDA 10 is stated as 10 kg in order for the robot to perform optimally, (RobotWorx, 2011). It is, therefore, essential that all parts manufactured and assembled are less than 10 kg. In order to ensure this, all of the components were machined out of aluminium. Where strength and machinability were an issue, aluminium 7075 was used.

Due to the fact that the system is operated with its servos motors disengaged, as previously explained, vibrations are assumed negligible. The various thick aluminium 7075 components also provide a large amount of damping. The majority of the system operation would also be conducted at low speeds, less than 5 mm/s. As a result, calculations to determine size and thickness of structures were done using static calculations.

8.4.1 Integration Configurations

Two diagrams were created in order to better illustrate the physical placement of components. In the figure, items in the hexagonal boxes are items to be machined, while the pictures are purchased items. The proximity in the di-

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agram represents physical proximity. An example of this would be that the Gripper Tips One and Two are connected to the Schunk Gripper. This is the case in the final assembly. Similarly, the Schunk Gripper is mounted onto the Gripper Force Sensor Mount. This is then attached to the Force Torque Sensor.

In order to assist in creating different test methodologies, two configurations were established. In the first configuration all of the components are on one arm, figure 8.3. The calibration method was developed for this configuration. In the second configuration, the camera and lens system are on one arm and the fine positioning system and gripper are on the other arm, figure 8.4. This would allow for the user to manipulate the vision system as needed. The manipulated object can thus be viewed from multiple angles.

8.5 Overall Combination Subsystems

The weight of the various subsystems, when in the micro-material handling configuration, is broken down as follows: Feinmess Fine Positioning System 6.510 kg, Vision System 0.730 kg, Gripper 0.01 kg, and Force Sensor 0.254 kg. In total, the system weighs 8.473 kg. This allows for additional sensor attachments if needed. When considering the micro-machining application, the gripper is removed and the micro-milling Nakanishi spindle is added. The weight of the system in the micro-machining configuration is 9.16 kg The various views of the assembly are as follows.

8.5.1 Configuration One Micro-Material Handling

In configuration one, all the system components are mounted onto one arm. This configuration is more appropriate for future implementation in automotive manufacturing as a single robot arm is needed. The overview can be seen in figure 8.5.

A CAD rendering of all the components assembled can be seen in figure 8.6. Next to this is picture of the actual components assembled. Note the wires need to have a certain amount of slack in order to allow for movement. It was made sure that the wires do not hamper the system functioning in any way.

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8.5.2 Configuration Two Micro-Material Handling

The overall layout of configuration two can be seen in figure 8.7. In this configuration the camera and lens system are mounted onto one of the robot arms. The fine positioning system and gripper are mounted onto the other arm. Functioning thus requires the involvement of both arms, one for vision and the other for the positioning and gripping.

The CAD concept of the vision system mount, camera and lens can be seen in figure 8.8. Next to this image in the same figure is a picture of the actual system.

In a similar manner to the previously mentioned diagram both the CAD rendering and the actual system can be seen in figure 8.9.

8.5.3 Configuration One Micro-Machining

It is important to note that the force toque sensor in this configuration is not used to determine the forces experienced during micro-milling. Micro-milling forces are to be determined using coarse micro-milling, see the Testing chapter. The force sensor in this instance is used as a means to zero the z axis during calibration. The Motoman moves the fine positioning system down until it experiences a force, i.e. contact with a gauge block, and then stops. In addition to the sensor, this configuration also contains the Nakanishi micro-milling spindle, and camera and lens subsystem. Both the vision subsystem and the spindle are mounted underneath the fine positioning system, see figure 8.10.

A CAD rendering of the micro machining setup can be seen in figure 8.11. In addition to this a photo of the configuration is seen adjacent to it. This figure clearly shows the position of the spindle and camera and lens.

8.6 Testing Repeatability and Accuracy of the Combined Subsystems

Testing of the Motoman and then the assembled coarse-to-fine positioning system and calibration system is difficult. This is owing to the fact that a high level of testing accuracy in three axes is needed over a large distance. In order to determine the accuracy and repeatability of a system, it has been decided to make use of the ISO 9283 testing standard. This standard revolves around measuring a number of points in space in the x, y, and z axes.

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Four feasible methodologies to measure x, y and z coordinates are as follows. The use of a camera and lens system, the use of a laser interferometer or triangulation, the use of a Linear Variable Differential Transducer (LVDT), and finally, the use of micro drilling as test methodology. The methodologies were analysed with the intent of feasible and practical application.

Central to the decision making process was input for collaboration partner Michael Mueller. Mueller (2011) served as the key correspondent for the collaboration with the University of Chemnitz. Mueller (2011) is also currently working on a Ph.D. in the area of developing a micro-material handling system. A large amount of information was thus exchanged, in particular with regard to testing methodologies.

8.6.1 Camera and Lens

One method identified by Greenway (2000) is that of videogrammetry. Two cameras in fixed positions make use of stereo-vision techniques as a means of measurement. The two cameras are used to determine the location and orientation of light sources on the measured object. The approach has similar disadvantages to that of laser measurement, i.e. a direct line of sight needs to be maintained. The major downside of this approach is the need for two expensive cameras and for processing equipment. In addition to this, accuracy and repeatability measurements down to 5 μm becomes difficult due to the large number of errors that need to be compensated for.

In the setup used by Mueller (2011), a camera and telecentric lens were used for verification. The difference between the telecentric lens setup and the setup developed in this project is the fact the telecentric lens project has a camera that is fixed. When trying to accurately determine the x, y and z coordinates using an overhead camera it is essential that the overhead camera remains fixed when measuring different points. This is because a small change in focus can result in a large change in accuracy, (Mueller, 2011). The telecentric lens used has a high numerical aperture. This results in the same error in the z axis being experienced in the x and y axes. If, for instance, the height of the camera and lens is altered by around 100 μm, then the x and y distance are also altered by hundreds of microns. Due to the height variance of camera position, this approach is thus not applicable to the system.

The use of a camera and lens is not a feasible method to test the accuracy and repeatability of the coarse-to-fine positioning system. It is, though, sufficient for use as a calibration system. One of the main reasons for this is the fact that the calibration system is designed to align the camera and a calibration symbol. It is not designed to accurately measure distance. This

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is illustrated by the fact that the calibration itself is iterated more than once to remove potential errors. During this calibration the camera is physically moved closer to the calibration symbol. This is simply not feasible when attempting to use a camera and lens to determine accuracy and repeatability. In addition to this, there is no manner in which the z axis distance can be accurately measured if the height of the camera and the lens varies.

8.6.2 Laser

Greenway (2000) states that laser-based system makes use of laser light to determine alignment and distance. One example of this is the use of interferometry. This is an incremental position measuring technique. Change in the reflected laser's beam is converted into a distance. This system is highly accurate. A major disadvantage of the system is the difficulty in aligning the reflecting surface and the laser. A direct line of sight also always has to be maintained when using this form of measurement. Not only this but the end effector also has to maintain the aligned orientation throughout measurement, (Greenway, 2000).

Another measurement method using lasers is that of laser triangulation. In laser interferometry the laser is emitted and reflected back through the same opening. In laser triangulation a laser is emitted from a diode. The reflection is then directed onto a position-sensing element, (Epsilon, 2012). This can seen in figure 8.12.

A number of problems to consider when implementing this method are as follows. In order to achieve the high level of measurement needed the laser triangulation units become very expensive. In addition to this, when making highly accurate measurements over large distances, the system becomes susceptible to minor angular errors. As an example consider a target measured 50 mm away. If there is an error of 1 degree, using trigonometry the measurement will be off by 873 μm.

8.6.3 LVDT

A LVDT generates a voltage directly proportional to the movement of its magnetic core. The focus of this sensor is detecting movements of small displacement with high accuracy, (Transducer, 2012). Due to construction of an LVDT, the smallest change between the magnetic core and the windings will produce a change in voltage. The resolution of this change is restricted solely on the sensitivity of the measuring equipment, and can assumed to be almost infinite. LVDTs also have excellent repeatability. One example is a repeata-

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bility of 0.6 μm as per (Transducer, 2012).

A problem with this testing methodology is that LVDTs only have a 1-5 mm range of measurement. In addition to this, measurement is achieved by physical contact. In order to achieve accurate 3-axis measurement the LVDT would have to be reorientated each time. If this process is to be repeated at a number of different locations, large re-positioning errors will result. These errors are due to the realigning and relocating of the LVDT for each new measurement. It also becomes difficult to ensure that contact is made at the correct angle; especially because the same movement needs to be iterated numerous times.

Robotics (2012) conducted testing in the afore mentioned manner. A problem with drift was noticed during the testing. This drift was accredited to temperature changes and errors in pitch.

8.6.4 Micro Drilling

Another option is to combine a micro-milling spindle with the Motoman and coarse-to-fine positioning system. The micro-milling spindle is then used to drill a number of holes. These holes can then be taken to the Coordinate Measuring Machine (CMM) to determine their exact position. The Nakanishi micro-milling spindle is highly accurate by design, (Dirkse Van Schalkwayk, 2012). As such, it is possible to use drilling to actively reflect robot positioning.

In a manner similar to the above Kao and Shih (2007) measured holes of 160 μm in diameter and 0.9 mm deep using a CMM. The aim was to determine the repeatability and reproducibility of the dimensions of the holes manufactured using electrical discharge machining. Despite the CMM's limitations when measuring holes of this size, large amounts of accurate information were successfully obtained about the dimensions of the holes i.e. a diameter repeatability of 0.3 μm.

The angular z axis errors associated with the camera and lens methodology are removed as drilling occurs on the surfaces of the material. This method is also cost effective as all of the necessary equipment is on hand. Another major advantage of this methodology is the fact that by drilling one hole, highly accurate information about x, y, and z axes can easily be obtained. A disadvantage of this method is that accuracy and repeatability measurements can be affected by the drilling vibrations and forces.

In addition to providing information about the accuracy and repeatability of the coarse-to-fine system, this testing method also gives information about

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how micro machining affects the accuracy and repeatability of the system. This is important when considering the system for use in precise micro machining applications.

8.6.5 Selected Method

The use of a camera and lens system leads to distortion due the the slight angular errors. The laser system is highly expensive and in addition to this errors result due to angular misalignment. The LVDT can only measure displacement in one axis and for a limited range. As a result, every time a new axis is to be measured, the system has to be reorientated. It was therefore decided to use a micro drilling method to perform highly accurate testing over a large range.

Due to the fact no significant literature on this relatively new methodology could be found, a number of interviews were conducted. Those interviewed were departmental figures with high levels of experience in this field, as can be seen in Appendix I. The aim of these interviews was to determine the feasibility of this test methodology. The results were positive, with the participants stating that this could be feasible as a test methodology. More importantly, a number of issues were raised. Most notably is the issue of the impact of vibrations and forces. It is essential that this forms an integral part of the testing methodology.

In addition to conducting interviews, it was decided to create a journal paper to assist in the validation of this test methodology. This journal paper is currently being written and is to be submitted to the journal *Precision Engineering* (Elsevier). In this manner further credence will be given to this unique testing methodology.

8.7 Conclusion

This chapter defined the seven subsystems. In addition to this conceptual design, preliminary design and interface concepts that apply to all of the subsystems were explained. These include the use of a functional analysis, the trade-off analysis process, general integration layouts, and testing approaches.

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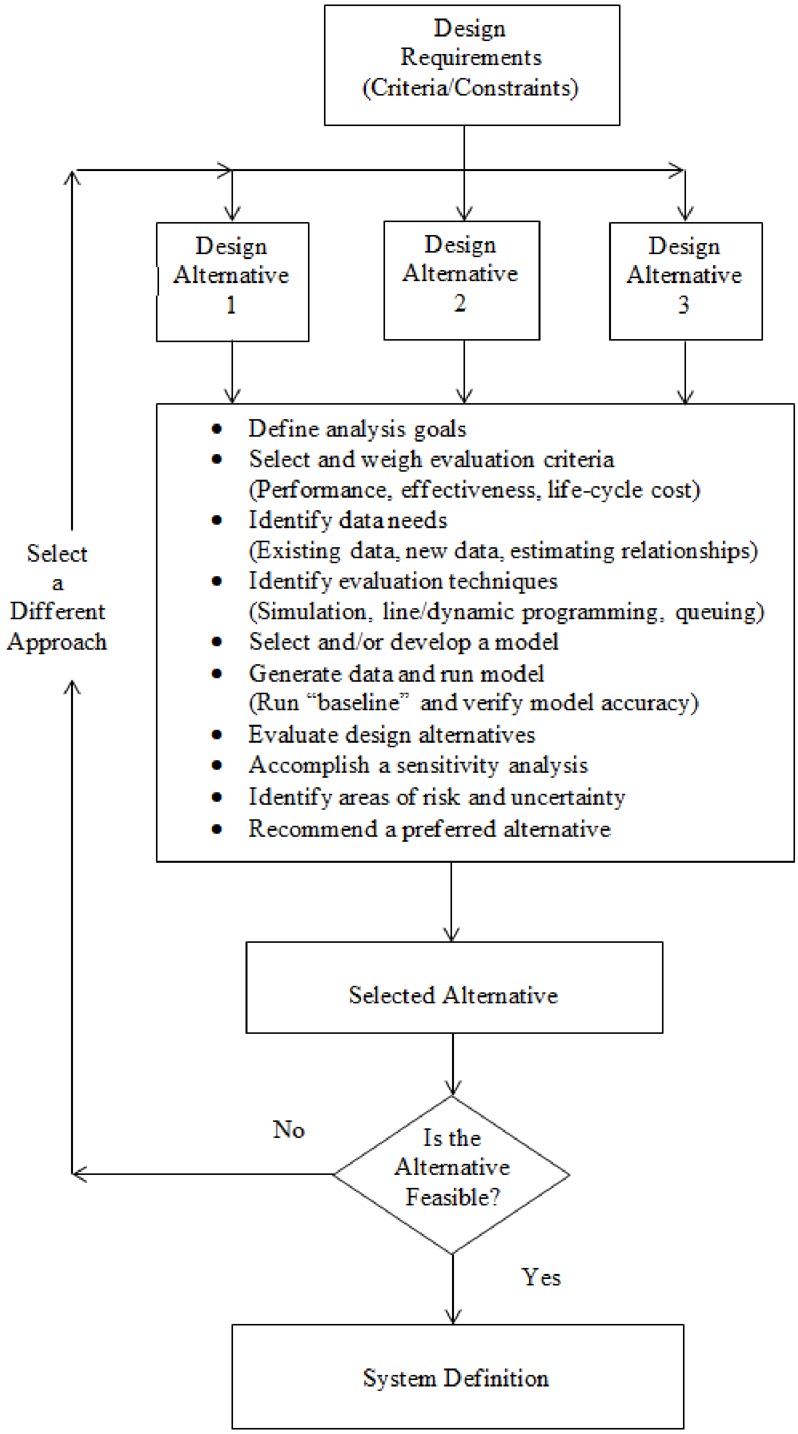

Figure 8.2: Trade off Analysis Process (Blanchard and Fabrycky, 2006)

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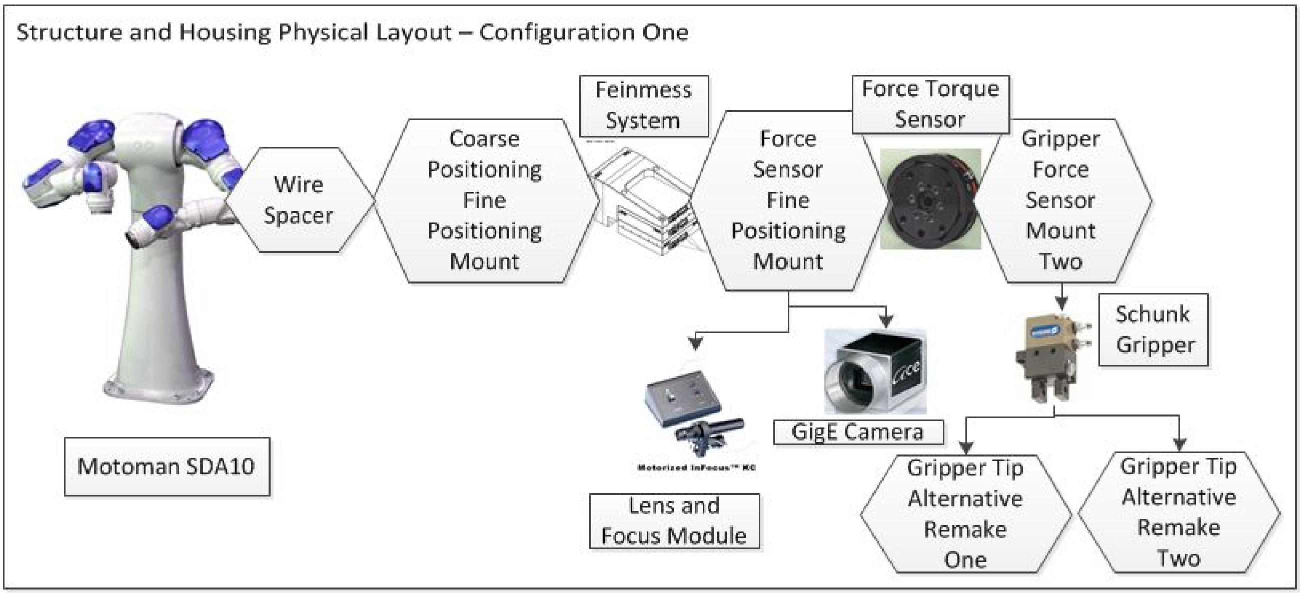

Figure 8.3: The Physical Layout of the Machined and Purchased Items Configuration One. Proximity in the Figure Symbolises Physical Proximity in the Set-up

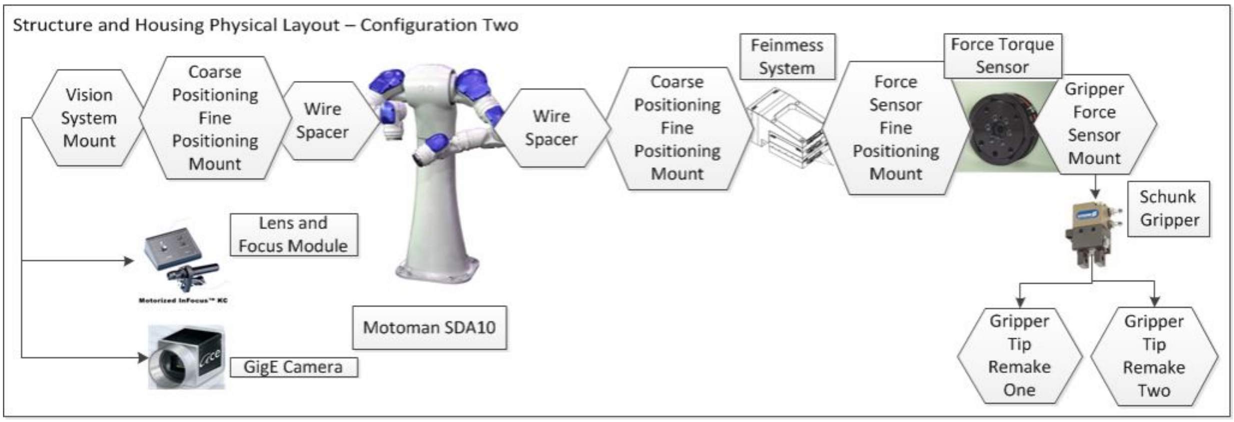

Figure 8.4: The Physical Layout of the Machined and Purchased Items Configuration Two. Proximity in the Figure Symbolises Physical Proximity in the Set-up

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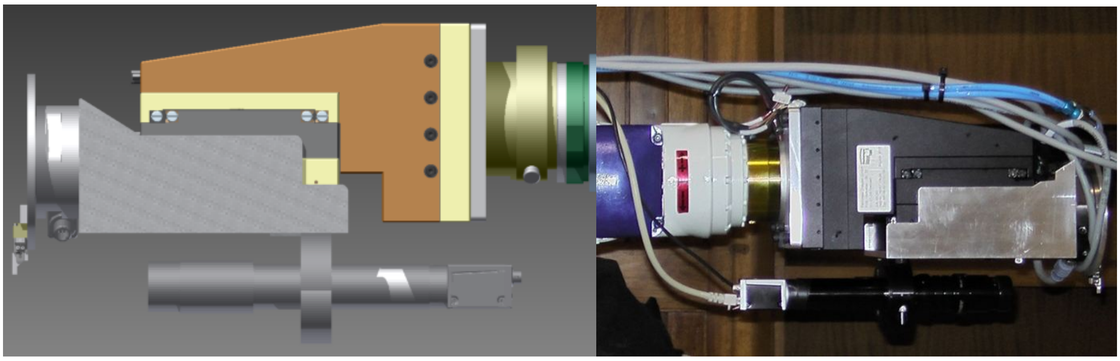
(a) Working Position (One Arm Used) (b) Arms Extended Position

Figure 8.5: Assembled Configuration One



(a) (b)

Figure 8.6: CAD Rendering of System (a) Adjacent to Assembled System (b)

(a) Working Position (b) Arms Extended Position

Figure 8.7: Assembled Configuration Two

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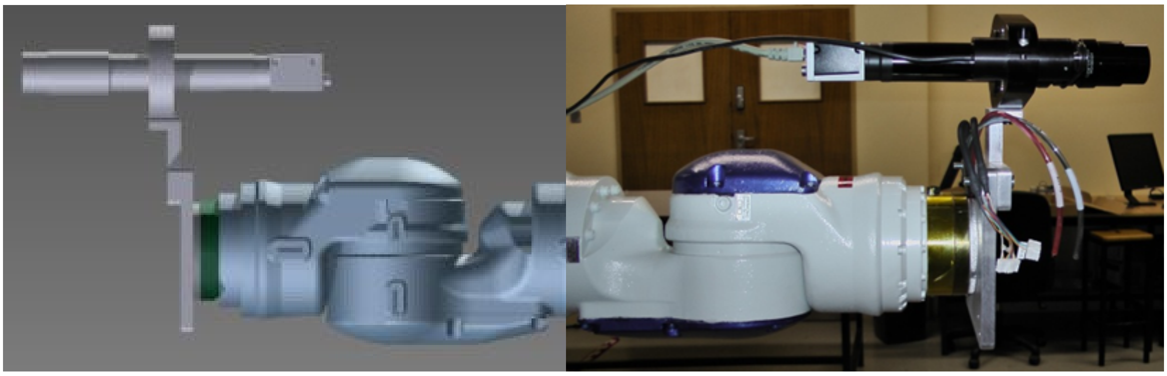
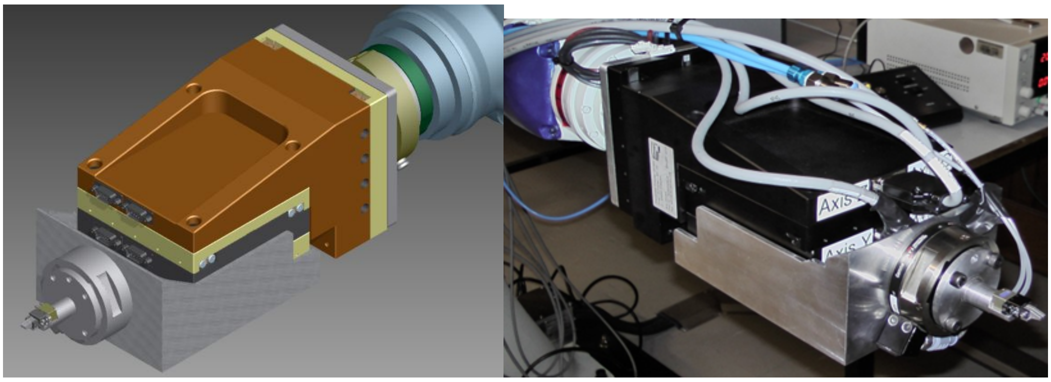


(a) (b)

Figure 8.8: CAD Rendering of Camera System (a) Adjacent to Camera Assembled System (b)



(a) (b)

Figure 8.9: CAD Rendering of Gripper System (a), Adjacent to Gripper Assembled System (b)

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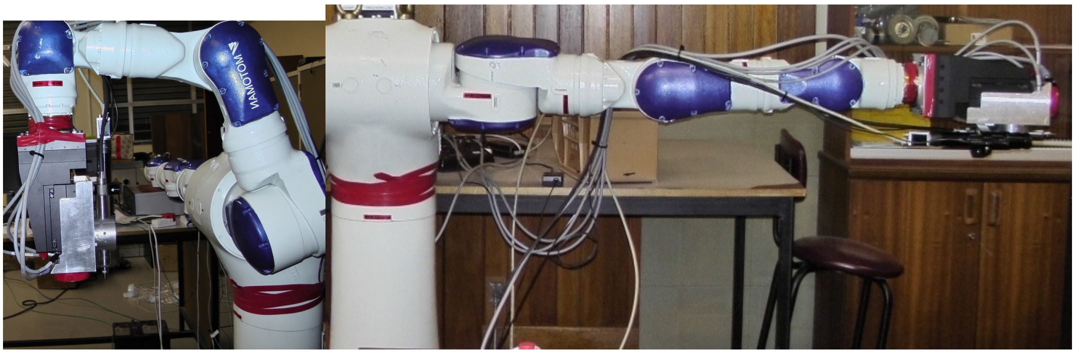
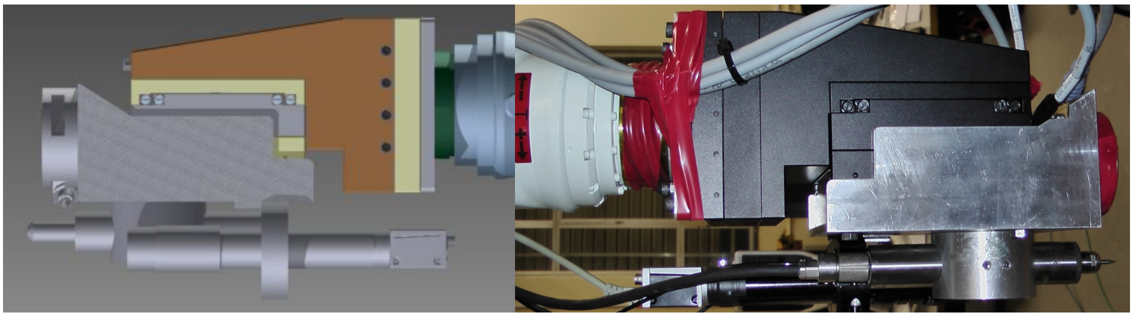


(a) Working Position (One Arm Used)

(b) Arms Extended Position

Figure 8.10: Micro Machining Assembled Configuration One



(a)

(b)

Figure 8.11: Micro Machining CAD Rendering of System (a) Adjacent to Assembled System (b)

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Figure 8.12: OptoNCDT 2300 Laser Triangulation Displacement Sensor, (Epsilon, 2012)

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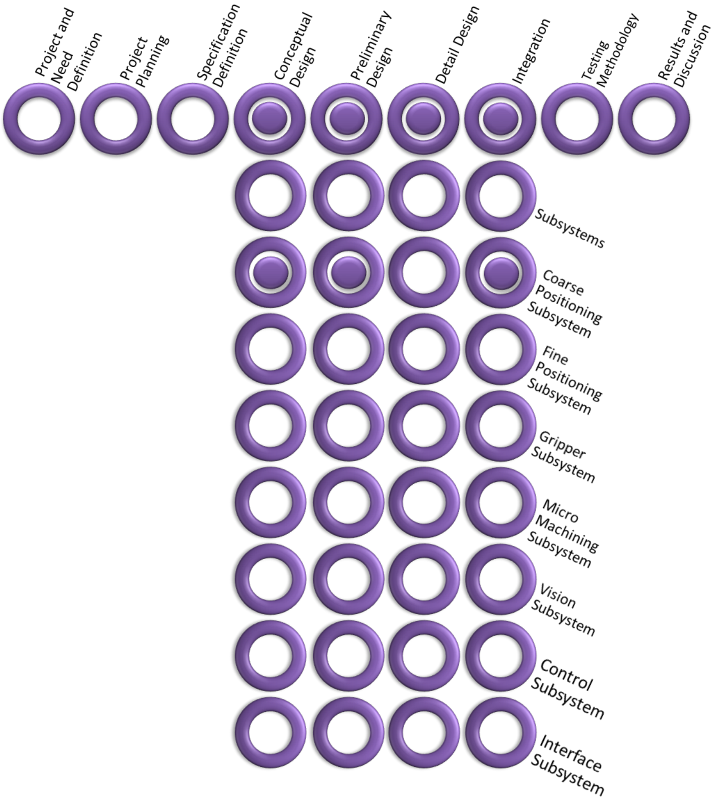
Chapter 9

Coarse Positioning Subsystem



The coarse positioning system provides the large yet less accurate movement. The purpose of this chapter is to explain which coarse positioning system was used and why. In addition to this, the coarse positioning integration components are discussed.

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9.1 Conceptual Design Coarse Positioning System

Robots with linear axes or joints have large workspaces when compared to parallel kinematic robots. One problem of this form of kinematic arrangement is that it is more susceptible to backlash, (Prusi *et al.*, 2011). The University of Stellenbosch currently has a Motoman SDA 10, which can achieve a repeatability of 100 μm, (RobotWorx, 2011). It was thus decided to use the serial kinematic concept for the coarse positioning system.

9.2 Preliminary Design Coarse Positioning System

The Motoman SDA 10 was originally purchased because a Motoman UP 6 was already in place in the University of Stellenbosch's laboratory. Another robot was needed for demonstration purposes and for the development of a haptic force feedback interface. Having two robots manufactured by the same company meant that communication interfaces and protocols and control would be similar. In addition to this easier maintenance and service could be obtained if a robot of the same manufacturer was purchased.

The Motoman SDA 10 was selected in particular because of its humanoid features. This relatively new two-armed robot has 7 degrees of freedom in each arm. This is similar to the arm of a human. Due to its advanced nature, it is ideal for research purposes, see figure 9.1.

An advantage of the Motoman SDA 10 is that it is able to manipulate a 10 kg load. All fine positioning systems lighter than 10 kg thus become feasible attachments. This is in contrast to the Motoman SDA 5 that can only effectively manipulate a 5 kg payload.

9.3 Integration Coarse Positioning

The Coarse Positioning Fine Positioning Mount connects the Feinmess system to the end of the Motoman SDA's arm, figure 9.2. Plate calculations were used according to Benham (1996) in order to determine the amount of deflection. The weight of the force torque sensor, the gripper, the Force Sensor Fine

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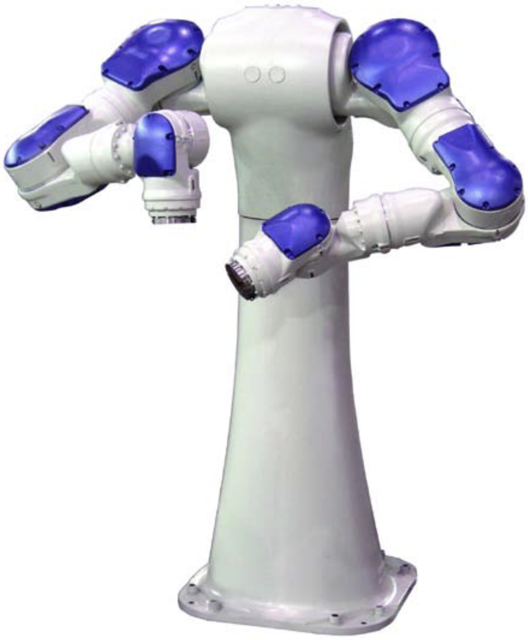

Figure 9.1: Motoman SDA 10 Macro Robot. RobotWorx (2011)

Positioning Mount and the Feinmess MP 130 system were added to determine the deflection. In this instance the deflection was calculated at 0.204 μm, see Appendix D. This figure is not high enough to disrupt normal functioning or calibration process. The thickness and dimensions specified in Appendix F do not need adjustment.

9.3.1 Spacer

In addition to the above, a spacer plate was created. Owing to the construction of the Motoman SDA 10, there are a number of unusable pneumatic and electric cables that emerge from the end of the robot arm. As a result, the spacer was designed to allow the Feinmess system to be mounted flush with the Motoman arm, without having to cut the cables and tubes, see Appendix F. A CAD rendering of the space can be seen in figure 9.3.

9.4 Conclusion

The rigid and dexterous Motoman SDA 10 was selected as the coarse positioning system. The Mount was designed to mount the fine positioning subsystem onto the coarse positioning subsystem. The spacer was designed and con-

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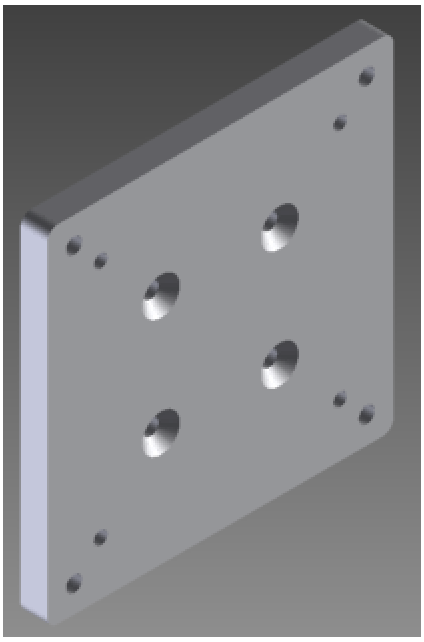

Figure 9.2: Coarse Positioning Fine Positioning Mount

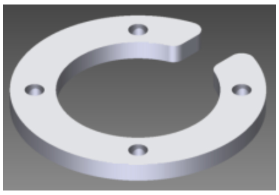

Figure 9.3: Wire Spacer

structed to provide a flush surface for mounting the Coarse Positioning Fine Positioning Mount. This chapter explained the reasons for using the Motoman SDA 10 and its integration into the system.

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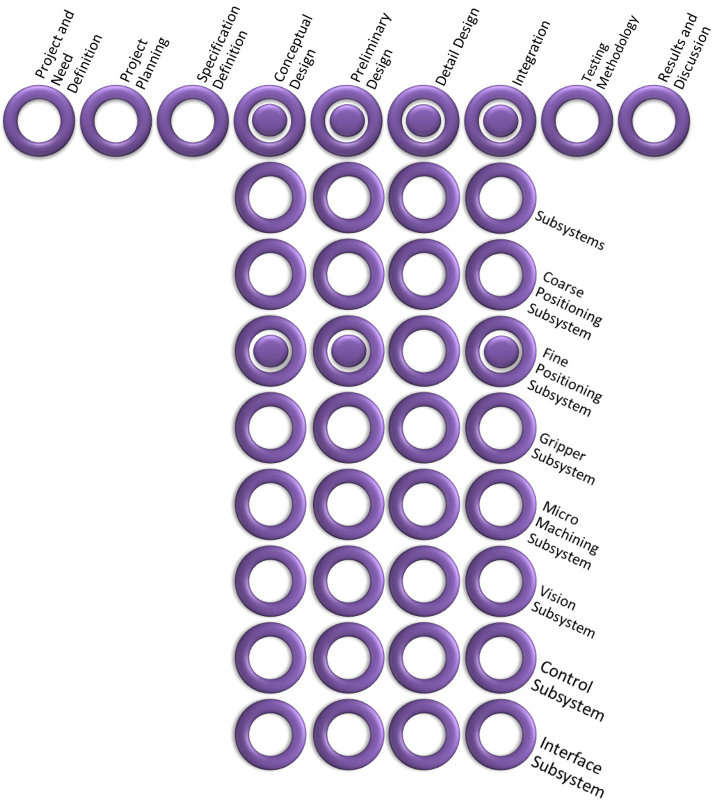
Chapter 10

Fine Positioning Subsystem



The fine positioning system is the key to ensuring micron-level accuracy, repeatability and resolution. It is therefore essential that the correct concept is selected. Once the correct concept has been selected, it is important to ensure that the correct component is selected. The purpose of this chapter is to ex-

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plain and justify the concepts and components selected. In addition to this, the fine positioning integration into the rest of the system is explained.

10.1 Conceptual Design Fine Positioning System

Mueller *et al.* (2012) states that there are only a small number of kinematic principles that can achieve the needed 5 μm repeatability:

- Cartesian Robots
- Parallel Robots (Parallel Scara Robots)
- Kinematics for coarse-to-fine positioning based on Cartesian robots, Scara robots, or articulated robot arms for coarse positioning

In addition to this list, it is necessary to mention the concept of micro robots, and the concept of a micro factory, as alternatives.

10.1.1 Cartesian Robots

Despite the initial perception of a Cartesian robot as being inflexible, the concept was used by Tamadazte *et al.* (2008). Tamadazte *et al.* (2008) successfully used two high-accuracy linear stages (0.007 μm) to form the X and Y motions of the system. A rotational stage was added to increase accuracy. The combination of the aforementioned stages was used to achieve an accuracy of 1.4 μm. An additional advantage to this approach is a wide variety of commercially available Cartesian robots from various sources: Smaract (2011), Feinmess (2011), Instrumente (2011) etc.

10.1.2 Parallel Kinematics

Another approach is to make use of parallel kinematic robots for fine positioning. According to Sulzer and Kovac (2010), parallel kinematic robots have high structural stiffness and a low inertia. High structural stiffness means that these robots are less susceptible to vibrations caused by closed-loop control. A problem with parallel kinematic robots, however, is that they have a limited workspace, (Sulzer and Kovac, 2010) and (Mueller *et al.*, 2012). This is especially the case when compared to robots with open kinematic chains.

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10.1.3 Micro Robots

An alternative to using a combination of macro robot and micro positioning system is the idea of using micro robots for micro- and nano-material handling, (Kortschack *et al.*, 2005) and (Cecil *et al.*, 2007). The mobile robots designed consist of three main parts: the mobile platform, the manipulation unit and the end effector. The designed micro-robots make use of piezo-ceramic components for actuation. The mobile platform transports the manipulator and end effector units around the workspace. These robots can thus access any area of the manipulation site. A 6 degrees of freedom robot was designed that could successfully manipulate micro and nano materials, (Kortschack *et al.*, 2005).

10.1.4 Micro Factory

In this approach, various stages of the micro factory manipulate the micro-material in a different manner. Neugebauer *et al.* (2010*a*) state that the designed system achieved assembly clearances of 0.015 μm. The clearances achieved are sufficient for the reliable assembly of the piezo-ceramic components. The system (or micro factory) was designed in a modular and reconfigurable manner. It rotates and assembles the piezo-ceramic components into the micro-cavities.

The material flow unit enables inspection of the piezo-ceramic material both before and after assembly. This inspection is accomplished using integrated position sensors, high-resolution microscope cameras and laser triangulation sensors, (Neugebauer *et al.*, 2010*a*).

10.1.5 Selected Alternative

Due to the highly accurate, rigid and commercial nature of cartesian and scara robots, they were selected above the other alternatives. At present parallel kinematic, micro robots and micro factories are in the minority when compared to Scara and Cartesian robots. This is evident as per Sanchez-Salmeron *et al.* (2005).

10.2 Preliminary Design Fine Positioning System

The purpose of this section is to select the appropriate, commercially available fine positioning system. This is the most expensive part of the system. It is

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also the most integral to smooth system functioning. As a result, emphasis is placed on exploring the different design alternatives and then selecting the correct one.

10.2.1 Functional Analysis

The functional analysis begun in the Conceptual Design phase is expanded upon in this chapter. In the aforementioned chapter the overall functioning of the system was considered. In this chapter, certain blocks of the functional flow analysis are expanded upon. The details of this expansion are thus used to assist in the creation or selection of solutions. This expansion can be seen in figure 10.1.

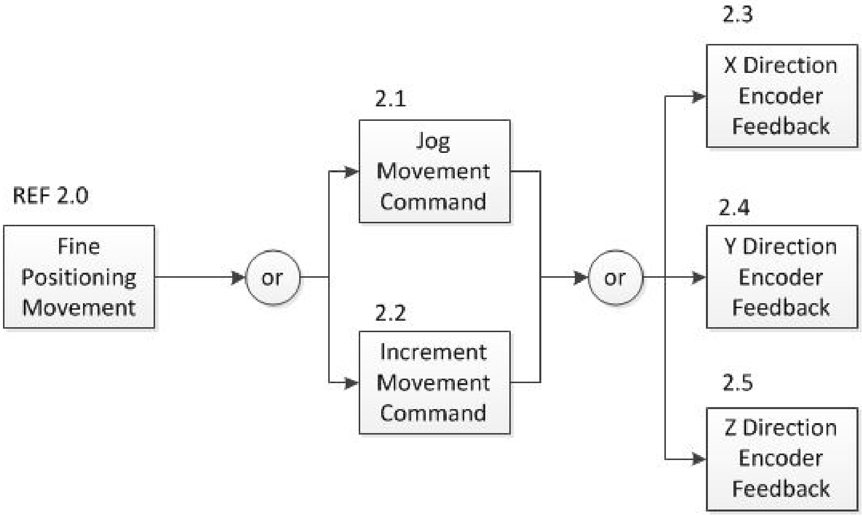

Figure 10.1: The Functional Analysis of the Fine Positioning System Movement

10.2.2 Preliminary Design Criteria

Functional Capability

Three of the fundamental technical performance measures used in the fine positioning selection are repeatability, accuracy and resolution. The technical performance measures are to be 5 μm, 8 μm accuracy, and 3 μm respectively as stated in the Specification Definition.

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In order to compensate for the displacement caused by unwanted vibrations in the first stage's operation, it is necessary for the micro robot to have an operating length of at least 1000 μm, (Freundt *et al.*, 2008*a*).

It was also determined that the fine positioning system should be able to transport a weight of at least 2 kg. This will facilitate the integration of a micro-milling spindle as well as a micro gripper.

The Motoman SDA 10 robot can only handle a weight of 10 kg, (RobotWorx, 2011). As previously explained, if the second stage or (fine positioning system is to be mounted to the Motoman, its weight has to be less than 10 kg. The weight of each of the micro robots was thus used to eliminate infeasible design alternatives.

In order to extend the functionality of the system outside that of a micro-material handling system, it is necessary to consider forces. A fine positioning system should be selected that is capable of handling not only the weight forces proposed but also those experienced during micro-machining. The force associated with 2 kg weight (minimum weight the fine positioning system should eb able to transport) is 19.62 N. Micro-machining forces are generally on the order of 3 N, Chae *et al.* (2006). The fine positioning system should thus be able to withstand forces of around 30 N.

Another less obvious decision is that the fine positioning system should have 3-axis motion. The repeatability of the coarse positioning system is 100 μm in the x, y, and z directions, (RobotWorx, 2011). Fine positioning is thus necessary in each of these axes in order to compensate for positional errors.

Sanchez-Salmeron *et al.* (2005) compiled a list of all the relevant micro-material handling systems commercially available, see table 10.1. Each item on this list was analysed according to the needs of the system, i.e. weight under 10 kg, 3 or more degree of freedom movement and a resolution of 1 to 5 μm.

Maintainability

It is essential to keep the system as modular as possible. It is preferable to have a system that can easily be repaired or, if need be, replaced. This will facilitate quick and effective maintenance.

The above-mentioned concept is illustrated by Sulzer and Kovac (2010) where the coarse or macro positioning robot is fitted with a tool change system, allowing different micro robots or end effectors to be mounted. The fine positioning system or micro robot was itself also constructed in a modular

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fashion, (Sulzer and Kovac, 2010). According to the source, the fine positioning system is combined with the MSW30 Schunk tool change system, allowing end effectors to be manually or automatically changed for different handling tasks.

Usability

A more qualitative aspect to consider is the manner in which the fine positioning systems in table 10.1 are controlled. In order to allow for flexible telerobotic operation, it is necessary to use Ethernet communication. This is a standard protocol that is built into most of the control units of the fine positioning systems. In addition to this, the fine positioning system should be provided with the needed libraries and SDKs in order to allow for easy integration with other programs.

Supportability and Serviceability

Feinmess (2011) supplies a micro robot system that fits the necessary design decisions. The controlling system for the second stage is supplied by Galil (2011). In terms of supportability and serviceability, it is preferable to have the overall system supplied by one company. If a problem occurs with the controller then the user can directly contact one entity for service. Shipping and lead times are also reduced as there only needs to be contact with one company. If the controller and micro robot are supplied by the same company, then they will have a greater knowledge of how the two interface. Again, technical problems can be solved by one body.

Affordability

A more pertinent aspect to be kept in mind is cost. It is essential that the system is cost-effective. Having a system that is affordable should not be at the cost of the accuracy or performance of the system. Having examined the various alternatives, the system should be less than around R 400 000.00, yet more than R 50 000.00. All of the alternatives within this price range fulfil the majority of the functional capability requirements.

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10.2.3 Trade-off Analysis

Methodology

A large number of robots are examined despite the fact that they are not necessarily feasible. This is simply to demonstrate method and the fact that all options have been considered. A prime example of this are Scara robots. Scara robots are simply too large and cumbersome to be manipulated by the Motoman SDA 10. There are also problems associated with mounting the robot on the tool mount of the Motoman. Despite the fact that robots of this form fulfil the necessary requirements, they are not a feasible solution owing to their geometry.

The table 10.1 illustrates various different characteristics of the most feasible second-stage fine positioning system. The table does not, however, contain information on the supplied control hardware and software, cost, country of origin, and weight. So it was decided to use table 10.1 as a guideline for analysing the different micro robot alternatives. The micro robots listed in the table and those mentioned in addition to the table are consequently evaluated in terms of the design decisions, and the aforementioned characteristics. The top three choices are then selected and compared.

Alternatives

Sanchez-Salmeron *et al.* (2005) summarised a list of all the feasible micro-material handling systems in the table 10.1, as seen below. The source continues on to state that, in general, the more precise the robot, the slower its maximum speed. Conversely, the faster the robot's speed the less accurate it is. Both speed and accuracy are important in an industrial reconfigurable type system.

In addition to the above, Freundt *et al.* (2008*b*) state that the following systems provide the necessary repeatability for micro-material handling: Klocke Nanotechnik, MicRohCell Rohwedder AG, Autoplace by Sysmelec, RP from Mitsubishi and micro positioning stages from Physik Instrumente. The systems offered by Nanotechnik, Sysmelec and Mistubishi have all been mentioned in table 10.1 by Sanchez-Salmeron *et al.* (2005). These systems are examined in the following sections. Rohwedder offers customised solutions for micro assembly production lines. These solutions do not offer the reconfigurability needed by the system. Finally, Physik Instrumente does not offer solutions with the combined precision and 3 degrees of freedom needed for the intended application.

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Table 10.1: State of the Art Industrial Micro Manipulators, (Sanchez-Salmeron *et al.*, 2005)

Model	**By**	**Type**	**DOFS**	**REP. ACC (μm)**	**WS (mm)**	**Load (kg)**	**Speed (mm/s)**
E2C	EPSON	SCARA	4	8	R250 Z100	5	P&P 0.39 s
RP-1AH	MISTUBISHI	SCARA	4	±5	150×105×25	1	400 P&P 0.28 S
YK-120X YK-150X	YAMAHA	SCARA	4	5-10	R110Z30	0.5	700-2000 P&P < 300
TURBOSCARA SR4-PLUS	BOSCH	SCARA	4	±50	R400 Z200	2	1600
AUTOPLACE 400	SYSMELEC	CART	4	±2.5	150×150×150, 85×85×75	4	
MP63-25DC	FEINMESS	CART	3	5	25×25×25	2	5
MP84	FEINMESS	CART	3	3	25×25×25, 100×100×100	1.5	250
1940	KOPF	CART	3	1	128×128×128		
MM3A	KLEINDIEK	RRR (antr)	3	1	100cm^3; z:12; x,y:180°		10
KLOCKE	NANOMANIP	RRR (spher)	3	0.001	5×5×19	0.2	5
MRSI							
EXFO	PCS-4100	RPPPR	5	0.4	25×25×25		2
SEMPREX	Univ. Pipette Manipulator	PPPRPP	6	75×33×25, 95°75,200			
SOMAPATCH	MW3R/L	CART	3	0.25	5×5×5		
MRSI	Newport	PPPR	4	±10	415×415		9000

Prusi *et al.* (2011) conducted a brief evaluation of current commercial micro-material handling systems. This study mentioned the RP from Mitsubishi, Pocket Delta Robot from Asyril, M-1iA robots from Fanuc, XYZ Manipulators from Klocke Nanotechnik, MM3A from Kleindiek, and the Schunk Scara. The robots from Mistubishi, Klocke Nanotechnik, and Kleindiek have been mentioned in the table 10.1 and will analysed in detail. The Fanuc and Schunk robots both did not have the necessary repeatability of under 5 μm. The Delta robot from Asyril is a feasible solution and will be examined.

Two micro-material handling systems not mentioned in the above table are the MiniROb SX from Milasys as used in Sulzer and Kovac (2010) and the Desktop Delta Robot from Asyril. These are to be analysed later on in this chapter. In addition to the aforementioned two companies, Piezojenna and Smaract also offer commercial micro-material handling systems. Piezojenna systems have high accuracy but have maximum motion range of 400 microns, (Jena, 2011). Smaract fulfil the majority of the requirements; however, they

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do not have the necessary Ethernet communication, (Smaract, 2011). This would mean the integration of a Barionet to convert communication. This would slow the system considerably.

10.2.4 Evaluation of Design Alternatives

Due to the fact that a large number of expensive component decisions had to be made, micro parts of system engineering were applied. In particular, the design trade off analysis as per Blanchard and Fabrycky (2006) was used to help differentiate between components. For a number of different parts the respective attributes were scaled. The results ranged from 0 to 5, i.e. the least desirable attribute in the range would be ranked at 0 while the most desirable would be ranked as 5. A weighting factor was then added in order to determine the total score. This methodology can be seen in the figures below. In addition to the chosen components, a desktop computer was used for interpreting and controlling subsystem.

The fine positioning subsystem dictates the functioning of the system. It was thus imperative that the exact model be selected. Sanchez-Salmeron *et al.* (2005) compiled a list of commercially available highly accurate positioning systems. This list served as the basis for the search. Once the list had been finalised, as seen in Appendix A, quotations and technical information were obtained. From the obtained information a comparison bar chart was created, see figure 10.2. The physical characteristics all deal with the performance of the positioning system, i.e. the work volume it operates in, the maximum load it can handle, etc. The software refers to whether the controller has available libraries and higher level controlling programs or not. The price refers to the overall cost of the system.

In order to provide a different perspective on the criteria, a web graph was created. This web graph can be seen in figure 10.3. It allows the reader to view how multiple alternatives fulfil multiple criteria in one snapshot.

10.2.5 Preferred Alternatives

The three concepts that best fulfil the design decisions and design criteria in order of importance are the XYZ manipulator from Klocke, the Desktop Delta robot from Asyril, and the MP63-25DC from Feinmess. As can be seen from the chart, the fine positioning system from Klocke obtained the highest score, due to the fact that the Klocke solution has the best overall control structure. Initially this system was perceived as the most feasible fine positioning system.

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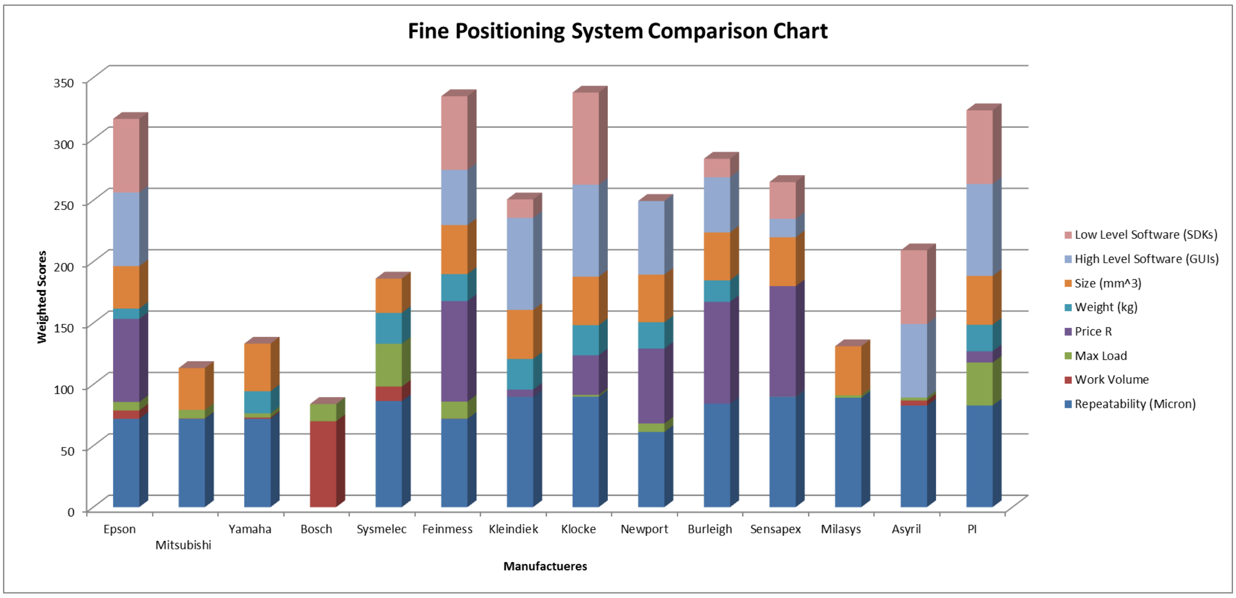

Figure 10.2: Excel Fine Positioning System Comparison Chart

10.2.6 Risk and Uncertainty

Although Klocke has been mentioned in two academic papers, Freundt *et al.* (2008*a*) and by Prusi *et al.* (2011), the system is only able to carry around 200 g, (Klocke, 2011). The initial design decision was around 2 kg. This immediately prevents the system from performing micro-milling. The Klocke system also has nanometer accuracy: this means that the system can only be operated in one orientation. One of the main aims of the micro-material handling system is performing dexterous manipulation. The system by Klocke (2011) is thus not feasible.

10.2.7 Selected Alternative

The Feinmess system was chosen after all the alternatives were examined in detail. After further consultation with Feinmess (2011), it was decided to purchase the MP 130 3-axis unit. This system was far more applicable to dexterous micro-material handling than was the MP 63.

The MP 130 system has a large number of favourable characteristics when compared to other positioning systems. The system is far less expensive, and has a larger working range (50 mm X 50 mm X 50 mm), (Feinmess, 2011). More importantly, the system has a repeatability of 1 μm and an accuracy of 3 μm. The system also facilitates Ethernet control with low level APIs and high-level controlling interfaces, (Feinmess, 2011). The 3-axis Feinmess system

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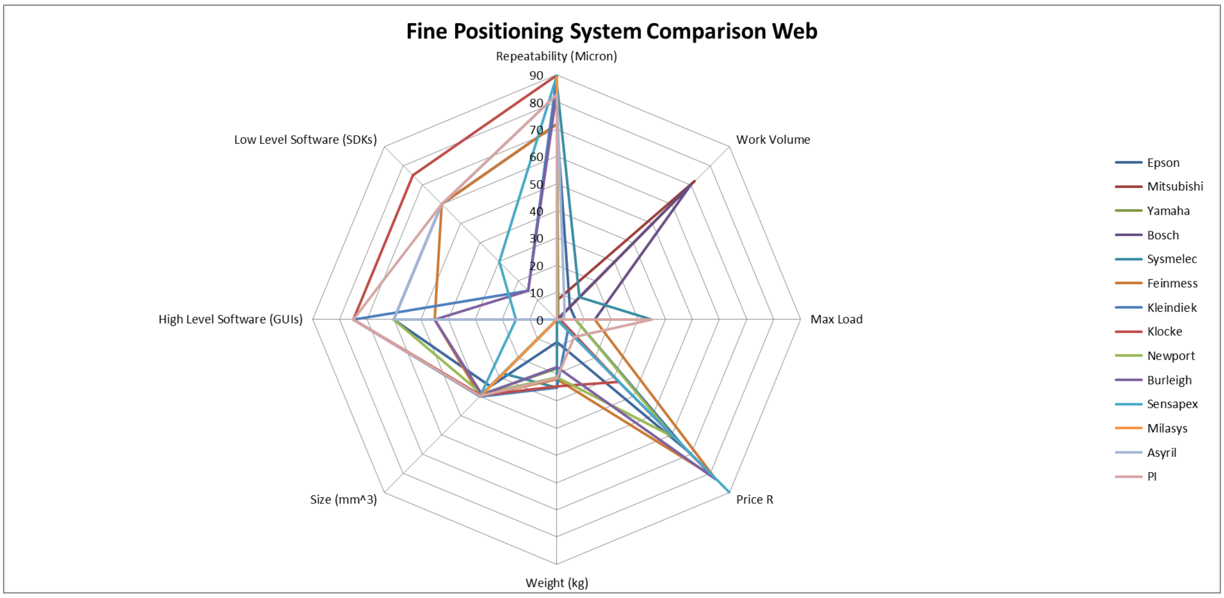
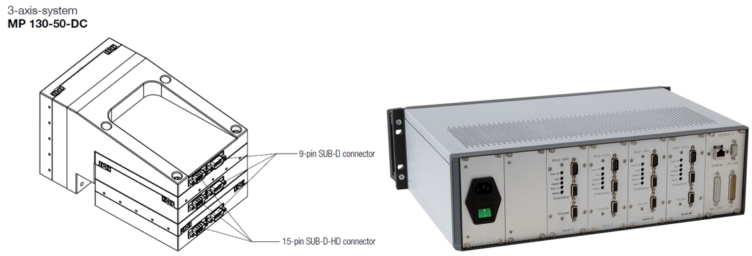


Figure 10.3: Excel Fine Positioning System Comparison Web

and controller were thus selected as can be seen in figure 10.4.



(a) Fine Positioning MP130 (b) Fine Positioning Controller

Figure 10.4: Finemss MP 130 Fine Positioning System and 3-Axis Galil Controller, (Feinmess, 2011)

10.3 Integration Fine Positioning

The Schunk gripper is placed on to Force Sensor Fine Positioning Mount. A great deal of exact alignment is required when using the pneumatic gripper tips, the camera and lens system and the micro-milling spindle. There are, therefore, a large number of geometric tolerances, for the position of the spigot (for positioning for force torque sensor) and for the position of the micro-milling

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spindle (round extrusions on front face and underneath the mount, respectively. See figure 10.5). There are also a number of geometric tolerances for the holes to support the camera and lens, as these need to be parallel to the surface of the force torque sensor. All of these tolerances can be seen in Appendix F.

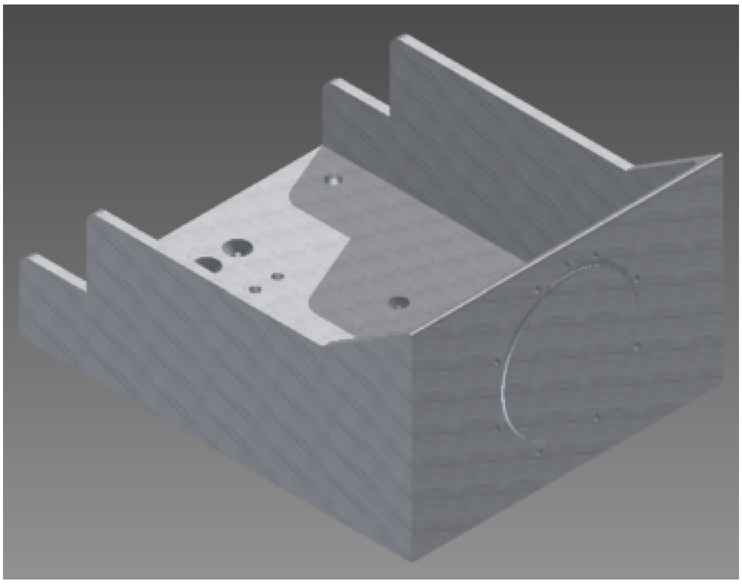

Figure 10.5: Force Sensor Fine Positioning Mount

In order to ensure that acceptable levels of deflection occurred, a large number of static strength calculations were performed. The moment areas of inertia were used to calculate the force experienced by the walls of the unit as per (Benham, 1996), see figure 10.5. This force used was that of the maximum weight exerted by the force sensor and gripper. This force, when converted to a normal force, was found to be 222 Pa, which is far less than the allowable 70 MPa.

The front of the structure (side with circular spigot) was also modelled as a plate in order to view possible deflection as per (Benham, 1996). Again, using the weight of the sensor and the gripper, a maximum deflection of 0.0486 μm was calculated. This is far too low to cause interference in the operation of the system. The calculations can be seen in Appendix D.

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10.4 Conclusion

When examining fine positioning concepts, the Cartesian robot was selected because of its favourable characteristics. After a lengthy process, the Feinmess MP 130 fine positioning system was selected. The key factor when considering the fine positioning integration into the system, is that of the Force Sensor Fine Positioning Mount. This component has a large number of tolerances in order to ensure correct alignment.

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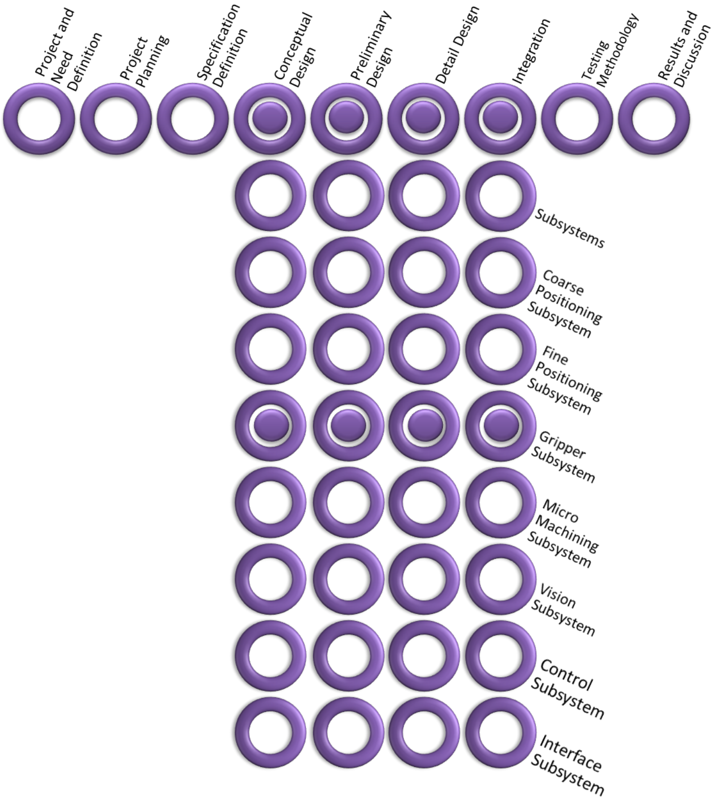
Chapter 11

Gripper Subsystem



The purpose of this chapter is to examine the various design steps of the gripper subsystem. Overall gripping concepts are analysed in the conceptual design phase. The preliminary design is used to select a friction force gripper. In addition to this, the component and preliminary experiment of the Van der

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Waals gripper (as per Arderne *et al.* (2012)) are examined. The friction force gripper tips are then designed in detail. Once this has been completed, the integration of the friction force gripper and the Van der Waals gripper are examined separately.

11.1 Conceptual Design Gripper

Arai *et al.* (1995) states that contact and sliding motion at the micro scale can cause small particles to be generated. These particles can interfere with accurate placement and manipulation. Motions such as these should thus be replaced with lift-and-place motions, where possible. Sanchez (2010) advocates the use of V-groove structures and datums in micro grippers in order to better aid positioning.

There are a number of different gripping principles that allow for a micro part to be maintained in a certain position. A number of principles are applicable in both micro and macro domains. These principles include friction-based gripping, form-closed gripping, suction-based gripping and magnetic gripping, (Sanchez, 2010). Sanchez-Salmeron *et al.* (2005) state that there are three basic types or methods of micro-material handling. These methods use the principles of friction, pneumatics and magnetics.

According to Sanchez (2010), gripping principles that are only applicable in the micro domain are based on adhesive forces. These forces include electrostatics, surface tension or capillary effect, Van der Waals forces, cryogenic gripping, ultrasonic gripping and the Bernoulli. The majority of these forces are applied only to sufficiently low-weight parts. A large amount of constraint is placed on the selection of the appropriate gripping principle by the surrounding environment. Surface tension forces, for instance, are difficult to control under humid conditions. Certain gripping techniques are also only limited to certain materials. Electrostatic grippers are not, for instance, applicable to non-conducting materials.

Sanchez (2010) continues on to state that contactless grippers exert a uniform force on the part and, as a result, fragile micro parts can be handled. The source continues on to state that a disadvantage of contactless grippers is that the latter requires additional equipment and are inflexible.

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11.1.1 Suction Grippers

A prime example of a suction gripper is a vacuum gripper. This gripper type is inexpensive when compared to other forms of grippers, as it is merely a combination of a vacuum pump and tubing, (Sanchez, 2010). These characteristics make this system easy to replace. The gripper's dexterous manipulation of parts once gripped is limited when compared to a two-fingered gripper. This is because vacuum grippers are generally bulky and require contact with most of the surface of the gripped object.

11.1.2 Electrostatics

According to Sanchez (2010), the easiest force to control is that of the electrostatic force. The system uses the electrostatic force to grip the various materials and uses their weight force to release them. According to Neugebauer *et al.* (2010*b*), electrostatics are particularly suited for moving bar-shaped objects. Machine vision is also aided as the grippers themselves can be transparent. A problem with this gripping principle is that it can only be applied to certain materials. A further problem is if there is a need for charge-sensitive devices such as Micro Electro Mechanical Systems (MEMS).

Example

Neugebauer *et al.* (2010*b*) analysed a gripper constructed of a silver-electrode printed onto silica slides. The designed micro-grippers were successfully used to place 0.25 by 0.25 by 10 mm^3 piezo-micro parts into micro-cavities with a positional accuracy of 15μm. A problem with this specific application is that the gripper can only be used to grip certain materials.

11.1.3 Friction

The principle is best explained by an example. The traditional tweezers or two-fingered micro gripper is based on the principle of friction. When the two 'fingers' close on the micro object, the friction between the surface of the object and the surface of the gripper increases. The force is increased such that it becomes greater than the force of gravity. The result is that the object remains firmly held in the gripper.

Menciassi *et al.* (2004) state that when dealing with micro-materials and adhesion effects, it is more appropriate to make use of a two-fingered manipulator as opposed to a three- (or more) fingered gripper. Although additional fingers provide more articulation, they also increase the contact surface area.

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This increase in surface contact area increases adhesion forces, and this hampers the release of the micro-material.

Friction-based micro grippers achieve a high placement accuracy, as objects can be put in a defined location after being gripped, (Sanchez-Salmeron *et al.*, 2005). There is also always a reference point when using this type of gripping. A disadvantage of this type of system is that the grippers themselves can be large in comparison to the micro object. This can limit the sizes of objects that can be handled, (Sanchez-Salmeron *et al.*, 2005).

Sanchez (2010) concurs with Sanchez-Salmeron *et al.* (2005) in stating that parts can more easily be aligned or centred with two-fingered tweezers, as a reference point is provided. By increasing the number of reference points, the number of sensors needed is decreased. A problem with using the two-fingered gripper is that only limited parts in a particular size range can be handled by a certain pair of grippers. It also becomes expensive and ineffective to design two-fingered grippers for parts that are smaller than a certain size range, (Sanchez, 2010).

Example

A two-fingered gripper configuration was successfully created by (Tanikawa and Arai, 1999). This system made use of two glass pipette needles as end effectors. The tips of the needles were heated and drawn to increase precision. The system was able to successfully handle glass balls having a diameter of 2 μm with an accuracy of 0.1 μm. The source stated an interesting solution to solving the problem of adhesive forces. The system was designed such that the manipulator achieved motion relative to one another. As a result, if an object was gripped at an area with a large contact area, it could be rolled towards the manipulator tips where there is less contact area. The decrease in surface area contact would mean less adhesive force and easier release of the object, (Tanikawa and Arai, 1999).

Example

Cecil *et al.* (2007) described a spring steel two-fingered gripper used to pick and place MEMS parts in assembly. The gripper has dimensions of 100 mm × 150 mm × 50 mm. This micro gripper could grip objects from 2 to 10 mm. An optical sensor for force feedback was integrated into this gripper in order to increase accuracy, (Cecil *et al.*, 2007).

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11.1.4 Van der Waals

According to Cecil *et al.* (2007) The Van der Waals force between a plane and a sphere is modeled using the following variables; H (the Lifshitz van der Waals constant), D (the diameter of the sphere), and d (adhesion contact distance between the sphere and the plane). Surface roughness and conductivity influence the existence of adhesion forces, (Cecil *et al.*, 2007).

Example

Van der Merwe and Matope (2011) state that Van der Waals forces can be effectively used to pick up micro-sized work pieces. A micro-gripper of this nature is simple and has no moving parts. A problem with using Van der Waals forces as a means of micro-gripping is that it becomes difficult to release the gripped material. The surface on which the object is to be placed has to have a higher Van der Waals force with the gripped object than the gripper has with the object. If this is not the case, the object will remain stuck to the gripper.

11.1.5 Other

The table in Appendix B, Comparison of Gripping Principles, summarises the various characteristics of the different principles used in micro-material handling. Other forces not listed in the table include ultrasonic levitation and air cushion gripping, (Sanchez, 2010). The majority of these forces are still in their infancy and are thus not commercially available.

11.1.6 Selected Alternative

Due to the simple and intuitive nature of the friction gripper. This concept was selected. This concept also facilitates easy design and integration into the rest of the system. Because of its simplicity however, the Van der Waals gripper can be used as an alternative to the friction gripper.

11.2 Preliminary Design Gripper

Two grippers are selected. The first is an off-the-shelf commercial gripper. This will provide for conventional pick-and-place operations. The second gripper is the Van der Waals gripper as proposed in Neugebauer *et al.* (2011*b*). The Van der Waals gripper has numerous advantages for the application. Owing to the

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relative immaturity of this technology it is important to incorporate a proven gripper as initially stated.

11.2.1 Functional Analysis

Gripper functioning is not complex when compared to that of the fine positioning system. It is highly likely that the selected system will offer remote control, however, through means other than Ethernet. The Barionet was included to interpret and execute commands. This functional flow can be seen in figure 11.1.

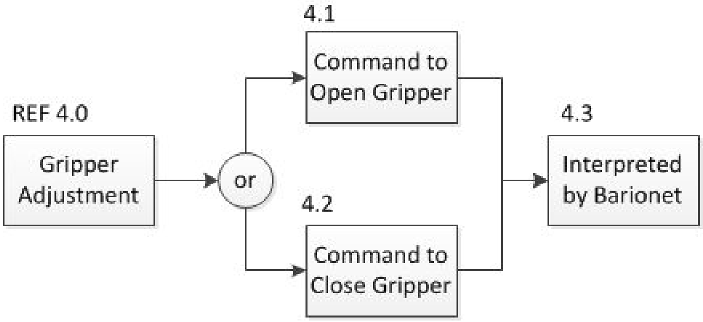

Figure 11.1: End Effector Functional Analysis

11.2.2 Preliminary Design Criteria

Functional Capability

A technical performance measure that needs to be fulfilled by the subsystem, is that the gripper should be able to grip various differently sized objects in order to ensure that its use can be varied. The parts to be gripped are the piezo-ceramic rods, which are 260 μm by 250 μm by 10 mm. So the gripper should be able to grip parts from around 220 μm up to around 500 μm in size.

If the gripper is controlled by positional feedback, then the exact dimensions of the object must be known. The object also has to be gripped at exactly the right orientation. If force feedback is applied, then a set force can be applied each time. The object will thus not be gripped until the exact force is exerted.

The gripping force applied should be larger than 165.54 μN in order to overcome the frictional coefficient of Al2O3 (similar to piezo-ceramic) of 0.15

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when in contact with steel, (MolTech, 2010). In addition to this, the force should be smaller than 1.875 N. This is the force roughly equivalent to the maximum compressive force of the piezo-ceramic PZT of 30 MPa, (Matthey, 2012).

In accordance with the weight limit of the coarse positioning system and the maximum allowable force of the fine positioning system, the gripper should be as light as possible. In order to allow weight for the mounting hardware and cables, the system should weigh less than 1 kg.

Usability

The functioning of the gripper should allow for some form of remote control. This remote control should also interface with the controlling program for the fine positioning system and the vision system.

Affordability

As explained, two gripper types are to be used for this project. The budgetary constraint for the gripper gets a lot tighter. The gripper is the least expensive of the three components examined in this chapter. It was decided to have a maximum gripper expense of around R 20 000.00.

11.2.3 Trade-off Analysis

Methodology

In this section various alternatives are presented and explained. There are, however, far fewer technical aspects to consider when selecting a gripper. There is thus no need to create a comparison bar graph. The main decision-making criteria are that of functionality and cost. In addition to this, qualitative aspects are considered.

11.2.4 Evaluation of Design Alternatives

Klocke

Klocke (2011) states that the NM Small gripper has a stroke of 0.7 mm, a gripping force of 20 mN, a resolution of 1 nm and is able to grip objects that are 0.02-5 mm in size. This is exactly within the requirements of both force

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applied and size of object. This gripper can be seen in figure 11.2.

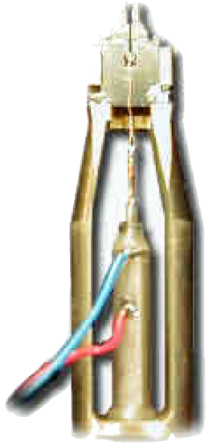

Figure 11.2: Klocke NM Small Gripper, (Klocke, 2011)

A major problem with this solution is that, according to Klocke (2011), the grippers have to be used in conjunction with the company's specific controller. This controller is expensive and has far more functionality than is required simply to operate a gripper, i.e. this is the same controller used to control a 3-axis positional stage system.

Femto

The FT-G102 system has been recommended by (Femto, 2011). The source states that the opening of the gripper is 100 μm. The stroke of the arms is also 100 μm. The opening distance of the grippers can be extended to 500 μm upon request. The resolution of the system is stated to be in the nanometre range. Another feature of this system is that it incorporates force sensors. This allows for force feedback usage. The gripper can be seen in figure 11.3.

Figure 11.3: Femto Gripper FT-G102, (Femto, 2011)

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A major issue with the Femto FT-G102 gripper is that the minimum order quantity is 5 units. The price for these is thus around R 80 000.00. Another issue is that the force needed to overcome friction is 170 μN. The maximum force offered by this gripper is in the order of 50 μN, (Femto, 2011).

Smaract

The gripper offered by Smaract (2011) is the SG-06 gripper. This gripper is equipped with a position sensor. This sensor works in conjunction with flexible hinges to effect gripping. These gripper tips can be replaced in a modular fashion. This allows tips to be replaced with varying size ranges. The gripper tips offered have a closing distance of between 0.3 mm to 1.5 mm, (Smaract, 2011). This system costs around R 13 000.00. The gripper can be seen in figure 11.4.

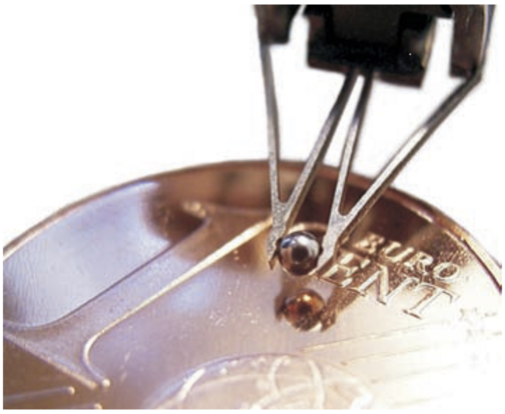

Figure 11.4: Smaract SG-06 Gripper, (Smaract, 2011)

Schunk

The MPG-12 has a stroke of 1.2 mm. Schunk (2012) states that the gripper has a minimum force of 3.3 Newtons. This force is high. If, however, the force is applied over a large area, then damage to the piezo micro part can be reduced to zero. These calculations were done in depth in the Appendix C. This gripper costs R 2 780.00, (Schunk, 2012) and can be seen in figure 11.5.

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Figure 11.5: Schunk MPG-12 Gripper, (Schunk, 2012)

11.2.5 Selected Alternative

Due to the low cost nature of the Schunk gripper and the fact that it fulfils all of the design criteria, it was selected. Two of these units were purchased. This was done to allow experimentation with the different configurations of the gripper and fine positioning system. These layouts are expanded upon in the Chapter Product Development Implementation. The University of Stellenbosch also has a good working relationship with Schunk. Due to a shipping problem on the side of the manufacturer, the two grippers were supplied at no cost.

11.2.6 Additional Hardware

Given the nature of the Schunk MPG-12 gripper selected, it is necessary to obtain gripper tips. Owing to the unique nature of this application, it was decided that the gripper tips be designed and manufactured in house.

The Festo solenoid valve is needed order to switch the flow of air from the compressor. This switching allows for the gripper to open and close. This solenoid valve can be seen in figure 11.6.

The relay of the Barionet is used to switch the voltage from the voltage source (i.e. positive to negative and negative to positive). This switching of the voltage allows for the opening and closing of the Festo solenoid valve. The Barionet can be seen in figure 11.7.

The Solenoid valve runs off 24 V DC as per Festo (2012). In order to engage the need switching a power supply is needed. This power supply can be seen in figure 11.8.

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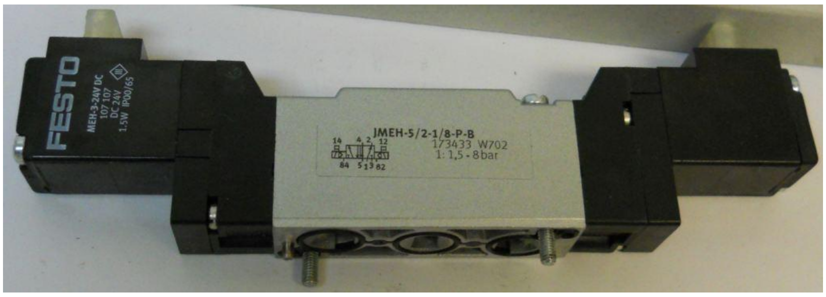

Figure 11.6: Festo JMEH 5/2 1/8 Pneumatic Solenoid Valve, (Festo, 2012)

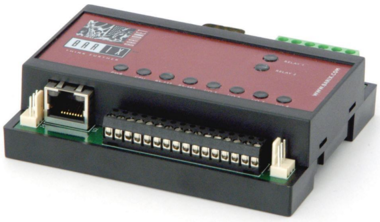

Figure 11.7: Barix Barionet 100, (Barix, 2012)

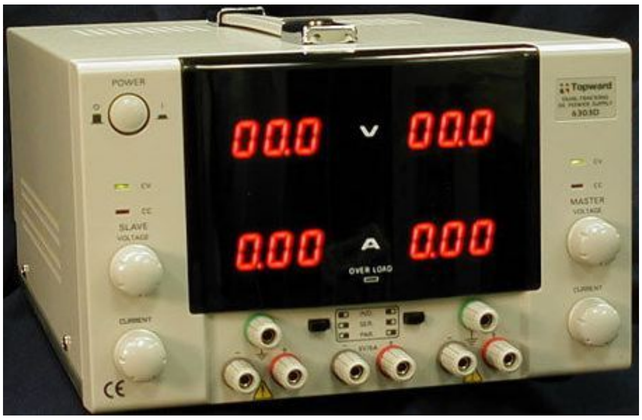

Figure 11.8: Topward TPS-6603D Triple Output Power Supply. Digital Display. Dual 60V/3A Plus 5V/5A, (Vartec, 2012)

11.2.7 Wiring

The solenoid valve is wired to the Barionet and power supply as seen in the following figure 11.9. When relay 2 is activated, the current travels from the power supply through the red live wire to the left terminal of the solenoid. It then enters and activates the solenoid. It then leaves the solenoid and travels to the number 2 pin of the Barionet Relay. It then enters the ground wire and

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travels back to the power supply. A similar series of events follows when relay 3 is activated, however it enters the right terminal of the solenoid and then pin 3 of the Barionet.

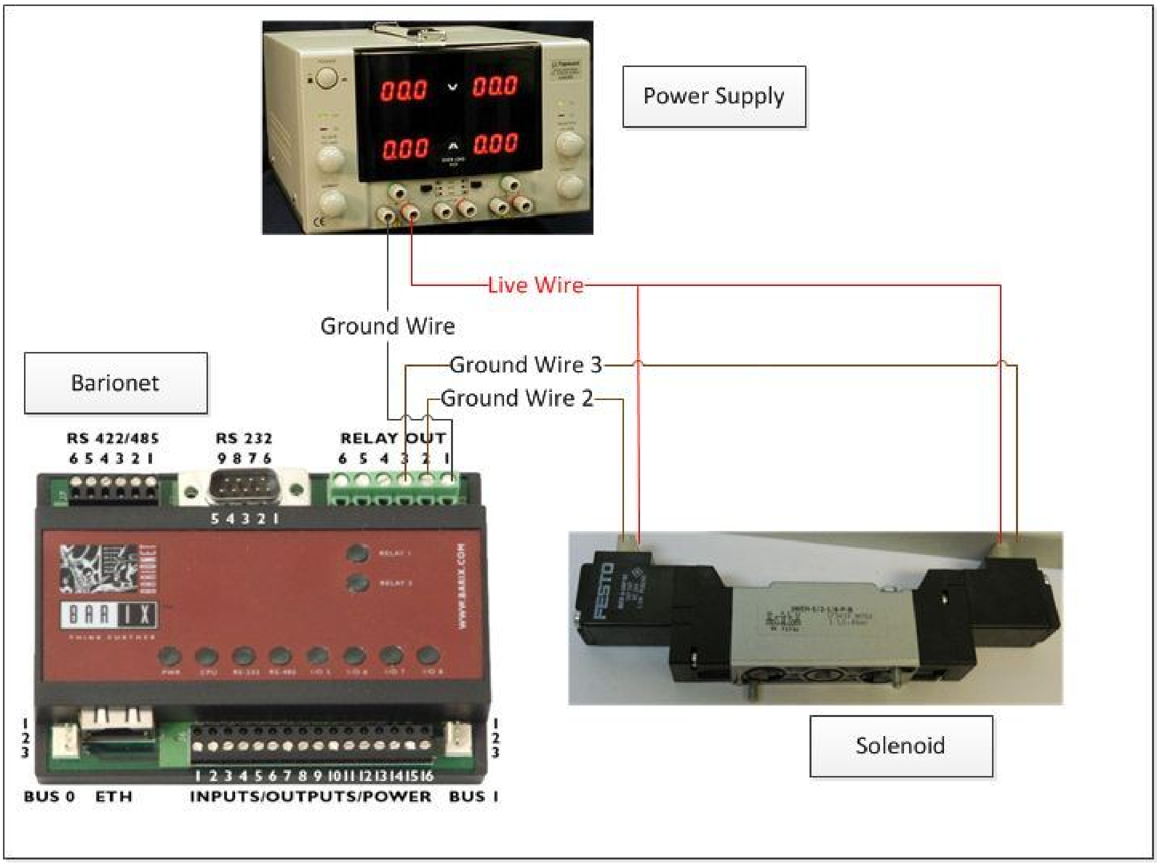

Figure 11.9: Barionet, Power Supply and Solenoid Valve Wiring Diagram

11.3 Preliminary Design Van der Waals Gripper

In addition to the Schunk gripper selected, it is necessary to consider the use of a Van der Waals gripper. This gripper, as per Arderne *et al.* (2012), would greatly simplify the gripping of the micro-materials. In addition to this, an accuracy increase can be expected because this form of gripper does not involve any motion, i.e. opening and closing of a pneumatic gripper.

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11.3.1 Applicability

Van der Waals forces are naturally applied by nature, e.g. scaling of walls by geckoes (Autumn *et al.*, 2002), (Glassmaker *et al.*, 2004). These forces occur on almost all surfaces of a given substance. Polyurethane material has been found to exert significant amount of Van der Waals forces (Murphy *et al.*, 2011), (Arderne *et al.*, 2012). Murphy *et al.* (2011) used it in their wall-climbing robots, and Arderne *et al.* (2012) used it as the gripping material for electronic components.

Given the relative softness of polyurethane, with its hardness generally ranging from a shore hardness of 10 A to 60 A (Smooth-On (2012)), it renders itself suitable for gripping brittle material such as piezo-ceramics. The piezo-ceramic micro parts required in the assembly of the piezo-metal sensor module are very fragile with a width-to-length ratio of about 1:10. A Van der Waals forces-actuated polyurethane gripper would therefore be suitable.

Product Used

Polyurethane of shore hardness of 30 A (trade name Smooth-On (2012), Smooth-On product, supplied by AMT Composites, Cape Town) was used to produce the desired grippers. The dimension of the gripper allowed the 10 mm-long piezo-ceramic micro parts to overlap so as to afford better precision during placement into the grooves.

11.3.2 Experiment

Arderne *et al.* (2012) conducted an experiment whereby the formed Van der Waals micro grippers were then mounted onto a Motoman SDA 10 in combination with a force torque sensor. This setup was similar to the experiment conducted as per figure 11.10. The 30 A Van der Waals gripper was successfully used 6 times to pick and place a flat copper circuit-board. During this picking and placing process, an average pre-load of 0.369281 N was recorded. The maximum force exerted by the gripper was roughly 1 N.

11.4 Detail Design Friction Gripper Tips

As with the two configurations, there are two sets of gripper tips. Note that for each configuration there are two different gripper tips, i.e. one left and one right. In total, there are four gripper tips to be manufactured, see Appendix F. The first set of gripper tips is for configuration one and can be seen in

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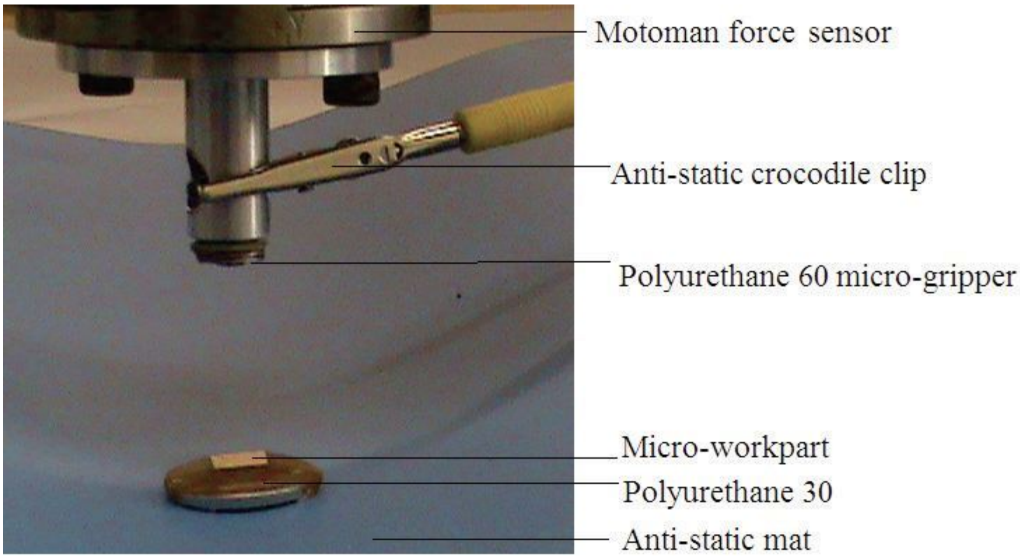
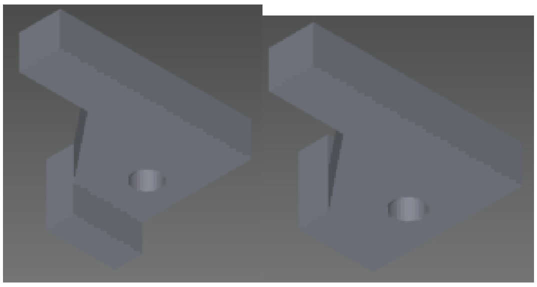


Figure 11.10: Van der Waals Gripper as per, (Neugebauer *et al.*, 2011*b*)

figure 11.11 and is referred to as Gripper Tip Alternative Remake. The set of gripper tips for configuration two can be seen in figure 11.12 and is referred to as Gripper Tip Remake.



(a) Gripper Tip Alternative Remake One (b) Gripper Tip Alternative Remake Two

Figure 11.11: Gripper Tip Alternative Remake One and Two (RHS and LHS)

A large number of calculations for the gripper tips were executed assuming the tips were to be constructed from steel. However, the gripper tips were manufactured using aluminium. The main problem with this is the difference in the amount of Van der Waals forces. If there is a large amount of Van der Waals force, the micro parts will stick to the gripper tips. The Hamaker constant for aluminium is lower than that of steel. Thus, there is less chance of sticking due from adhesion forces, (Matope, 2012). It is thus feasible to use

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(a) Gripper Tip Remake One (b) Gripper Tip Remake Two

Figure 11.12: Gripper Tip Remake One and Two (RHS and LHS)

aluminium gripper tips in place of the steel gripper tips as calculated.

The force calculated as a direct result of Van der Waals forces is 4.74 μN. The weight of the actual part was calculated at 49.67 lmuN. Van der Waals forces do not affect the picking and placing when using the grippers as described above. All the calculations for the gripper tips can be seen in Appendix C.

11.5 Integration Gripper Sensor

The Gripper Force Sensor Mount required no calculations. This is due to the fact the maximum weight on the mount is simply that of the gripper and gripper tips, around 10 grams, (Schunk, 2012). Owing to manufacturing considerations, the plate chosen was 5 mm thick. This ensures no deflections will occur. The two gripper mounts can be seen in figure 11.13.

As can be seen in the above figure, there are a number of highly accurate tolerances to observe in the manufacturing. These tolerances are in place to ensure the gripper is correctly aligned with the camera and lens system. A block was machined onto the surface to serve as a reference mounting block for the Schunk gripper. This information can be seen in Appendix F.

11.6 Integration Van der Waals Gripper

When making use of the force teach technique interfacing subsystem (see Interface Subsystem chapter) and the Van der Waals gripper, the configuration

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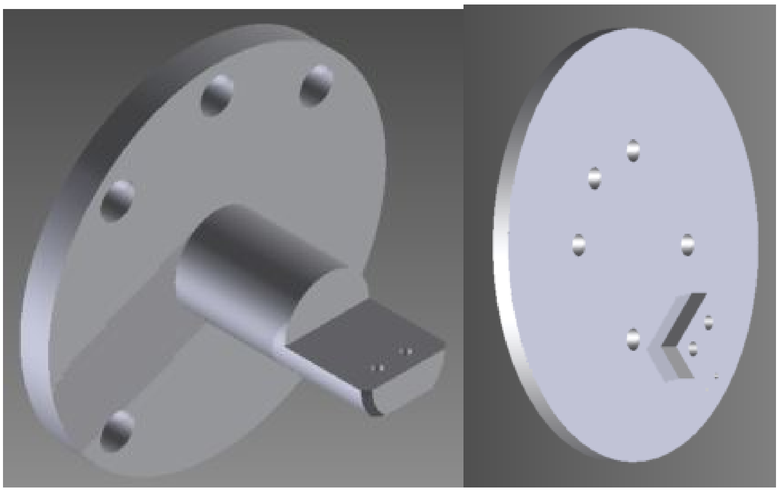

(a) GFS Mount (b) GFS Mount Two

Figure 11.13: Gripper Force Sensor Mounts (For Configuration One and Configuration Two)

similar to configuration one is used. Instead of the gripper, however, there is a simple extrusion. This extrusion was previously used by Pretorius (2011). The polyurethan material is mounted onto this extrusion. The extrusion provides a point for the user to input forces and torques. This assembly can be seen in figure 11.14.

11.7 Conclusion

This chapter successfully examined the creation of gripper tips for use with a commercially purchased pneumatic gripper. In addition to this, the functioning and feasibility of a Van der Waals gripper, as per Arderne *et al.* (2012), for use with the coarse-to-fine system was examined. Finally, the integration of both gripper types into the system was discussed.

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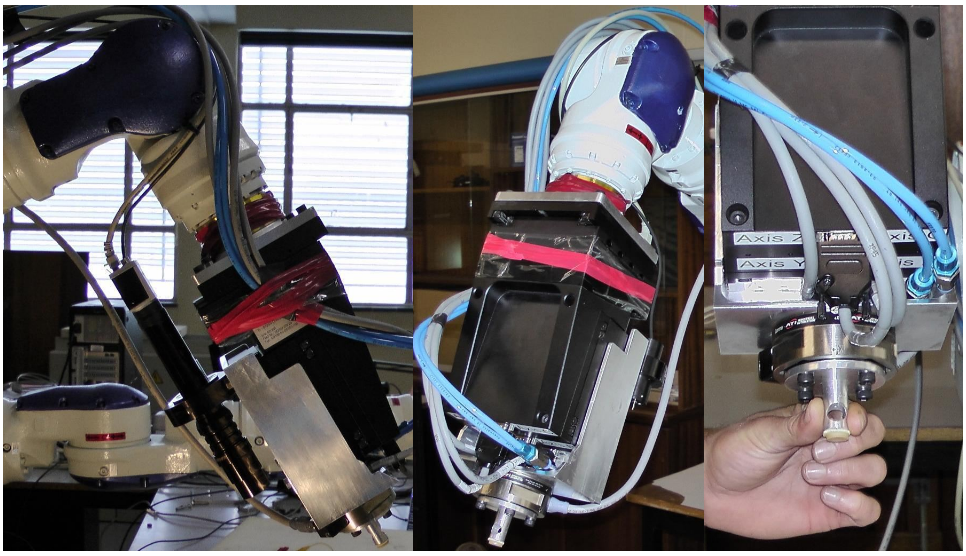

(a) Assembled System One (b) Assembled System Two (c) Assembled System Three

Figure 11.14: Overall Assembled Coarse-to-Fine Positioning System with Van der Waals Gripper

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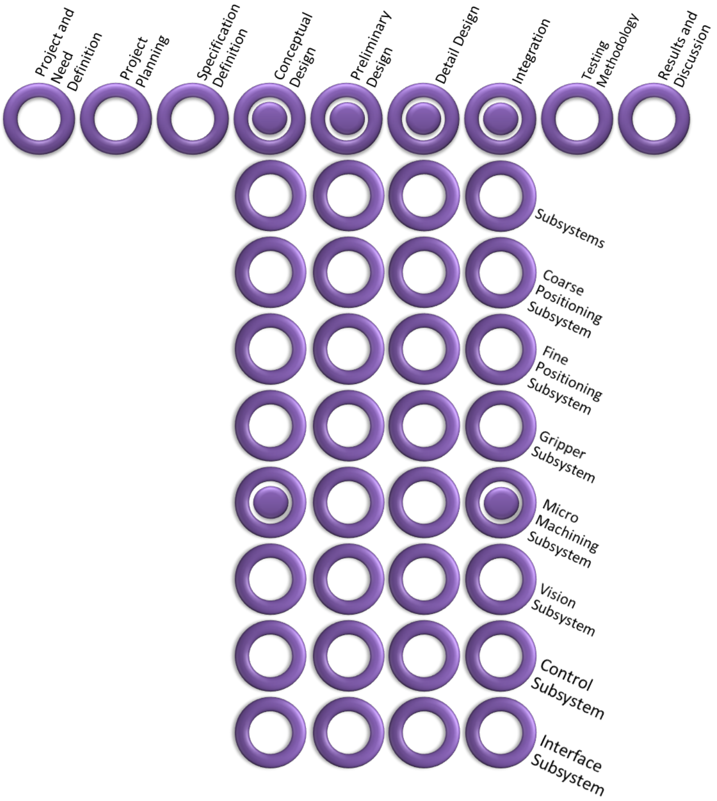
Chapter 12

Micro-Machining Subsystem



The purpose of this chapter is to examine the concept of micro-machining using a coarse-to-fine positioning system. In addition to this the integration of a pre-existing Nakanishi micro-milling spindle into the coarse-to-fine positioning system is examined. It is important to note that from research conducted,

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micro-machining with a coarse-to-fine positioning system is a relatively new concept. As such, there is very little literature available. Only issues relating to micro-machining and robot macro machining can be examined. There is also no preliminary design or detail design work to be completed for this subsystem.

12.1 Conceptual Design Micro-Machining

One of the possibilities for an end effector, as previously mentioned, is that of a micro-milling spindle. Chae *et al.* (2006) state that high accuracies can be achieved in micro-machining by using ultra-precision stages. One of the major disadvantages of using a conventional CNC milling machine is that it has a limited working area. Robot micro-machining can potentially machine parts with complex shapes and intricate details. These would not otherwise be achievable with conventional CNC machines, (Pandremenos *et al.*, 2011).

12.1.1 Deviation and Vibration

Problems that are encountered when performing macro machining are likely to be experiences during micro-machining. One of the major issues with macro machining using articulated robots is that of deviation. Some researchers have shown that a measurable deviation in the X-axis may be present when travelling in the Y-axis, (Pandremenos *et al.*, 2011). The results was an error region of approximately 0.7 mm.

According to Pandremenos *et al.* (2011) another issue is that there is a constant deviation in the Z-axis while machining. To this effect, 500 kHz accelerometers were used to make measurements. This Z-axis vibration is particularly relevant when considering the first contact of micro-machining. The data recorded suggests accelerations as high as 2 g, (Pandremenos *et al.*, 2011).

12.1.2 Chatter

A major issue identified in Pan *et al.* (2006) is that of chatter. Chatter is the unwanted vibration of the machining tool such that poor dimensional accuracy and reduced tool life result. Chatter in this instance was measured around 10 Hz, which is the natural frequency of the robot arm. This is due to an approximate robot arm stiffness of 1 N/μm, compared to the 50 N/μm of a CNC machine. Depending on the mass of the system, this translates to roughly 10 Hz for the robot and around 1 kHz for the CNC, (Pan *et al.*, 2006).

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In concurrence with the above, Pandremenos *et al.* (2011) states that robot arms generally have a low natural frequency. The result of this is that resonance can easily occur. This, however, can be avoided if a high enough speed is used, (Pandremenos *et al.*, 2011).

12.1.3 Feed Direction

Feed direction can directly affect an unstable process. When using this method it was found that chatter characteristics vary a great deal depending on the orientation and pose. When performing machining using a robot, it is preferable to make use of down-milling in order to prevent chatter, see figure 12.1. This is due to the fact that the robot axis with the smaller stiffness is more likely to be between the force vector and normal workspace direction during up-milling, (Pan *et al.*, 2006).

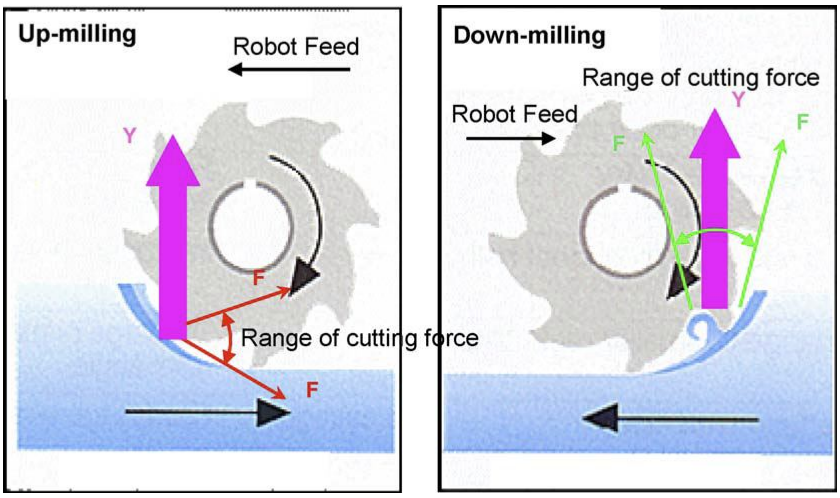

Figure 12.1: Up-Milling vs Down-Milling in Mode Coupling Chatter Analysis, (Pan *et al.*, 2006)

12.1.4 Forces

Of primary concern during micro-machining is the effect of forces. If large enough, these forces can easily damage sensitive positioning equipment. Chae *et al.* (2006) state that the forces measured during the cutting of Aluminium 7075 were compared to their predicted results. These measurements assumed that run-out was compensated for and that the material machined was uniform. The forces experienced when machining Aluminium 7075 were no larger

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than 3 N. These forces are minor when considering possible damage Pan *et al.* (2006) successfully mounted an ATI Force Torque Sensor between a robot and a milling spindle. This setup allowed for accurate force measurement.

12.1.5 Dynamic Tool Displacement

A final issue to consider is that of the actual displacement experienced by the machining tool bit. If this displacement is large, it will greatly degrade the accuracy and quality of the machining. To this end, Chae *et al.* (2006) plotted tool displacement. The results indicate very small displacements of around 2 μm, as can be seen in the figure 12.2.

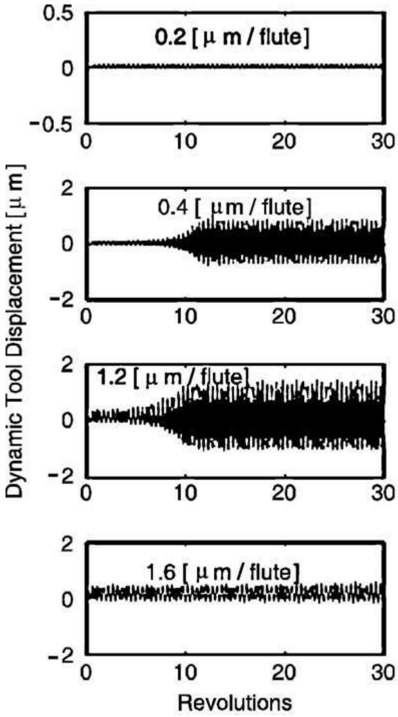

Figure 12.2: Tool Vibration for Machining Pearlite, (Chae *et al.*, 2006)

12.2 Integration Micro-Machining

In order to effectively measure the forces during micro-machining, while at the same time providing the machining spindle with the needed positional accuracy, it was decided to design an attachment that places the spindle directly onto the force torque sensor, see figure 12.3. In this manner, once gripping

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has been completed, the gripping mount is removed and the Micro Mill Sensor Mount Remake part is then placed onto the force sensor. Micro-machining can thus begin. The micro-machining spindle is fastened in place by using two grub screws. In order to prevent damage, soft plastic pieces were inserted between the grub screw and spindle, see Appendix F.

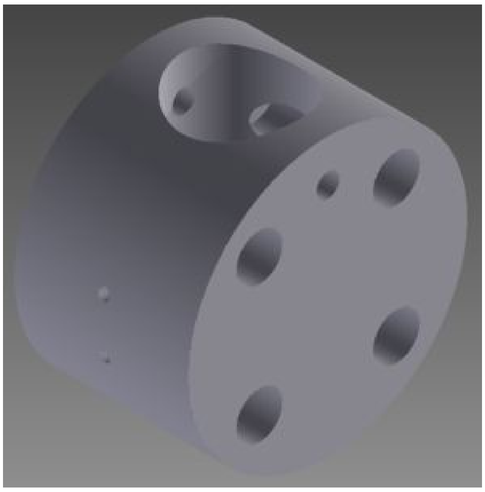

Figure 12.3: Nakanishi Micro-Machining Spindle Mount

12.3 Conclusion

This chapter highlighted a number of key issues to consider when performing micro-machining with a coarse-to-fine positioning system. The various testing procedures (Testing Methodology chapter) are therefore created in order to determine the extent to which these issues affect micro-machining. A final aspect considered in this chapter, is what parts are needed in order to integrate the micro-milling spindle into the system.

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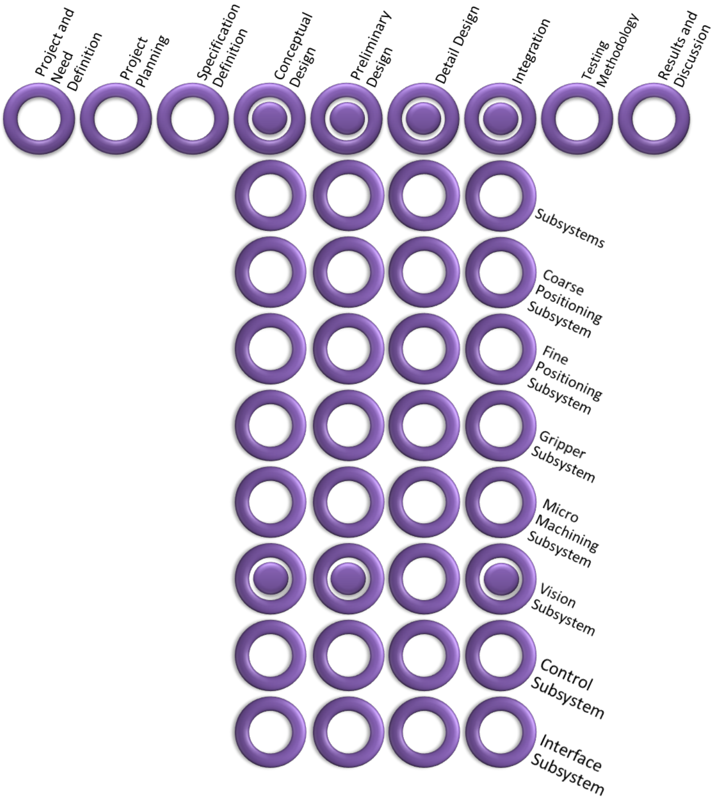
Chapter 13

Vision Subsystem



The vision subsystem comprises the camera and lens components. The purpose of this chapter is to examine the conceptual and preliminary designs of this subsystem. In addition to this, the manner in which the vision subsystem integrates into the system is examined. It should be noted that the calibration

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subsystem makes wide use of the vision subsystem; it does not form part of it. As such, it is discussed in the Control Subsystem chapter.

13.1 Conceptual Design Vision System

Vikramaditya and Nelson (1997) state that in macro-material handling applications it is possible to achieve accurate object placement simply by ensuring well-calibrated manipulators and simple visual inspection. However, in micro manipulation, calibration is dependent on accurately modelled kinematics. This modelling is highly dependent on thermal growth factors, (Vikramaditya and Nelson, 1997) and (Sanchez, 2010). The sources continue on to state that these thermal growth factors are difficult to predict and control at the micro level. Two solutions to this problem are simply to purchase expensive cooling systems, or to wait for a long-enough period for the system to reach thermal equilibrium, (Sanchez, 2010). Real-time visual feedback does, however, allow for compensation of the above-mentioned inadequately modelled micro-manipulator kinematics as well as relatively unpredictable micro forces, (Vikramaditya and Nelson, 1997).

In order to best achieve micro-handling flexibility, one solution is to handle different parts at the same material handling station with only software changes being made, (Sanchez, 2010). The source goes on to state that the most common principle for achieving the aforementioned flexibility is by incorporating a live video streaming for part identification.

According to Sanchez (2010), however, there are a number of problems associated with using visual feedback. These problems include high cost, programming difficulties, low speed and susceptibility to direct sunlight. There are also issues with installing the camera system. The most challenging aspect of this approach is focusing and aligning the camera so that the micro parts can be observed. Sulzer and Kovac (2010) state that when using vision-guided techniques, the only accuracy-limiting factor is that of the step size of the fine positioning system.

13.1.1 Camera Layout

Having established that real time visual feedback is important for micro manipulation, another major consideration is the number and placement of cameras. Dixon *et al.* (2002) state that there are a number of advantages to employing more than one camera for visual feedback. The two positional groups mentioned in the source are fixed cameras and cameras in hand. Cameras in hand

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refers to cameras mounted on a moving surface, such as a robot arm.

Dixon *et al.* (2002) states that employing both types of positional groups combines the separate advantages of each group. The fixed camera group allows for a larger area of the workspace to be monitored when compared to the camera in hand group. Fixed cameras tend to be further from the object to be viewed than cameras in hand. The image produced by fixed cameras has a low resolution. This low resolution decreases positional accuracy. A camera in hand allows for a higher resolution viewing of the objects to be manipulated. The source continues on to state that close viewing reduces the field of view, while fixed cameras are better able to determine the velocity of a moving object, (Dixon *et al.*, 2002).

13.1.2 Selected Alternative

Due to the cost of the system, initially an in hand camera concept will be used. This is the only method that allows for the needed micron scale resolution. At this stage of the design, a broader view of the system operation can be achieved manually.

13.2 Preliminary Design Vision

The vision system is actually divided into two sections: the lens and then the camera section. These two components are not separate. Their functioning together achieves the needed characteristics. Both of these elements are thus analysed under the same sections. When using vision, it is important to ensure that the camera resolution is compatible with the size of the object to be manipulated, (Sanchez, 2010). The purpose of this section is to select the appropriate lens and camera system in order to successfully view the micro materials.

13.2.1 Functional Analysis

The main aspect of the functional analysis in this section is centred around the remote alteration of the lens focus module. There are very few remotely operated adjustable focus lenses. It was thus presumed Ethernet communication would not be a standard. In addition to this, there is mention of the GigE live streaming. These functions can be seen in the figure 13.1.

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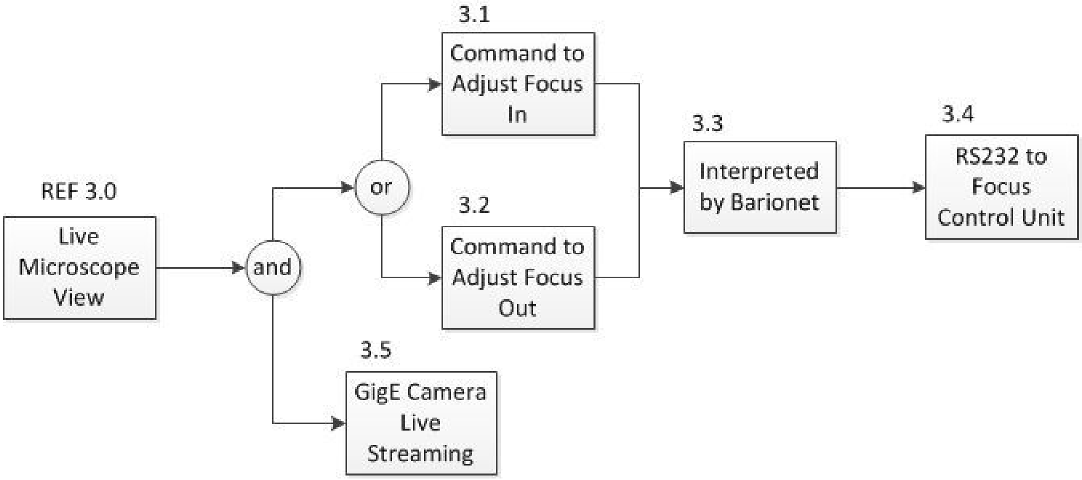

Figure 13.1: Vision System Functional Analysis

13.2.2 Preliminary Design Criteria

Functional Capability: Lens

In order to select a camera and lens combination, it is necessary to establish four parameters. Firstly, the Field of View (FOV) is selected at around 2 mm by 2 mm. Secondly, the camera and lens combination should achieve a very high resolution. According to numerous sources, a resolution of 1 μm is not yet attainable. It is, therefore, more realistic to aim for a 2 to 5 μm resolution. Thirdly, a working distance of 100 to 300 μm is needed. Finally, the micro materials to be handled are approximately 250 μm $\times$ 250 μm $\times$ 1 mm. Consequently, it is necessary to have a depth of field of approximately 300 μm.

The gripper is to be placed on an fine positioning system which is, in turn, attached to the Motoman robot arm. The robot arm needs to remain stationary during operation in order to reduce vibrations. The camera and lens combination are to be mounted onto the robot arm. If the arm is stationary and so is the lens, then the lens needs to be adjustable in order to focus on the different distances of objects that the micro gripper will be manipulating. It is essential that the lens has a tele-operated focus/zoom function, i.e. for both z and y/x directions (pan out). The distance between the object and the camera is going to vary, it is therefore necessary to have a motorise zoom/focus lens.

According to Qioptiq (2011), when changing the working distance of the camera and zoom lens system, it is necessary to adjust the focus of the system. The source goes on to state that a zoom module only increases or decreases the magnification and not the working distance.

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Functional Capability: Camera

In order to obtain the best quality image for tele-operation it is necessary to use GigE cameras. According to Cameras (2010) these are high bandwidth Ethernet cameras. GigE cameras can transmit images at 1000 megabytes per second through an Ethernet connection (1stVision, 2010). Cameras (2010) states that these cameras can accommodate extremely long cables (100 m). This is useful when considered in the context of an industrial environment.

A major problem with having a long Ethernet cable is that in most cases a long power cable has to be used. Long power cables use more power. A new option that is only available on low power-consuming cameras is that of Power over Ethernet or (PoE), (1stVision, 2010). The source continues on to state that PoE reduces the need for a power cable; however, an additional power booster may be needed for the ethernet cable.

According to Allied (2011) and Instruments (2011), when comparing a colour and monochrome camera of the same model and manufacturer, the monochrome camera gives a higher resolution than the colour camera. Interpolation and filters are combined to produce colour. Interpolation reduces resolution. Monochrome cameras, on the other hand, do not need this interpolation and so have a higher resolution and better contrasts. Better contrasts are needed when performing precise pick and place operations.

Usability

According to Cameras (2010), the programming interface used for GigE cameras is a registered trademark. There are few open-source drivers for this type of camera. Despite this disadvantage, 1stVision (2010) states that both Dalsa and Jai GigE cameras can be operated from a network. In addition to this, the camera gets an IP address from a router. The software package then identifies this IP address and thus enables the user to view the video from the camera.

Supportability and Serviceability

There is a price disadvantage to purchasing from a camera and lens dealership. However, it is important to consider the services that they offer. According to Optics (2011), the company offers a large inventory of optic products and provides 24-hour technical support. It is also not possible to purchase components directly from the manufacturer. This is the case with the K2/SC long-distance microscope and its manufacturer Infinity. In addition to this, purchasing both camera lens from a single company ensures that the parts will interface cor-

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rectly.

Due to the variance in the wiring of the cabling for the aforementioned camera, only specific POE cables will work. Similarly, the POE injector needs to be at a corresponding wattage to the camera. It is therefore necessary to purchase both cables and a POE injector specifically for the appropriate camera.

13.2.3 Trade-off Analysis

Methodology

Tables are constructed of the relevant camera and lens alternatives. This allows all the relevant information to be easily understood. The alternatives are then compared by using comparison bar charts and web charts. These charts incorporate the necessary design criteria.

Alternatives

There are numerous camera GigE camera alternatives. These were found simply by searching the Internet and by examining those mentioned in academic journals. Due to the magnitude of options available, there is no need to examine a specific list, as was the case with the fine positioning system. The table 13.1 summarises all the relevant information. Again, relationships were formed with the appropriate companies. From these relationships price and other technical details were determined.

In contrast to the GigE cameras there are relatively few remotely operated zoom-and-focus lenses for use in microscopy. A number of alternatives were found from academic journals. Owing to the unique nature of this product, in the vast majority of cases it was necessary to form a relationship to obtain any technical information at all. The results of this information collection can be seen in table 13.2.

13.2.4 Evaluation of Design Alternatives

The GigE camera and lens selection was performed in a similar manner to the selection of the fine positioning system. Due to the aforementioned reasons, the GigE camera was deliberately chosen in monochrome. Other attributes considered were whether the camera could be powered over Ethernet (POE) or not. They also include the frames per second (fps), pixel, price, etc. The

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camera comparison chart can be seen in figure 13.2.

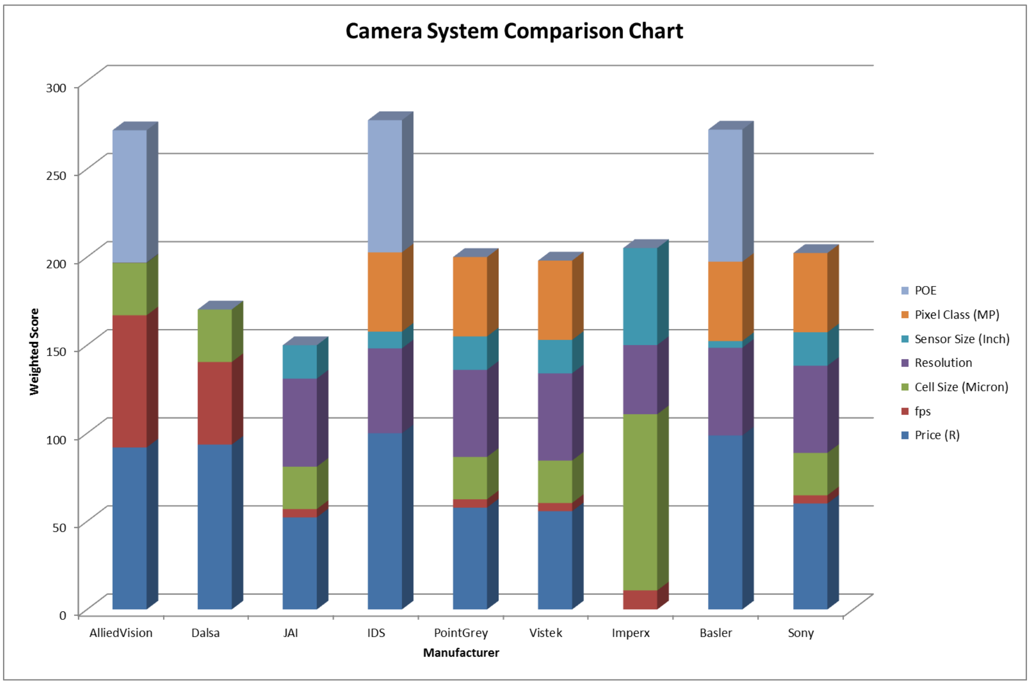

Figure 13.2: Camera System Comparison Chart

The web comparison chart can be seen in figure 13.3. An example of how this chart enhances the view of multiple criteria is as follows. Immediately from examining this chart one can see that the Imperx camera far exceeds the cell size and the sensor size requirement.

When evaluating the lens alternatives, one similar criterion as used in the camera comparison is that of resolution. Other characteristics include those mentioned in the Preliminary Design criteria. Two defining features of the lenses, as per the functional analysis, is the remote focus and the remote zoom. Remote focus is essential for basic functioning. Remote zoom enhances the ease of use of the system. Both can be seen in figure 13.4.

From the perspective of the web chart it becomes apparent that the KC/S lens is a strong contender in the Working Distance, Field of View and Resolution categories. One feature this system does not have is that of remote zoom. The web chart can be seen in figure 13.5.

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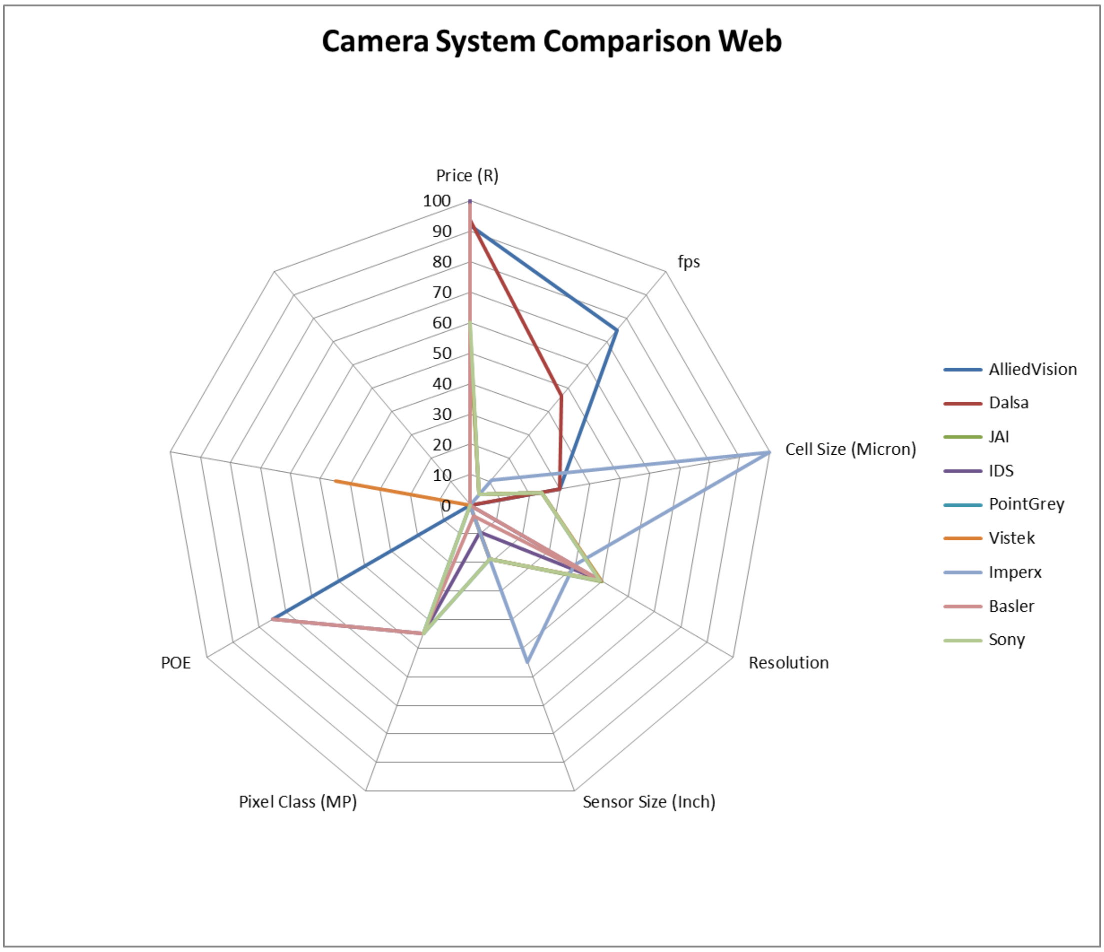

Figure 13.3: Camera System Comparison Web

13.2.5 Selected Alternative

The Basler system only achieved the second-highest score. It was chosen owing to the fact that the product is sold by Edmund Optics. Edmund Optics supplies the needed lens and camera. They also provide constant support. It is thus more feasible, faster and more cost-effective to purchase from a single well-established distributor. These items can be seen in figure 13.7 and 13.6.

When considering the lens a list of attributes was compiled and, in this instance, the KC/S video microscope lens achieved the highest score. It was thus selected. This can be seen in figure 13.6. Here a number of attributes are compared.

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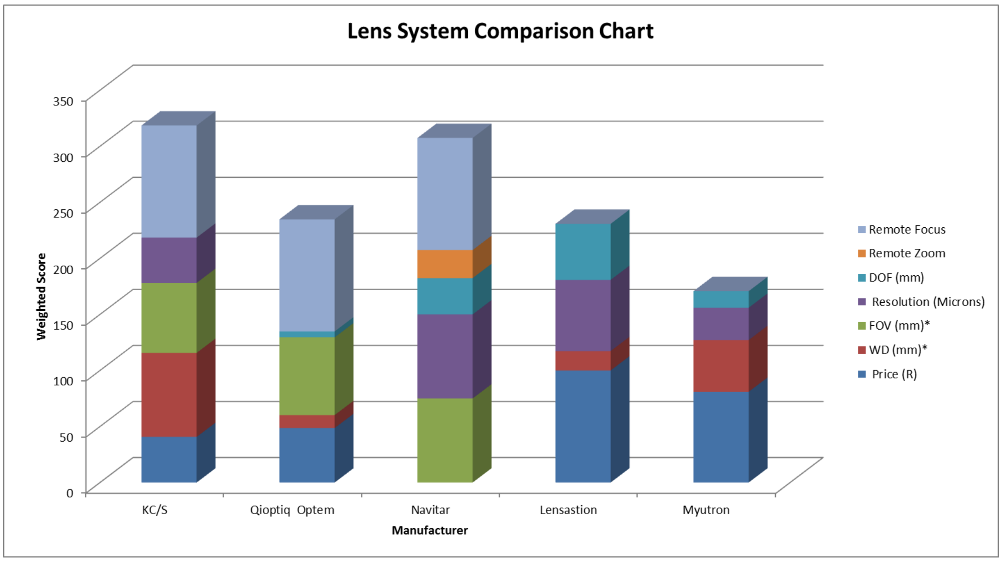

Figure 13.4: Lens System Comparison Chart

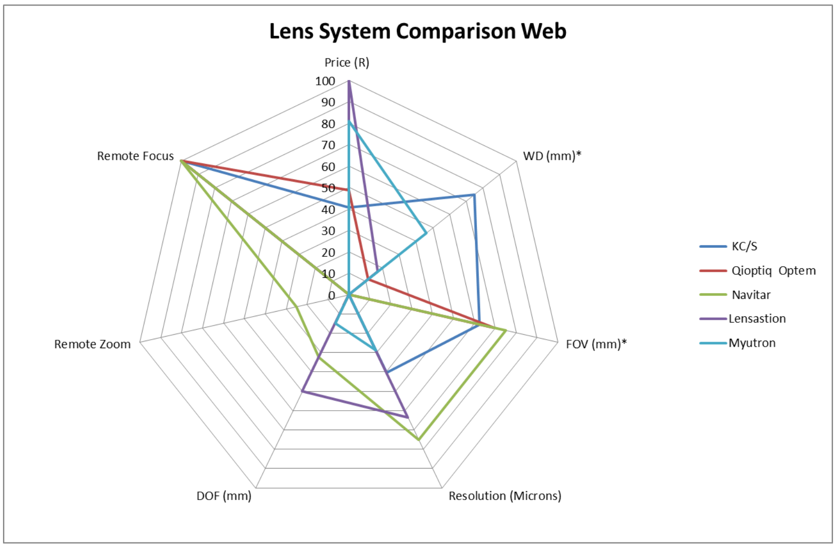

Figure 13.5: Lens System Comparison Web

13.2.6 Additional Hardware

The focus control system of the video microscope from Edmund Optics can be controlled via serial RS-232 communication. In order to allow for remote access and control the RS-232 is plugged into the Barionet controller. The Barionet controller is the same device used to control the solenoid valves for the pneumatic gripper.

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Figure 13.6: Edmund Optics KC/S Video Microscope (Motorised) (Optics, 2011)

Figure 13.7: Basler Camera ACA2500 (Basler, 2011)

13.3 Integration Vision Integration

In configuration two, the camera and lens system are mounted onto the second robot arm. In order to facilitate an easy transition, the Vision System Mount was created as seen in figure 13.8. This part mounts onto the Coarse Positioning Fine Positioning Mount. Basic calculations were done in order to determine the effects of normal and bending stresses on this part, see Appendix D.

13.4 Conclusion

The camera in hand layout was selected as the only feasible alternative to providing micron resolution. After this had been established, the camera and lens system from Edmund Optics was selected. The integration of this subsystem into the system as a whole was then examined by discussing the design of the Vision System Mount.

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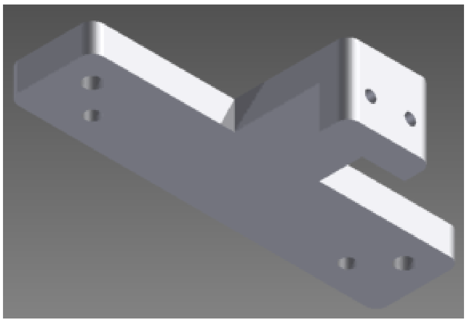

Figure 13.8: Vision System Mount CAD

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Table 13.1: Summary of Camera Properties

Model	**By**	**Country**	**Price (R)**	**Colour**	**fps**	**Cell Size (μm)**	**Res.**	**Sensor Size (inch.)**	**Pixel Class (MP)**	**POE**	**SDK**
Manta G-125	Allied Vision	South Africa	9 990.00	Optional	30	3.75	1292 × 964	1/3	1.2	Yes	Yes
C1280	Dalsa	Canada	9 288.00	Colour	24	3.75	1280 × 960	1/3		No	Yes
BM-500 GE	JAI	South Africa	27 160.00 (Camera)	Optional	15	3.45	2456 × 2058	2/3		No	Yes
UI-5480CP	IDS	Germany	6 495.00	Optional	14	2.2	2560 × 1920	1/2	5	Yes	Yes
GS2-GE-5055	Point Grey	Germany	24 760.00	Optional	15	3.45	2448 × 2048	2/3	5	No	Yes
SVS625	Vistek	Germany	25 650.00	Optional	15	3.45	2448 × 2050	2/3	5	No	Yes
IGV-B2020	Imperx	U.S.A.	49 800.00 (Camera)	Optional	16.3	7.4	2056 × 2060	1.3		No	Yes
ACA2500	Basler (EO)	South Africa	7 040.00	Optional	14	2.2	2592 × 1944	1/2.5	5	Yes	Yes
XCG5005CR	Sony	South Africa	23 765.00 (Camera)	Colour	15	3.45	2448 × 2048	2/3	5	No	Yes

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Table 13.2: Summary of Lens Properties

Model	**By**	**Country**	**Price (R)**	**WD (mm)**	**FOV (mm)**	**Resolution (μm)**	**DOF (mm)**	**Remote Zoom**
KC/S Video Microscope	Edmund Optics	U.S.A.	33 160.00	100	2.81 × 2.11	2.6	0.033	Yes
Qioptiq Optem Zoom 125C	Allied Vision	South Africa	3106.00	89	0.74 × 0.98	3.3	0.057	Yes
Navitar Zoom 6000 Lens	Dalsa (Benelux)	Belgium	43 896	113	1.8 × 1.3	2	0.18	Yes
Lensation TC5M-10-110/C	IDS	Germany	17 500	110	5.63 × 4.22	2.2	0.26	No
Myutron Macro-Zoom Lens CMZ0745	Basler (Westplex)	South Africa	22 532.10	95		2.8	0.1	No

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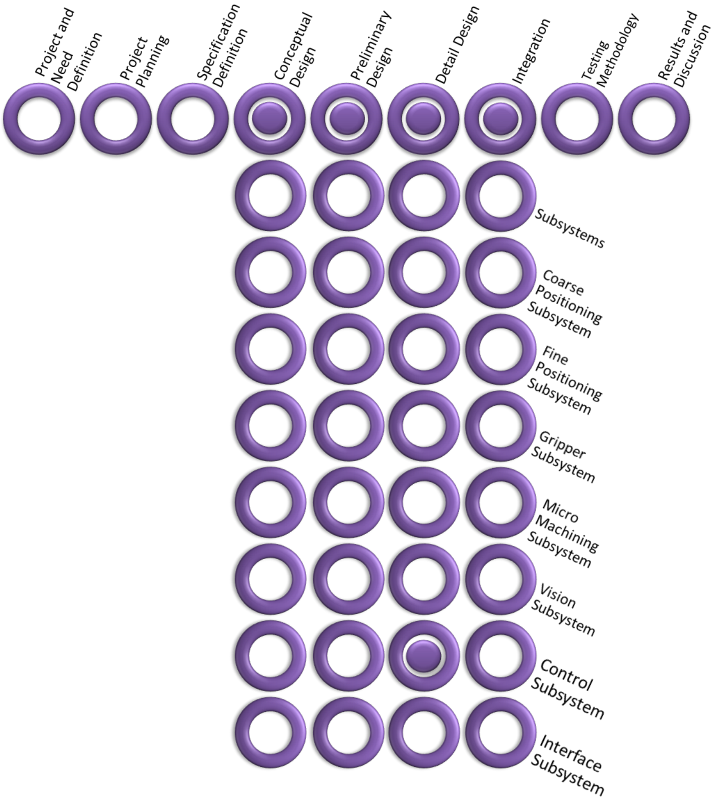
Chapter 14

Control Subsystem



The control subsystem deals with low-level functioning of the system when compared to the human robot interface system. Despite this, a large amount of time and effort was spent ensuring that the created Graphical User Interface (GUI) was intuitive. In addition to this, other features such as live video

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feedback, were included in order to allow for efficient system use. The functionality of the system is further expanded by concepts such as the movement and gripping record and playback function and that of the calibration function. Owing to the nature of this system only a detailed design was performed.

14.1 Detail Design Control

The major focus of this section is explaining the detailed design of the controlling code. A key manner in which this is achieved is through the use of the functional analysis. Nicholas and Steyn (2003) states that the detail design involves converting ideas into realisable plans. A major part of this is determining how subsystems integrate into the system as a whole.

The functional analysis begun in the Conceptual Design chapter is now used to frame the more detailed design. The connection function specifically is used to assist in the programming development. This functional flow block diagram can be seen in figure 14.1.

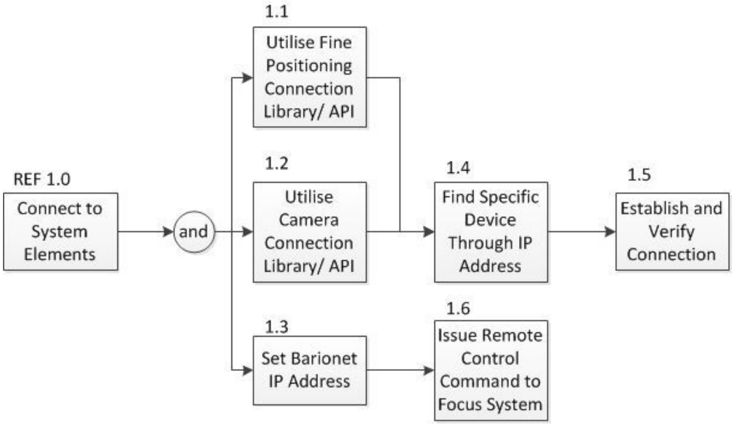

Figure 14.1: Functional Analysis of the Connection Process

In addition to the connection flow diagram, the fine positioning diagram is expanded. This expansion allows for three methods of effecting movement: through haptic control, through the gui, or through the calibration program. Each of these approaches serves as the basis for the program code in this chapter and in the Detail Design Interface chapter. The figure can be seen in figure 14.2.

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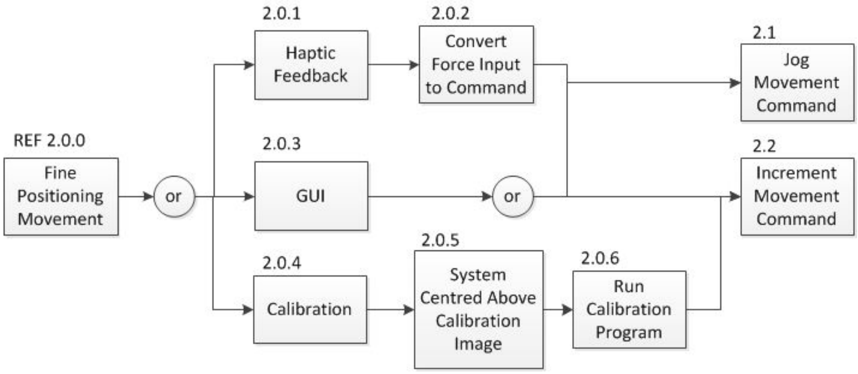

Figure 14.2: Functional Analysis Detail of the Fine Positioning Movement Through the Haptic Control, Graphical User Interface, or the Calibration

14.1.1 System Connections

In order to better understand the functioning of the developed micro-material handling system, it is necessary to view the system connections. These system connections can be seen in the figure 14.3. The figure gives a clear illustration of how the different components interact.

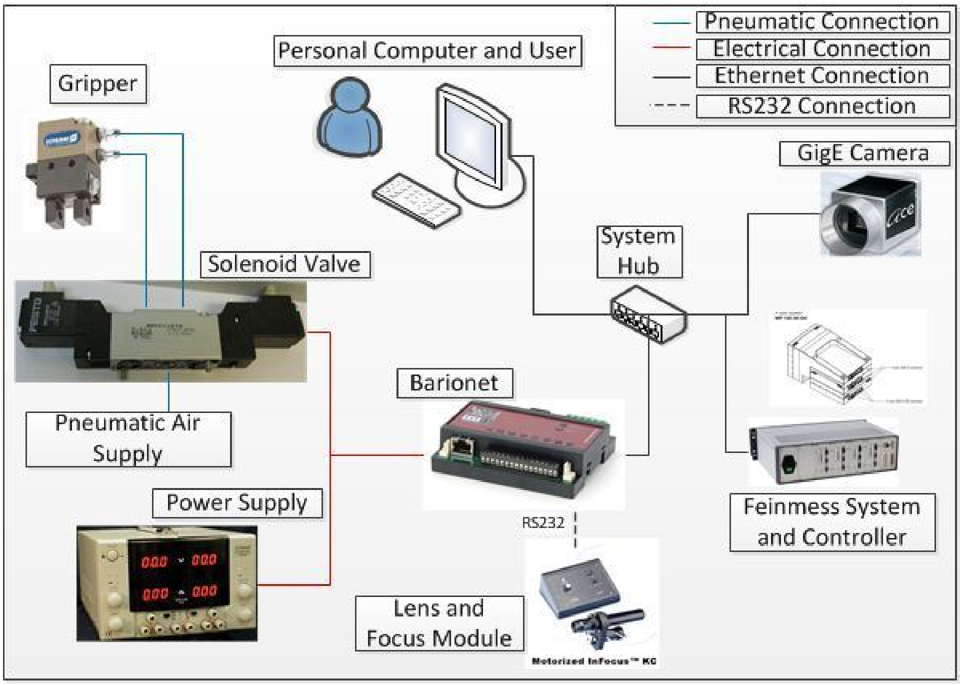

Figure 14.3: Pneumatic (6 bar), Electrical (24 V), Ethernet and R-S232 Connections

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14.1.2 Control Software Differentiation

In understanding the functioning of the system it is important to make a clear differentiation between the different types of controlling software, see figure 14.4. As can be seen in figure 14.4, the Feinmess system is controlled by newly created graphical user interface. The Motoman SDA 10 is controlled by the already existing Andre Smit's Interface program. Andre Smit's Program also incorporates and improved version of the haptic control developed by Pretorius (2011). This haptic control only controls the Motoman and the SDA 10. The Feinmess Haptic Code was thus developed in order to implement this haptic control in the Feinmess system. Haptic control and force teach techniques thus become operational at the micro level.

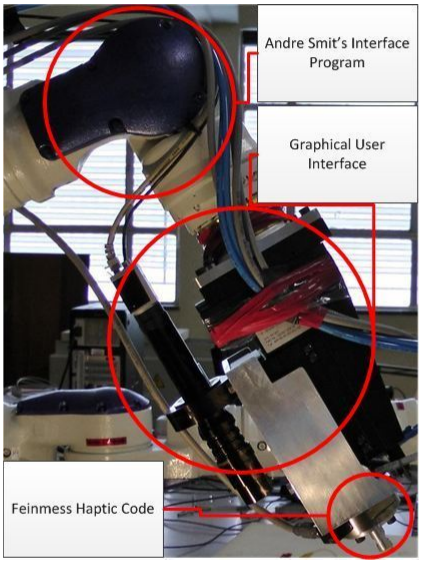

Figure 14.4: The Assembled System and the Different Programs and Codes that Control It

14.1.3 Graphical User Interface

A great deal of research and basic control testing was conducted in order to gain a well-rounded knowledge of the Feinmess MP 130 and 3-axis Galil controller. This full knowledge allowed for an understanding of not only how a graphical user interface could interact with the system, but also what could be achieved. A programmer was thus hired. This programmer was given detailed instructions on the functioning and layout of the Graphical User Interface

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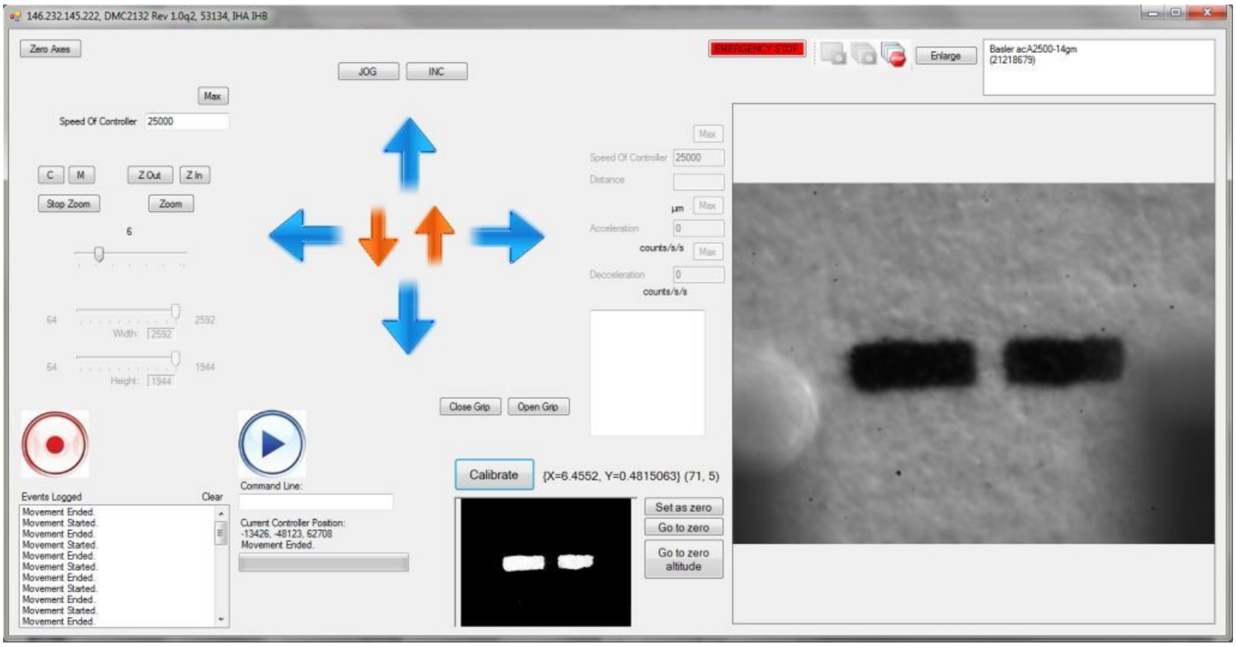
(GUI). This GUI can be seen in the figure 14.5. This facilitated intuitive control of the Feinmess MP 130 system.



146.232.145.222, DMC2132 Rev 1.0q2, 53134, IHA IHB

Speed Of Controller 25000

Width: 2592

Height: 1944

Speed Of Controller 25000

Distance

µm

Acceleration 0

counts/s/s

Deceleration 0

counts/s/s

Basler acA2500-14gm
(21218679)

{X=6.4552, Y=0.4815063} (71, 5)

Current Controller Position:
-13426, -48123, 62708
Movement Ended.

```
Movement Ended.
Movement Started.
Movement Ended.
Movement Started.
Movement Ended.
Movement Started.
Movement Ended.
Movement Started.
Movement Ended.
Movement Started.
Movement Ended.
```

Figure 14.5: Screen Shot of the Graphical User Interface

This user interface incorporates a number of features in order to ensure smooth functioning of the system. The GUI was programmed in the C Sharp programming language. As such, a panel is created as seen in figure 14.5. This panel has a series of buttons, displays and functions. An interrupt-type event is triggered every time a button is pushed.

The overall functioning of the code of the GUI can be seen in the program flow diagram of figure Overall System Functioning in the Appendix H. (In this chapter only, the word 'appendix' implies the Appendix H). Due to the extensive nature of the code, the program flow diagram is split up according to the various button functions. In the appendix a square represents an action, a triangle represents a choice, and a square without a corner represents a button or interrupt.

Movement

The most notable feature of the GUI are the direction arrows. The system can be operated either in a jog or increment function, as can be seen in the ap-

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pendix figure Feinmess Control Code 2 . If operated in the jog mode, pressing down and holding the arrows creates a continuous movement until the arrow is released. When executing an increment function, a distance, speed, and acceleration are entered. Once an arrow has been clicked, the preprogrammed distance will be executed in the chosen direction. The program flow of these two types of commands can be seen in the appendix in figure Feinmess Control Code 1.

Gripper Functioning

The system also incorporates two buttons to open and close the Schunk gripper. The program flow of these buttons can be seen in figure Gripper Buttons 1 in the appendix. These two buttons send a message directly to the IP address of a Barionet micro controller system. The Barionet then activates a relay. The relay can switch between relay pins 2 and 3. In both cases both pins are connected to pin 1 but are not connected to each other.

The relay is connected to a power supply and a solenoid valve. The valve system has three inlets and two outlets. The two outlets go directly to the Schunk gripper. One of the inlets is from the compressor and the other two are dump valves. Engaging and disengaging the relays thus opens and closes the gripper.

Video Feedback and Focus

As per the functional flow block diagrams in the Conceptual Design Chapter, the GUI contains a large display of the GigE camera output. This streaming was done by integrating the Basler API into the GUI. In order to ensure correct functioning it is essential that there is a large amount of light for the system.

The focus motor control module supplied with the Edmund Optics KC/S lens can only be controlled via RS-232. The rest of the micro-material handling system can be controlled via Ethernet. It thus necessary to use the Barionet to receive Ethernet communication and then convert this into RS-232 communication. The Barionet thus intercepts Ethernet commands from the host computer. These commands then perform a variety of actions. The functioning of this Barionet program can be understood by examining the program flow diagram in figure 14.6. Much tuning was done in order to render this function usable as the controller box is slow in interpreting commands. Having corrected the function, it was possible to perform remote focus at different

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speeds.

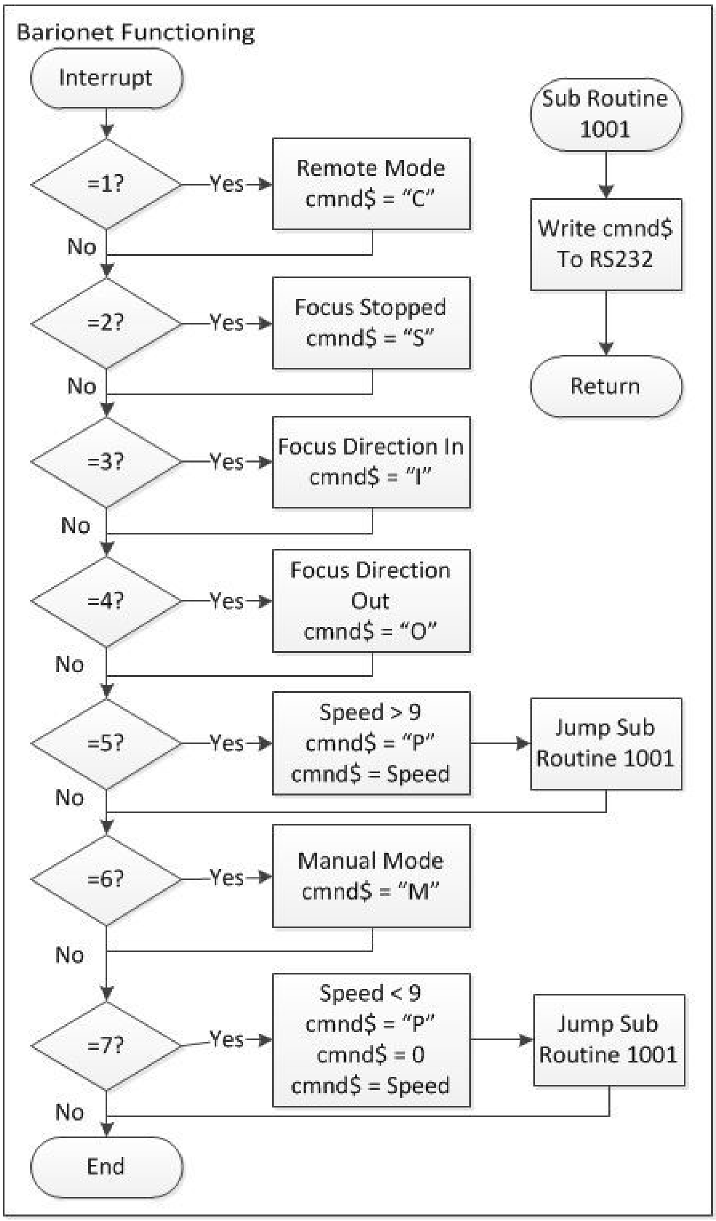

Figure 14.6: Focus Control Barionet Program Flow Diagram

The program flow diagram as seen in figure 14.6 is loaded directly onto the Barionet module. The commands for the zoom capability still have to be issued by the GUI program. The basic functioning of this series of buttons can be seen in figure Zoom Control 1 in the appendix.

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Record and Playback Function

One of the more important functions is that initiated by the record button and the play button. Once this button is pushed the various steps are recorded. In manual mode it is necessary to record 'way points'. When the function is played back, the Feinmess system moves sequentially from waypoint to waypoint. The functioning of this section of code can be seen in figure Record and Playback 1 in the appendix. When performing the force teach operation, this waypoint function is set to record every time a new movement instruction is executed. The program flow of this aspect of the code can be seen in the chapter Interface Subsystem.

Safeguards

A number of safeguards were added into the GUI in order to ensure that the user does not damage the system, in accordance with (Galil, 2011). The maximum distance in each direction when considered from the zeroed point was taken as 20 mm. The maximum speed was taken as 50 000 counts/s or 5 mm/s. The maximum acceleration was set to 300 mm/s or 0.3 m/s. In order to generate a smooth motion profile and prevent damage to the system, it is necessary to monitor the increment input. Thus the user can enter in a distance and the equations will convert it into the appropriate velocity and acceleration. This ensures a smooth velocity profile when executing movement.

$$v = 10 \times d \tag{14.1.1}$$
$$a = v^2 \div 2 \times d \tag{14.1.2}$$

Functioning

A screen shot of the system while in use can be seen in figure 14.7 and figure 14.8. In order to ensure the piezo micro part was clearly visible, a light source was placed beneath a translucent surface. The micro part can be seen in the centre of the camera view figure 14.7, and appears as a rectangular shape. In the same figure the two blurred shapes are the tips of the gripper. The system is focusing on the micro part and, as such, the gripper tips are blurry.

Having identified the piezo micro part, the gripper tips were closed using the close button. This can be seen in the small red button in the centre of the figure 14.8 having shifted from when compared to the previous figure. The micro part is thus gripped and removed from the surface.

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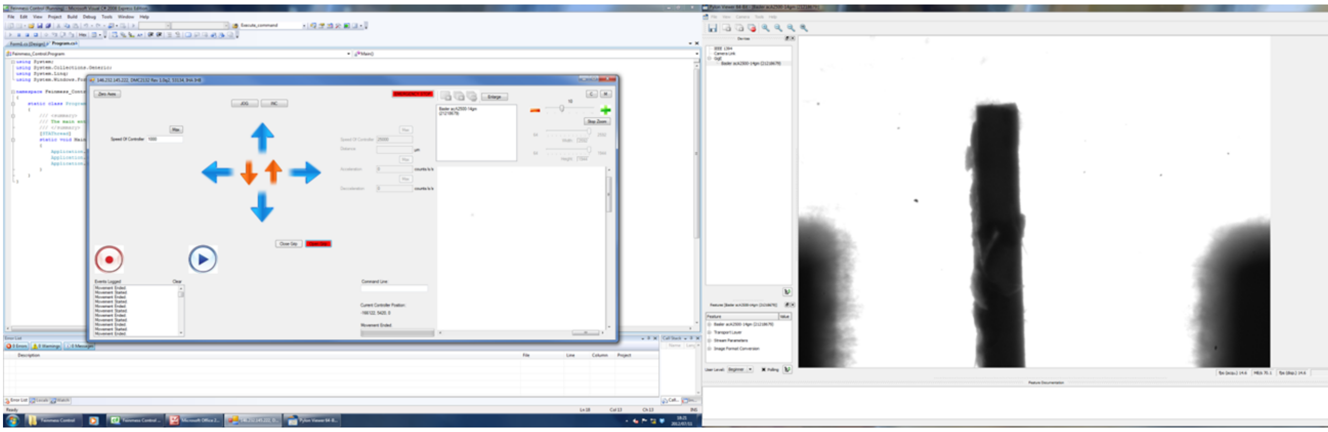

Figure 14.7: Screen Shot of System Function with Gripper Open, Micro Part in Middle of Open Grippers

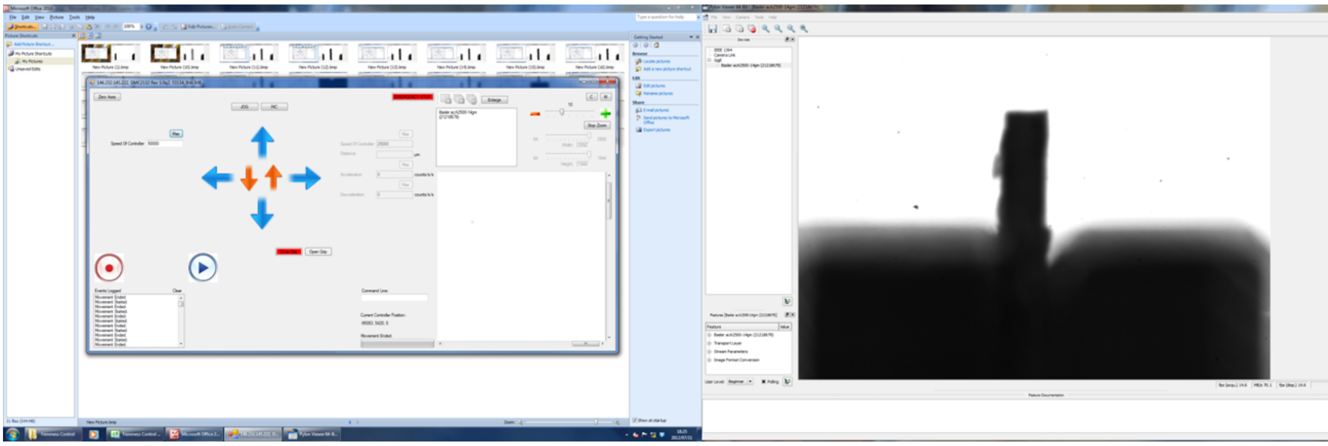

Figure 14.8: Screen Shot of System Function with Gripper Closed, Micro Part in Middle of Closed Grippers

14.1.4 Calibration

The Motoman SDA10 system has a repeatability of 100 μm according to RobotWorx, (RobotWorx, 2011). The Feinmess system on, the other hand, has a repeatability of 1 μm, (Feinmess, 2011). There is a discrepancy between the position of the Motoman and the position of the Feinmess system. A calibration system is thus needed to provide a referenced position.

A programmer was hired to create a calibration system based on the figure 14.9a as seen below. The symbols in this figure are simply two 8-point font dashes printed onto a piece of plain white paper, using a standard printer. This was done purposefully as a simple proof of concept. More accurate symbols

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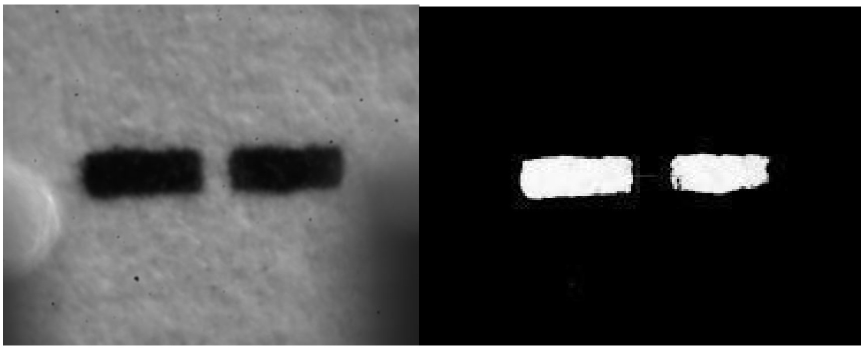
can be created as needed. The figure 14.9b shows the normal image inverted. This inverting is part of the calibration algorithm.



(a) Normal (b) Inverted

Figure 14.9: Calibration Symbols

A scenario is best used to explain the functioning and the need for the calibration system. A piezo-ceramic element is placed at an exact known distance from a cavity. The Motoman is further than 50 mm away (maximum working envelope of the Feinmess system, (Feinmess, 2011)), as such coarse positioning is needed. The Motoman therefore moves the fine positioning system within 2 to 3 mm of the calibration mark such that it is visible through the long-distance microscope. The Motoman's servo motors are disengaged and the brakes applied. The calibration button is then pushed and as a result the fine positioning system is exactly aligned with the calibration symbol. This aligning is achieved as per the program flow figure 14.10.

The Feinmess system is then instructed to move in the z direction until the system makes physical contact with the surface. Contact is dictated by the force sensor. This position is then set to zero. Preprogrammed instructions can thus be executed to achieve picking and placing of the micro element at the known distances. This calibration process allows the accuracy of the fine positioning system to be utilised with numerous different calibration marks over a relatively large distance (500 mm). It should be noted that this calibration system can be applied for both material handling and the machining of different geometries.

It is important to note than in the above example the calibration symbol is simply used to help centre the fine positioning system. It is in no way intended to be used for angular alignment. By using two calibration symbols, the angle variation can be determined. This information can then be used

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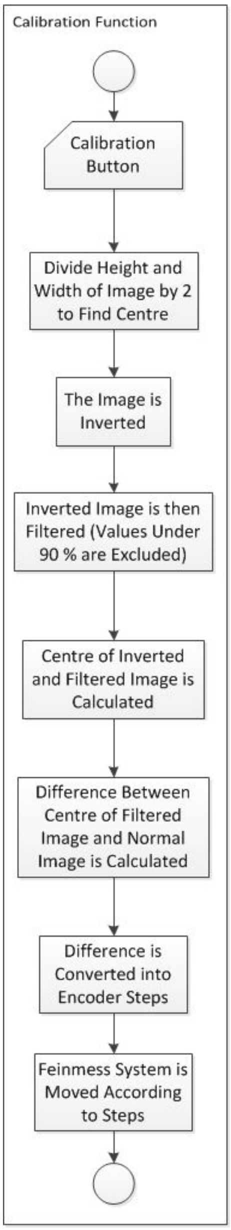

Figure 14.10: Calibration Program Flow Diagram

to ensure the coarse-to-fine positioning system is angled in the exact manner as the calibration system. In order to achieve this, however, the axes layout of the camera and lens, the Motoman, and the Feinmess System must all be exactly aligned. This large source of error means that using the calibration symbols for angular alignment is beyond the scope of the project. As such, a single calibration symbol is used for alignment.

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Problem

The calibration function was intended to take the form of a black box component as per the OOSEM innovation architecture, (Estefan, 2007). To this end, the programmer was hired and instructed on how the calibration system should function. The programmer then created and implemented the necessary coding. After the contract had been signed and the code delivered, initial testing began. The initial tests seemed to indicate that the code was functioning as intended. It was not until detailed testing began that a problem was discovered.

It is highly important to note the calibration function was programmed using pixel size as a measurement unit. In order to convert pixels into distance such that it can be instructed to the fine positioning system, it is necessary to multiply it by the microns per pixel factor. For the Basler Ace Aca2500-14gm camera this is stated as 2.2 μm/pixel, Basler (2011). The problem is that this factor is altered by the addition of the KC/S lens. In addition to this, the figure actually changes depending on the working distance. Some initial calculations show that this factor can vary from 1.05 μm/pixel width, 1 μm height at 87.8 mm to 1.28 μm/pixel width, 0.926 μm height at 96 mm.

Solution

One solution to the above problem is to create a function (within the calibration function) that measures the length of a calibration symbol in pixels. If the exact length of this symbol is known then an accurate μm/pixel figure can be calculated. This figure is then applied to the pixel distance output of the calibration function. In this way, the fine positioning system is instructed to move an exact distance regardless of the working distance.

In order to create the above-mentioned solution, the author had to open the black box and understand it. The calibration function captures the calibration symbol image as explained above. For ease of explanation and to reduce angular errors, a round calibration symbol is used. The image is 2592 pixels in width and 1944 pixels high. The first thing the function does is create a 2592 x 1944 matrix of the information of the image. Each point of the matrix is a number representing the colour of the image at that pixel. The second step is that every element in the matrix is normalised to a value of between 0 and 1. In doing this, the colours of the image are inverted and simplified into black and white. The number represents completely black pixel and 0 represents completely white pixel. The third step is that the image is filtered according to a pre-set value. If the filter value is chosen as 90 percent, then every value in the matrix that has a value below 0.9 becomes zero. The image captured

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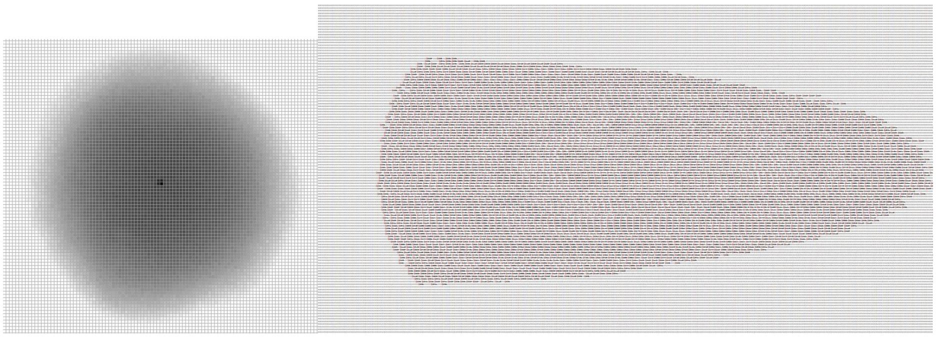
by the camera and the filtered matrix can be seen in the figure 14.11.



(a) Round Calibration Symbol

(b) Calibration Symbol Matrix

Figure 14.11: Round Calibration Symbol Zommed 800 X and the Calibration Symbol Matrix After Being Normalised and then Filtered

Once this has been concluded, the fourth step is that the sum of each row and each column is taken. Each column summation figure (2592 of them) is then divided by the sum of all the column summation figures. This is also applied to the row summation figures (1944 of them). Each of these figures is then multiplied by their distance to the x- and y-axis and summed again. The result is the centre of the object.

In order to find the length and height of the object (in pixels) the first step is to create an identical 2592 x 1944 matrix. This second matrix is then put through the normalising and filtering steps. In the filtering step, every value that is below 0.9 is set to 0 and every value that is above it is set to 1. In this way the whole image is converted into zeros and ones. In a similar manner to step 4, all of rows and columns are summed. The maximum sum of the row and the maximum of the column is then found. This value is the maximum width and height of the calibration symbol. Knowing the exact width and height of the symbol that was processed, it is possible to calculate a μm/pixel figure. As stated, this is applied to the output of the calibration function.

Limitations of Solution

A problem associated with this solution is that it can only be applied to calibration symbols composed of one shape. The two rectangles previously used would interfere with the maximum calculations. Similar problems with the maximum calculation occur if a square or rectangular symbol is used and the

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angle it is viewed at is not exactly aligned with its edges. The most appropriate symbol is therefore a circle of known diameter. A final limitation of the solution is that it has to be repeated each time the system moves to a new calibration symbol.

14.2 Conclusion

The thought process behind the graphical user interface was examined in detail in this chapter. In addition to this, the GUI's functioning was examined. One of the major additions to this functioning software is that of the calibration function. This function ensures the system is exactly centred over the calibration system. All of these elements are combined to create a functional and intuitive control subsystem.

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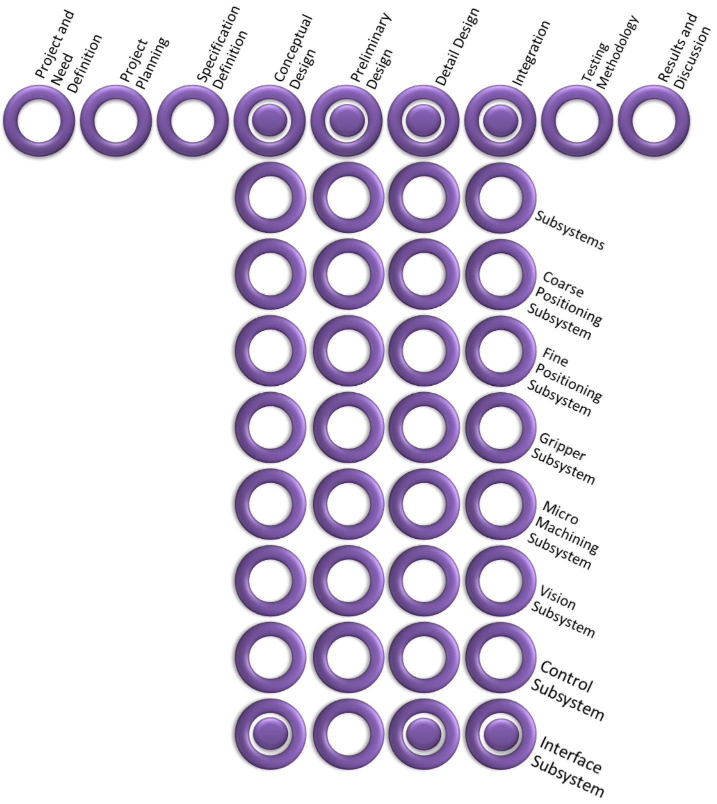
Chapter 15

Interface Subsystem



The purpose of this chapter is to examine the creation of the human robot interface system. One approach to this is to implement a force teach technique and haptic control. The force teach technique is a method whereby the user grips the robot end effector and moves it to perform a certain task. The whole

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movement is then recorded and can be easily played back. Haptic control is a system whereby a force experienced by the end effector on a slave robot is transmitted to the user on the controlling robot. In order to explain how a feasible solution was created, it is necessary to examine the haptic force feedback system that was in place before the created coarse-to-fine system.

15.1 Conceptual Design Interface

Ando *et al.* (2000) successfully used a master and slave device for tele-operation. The serial link master device had 6 degrees of freedom with built-in haptic feedback. The slave device had a parallel mechanism end effector.

Haptic feedback is the most important form of feedback after visual feedback, (Kortschack *et al.*, 2005). According to Chen *et al.* (2007), haptic feedback is used to generate skin-based and proprioceptive (body position, orientation, and movement) information. Forces experienced by the end effector are transmitted back to the master controller. This information helps to increase the user's situational awareness when performing robot remote control or tele-operation.

One of the main aims in the design of the system is to ensure ease of use. Incorporation of haptic and visual feedback will ensure user immersion. These two features can be used to increase the usability of a teach function.

15.2 Detail Design Interface

The purpose of this section is to explain the detail design of incorporating haptic feedback when using the Feinmess system. The Feinmess haptic functioning is only possible because of previous work done by Pretorius (2011) and work currently being done by Mr. Andre Smit. In order to fully understanding the functioning of the Feinmess haptic interface, the previous and current work has to be fully explained.

15.2.1 Development and Implementation of a Telerobotic System with Video and Haptic Feedback

A teleoperated haptic feedback system developed by Pretorius (2011) will be integrated with the micro-material handling system being developed. The

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system incorporates two industrial robots each with their own force torque sensors. The robots are the Motoman SDA 10 and the Motoman UP6. The robots are controlled by the DX100 and the XRC controllers respectively.

Using visual feedback, an operator applies a force to the master robot as shown in 15.1. A slave robot (remotely positioned robot linked to the master robot, in this case the SDA 10) then replicates the applied force. The system can either be operated in passive or active mode. In active mode the forces applied at both sensors are subtracted. The difference then determines the direction of motion. In passive mode the feedback from the slave will only serve to slow or hinder the motion of the master.

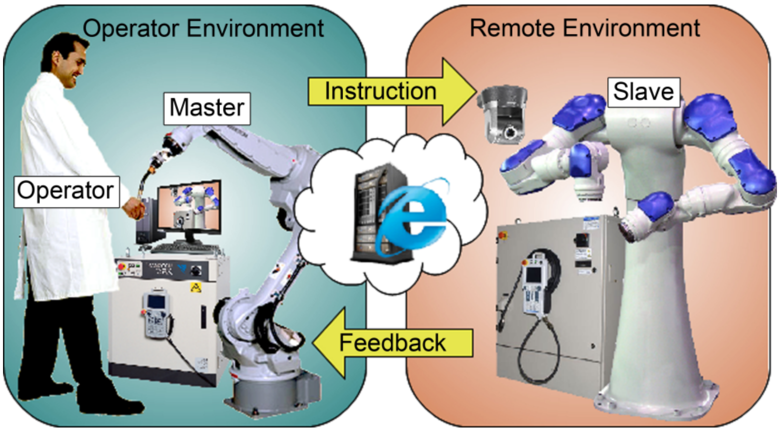

Figure 15.1: Telerobotic System Overview, (Pretorius, 2011)

Force Sensors

In order to implement the above, Pretorius (2011) made use of two ATI sensors and their Net Boxes as seen in figure 15.2. According to Pretorius (2011), the human hand can perceive a force of around 0.025 N in any orientation and combination at a rate of around 500 Hz. The sensors can record multiple axis forces of around 0.025 N and moments of around 0.00125 Nm at a rate of 7000 Hz. In addition to this, the Net Box houses a web server. This broadcasts data packets containing the force and torque data over an Ethernet connection using UDP protocol. This is favourable as the computer does not have to acknowledge that it has received the information from the sensor.

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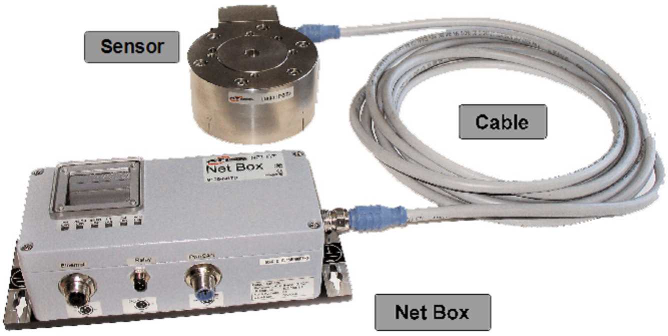

Figure 15.2: ATI Force Torque Sensor with Net Box, (Pretorius, 2011)

Interpreter

This system was developed to be operated over a network. This allows for remote access and control; this is particularly relevant when considering tele-operated haptic devices. A drawback of the hardware used by Pretorius (2011) is that the XRC or UP6 controller does not support Ethernet control. The Barix Barionet 100 was thus used to enable network communication for this controller and robot.

Due to the fact that the Barionet modules are not able to interpret information directly from the F/T sensors, Pretorius (2011) decided to make use of an interpreting personal computer. The following system architecture was thus created, figure 15.3. The Barionets thus handle communication to the robot controllers, while the computer receives and interprets information and issues commands, (Pretorius, 2011).

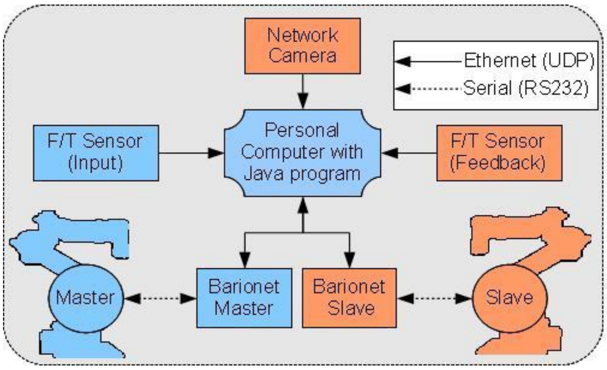

Figure 15.3: Java Based Communication Architecture, (Pretorius, 2011)

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Control System Design

According to Pretorius (2011) the two sensors, one on the UP6 and the other on the SDA 10, both need to be in the same orientation. If this is not the case, the force resultant force will be registered on different axes. It is thus essential that before the start of the operation, both sensors, mounted on robot end effectors, are in the exact same orientation.

The instruction function IMOV was used to move both robots. This instruction effects movement as per the tool coordinates. This function requires both a velocity and a displacement. A single velocity is applied to all of the axes. The displacement, however, needs to be calculated separately for each of the individual axes, (Pretorius, 2011). The forces applied to the pencil-type end effector were thus converted to a distance and a velocity using the following equations figure 15.4. Equations making use of angular velocities and inertias were used to calculated the applied torques. The intended experience is that the user feels as if they are physically pushing the end effector on the slave robot.

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \frac{F_x}{2m} \\ \frac{F_y}{2m} \\ \frac{F_z}{2m} \end{bmatrix} t^2 + \begin{bmatrix} \dot{x}_0 \\ \dot{y}_0 \\ \dot{z}_0 \end{bmatrix} t + \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} \frac{F_x}{m} \\ \frac{F_y}{m} \\ \frac{F_z}{m} \end{bmatrix} t + \begin{bmatrix} \dot{x}_0 \\ \dot{y}_0 \\ \dot{z}_0 \end{bmatrix}$$

Figure 15.4: Displacement and Velocity Equations, (Pretorius, 2011)

Adding Haptic Feedback

Pretorius (2011) states that haptic feedback can either be incorporated in an active or passive manner. In passive feedback a force and torque applied to

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the master robot effects movement on both the master and slave robots. The forces and torques applied to the slave can, at most, provide resistance to the master and slaves motion.

In active feedback the sensor readings from both the master and slave are combined. When the force acting on the slave is the same direction as the force acting on the master, then the largest magnitude controls the master and slave, (Pretorius, 2011). The difference between active and passive feedback can best be summarised in the figure 15.5.

$$A_i = \begin{cases} Maximum(M_i, S_i) & \text{if components } M_i \text{ and } S_i \text{ are aligned} \\ M_i + S_i, & \text{if components } M_i \text{ and } S_i \text{ are opposing} \end{cases}$$

$$P_i = \begin{cases} M_i, & \text{if components } M_i \text{ and } S_i \text{ are aligned} \\ M_i + S_i, & \text{if components } M_i \text{ and } S_i \text{ are opposing, where } |M_i| > |S_i| \\ 0, & \text{if components } M_i \text{ and } S_i \text{ are opposing, where } |M_i| \leq |S_i| \end{cases}$$

Figure 15.5: The Difference Between Active Ai and Passive Control Pi, (Pretorius, 2011)

Software Interface

In order for real time live control and feedback to be realised, the Java interface must read the force and torque data from both robots, calculate and execute the appropriate actions via the Barionet, and display the video feedback on the graphical user interface, (Pretorius, 2011). The graphical user interface can be seen in figure 15.6.

Limitations

Pretorius (2011) states that due to a hardware limitation of the robots, after a command is received, the robots execute it and then stop. Stopping after the completion of each command greatly simplifies the equations of motion. The result of this lack of real-time operation is that the motion of the robots appears jittery. A solution to this was to limit the velocities applied and make use of small incremental commands. The effects of this jittery motion were thus greatly reduced, (Pretorius, 2011).

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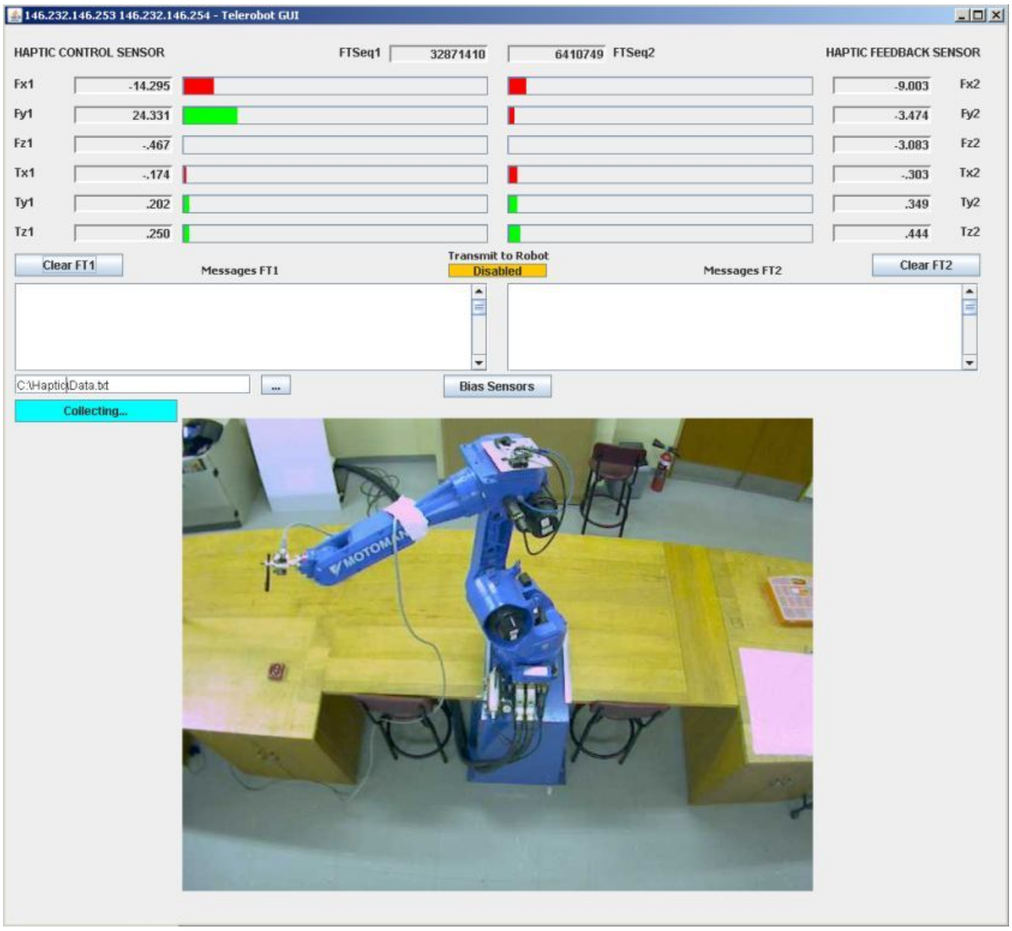


146.232.146.253 146.232.146.254 - Telerobot GUI

HAPTIC CONTROL SENSOR			HAPTIC FEEDBACK SENSOR
FTSeq1	32871410	6410749	FTSeq2
Fx1	-14.295	-9.003	Fx2
Fy1	24.331	-3.474	Fy2
Fz1	-.467	-3.083	Fz2
Tx1	-.174	-.303	Tx2
Ty1	.202	.349	Ty2
Tz1	.250	.444	Tz2

Transmit to Robot: Disabled

C:\HapticData.txt

Collecting...

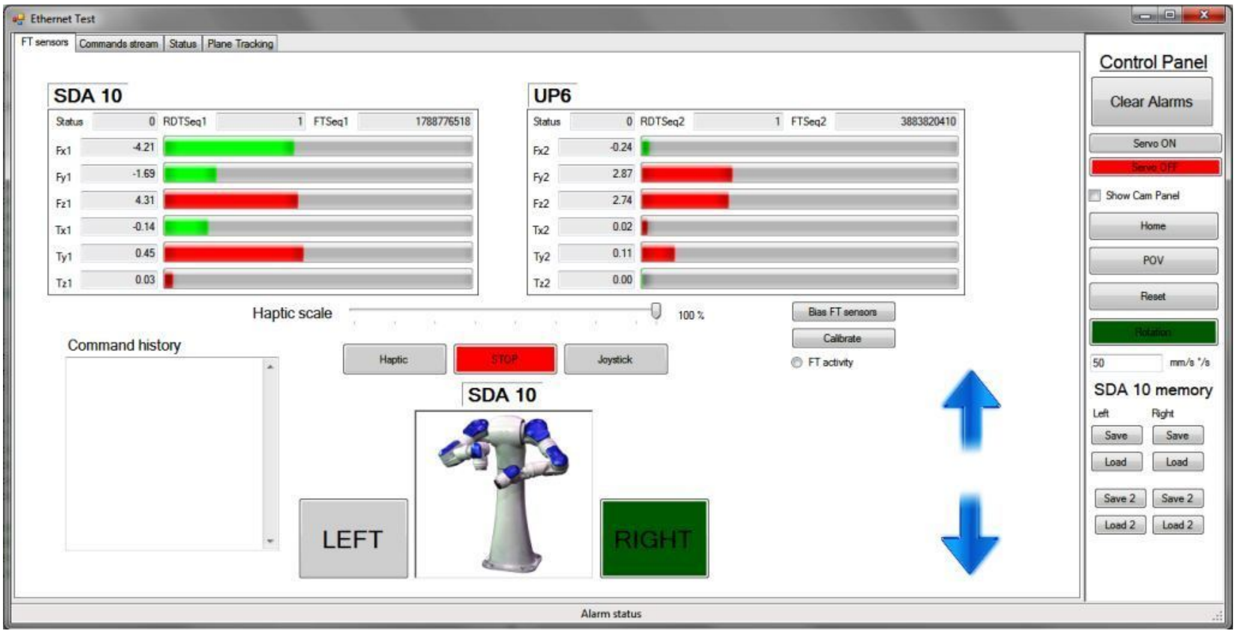
Figure 15.6: Graphical User Interface, (Pretorius, 2011)

15.2.2 Interface Program Already in Place

The system currently in place can be considered a comprehensive improvement of the work done by Pretorius (2011). The improvement coordinated by Mr. Andre Smit can be considered to be an implementation of software based telerobotics. In this improvement all key issues previously stated are addressed.

A key example of this is that of the communication. As previously stated, the XRC did not support Ethernet communication. As a result it was necessary to use a Barionet interpreter. A network card was purchased and integrated into the XRC controller for the UP6 robot. It is now possible to directly communicate and control the UP6 robot via Ethernet communication. The work done by Mr. Andre Smit thus completely removes the need for the Barionet interpreters. Instead, a computer controls all components of the force feedback and motion control of both robots via a local network.

In addition to this, Mr. Andre Smit created an intuitive GUI for controlling the Motoman SDA 10 as well. This GUI, known as Andre Smit's Interface Program, is also used to control the haptic feedback between the XRC and SDA 10. This interface program clearly displays the forces experienced by both force and torque sensors, this can be seen in figure 15.7. This program is thus used in conjunction with the GUI developed in this project to control the micro-material handling system.



SDA 10

Status	0	RDTSeq1	1	FTSeq1	1788776518
Fx1	-4.21				
Fy1	-1.69				
Fz1	4.31				
Tx1	-0.14				
Ty1	0.45				
Tz1	0.03				

UP6

Status	0	RDTSeq2	1	FTSeq2	3883820410
Fx2	-0.24				
Fy2	2.87				
Fz2	2.74				
Tx2	0.02				
Ty2	0.11				
Tz2	0.00				

Haptic scale 100 %

50 mm/s °/s

Figure 15.7: The Graphical User Interface Developed by Andre Smit

15.2.3 Communication Hardware

The system is comprised of two Ethernet hubs. These allow for easy communication between the controlling computer and the various Ethernet devices. As stated, the SDA 10, XRC and force sensors are all used by Andre Smit's Interface Program for haptic control. These are incorporated into the Feinmess haptic control. The communication hardware can be seen in figure 15.8.

15.2.4 Initial Feinmess Haptic Code

In order to create a smooth transition from the force-teach operation of the SDA 10 to the force teach of the Feinmess, it was decided to use the same

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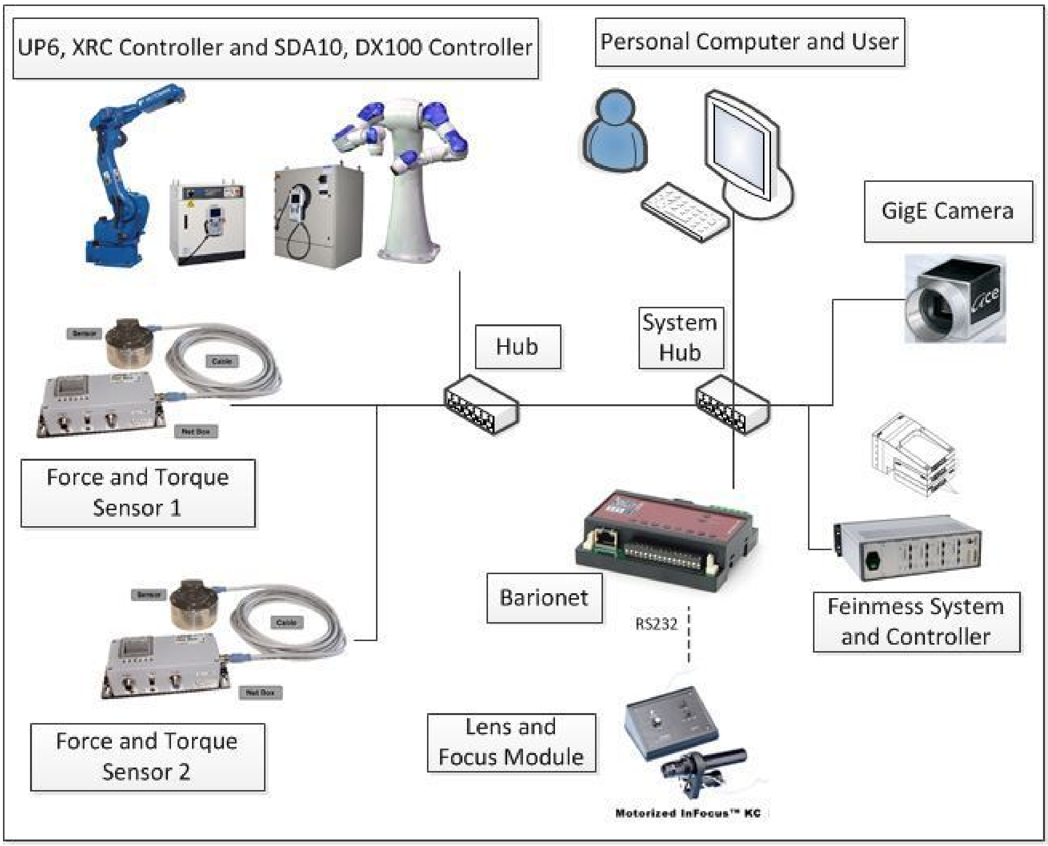

Figure 15.8: The Ethernet Communication Between System Components in Combination with Components Used by Mr. Andre Smit and Mr. Jonathan Pretorius. The Dotted Line Represents RS-232 Communication

kinematic model as (Pretorius, 2011). Much of the existing code can thus be incorporated. This prevents having to reinvent the wheel, so to speak.

Force Teach

As explained the two modes of operation of the Feinmess system are a jog and an increment operation. The increment option requires a displacement, while the jog option requires a velocity. Once an increment command is sent, the system pauses all communication until the action is completed, (Galil, 2011). The jog function, on the other hand, continues to execute a command until a stop or change of command is issued, (Galil, 2011).

Owing to the nature of the control system, and the need for a responsive system, only the jog function and therefore velocity, can be used. The user applied force is thus converted into a velocity using the equation as per figure

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15.9.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} \frac{F_x}{m} \\ \frac{F_y}{m} \\ \frac{F_z}{m} \end{bmatrix} t + \begin{bmatrix} \dot{x}_0 \\ \dot{y}_0 \\ \dot{z}_0 \end{bmatrix}$$

Figure 15.9: Equation to Determine Velocity from Force, Mass and Time

The time interval over which the velocity is calculated is taken as a discrete 0.03 seconds. The calculated velocity is converted from m/s into counts/s. This conversion is done based on the resolution of the encoder 1 count per 100 nm. After the conversion, the data runs through a number of checks. The checks are simply in place to prevent the program from issuing velocities, displacements or accelerations that would damage the Feinmess system in any way.

The force teach function is thus operated by using two programs simultaneously as in figure 15.10. The program currently in place has been altered as previously mentioned in order to convert the acquired forces into movement using the Feinmess system. The newly created program performs the calibration, record and playback, and additional movements operations. It is essential that forces are monitored during the operation in order to prevent damage to both systems.

Problems with This Approach

In order to implement the conversion from force and mass to velocity, it is necessary to take the initial velocity into account as well as the duration of application of the force. The function updating the force sensor input readings is iterated every 30 milliseconds. If no change in force occurs, then the amount of time the force is applied for is simply accumulated and included in the aforementioned equation. The initial velocity is simply equal to the velocity of the previous calculation. Together, these two provide an accurate representation of the velocity as a result of the force applied over a certain duration.

In order to do determine whether a force has been applied, the code is created such that if the force measured varies by a certain amount (1 N), then

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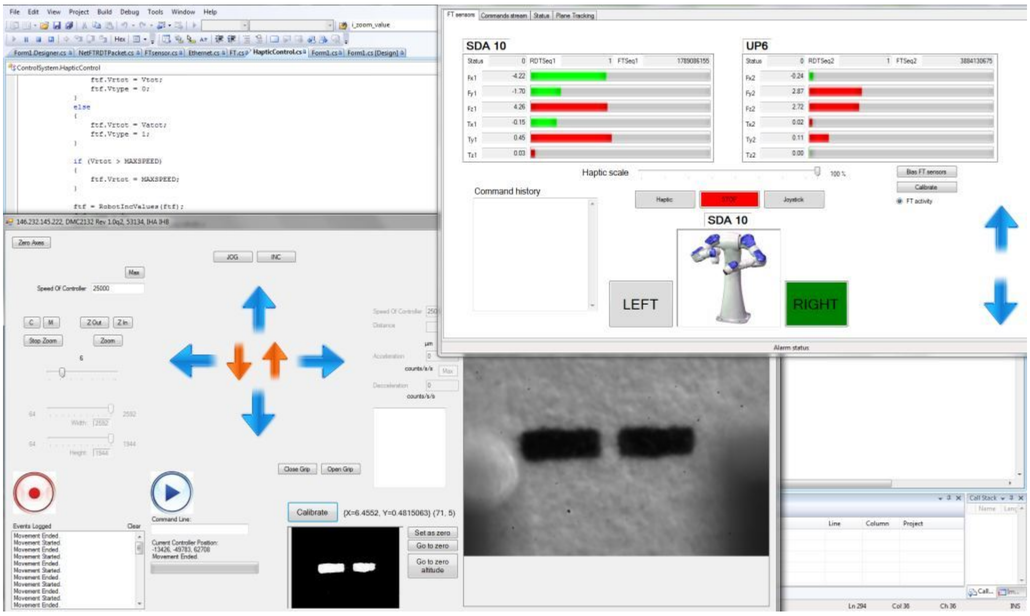

```
        ftf.Vrtot = Vtot;
        ftf.Vtype = 0;
    }
    else
    {
        ftf.Vrtot = Vatot;
        ftf.Vtype = 1;
    }

    if (Vrtot > MAXSPEED)
    {
        ftf.Vrtot = MAXSPEED;
    }

    ftf = RobotIncValues(ftf);
```

146.232.145.222, DMC2132 Rev 1.0q2, 53134, IHA IHB

Speed Of Controller 25000

SDA 10

Status 0 RDTSeq1 1 FTSeq1 1789086155

Fx1 -4.22
Fy1 -1.70
Fz1 4.26
Tx1 -0.15
Ty1 0.45
Tz1 0.03

UP6

Status 0 RDTSeq2 1 FTSeq2 3884130675

Fx2 -0.24
Fy2 2.87
Fz2 2.72
Tx2 0.02
Ty2 0.11
Tz2 0.00

Haptic scale 100 %

Figure 15.10: Screen shot of Feinmess Graphical User Interface and Andre Smit's Interface Program, with Integrated Feinmess Haptic Code

a 'new' force is said to have occurred. The fact that a new force had been registered, means that firstly, the total time being accumulated should be zeroed. The length of time that the new force is being applied is thus taken from zero. It then begins accumulating once again. When a new force is realised, it is also important that the initial velocity is zeroed. If this were not the case, the calculated velocity would explode.

A significant problem with the above approach is that a stop command has to be issued every time a new force is calculated. This is simply due to the nature of the formula. Due to the high processing rate of the program, stop-and-start commands can be issued every 30 milliseconds. Although this is factually accurate, the Feinmess controller cannot react to these commands fast enough. The attempted implementation of the above results in the Feinmess system vibrating and acting erratically. True force teach or haptic interfacing thus cannot be realised.

In order to circumvent this problem, the exact time the force has been applied for and the initial system velocity were discarded. The system is thus not instructed to stop every 30 milliseconds. The system is simply given different velocities. This means that the system does not have to come to a complete standstill every time a new force is realised. The time the velocity is calculated is 30 milliseconds. The result of this implementation is a smooth and intuitive functioning force interface system.

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Final Feinmess Haptic Code

A new section of code was thus created in the already existing SDA 10 and UP 6 haptic interface code. This code allows the implementation of haptic feedback using the UP6 and the Feinmess system.

The forces are updated every 25 ms. Once the haptic or force teach (joystick) buttons are pushed, the Feinmess system will move according to forces applied to the force sensors. As stated above, and as can be seen in figure 15.11, it is necessary to incorporate a scaling factor. This factor ensures smooth, intuitive functioning of the system. It is also essential to ensure that the system does not exceed 50 000 counts/s and does not go below 2 counts/s. Excessive speed will cause damage to the Feinmess system, (Feinmess, 2011). A speed of 0 counts/s can also not be issued as this will cause the system to stall.

After the above section of code has been initiated, is is then necessary to initiate the record function. This record function takes place within the newly programmed graphical user interface. The two programs thus run simultaneously, as can be seen in the screenshot figure. The program flow of the record function in the GUI can be seen in figure 15.12.

15.3 Integration Interface Sensor Orientation

From the outset, the idea was to implement haptic feedback using the fine positioning system. It is difficult to continually compensate for an acting force. If, for instance, the fine positioning system was placed on top of the force sensor, the force sensor would continually register the weight force of the fine positioning system. It is therefore appropriate to place the force sensor where it is least likely to experience constant disturbing forces. The force sensor was thus placed on top of the Force Sensor Fine Positioning Mount which is attached to the fine positioning system.

Having established that the force sensor should be placed on top of the fine positioning system, it then becomes necessary to determine the exact location. The orientation of the force sensor on the UP 6 robot can be seen in figure 15.13a as per Pretorius (2011). In order to ensure seamless integration of the fine positioning module both into the code and the physical system, it was decided to place it in a similar orientation to that of the end effector of the Motoman. This orientation can be seen in figure 15.13b.

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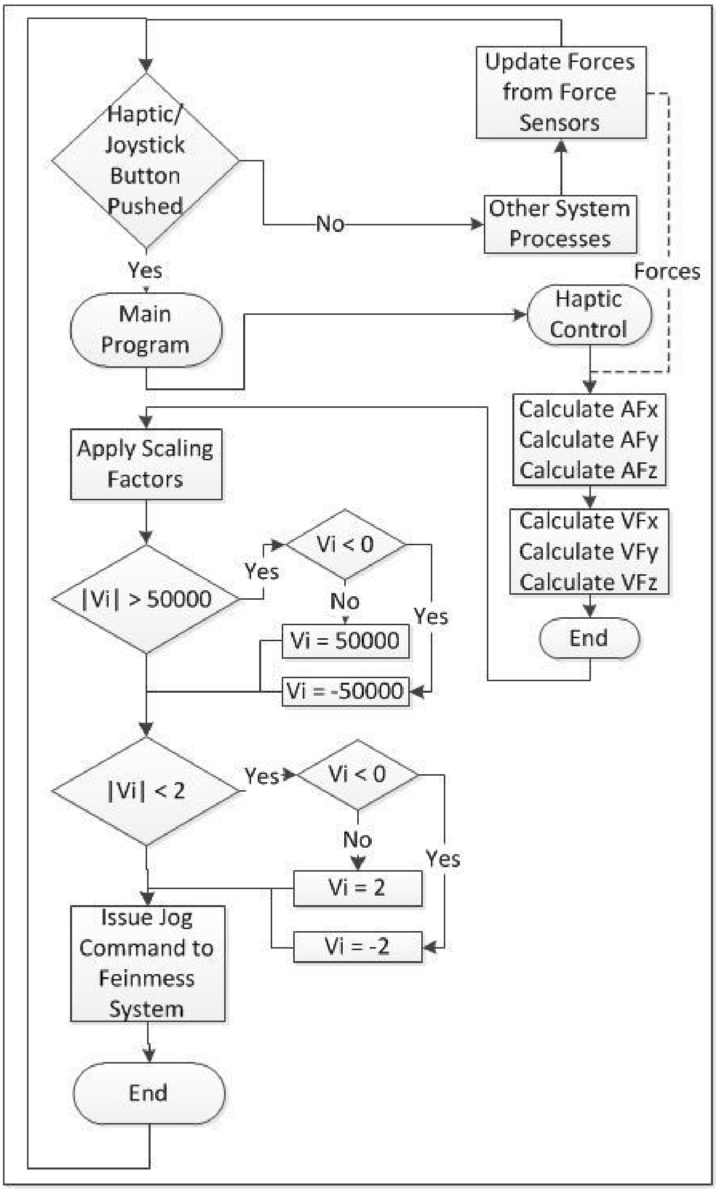

Figure 15.11: Program Flow of Haptic Force Feedback Integrated into A. Smit's Improvement on J. Pretorius Program

15.4 Conclusion

Having examined the functioning and development of the force teach system, it was necessary to explain how it integrated into the rest of the system. The exact nature of the current force feedback system meant that a number of code alterations had to take place before this force feedback could be realised with the coarse-to-fine positioning system. Once these issues were sorted out, a functioning and intuitive user-force interface was functioning with the coarse-

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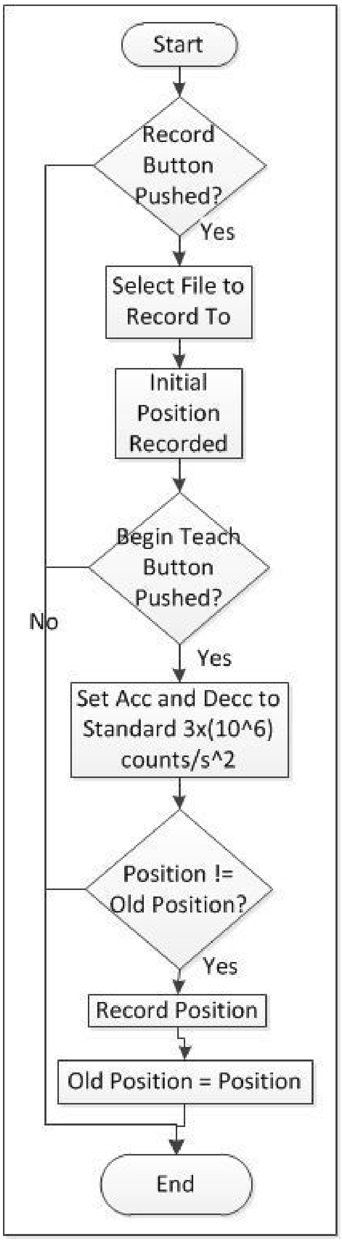

Figure 15.12: Program Flow of Feinmess Positional Record Program

to-fine positioning system.

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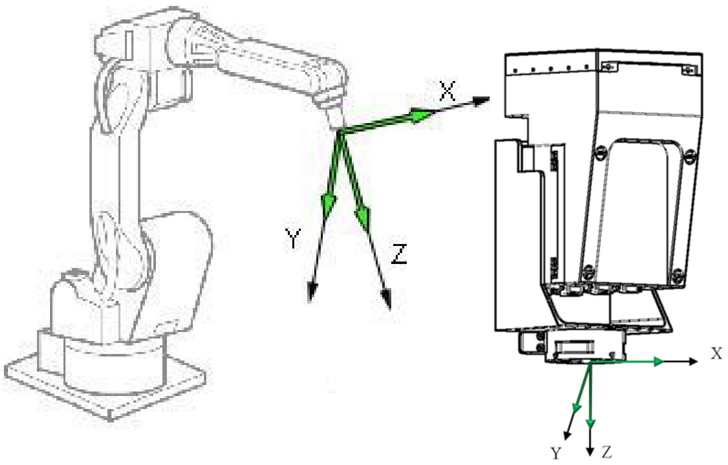

(a) UP6 Force Sensor Orientation

(b) Fine Positioning System Sensor Orientation

Figure 15.13: Orientation of Force Sensor and Fine Positioning Mount Compared to the Orientation of the Force Sensor and UP6 Robot as per , Pretorius (2011)

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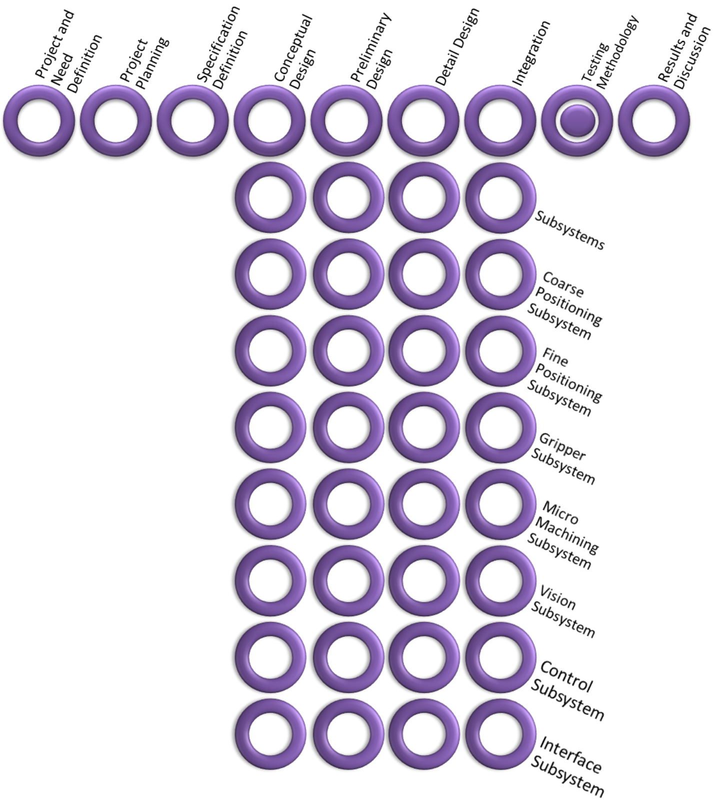
Chapter 16

Testing Methodology



The purpose of this chapter is to describe and justify the various testing or verification methods used. INCOSE (2007) states that the verification process confirms that elements perform in accordance with the relevant requirements. Verification includes developing verification procedures, scheduling, installing

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and selecting needed systems, executing and then documenting verification procedures.

There are four themes of the testing. The first deals with a brief test of the Van der Waals gripper. The second deals with testing of the calibration system. The next test deals with the Motoman SDA 10. Lastly the Motoman, calibration and the Feinmess system are tested together. In the chapter Results, the tests will be carried out and the results discussed.

16.1 Methodology Van der Waals Gripper and Coarse-to-Fine Positioning System

The gripping of the micro elements was achieved with a level of success when using the coarse-to-fine positioning system and the Van der Waals gripper. The Schunk pneumatic gripper and designed gripper tips successfully gripped and released the micro components without damage. A source of errors, however, is the result of the jerky motion of the pneumatic gripper. The extremely rapid opening of the gripper jaws meant that the micro element did not drop vertically. This makes accurate testing extremely difficult. It was therefore decided to perform testing with the Van der Waals Gripper.

16.1.1 Machining of the Piezo-Ceramic Components and Aluminium Cavities

In order to test the coarse-to-fine system and the Van der Waals gripper, micro cavities were machined into aluminium using a fixed micro-milling CNC machined. This ensured the accuracy and quality of cut for this particular test. In addition to this, the CNC was used to machine piezo-ceramic micro components from a piezo-ceramic sheet. The 250 μm by 260 μm by 10 mm piezo-ceramic elements were machined from a piezo-ceramic blank of 50 mm x 10 mm x 260 μmm using a 254 μm diameter milling tool made of carbide material. The spindle speed was 40 000 revs/min, the depth of cut was 260 μmm and the feed rate was 1.6 mm/s. The aluminium cavities of dimensions 300 μm wide x 220 μm deep x 10 mm length, shown in figure 16.1, were machined using a using a 254 μm diameter milling tool made of small-grained carbide material. The adjacent cavities were 300 μm apart. The spindle speed was 40 000 revs/min, depth of cut was 220 μm and the feed was 6.67 mm/s. Both cutting processes used flood cooling, with a water-and-cutting oil mix.

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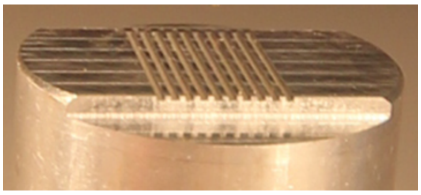

Figure 16.1: Dimensions of the Micro Cavities in Aluminium Alloy Carrier

16.1.2 Preparation of Polyurethane Gripper

Polyurethane 20 A (polyurethane with a shore hardness of 20 A), trade name VytaFlex 20 was used to make the gripper, (Smooth-On, 2012). This product was chosen because of its proven viability (Arderne *et al.*, 2012) and (Murphy *et al.*, 2011). This polyurethane material was supplied in two parts, A and B (liquid ingredients), which were later mixed in equal parts as per Smooth-On (2012). Thorough mixing took place for at least three minutes as recommended by the manufacturer. A steel needle (any other suitable rigidity material may be used) was dipped into the polyurethane mix and then suspended vertically in air to allow the mix to form a spherical polyurethane-tipped gripper as shown in figure 16.2. The gripper was allowed to cure under ambient conditions for 24 hours.

Figure 16.2: Polyurethane Spherical Micro Gripper of Approximately 1 mm

16.1.3 Coarse-to-Fine Positioning Subsystem

Due to the nature of the Van der Waals gripper, it is necessary to employ a highly accurate and sensitive positioning system. To this effect, the aforementioned polyurethane gripper was attached to the force sensor as part of the designed coarse-to-fine positioning system. This setup allowed for both the control through graphical user interface and the more intuitive force teach

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technique to be used.

16.1.4 Forces and Pre-Loads

For the polyurethane micro-gripper to pick the piezo-ceramic element a pre-load of approximately 0.2 N was applied. This pre-load was found in preliminary experiments to provide an optimum Van der Waals force on materials being picked and placed, (Arderne *et al.*, 2012).

The piezo-ceramic elements are 250 μm thick; therefore the contact area of this soft polyurethane gripper is a circle of a diameter of roughly 250 μm. The aforementioned pre-load is assumed to be applied at the centre of this circle on the piezo element. The resulting stress would be approximately 4.07 MPa, which is far less than the 30 MPa depolarisation pressure and compressive strength of 600 MPa, (Matthey, 2012). This assures that no damage will occur.

16.2 Methodology Calibration Function

In order to test the visual calibration system, a more accurate system than aforementioned printed lines is needed. To this effect, a needle was used to prick holes of roughly 80 μm in diameter into white paper. The lighting was adjusted such that all that could be seen was a black micro dot, see figure 16.3. The calibration program was then run. The calculated distance between the centre of the 2592 x 1944 pixel image and the centre of the calibration mark was then recorded in x and y pixel coordinates.

The image was then captured and analysed visually in the following manner. A grid of blocks sized 1 pixel by 1 pixel was overlaid onto the image. Zooming into the calibration system 800 X, see figure 16.3, the centroid of the image was found by inspection. By subtracting this centroid from the exact centre of the image (1296 pixels in the x direction and 972 pixels in the y direction), a distance was recorded similar to that of the calibration function. The two sets of values were then recorded and analysed.

It should be noted that this test method makes use of rough visual inspection. It is not intended to achieve absolute accuracy and is estimated around 10 μm. There is no justification for duplication by creating another highly accurate calibration-type system simply to test the original calibration system.

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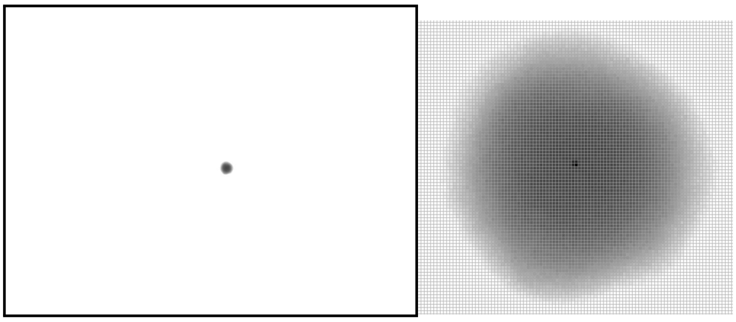

(a) Calibration Test 1

(b) Calibration Test Zoomed 1

Figure 16.3: Calibration Mark in Both Full Image and 800 X Zoomed Image. Each Block is One Pixel

The test is to be conducted 32 times by manually moving the calibration symbol to different parts of the field of view and then recording the calibration function's distance and that from visual inspection. In this manner 32 random x and y coordinates can be compared. From the comparison it should become clear whether the calibration function is accurate or not.

16.3 Methodology Motoman SDA 10

In order to best examine the system it is first necessary to create a testing methodology. It is important that this methodology is validated before being applied to the coarse-to-fine positioning system. This testing methodology forms the first of two concurrent themes in a journal paper to be written. The second theme deals with qualitative and quantitative information obtained from performing actual micro-machining using the coarse positioning system. This information can be used to determine the appropriateness of this type of kinematic for micro-milling and whether or not a coarse-to-fine positioning system is indeed needed for accurate micro-milling. In addition to this, it will also provide information about possible effects that the fine positioning system will experience when performing micro-milling. Allowable force and vibration calculations can be compared to actual forces and vibrations experienced. This is important as it will help to ensure that potential risk to the delicate fine positioning system is mitigated.

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16.3.1 Equipment

In order to determine the forces and vibrations associated with machining, a 6 axis ATI force torque sensor is mounted in between the Motoman SDA 10 and the Nakanishi EM 3060 micro-milling spindle. According to ATI (2010), the force torque sensor has a resolution of 1/40 N in the x and y directions, and 1/20 N in the z direction. It can handle forces up to 130 N in the x and y directions. The force torque sensor was attached to a Net Box which creates a live stream of the force information. A program created by Pretorius (2011) interpreted and recorded the forces measured.

In addition to this, two PCB Piezotronic ICP shear accelerometers were attached in the x, and y directions. The PCB shear accelerometers each had a frequency range of 0.5 to 10 000 Hz, (Piezotronics, 2012). The voltage senstivity for the accelerometer in the y axis is 100.6 mV.g-1, while the sensitivity for the acceleromter in the x axis is 99.2 mV.g-1, (Piezotronics, 2012). The accelerometers' outputs were interpreted by an HMB Quantum X (MX410) data acquisition system. The combined components can be seen in figure 16.4.

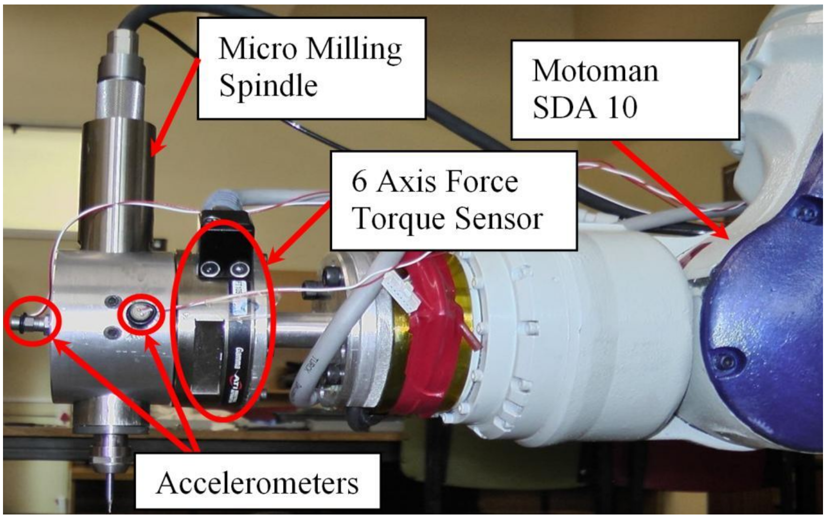

Figure 16.4: The Assembled Test Equipment Used

Axis Configuration

The Motoman SDA 10, the ATI force torque sensor, the accelerometers, the fixed CMM and the portable CMM each have their own configuration of the x, y, and z axes. It was therefore decided to create one set of axes as per the configuration of the Motoman SDA 10. This configuration can be seen in

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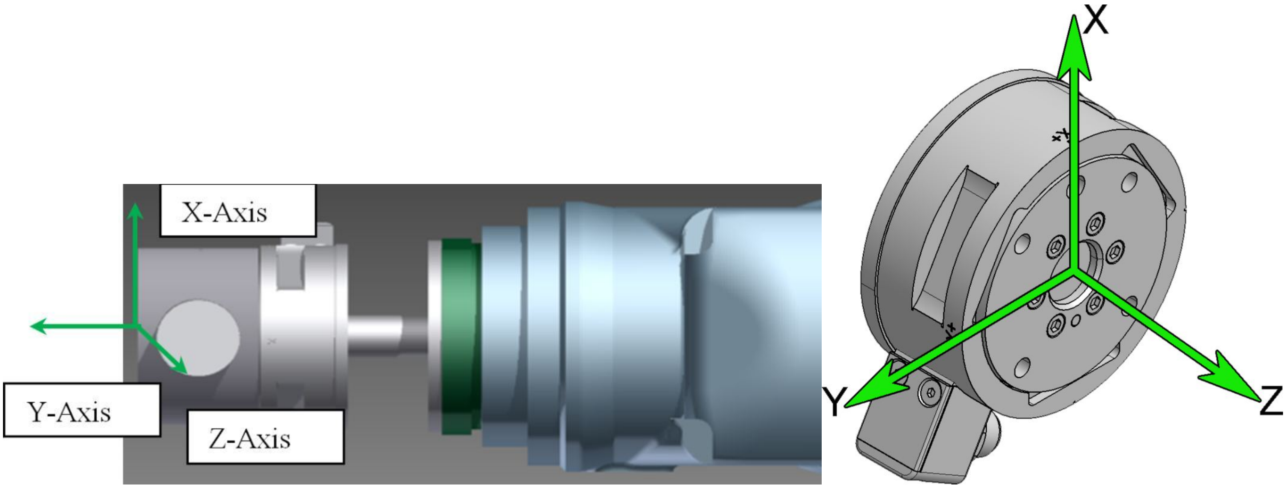
the above view of the system in figure 16.5. Data from all of the other systems was therefore converted into this coordinate system. Information from different sources can thus be viewed simultaneously on the same axes. A key example of where the axes were switched is with the force torque sensor. The z direction replaces the x direction, the x direction replaces the y direction and the y direction replaces the z direction see figure 16.5.



(a) Overall Axis Layout (b) Sensor Axis Layout

Figure 16.5: The Chosen Axis Configuration and the Force Sensor's Axis Configuration Prior to Adjusting

Future Testing Configuration

The intended configuration for micro-machining using the coarse-to-fine positioning system is as follows. The micro-milling spindle is attached to the force sensor. This is then attached to the Feinmess fine positioning system. The fine positioning system is then attached to the Motoman or coarse positioning system, see figure 16.6. Another possibility is to have the camera and lens and milling spindle underneath the Feinmess system. In this way the calibration function can be used. The Feinmess system is comprised of three precise linear stages.

Motoman SDA 10 Performance

Communication to the SDA10 D is done from PC using TCP/IP. An interface program developed by A. Smit allows users to upload Comma Separated Value

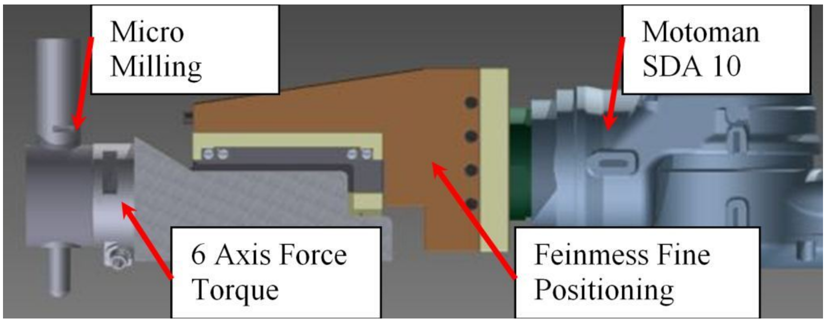
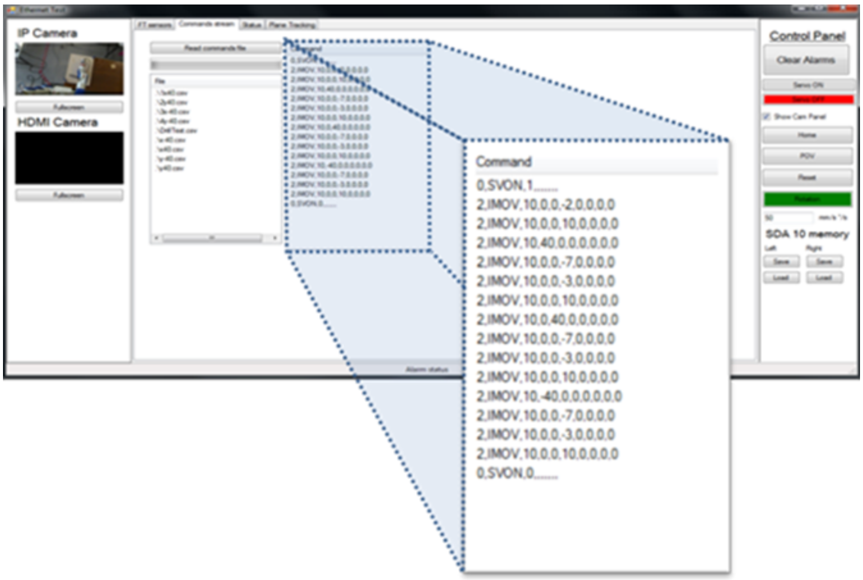


Figure 16.6: The Configuration of the Coarse-to-Fine Drilling Setup

(CSV) files with relative co-ordinate data. In combination with this file type, the relative motion command IMOV was used as it does not require intensive communication with the controller. IMOV generates an incremental command with speed ranging from (0.1mm/s to 100's of mm/s) , (RobotWorx, 2011). The maximum allowable speed is determined by the maximum speed of the slowest joint rotation, which will not exceed the safety limits introduced by the robot control system. The concept is to position the robot manually and then from this position the command set is read in by the dashboard and the sent sequentially to the robot for execution, (Read *et al.*, 2012). A screenshot of the graphical user interface as well as a zoomed view of the commands being executed can be seen in figure 16.7.



```
0,SVON,1,,,,,,,
2,IMOV,10,0,0,-2,0,0,0,0
2,IMOV,10,0,0,10,0,0,0,0
2,IMOV,10,40,0,0,0,0,0,0
2,IMOV,10,0,0,-7,0,0,0,0
2,IMOV,10,0,0,-3,0,0,0,0
2,IMOV,10,0,0,10,0,0,0,0
2,IMOV,10,0,40,0,0,0,0,0
2,IMOV,10,0,0,-7,0,0,0,0
2,IMOV,10,0,0,-3,0,0,0,0
2,IMOV,10,0,0,10,0,0,0,0
2,IMOV,10,-40,0,0,0,0,0,0
2,IMOV,10,0,0,-7,0,0,0,0
2,IMOV,10,0,0,-3,0,0,0,0
2,IMOV,10,0,0,10,0,0,0,0
0,SVON,0,,,,,,,
```

Figure 16.7: Screen Shot of Existing Motoman Graphical User Interface, with Expanded View of Hole Drilling Commands to be Executed

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As per Read *et al.* (2012) the movement file's contents is executed sequentially. As such the robot comes to a complete stop before executing the next command. It is accepted that the robot will move at the predefined speed in the instruction set. Due to the nature of the Motoman's hardware, a short distance is required for the robot to accelerate to the speed required. It is therefore important that provision for this be made when considering micro-milling.

16.3.2 Force and Vibration Limitations

It is essential to consider both the allowable forces and the natural frequencies of components when attempting micro-milling with the material handling system. The items of concern are the force sensor, camera and lens system, and particularly the delicate Feinmess MP 130 system as previously mentioned. If the milling spindle reaches a speed equal to that of the natural frequency of either of the two aforementioned items, resonance and damage could result. Similar mechanical failure could result if the allowable forces are exceeded.

The figures calculated in this section for all the components will later be compared to actual force and vibration information obtained. It can thus be determined whether drilling or milling operations will cause damage to any of the components both during the current testing and during future machining operations with the coarse-to-fine positioning system.

Feinmess Allowable Forces

From a mechanical point of view, it is important to ensure that performing micro-milling does not result in maximum forces and torques being exceeded. A large number of calculations were conducted in this regard in Appendix E.

It was found that the machining/drilling force in the z direction must be less than 14 N in order for operation to remain beneath the maximum torque of 3.4 Nm, (Feinmess, 2011). The maximum forces for milling allowed in the x and y axes are 33.66 N when performing calculations with the 3.4 Nm max, (Feinmess, 2011).

Feinmess Allowable Vibrations

Feinmess (2011) listed a vertical and a lateral stiffness for each of the three stages that make up the Feinmess positioning system. From this stiffness it is possible to determine natural frequencies. It is important to ensure that the natural frequencies calculated are not in any way achieved when micro-

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machining. If this is the case, prolonged resonance and damage can result.

The calculated natural frequencies can be seen in the Appendix E and are as follows for the vertical orientation 1591.55 Hz, 742.06 Hz, 459.44 Hz for stages 1 to 3 respectively. For the lateral orientation the natural frequencies are 1125.4 Hz, 524.72 Hz, and 324.87 Hz for stages 1, 2 and 3 respectively.

The frequencies to be milled at are 800 Hz for 24 000 rpm speed. This is a standard test speed that has been successfully used for milling with a 1 mm tool bit. This 800 Hz is close to the 742.06 Hz frequency of the 2nd stage and should perhaps be increased. When milling with the smaller 0.396 mm tool bit it is necessary to increase the speed to 48 000 rpm. This is converted to 1600 Hz.

Force Sensor Allowable Vibrations

As per ATI (2010), the force torque sensor's maximum allowable force is around 130 N. This is far above the range of forces considered here. The high force tolerance of the force torque means that it is not at risk of being damaged by the machining operations. This sensor does, however, have a natural frequency within the range being machined. The resonant frequency of the ATI force torque sensors is 1400 Hz or 1.4 kHz for force in the x and y axes and 2000 Hz or 2 kHz for forces in the z axis, (ATI, 2010). The frequency of 1.6 kHz experienced when micro-milling with the 0.396 mm tool bit is just in between the two frequencies. This means that the force sensor will experience resonant vibration for only a very short duration.

Camera and Lens System Vibrations

Due to the fact that the vision subsystem (camera and lens) does not come into direct contact with the micro-milling spindle, there is no need to calculate the forces it experiences. According to Basler (2011), the camera has been tested to withstand vibrations of up to 500 Hz. The vibrations experienced by the system are far higher than this. It should be noted that damping will be provided by the Feinmess system and the aluminium interfacing parts.

16.3.3 Test Methodology ISO 9283

The testing can be thought of as having two sections. The first is drilling a number of holes and then measuring them with the fixed CMM. The second is milling a number of lines using two different tool bits. The purpose of this

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section is to determine the quality of the cuts and the potential for this type of milling using the fine positioning system.

Both the milling and drilling are to be performed on an an aluminium 6063 T6 material. This material was chosen specifically for the ease with which it is machined. In addition to this the piezo-ceramic elements previously mentioned are to be integrated into aluminium 7075, (Neugebauer *et al.*, 2010*a*). Saxer (2012) states that micro-machining of this form should be started off by using a short, relatively large tool on a relatively soft material such as tool board or aluminium.

In order to be able to compare the calculated maximum forces and vibrations with those measured, it is essential that both vibration and force information is captured for milling and drilling. The force torque sensor and the two accelerometers are to collect data for both the milling and the drilling operations in this regard.

Drilling

ISO 9283 is a set of international standards that deals with the functioning of industrial robots. This standard is particularly useful because it deals specifically with determining the accuracy and repeatability of a robotic system. The testing standard proposes a test cube with a number of points on its surface. The robot is instructed to move to different points on this surface. At each point positional information is measured. This information is then used to determine the accuracy and repeatability of the system, (ISO).

Test Path
The ISO standard recommends a test path with dimensions according to the work envelope of the measured system. An example of the test path can be seen below. The ISO standard states that if a system has six axes of motion the test path should be located at a 45 degree angle similar to the figure 16.8. Robots with fewer degrees of freedom can be tested using a test path that is parallel to the table surface or horizontal. The end goal of this methodology is its application to the three axis Feinmess system. In addition to this lubrication and jig complications arise when performing machining at 45 degree angles. It is thus appropriate to make use of the horizontal test path as seen in figure 16.8.

This testing methodology is to be applied to the Feinmess system at a later stage. For practicality and in order to ensure that the conditions of the test are similar to the Feinmess test, the test path was constructed around the maximum work envelope of the Feinmess system (45 mm in each direction).

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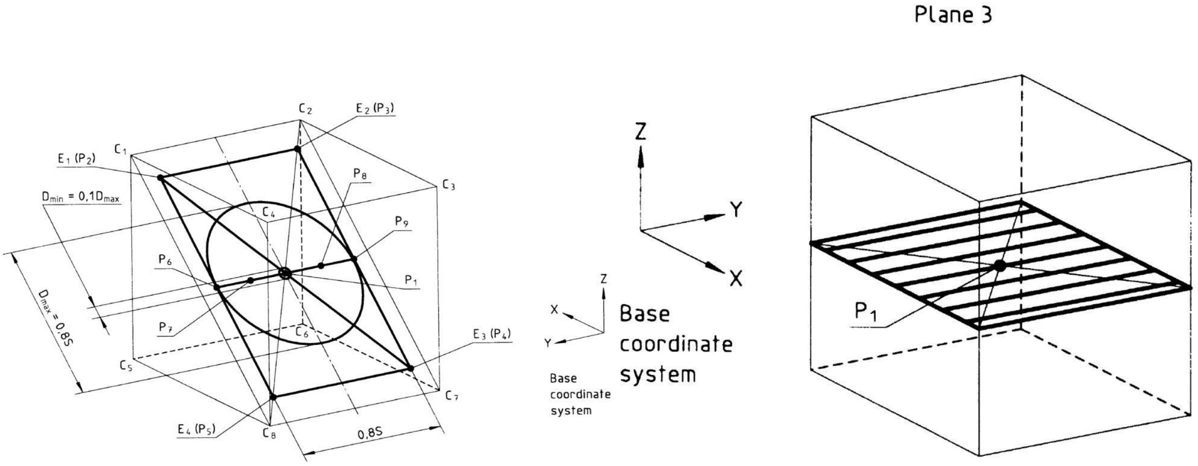

(a) Testing ISO Test Path

(b) Testing ISO Horizontal

Figure 16.8: The Standard 45 Degree ISO 9283 Test Path and the Horizontal ISO 9283 Test Path, (ISO)

The appearance of the testing points can be seen in figure 16.9.

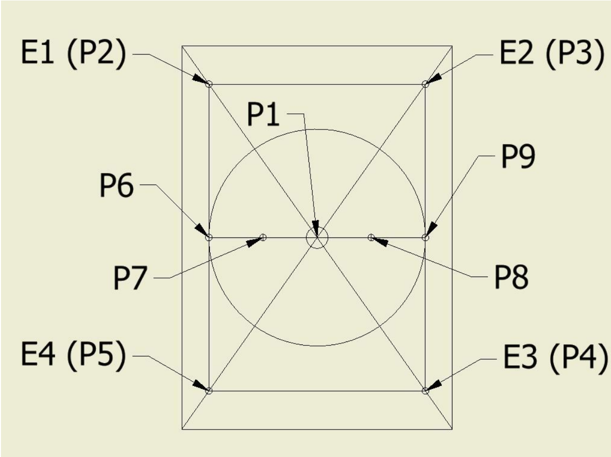

Figure 16.9: A Possible Layout for the ISO 9283 Test Path, (ISO)

The relevant distances between points (P) 1 to 5 were calculated according to the ISO standard and resulted in the following:

Cycles

In order to determine the accuracy and repeatability, it is necessary to perform 30 cycles. This involves moving the robot from points P5 to P1 through

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Table 16.1: Sequence of Actions in Pick-and-Place Task, (Sanchez, 2010)

Starting Node	End Node	Distance (mm)
P1	P2	30
P2	P3	36
P3	P4	48
P4	P5	36
P5	P6	24

points P4, P3 and P2 30 times. This is illustrated in the following figure 16.10.

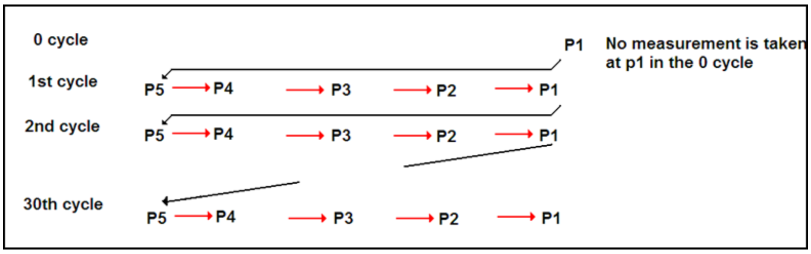

Figure 16.10: The 30 Test Cycle to be Executed, (ISO)

Drilling

The ISO methodology is to be applied to the Motoman SDA 10. However in this instance a micro-milling spindle is to be attached to the Motoman. The 1 mm tool bit is to be used at a speed of 24 000 rpm and a feed rate of 1 mm/s for both the drilling and the milling. It was decided to perform micro-machining with a 1 mm tool bit because of its robust nature when compared to smaller tools. The slow feed rate of 1 mm/s was chosen to preserve the tool bit used. In order to reduce the variability of the forces, the vibrations and the concentric error of the holes, a holes of standard 1 mm deep was drilled.

Using the above parameters a one 1 mm deep hole was drilled at each of the five points, P1 to P5. These five holes constitute a complete cycle or set. Due to the dimensions of the aluminium 6063 T6 four sets of holes were drilled on the surface of each plate. The plate was then turned over and another four sets of holes were drilled. In total 8 surfaces with drilled with 4 sets of 5 holes on each.

Testing Fixed CMM

Once the 160 holes had been drilled, it was then necessary to measure them using the CMM. The information from the CMM is used then to compare

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the instructions given to the systems, and what was actually achieved by the system. A Mitutoyo Bright 710 Apex CMM from RC Engineering was used in this regard. According to Mitutoyo (2012) this CMM has a resolution of 100 nm. A 500 μm probe tip was used in combination with this in order to be able to measure inside both 1 mm diameter holes and 1 mm wide milled slots.

The surface of the plates is not even. In order to ensure that the depths of the holes were measured relative to a standard and not the surface of the plates, the following procedure was executed. Thirteen points were measured on the plate surface. This was done such that a point was measured in the gap between each hole. The heights of these points were then averaged to give a uniform surface flatness. The depth of each hole was thus measured relative to the averaged surface of each plate. This greatly reduced the errors associated with local deformations on the plate itself.

In addition to this, the holes themselves were measured using a certain procedure. The CMM probe would enter the 1 mm hole at a specific distance and then measure ten points 36 degrees apart. These points were then averaged to give not only an averaged centre of the hole but also a concentricity. This averaged hole centre was used when measuring distances. This further reduced the error associated with the repeatability and accuracy measurements.

Testing Portable CMM

The manufacturer states a 100 μm repeatability, (RobotWorx, 2011). This figure is subject to a host of factors in a serial kinematic robot arm. In addition to this, the portable CMM is used to confirm the accuracy and repeatability findings of the Mitutoyo Bright 710 Apex CMM. In light of this, the portable Infinite Cimcore CMM model is used. A similar version of the portable CMM, the Infinite 2.0 from CimCore, has a repeatabiliy of 10 μ and an accuracy of 16 μm, (CimCore, 2012). An attachment was designed and manufactured such that it would securely fasten the metal probe tip of the Portable CMM, see Appendix F. This attachment was then fastened in exactly the same manner as the micro-milling spindle is attached to the force sensor. Both the attachment and the CMM arm can be seen in figure 16.11.

The same file used to create to the 1 mm holes is executed by the Motoman. However, in this instance, there is no micro-milling spindle or aluminium plate. The Motoman thus runs through the same set of motions that it did when micro-milling. Using the portable CMM a point cloud is to be measured. This allows the user to visualise and interpret the exact path followed by the Motoman. After large amounts of data filtering, the result is positional information similar to that given by the fixed CMM. This can be

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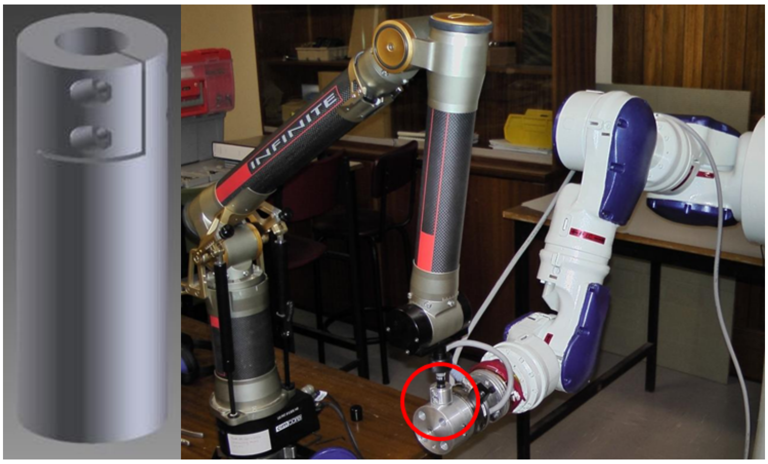

(a) Testing Portable CMM Attachment

(b) Testing Portable CMM

Figure 16.11: The Portable CMM Attached to the Motoman SDA 10, With Designed Attachment

used in a comparison of the repeat abilities and accuracies during both with and without machining.

It should be noted that the portable CMM could be used by itself in determining the accuracy and repeatability of the Motoman SDA 10. The aim of this project, however, is to examine the validity of a test methodology to be applied to a highly accurate coarse-to-fine positioning system. The portable CMM does not have the required resolution to measure the accuracy and repeatability of the coarse-to-fine positioning system (1 micron repeatability and a 3 micron accuracy).

16.3.4 Test Methodology Milling

The tests performed during the milling theme of this experiment are far more qualitative than those performed during the drilling test methodology. It is important to note that drilling is only being performed with this system in order to determine its validity as a testing methodology. Micro-milling, on the other hand, is being performed to fulfil a specific purpose, i.e. mill slots for the piezo-ceramics. In addition to this, micro-milling is being performed to determine the quality of the slots machined with a Motoman coarse positioning system as well as to determine the forces and vibrations experienced. The quality of the slots milled will help to determine whether the coarse-to-fine positioning system is needed to produce a high-quality slot or whether the

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coarse positioning system is ample.

Milling

The piezo-ceramic micro parts are 10 mm long. The cavities to be milled in this instance are thus also to be 10 mm long. A zigzag-type formation is employed for each of the two axes, with 10 lines being machined in each direction. For the X direction the first line is milled from left to right, the second lines is milled from right to left, third line is from left to right and so on. The milled slots are to be 4 mm apart as this will ensure the actual milling of one slot does not affect another in any way. For the Y direction the first line is milled from top to bottom, second line bottom to top, and the third line top to bottom. Again, the lines are to be 4 mm apart.

As a precautionary measure a pre-test is done by milling with the 1 mm tool and the 396 μm into soft tool board. If these tests, are successful, then the aforementioned process is to be executed with a 1 mm tool bit, with a feed rate of 1 mm/s, a depth of 1 mm and a speed of 24 000 rpm into the state aluminium. The process is then to be executed with a 396 μm tool bit into aluminium, with a feed rate of 0.5 mm/s, a depth of 0.3 mm a speed of 48 000 rpm. The result is 20 milled slots milled using the 1 mm tool and 20 milled slots milled with the 396 μm tool.

Testing Fixed CMM

The smallest CMM probe available is a 500 μm probe. Due to cost and time constraints a smaller probe could not easily be procured. Consequently, the 396 μm milled slots could not be measured. When testing the milled slots, 50 points were measured over 5 mm on both sides of the slot as well as over the bottom surface. The points for each face were used by the CMM to determine a best-fit line. In addition to this, the flatness of each of the faces can then be determined. In order to determine the width of each slot, one could simply compare the coordinates of the points along the averaged lines. Another method is to measure one point and then compare it to the averaged line.

Testing Optical Microscope

The optical micro can provide magnifications from 5 X to 100 X. In addition to providing clear images, the software can also be used to make measurements on the captured images. The information provided is highly qualitative and is open to interpretation. Despite this, when using deductive reasoning, it is possible to make assumptions about the nature and quality of the cut from

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images. This is particularly relevant when considering the slots milled by the 0.396 mm tool bit. These slots are too small to be analysed by the CMM. The only manner in which to get additional information is to examine them under a microscope.

Testing SEM

Another method in which the qualitative nature of the cut can be determined is by examining the various chips created. These chips are too small to be examined under an optical microscope. It is thus necessary to take a number of samples to the Scanning Electron Microscope (SEM) at the University of Stellenbosh. In a similar manner to the optical microscope, assumptions about the quality and the nature of the milling can be determined from these images. Again, this is another method of obtaining information about the small 396 μm mm milled slots.

16.4 Methodology Coarse-to-Fine System and Calibration Function

Having proved that the forces and vibrations are not significant enough to cause damage to the Feinmess fine positioning system, testing using the coarse-to-fine positioning system can begin. The nature of the testing is very similar to that conducted with the Motoman SDA 10. The testing is composed of two themes. The first is performing micro drilling for accuracy and repeatability testing. The second is performing micro-milling in order to achieve a better quality cut than that achieved with the Motoman. Another major difference to the previous coarse positioning testing is the inclusion of the calibration function. This inclusion helps to test the system as a whole.

16.4.1 Equipment

The equipment to be used in the coarse-to-fine positioning micro-machining testing is the Nakanishi EM 3060 micro-milling spindle. In addition to this the Feinmess MP 130 DC 50 3 axis Cartesian fine positioning system is to be attached to the Motoman SDA 10. The KC/S long distance microscope with IF 3.5 objective and Basler Ace 2500-gm GigE camera are to be attached to the fine positioning system in accordance with the system integration design.

The previous series of testing was conducted to determine the forces and vibrations associated with micro-machining. From the chapter Results and

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Discussion, it is clear that both the vibrations and forces measured were not significant enough to cause damage to the Feinmess fine positioning system. When considering the nature of the tests to be performed, there is no need to measure vibrations and forces. As such the 6 axis ATI force torque sensor and two Piezotronic accelerometers were not included. The assembled system can be seen in figure 16.12.

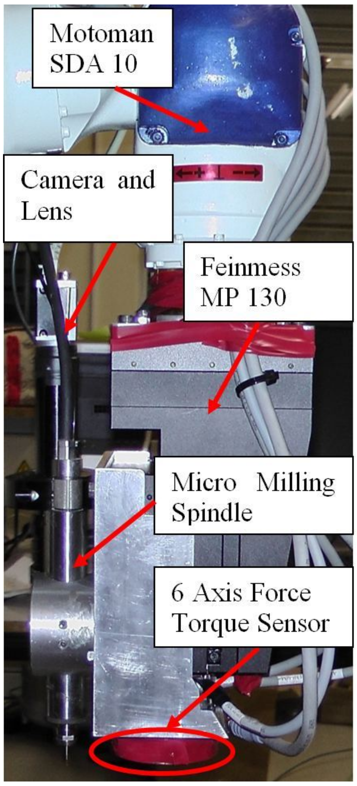

Figure 16.12: The Assembled Coarse-to-Fine Test Equipment Used

16.4.2 Testing with the Calibration System

In order to test the system as a whole is it necessary to test the functioning of the calibration system in the context of coarse-to-fine micro drilling. In light of this a single calibration mark is drilled into the plate per set of 5 holes to be drilled. The calibration symbol drilling is not done with the Motoman but with a highly accurate micro-machining CNC machine. Once this is complete, the drilling tests can be conducted using the coarse-to-fine system.

Initially, as previously explained, the Motoman coarsely aligns the fine positioning system (with camera and lens and spindle attached to it) with the

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calibration symbol. The brakes of the Motoman are then activated and the Feinmess or fine positioning system begins movement. The calibration function is then run. This function ensures that the fine positioning system (and attached camera and lens, and spindle) is exactly centred over of the calibration mark.

A 30 mm gauge block is then placed in between the force sensor and the plate to be drilled. The Feinmess system lowers the force sensor until the force sensor touches the block and a force is detected. The coordinate system of the Feinmess fine positioning system is then set to zero in all directions. The exact distance between the force sensor and micro-milling tool tip was determined as 22.704 mm by using the CMM. Once zeroed in contact with the gauge block, the distance from the micro-milling tool tip to the plate is 7.296 mm (30 mm minus 22.704 mm). The Feinmess system is then moved up by 1 mm and the gauge block is removed.

The fine positioning system then moves down the exact distance necessary to drill a hole 1 mm deep. The Feinmess is then retracted by 2 mm. It is then moved to the site of the second hole to be drilled. Once drilled, the system moves onto the next hole. In this manner all five holes of the first set are drilled. The Motoman then moves the Feinmess system to the next calibration symbol to be drilling the first hole of set two. The process is then repeated for all four sets of the plate.

Owing to the construction of the coarse-to-fine system, the camera and lens (for viewing the calibration symbol) have a specific distance from the micro-milling tool tip. The first hole drilled when the system is exactly aligned with the calibration mark, therefore, has a specific distance from the calibration symbol. (Due to complications with plate, CMM, and robot axes alignment, the calibration symbol is only used to ensure correct distance and not angle). The layout of the 4 sets of 5 holes and the calibration symbols (large circle is the diameter of the lens, within this large circle is the calibration symbol), can be seen in the figure 16.13.

As stated there is a fixed offset in the setup. This fixed offset is the physical distance between the micro-milling spindle tool tip and the centre of the camera and lens system. In order to determine if the calibration symbol is functioning when performing the micro drilling it is first necessary to determine the exact offset by using the CMM. It is also necessary to determine if the physical centre of the lens is in the exact position of the centre of the image captured by the GigE camera. If this is not the case, it means the calibration system is aligning the Feinmess system up with the centre of the image and not the centre of the lens. This makes determining the exact distance from the centre of the image to the centre of the micro-milling spindle, difficult.

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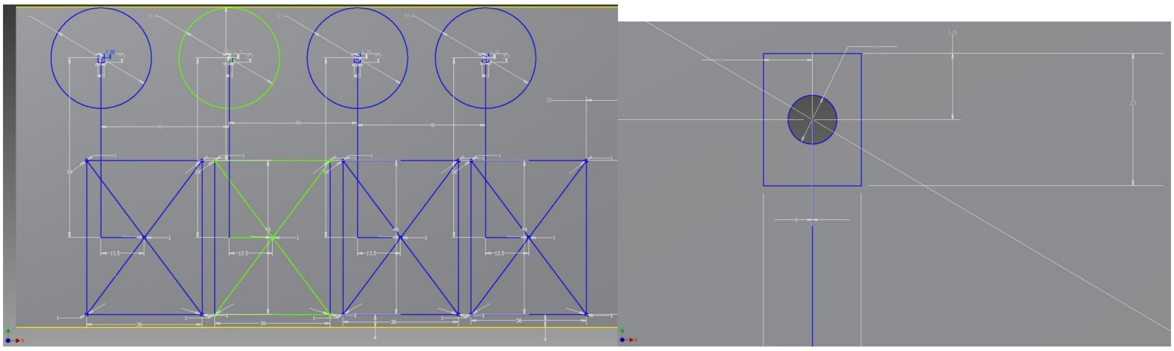

(a) Calibration Symbols

(b) Zoomed Calibration Symbols

Figure 16.13: The 4 Sets of 5 Holes and the 4 Calibration Symbols. The Single Calibration Holes are Within the Large Circles (The Large Circles Represent the Positioning of the Lens). In Addition to this a Zoomed View of a Calibration Hole is Included

16.4.3 Test Methodology ISO 9283

Drilling

As has been previously stated, once the fine positioning system has been centred over the calibration mark the first of the 5 holes is immediately drilled. The fine positioning system is then moved to drill the second hole as per the ISO 9283 testing layout. The 3rd, 4th and 5th holes are then drilled. This is then repeated for the four sets of holes on the eight different plates. The aim is to replicate the coarse positioning system drilling, however, with the inclusion of a calibration system. In light of this the spindle speed, feed rate, tool diameter and depth are all the same as those of the previous test.

Testing Fixed CMM

The holes drilled are then taken to the CMM machined. Using a 500 μm probe the exact position, and dimensions of all of the holes can be determined. This is done in a similar manner to the previous series of tests. This information is then collected and run through the ISO 9283 formulas in order to determine accuracy and repeatability.

In addition to the position and dimensions of the holes drilled by the coarse-to-fine system, the holes drilled by the CNC machine are also measured by the CMM. The exact distance between the calibration symbol and the first hole

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drilled can then be determined. This distance should be exactly the same as the offset between the camera and lens and the micro-milling spindle (for the sake of simplicity the centre of the image produced by the camera and lens system is presumed to be the same as the physical centre of the lens and camera system). This is owing to the fact that the calibration function ensured that the system was directly centred over the calibration mark before drilling began. The comparison between the achieved distance and the setup-offset distance can thus be used to determine the distance accuracy of the calibration function.

16.4.4 Test Methodology Milling

It is important to ensure that the lines milled with the coarse-to-fine positioning system are exactly in the same orientation and nature as those milled with just the coarse positioning system. This includes the feed rates, depth of cuts, spindle speeds and tool diameters. In this manner a meaningful comparison can be drawn about the quality difference in lines machined.

Milling

Ten lines are to be milled in both x and y directions for both the 1 mm tool and the 396 μm tool. The result is two plates each with 20 milled cavities or lines. As was previously the case, the lines will be milled in a zigzag pattern.

Testing Fixed CMM

The 1 mm lines are to be measured with the CMM. In this manner the exact dimensions and linearity errors of the lines can be determined. This will facilitate an accurate comparison to the lines which have been previously milled. The lines milled with the 396 μm tool bit are too small to be measured with the CMM.

Testing Optical Microscope

Both the 1 mm lines and the 396 μm lines are to be examined under the optical microscope. In this manner qualitative information about the nature of the cut can be visually determined. Due to time constraints, the chips were not examined under the SEM.

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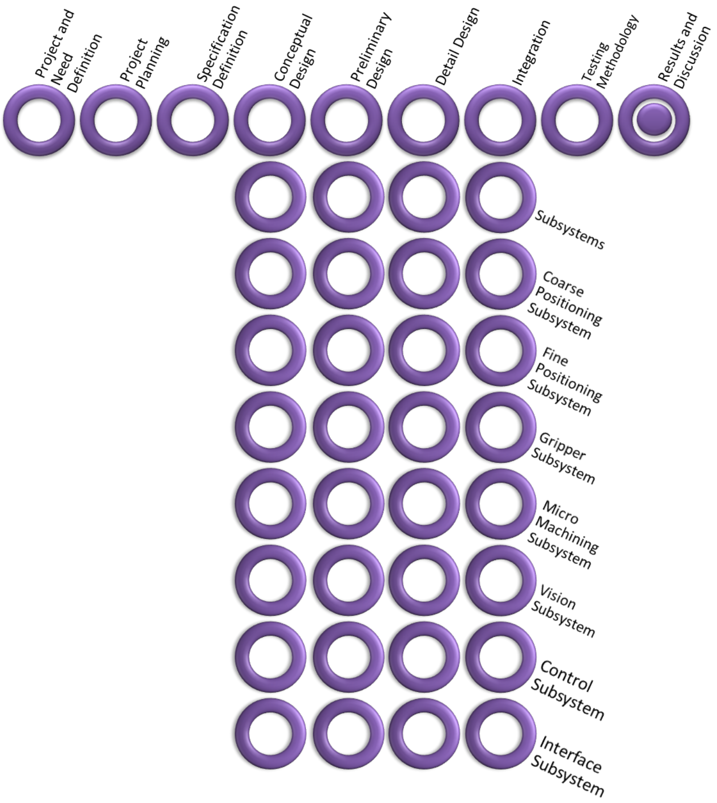
16.5 Chapter Conclusion

The methodology and justification for various test methods were clearly examined in this chapter. Testing methods were also explained in detail. Whether the system functions according to the specification definition is to be determined in the Results and Discussion chapter following.

Chapter 17

Results and Discussion



The purpose of this chapter is to document and discuss the results of the four different themes of testing. These themes are: Van der Waals gripper testing, calibration system testing, Motoman SDA 10 testing and, lastly, the testing of the combined system using machining.

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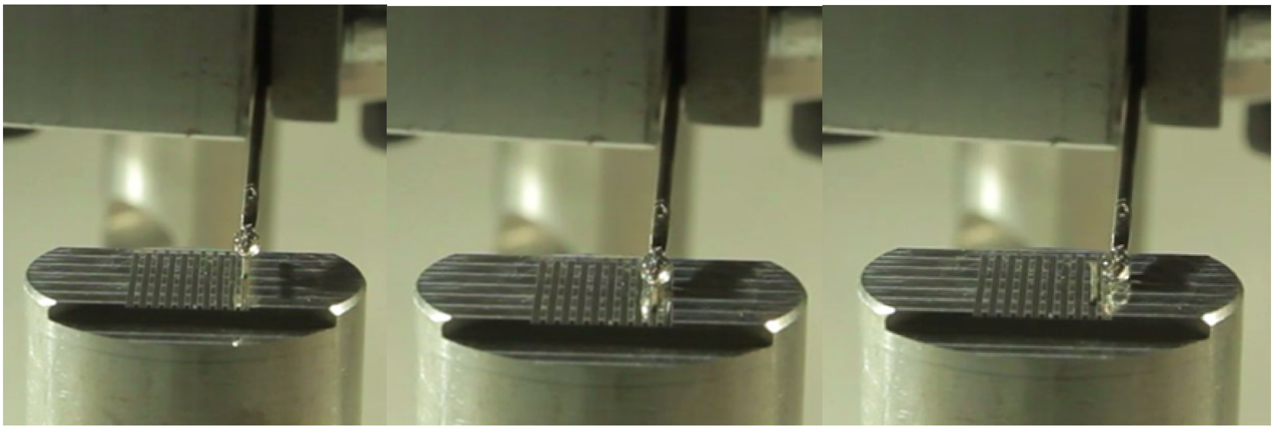
17.1 Results Van der Waals Gripper and Coarse-to-Fine Positioning System

As can be seen in figure 17.1 the coarse-to-fine positioning system and the Van der Waals gripper were combined to successfully pick and place the micro elements in an intuitive manner. Both the developed GUI and the more intuitive force teach technique were used to accurately pick and place the components.

The accuracy of the system was illustrated by the fact that gripped 264 μm by 250 μm by 10 mm piezo-ceramic micro parts were successfully inserted into the 300 μm by 300 μm by 10 mm micro-cavities. The polyurethane gripper was then slowly retracted (around 0.1 mm/s) until the pre-load was zero. By moving the coarse-to-fine positioning system away from the cavity in a horizontal fashion, the micro part was successfully detached from the gripper. A video of the picking and placing can be seen as per Arderne (2012).



(a) Gripping Process 1 (b) Gripping Process 2 (c) Gripping Process 3

Figure 17.1: Polyurethane Gripper and Coarse-to-Fine Positioning System Picking and Placing a Piezo Element

An advantage observed from this experiment is the fact that the spherical polyurethane gripper is small. It therefore provides an excellent frame of reference when compared to the piezo-ceramic micro part. This makes manipulating the gripped component with visual feedback far easier. Another interesting feature which was observed about this gripping process was the gripper's ability to remove a piezo-ceramic element once it ha already been placed in a cavity. This might be a necessary operation, especially when con-

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sidering the misplacement or misalignment of a micro part.

17.2 Results Calibration Function

After conducting 32 tests as per the method mentioned in the previous chapter, a conclusion can be made about the accuracy of the calibration system. The x and y pixel distance between the centre of the image and the centre of the calibration symbol, for both the calibration function and the visual inspection test, were compared. Thirty-two x and y pixel errors were calculated by subtracting the absolute x and y values of the two distances. The largest two errors of 18 and 39 μm were excluded to give 30 sets of x and y error data. The averaged error in the x direction was 2.67 μm and the averaged error in the y direction was 2.49 μm. This small error can be attributed to the fact that the centroid was determined visually.

Having thoroughly examined and understood the nature, mathematics and function of the calibration function, it can be deduced that it can potentially provide 100 percent accuracy. It is clear from having thoroughly examined the nature and method of the calibration function that its accuracy is limited by the μm/pixel as discussed in the Detail Design chapter. This is on the order of 1.1 μm. Presuming the lighting, calibration symbol and quality of the image were all ideal, a 1.1 μm accuracy could be achieved.

17.3 Results Motoman SDA 10

The testing of the Motoman SDA 10 serves as a precursor to the testing of the coarse-to-fine positioning system. The results detailed in this section should thus be considered in light of the methodology being applied to the assembled coarse-to-fine system. It is important to determine if the coarse positioning system can achieve the 5 μm repeatability and the 8 μm on its own when micro drilling. This would remove the need for the fine positioning system.

17.3.1 Test Results and Discussion: ISO 9283

A sample of plate 17 from the 8 plates drilled can be seen in figure 17.2. For the first set the holes are highlighted by a red ring. The direction of the test path is illustrated from hole 1 to hole 5 using arrows. In total, 20 holes are drilled per plate.

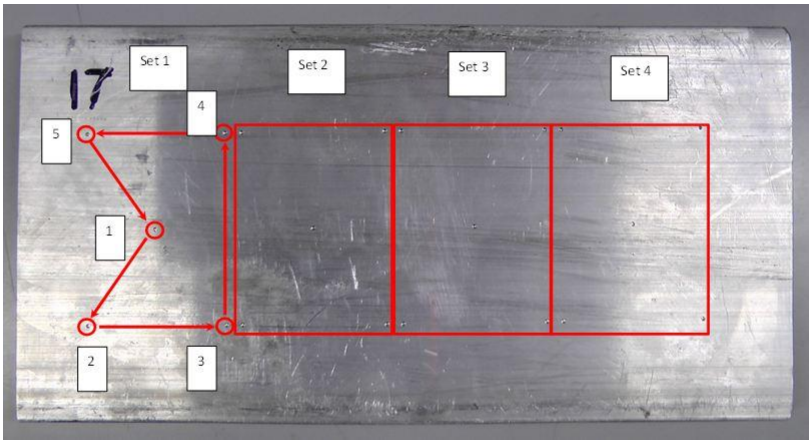
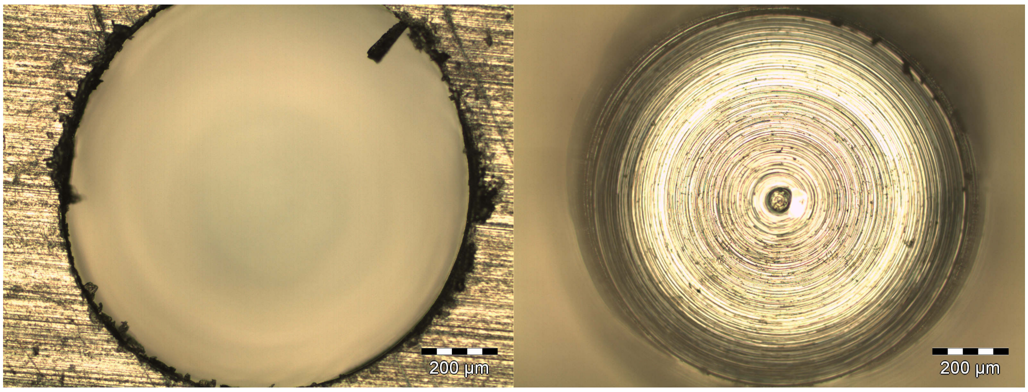


Figure 17.2: The 4 Sets or Cycles on Test Plate 17

Photos of hole 5 of set 19 on plate 17 were taken with the optical microscope on 10 X magnification. Despite a number of surface imperfections, it is clear from the photos that the holes drilled were of a good quality. The edges appear circular and the machining marks at the bottom of the drilled hole appear smooth and uniform, see figure 17.3.



(a) Surface of Drilled Hole (b) Bottom of Drilled Hole

Figure 17.3: Comparison of the Surface and Bottom of Hole 5 Set 19 on Plate 17

The forces for the 20 holes drilled can be seen in the figure 17.4. Each of the holes is clearly defined by a spike of the forces in the z axis. It is interesting to note that the forces in the x axis are around the zero mark, while forces in the y axis are roughly around the -0.25 N mark. Despite the relatively large

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spike in the z axis, the forces are well below that of the maximum 14 N.

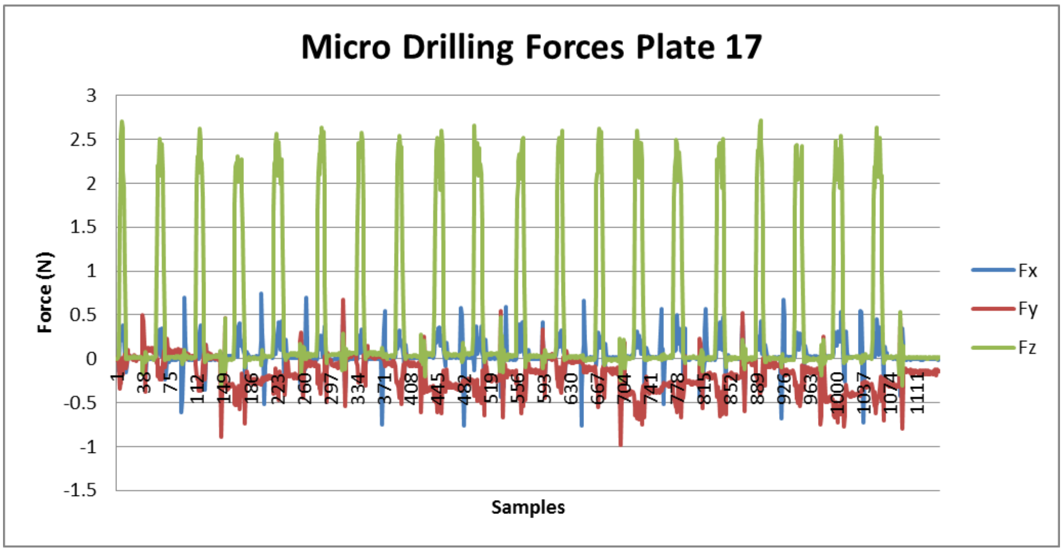

Figure 17.4: The Forces of Drilling 4 Cycles Plate 17

The peaks of the vibrations when examined in the frequency domain can be seen in figure 17.5. The first peak, as can be seen on the right of the image, is around 400 Hz. This is close to the 495.44 Hz natural frequency of the third stage. However, as can be seen from the graph, this vibration dips quickly on either side of its peak. This vibration is therefore not a concern. The next peak on the graph is around 2.5 kHz. This does not come close to the natural frequencies of any of the equipment.

ISO 9283 Fixed CMM

The fixed CMM, in accordance with the methods previously mentioned, provides x, y and z coordinates for each of the holes provided. In addition to positional information, information about the dimensions of each hole is provided. The average diameter of the all of the 160 holes drilled according to the CMM was 1.091 mm. This is a 91 micron deviation over the 1 mm instructed. The variation (concentricity) of all the holes was averaged at 0.041 mm. This information together with the positional information is outputted into an Excel file, but can also be viewed in a CAD format. The CAD file for plate 17 is seen in figure 17.6.

The sets of holes or cycles are 40 mm apart. By subtracting the 40 mm increment between each of the sets of holes, all of the holes from the same

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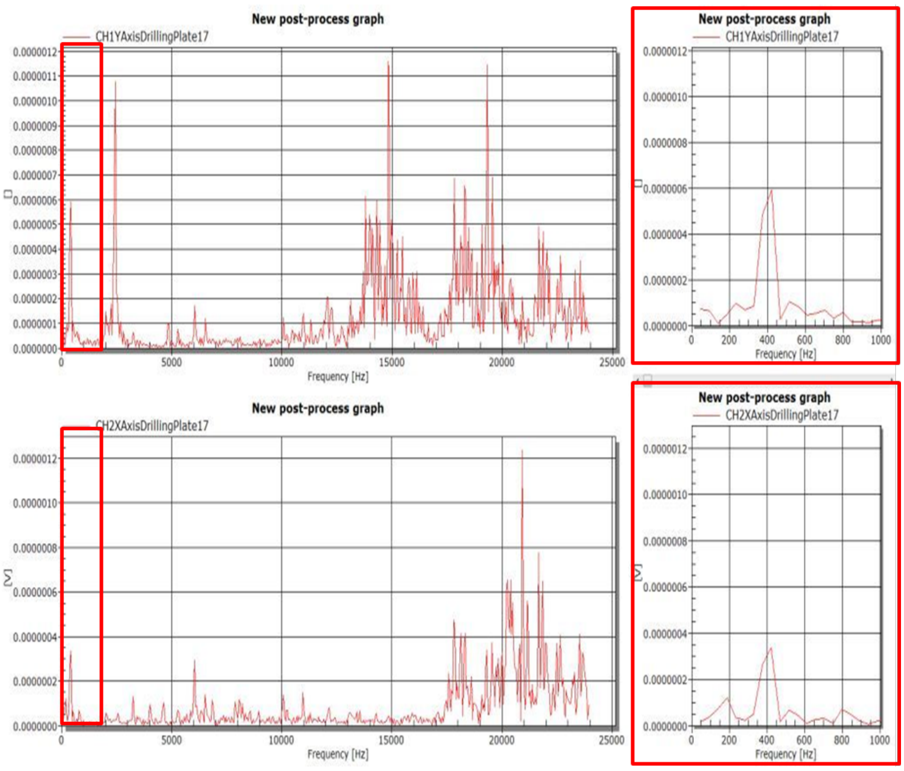

Figure 17.5: The Frequency Measured Whilst Drilling Plate 17; Information from the Accelerometer on the Y Axis and on the X Axis. The First 1000 Hz of Information is Zoomed On the Right of the Image

plate can be meaningfully compared. In addition to this, the first hole of each set was set to zero by subtracting the initial offset of the first hole of the plate. This then served as a reference. Having removed the error from the data and put it into a comparable format, the data for all of the 160 holes can be meaningfully compared on the same set of axes. The refined data was plotted in 3D space using Scilab. An interesting trend can be noticed. The holes in the negative y direction (holes 2 and 3) are generally higher up than holes 4 and 5.

After all 160 points of data had been combined each hole of the five holes (32 data points) was examined individually. The points in figure 17.7 appear to be clustered together, with the majority of the variance in the z-direction. This is mainly due to the scale of the axes and the small scale of the variations in the other axes. As an example, the data from hole 1 can be seen in the figure 17.8. This figure helps to better visualise the need for accuracy and repeatability calculations in each axis.

Accuracy

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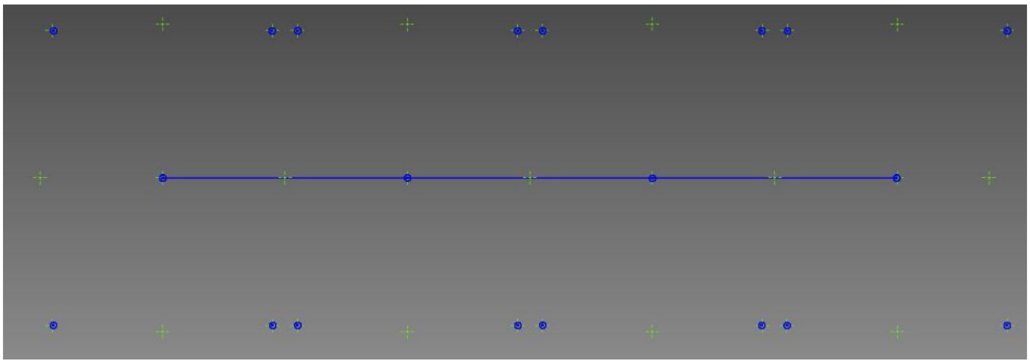
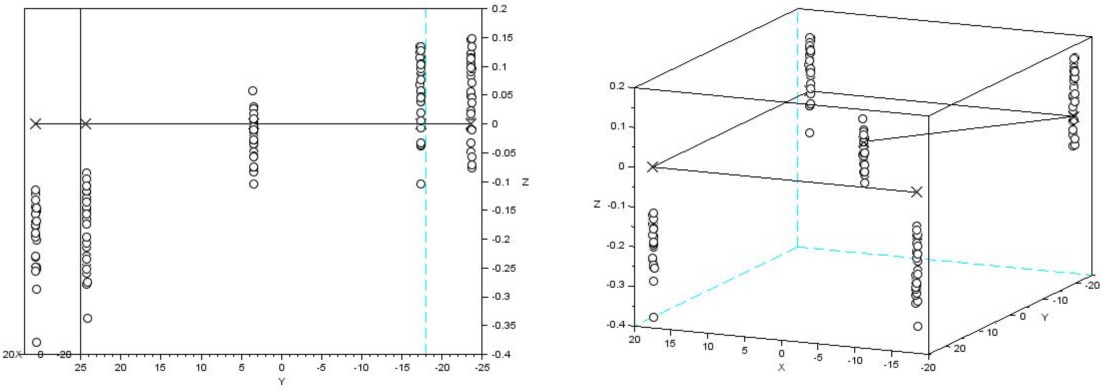


Figure 17.6: The CAD File Output of Holes Measured on Plate 17



(a) Fixed CMM Data 1

(b) Fixed CMM Data 2

Figure 17.7: Different Views of the Data from the Fixed CMM Machine. The Line in the Middle of the 3D-Plot Indicates the Commanded Location for Each of the Points

From this data the accuracy and repeatability could be obtained for each hole. Both accuracy and repeatability were calculated according to the formulas in the ISO 9283 testing standard. This deals predominantly with calculating the average of each holes and then from this determining variance and difference to command positions.

The accuracy according to the formulas in the ISO standard were calculated as per the bulleted list below. The averaged accuracy for the system was calculated as 0.136 mm.

- 0.206 mm for hole 1

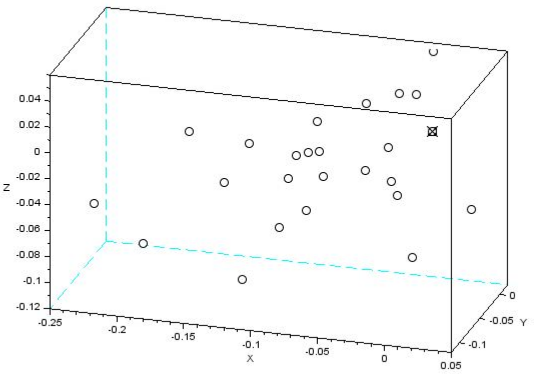


Figure 17.8: Hole 1 of All the Cycles Combined (32 Holes in Total)

- 0.229 mm for hole 2
- 0.103 mm for hole 3
- 0.074 mm for hole 4
- 0.065 mm for hole 5

$$AP_P = \sqrt{(\overline{x} - x_c)^2 + (y - y_c)^2 + (\overline{z} - z_c)^2} \tag{17.3.1}$$

$$\tag{17.3.2}$$

$$AP_x = (\overline{x} - x_c) \tag{17.3.3}$$

$$AP_y = (\overline{y} - y_c) \tag{17.3.4}$$

$$AP_z = (\overline{z} - z_c) \tag{17.3.5}$$

$$\tag{17.3.6}$$

$$\overline{x} = \frac{1}{n}\sum_{j=1}^{n} x_j \tag{17.3.7}$$

$$\overline{y} = \frac{1}{n}\sum_{j=1}^{n} y_j \tag{17.3.8}$$

$$\overline{z} = \frac{1}{n}\sum_{j=1}^{n} z_j \tag{17.3.9}$$

Repeatability

The repeatability of the various holes was calculated using the following formulas to be:

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- 0.233 mm for hole 1
- 0.192 mm for hole 2
- 0.215 mm for hole 3
- 0.223 mm for hole 4
- 0.192 mm for hole 5

The repeatability of the entire system, was calculated by averaging the l values and combining the Sl values. The result is an overall repeatability of 0.210 mm.

$$RP_l = \bar{l} + 3S_l \tag{17.3.10}$$

(17.3.11)

$$\bar{l} = \frac{1}{n}\sum_{j=1}^{n} l_j \tag{17.3.12}$$

(17.3.13)

$$l_j = \sqrt{(x_j - \overline{x})^2 + (y_j - \overline{y})^2 + (z_j - \overline{z})^2} \tag{17.3.14}$$

(17.3.15)

$$S_l = \sqrt{\frac{\sum\limits_{j=1}^{n} (l_j - \bar{l})^2}{n-1}} \tag{17.3.16}$$

ISO 9283 Portable CMM

As stated, the output from the portable CMM is a point. These can be seen in the figure 17.9 for plate 17. A difficultly arises when making meaningful interpretations of the data. This is due to the sheer volume of points given. An Excel sheet was thus created to find the minimum points recorded. After these minimum points were verified, the result was a set of data similar to that of the fixed CMM. The axes of the portable CMM also had to be adjusted such that they were in line with the configuration of the robots' axes. This involved simply inverting the direction of the x-axis. In a similar manner to the method used for the fixed CMM data, the 40 mm increment was subtracted and all the 160 points were collected onto a similar set of coordinates. A similar trend to that with the fixed CMM was noticed, whereby holes 2 and 3 appeared to be higher than holes 4 and 5. It is thus meaningful to conclude that this is a result of the Motoman's motion.

After the data had been compared on a similar set of axes, it could then be analysed one hole at a time. Again the amount of variance of the first hole

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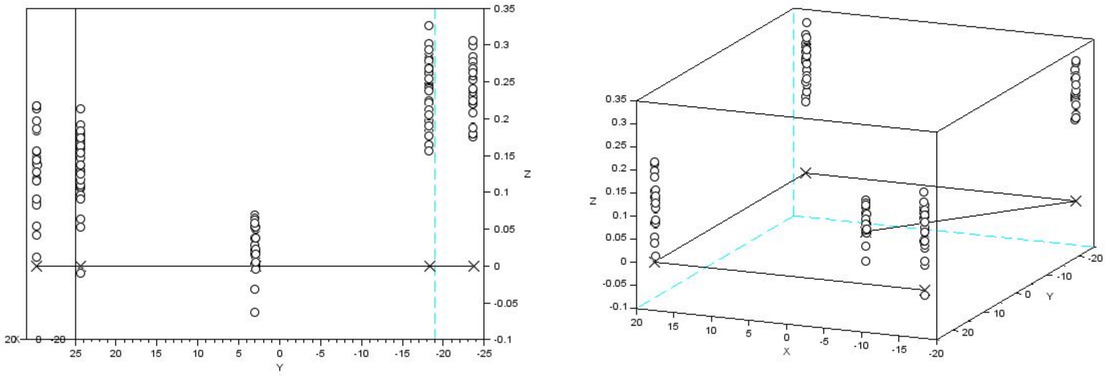

(a) Portable CMM Data 1 (b) Portable CMM Data 2

Figure 17.9: Different Views of the Data from the Portable CMM Machine. The Line in the Middle of the 3D Plot Indicates the Commanded Location for Each of the Points

can be seen in the figure 17.10. The variance for the 32 points associated with hole 1 is completely different to that observed for hole 1 with the fixed CMM. Using this data for each hole and the formulas for accuracy and repeatability as previously mentioned, the accuracy and repeatability for the Motoman SDA 10 using the portable CMM could be determined.

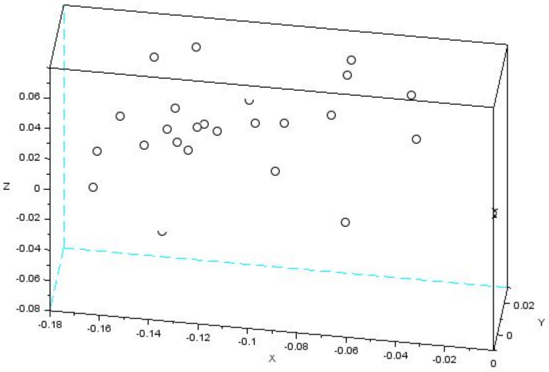

Figure 17.10: Hole 1 of All the Cycles Combined (32 Holes in Total) as Measured by the Portable CMM

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Accuracy

The accuracies of the various holes were calculated as follows:

- hole 1 was calculated as 0.143 mm
- hole 2 was calculated as 0.152 mm
- hole 3 was calculated as 0.279 mm
- hole 4 was calculated as 0.252 mm
- hole 5 was calculated as 0.085 mm

Both the fixed CMM and the portable CMM show that the accuracy of the robot tends to increase towards holes 4 and 5. The average accuracy of the system according to the portable CMM was calculated at 0.182 mm. This is a decrease when compared to the 0.136 mm accuracy of the Motman when performing drilling. This translates into a 50 μm increase in accuracy when micro drilling.

Repeatability

The repeatability for the various holes calculated according to the ISO formulas are as follows:

- hole 1 was calculated as 0.160 mm
- hole 2 was calculated as 0.147 mm
- hole 3 was calculated as 0.117 mm
- hole 4 was calculated as 0.136 mm
- hole 5 was calculated as 0.128 mm

When combined, the overall system repeatability according to the portable CMM was 0.138 mm. This gives a 72 μm decrease in repeatability when performing micro drilling. It should be noted as per CimCore (2012) that the portable CMM has a repeatability variance of 10 μm, and an accuracy variance of 16 μm.

An 80 μm deviation in both accuracy and repeatability is expected when considered in light of the relatively coarse nature of the Motoman SDA 10. This result is further strengthened by the fact that micro drilling was used as a test methodology. It is clear from this data that the 5 μm repeatability and 8 μm accuracy is not achieved. However, the objective of this testing was to determine the feasibility of this form of testing. Repeatability and accuracy were measured despite some degradation. This degradation will not be present

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with the coarse-to-fine positioning system as the brakes of the coarse positioning will be engaged and only the fine positioning system will move.

17.3.2 Test Results and Discussion: Milling

The two plates milled with 20 lines each can be seen in the figures 17.11 and 17.12. The order and the direction that the difference slots were milled in can be seen next to the highlighted slots. The plates also have the tool size, feed rate, and depth written on them as a reference. The forces, vibrations and optical microscope images will be examined for 4 slots in total, 2 for the 1 mm tool and 2 for the 0.396 μm tool.

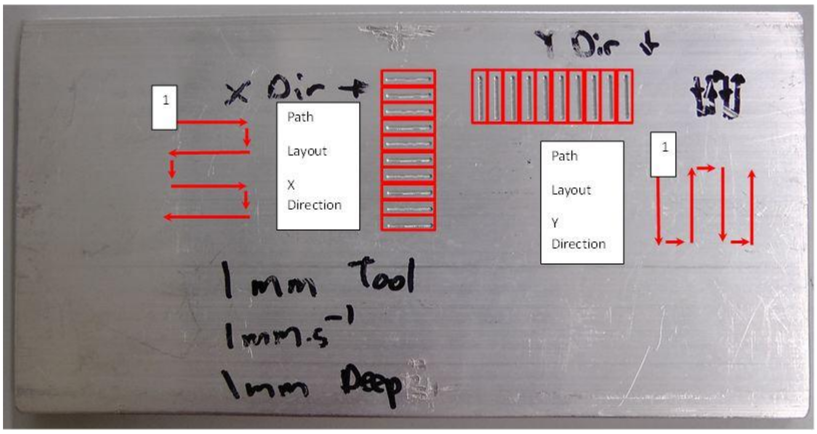

Figure 17.11: Plate Milled by 1 mm Tool

Fixed CMM

The 396 μm slots were too small to be measured with the 500 μm probe tip. As a result, is necessary to measure them using the optical microscope. Using the CMM for the 1 mm slots, the average width of the 10 slots in the x-direction was 1.003 mm. The average depth of the ten slots was 1.063 mm. In the y-direction the average width for the ten slots was 1.032 mm while the average depth was 1.174 mm. The CAD images can be seen in figure 17.13.

Optical Microscope

1 mm Lines (20 X Magnification) X Direction Line 5
What can be seen from the images 17.14 is that there is some level of external

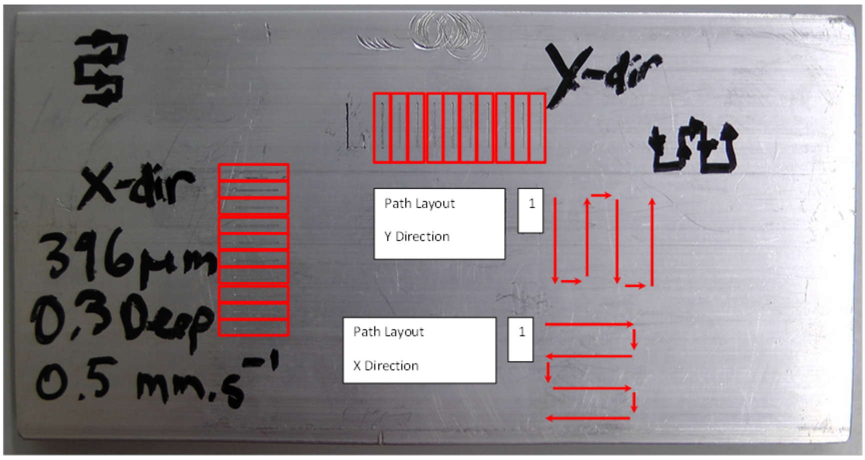

Figure 17.12: Plate Milled by 396 μm Tool

vibration influencing the cut. In this particular line, this vibration seems to have reached predictable equilibrium. The edge of the cut appears relatively smooth, see figure 17.14.

As expected, the forces measured when milling with a 1 mm tool in the x- and y-axes are larger than those measured when drilling, see figure 17.15. Despite this the z-axes forces are still the largest. Again there is a clear distinction between the 10 slots milled. For the first slot, the x force is negative as expected, while the force in the y-direction is positive. The large magnitude of the force in the y-direction is due to the nature of the tool contact with the material. As was previously discussed when executing up-milling or down-milling in the x-direction, a force in the y-direction always results. What is clear from the graph is that all of the forces are well below the 14 N mark. There is thus no risk of damage.

The vibrations measured for line 5 in the x-direction appear to be relatively uniform across the length of the cut, as seen in the figure 17.16. This corresponds to the repeating nature of line 5 as seen in the optical microscope photo. When considered in the frequency domain, there is again a spike around the 400 Hz mark (half of the calculated tooth passing frequency). However, there are no other spikes that could result in resonance.

1 mm Lines (20 X Magnification) Y-Direction Line 2
When examining line 2 as milled in the y-direction, there is again the noticeable vibration pattern. In this instance however, it appears that it has not reached any sort of equilibrium. Again, the sides of the slot seem relatively straight, see figure 17.17.

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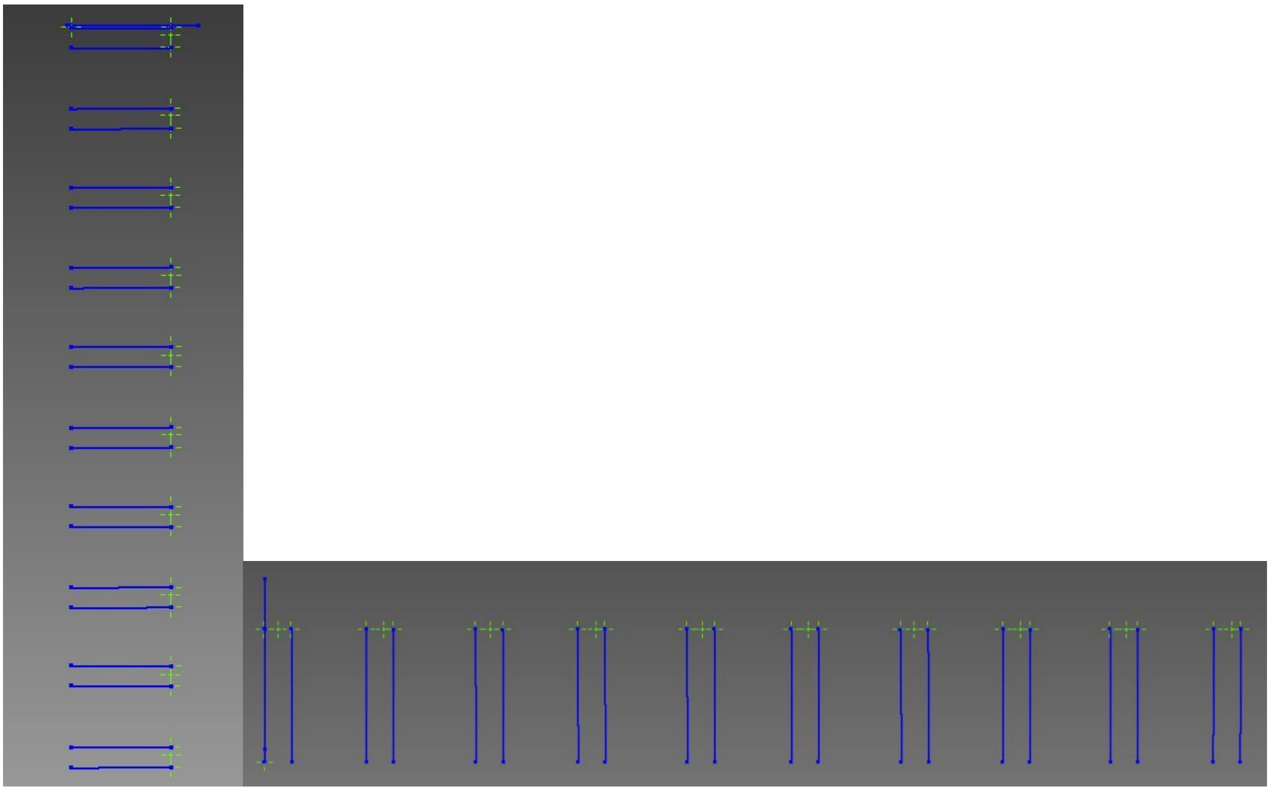

(a) Milled CAD X

(b) Milled CAD Y

Figure 17.13: The CAD Data of the 20 Slots Milled with a 1 mm Tool

The peak of the force in the z-axis is reduced by around a Newton when milling in the y-direction. For the first slot milled the force in the y-axis is positive as expected. This is due to the fact that the robot is moving in the negative y-direction. As previously mentioned, the large force in the x-axis when milling in the y-direction is due to the perpendicular forces associated with up-milling an down-milling, see figure 17.18.

When compared with the vibrations of line 5 in the x-direction, the vibrations of line 2 in the y-direction appear slight less uniform. This is reflected by the slightly less uniform nature of the line 2 figures 17.19. When considered in the frequency domain, there are almost no spikes to mention, except around 12.5 kHz. There are thus no spikes that could result in resonance.

396 μm (20X Magnification) X-Direction Line 1
The slots milled with the smaller 396 μm tool tip are obviously far smaller than those milled with the 1 mm tool. The vibration patterns noticeable in the 1 mm x-direction slot are again noticeable in figure 17.20. The vibrations in this instance appear to be relatively regular.

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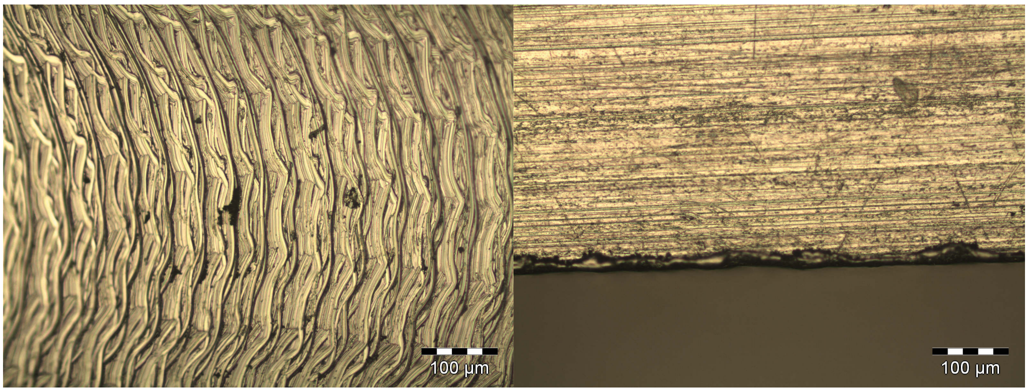

(a) Milled 1mm X 01 (b) Milled 1mm X 02

Figure 17.14: Line 5 Milled in the X-Direction Using a 1 mm Tool, Milled from Left to Right

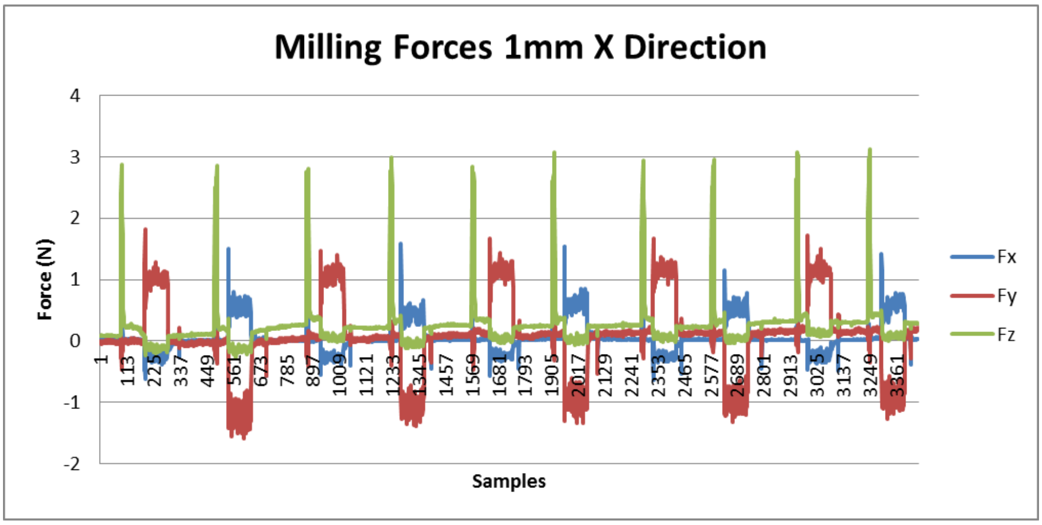

Figure 17.15: The Forces of Milling 10 Lines in the X-Direction Using a 1 mm Tool

The forces of the 396 μmm tool bit are remarkably lower than the forces measured when milling with the 1 mm tool bit. The reduction in forces is due to the smaller tool tip and contact area, as well as to the reduced feed rate and depth, see figure 17.21. The chances of the system exceeding the 14 N mark and damaging the Feinmess system are negligible.

The vibrations when milling in the x-direction with a 396 μm tool appear relatively uniform, see figure 17.22. This seems to iterate the smooth nature

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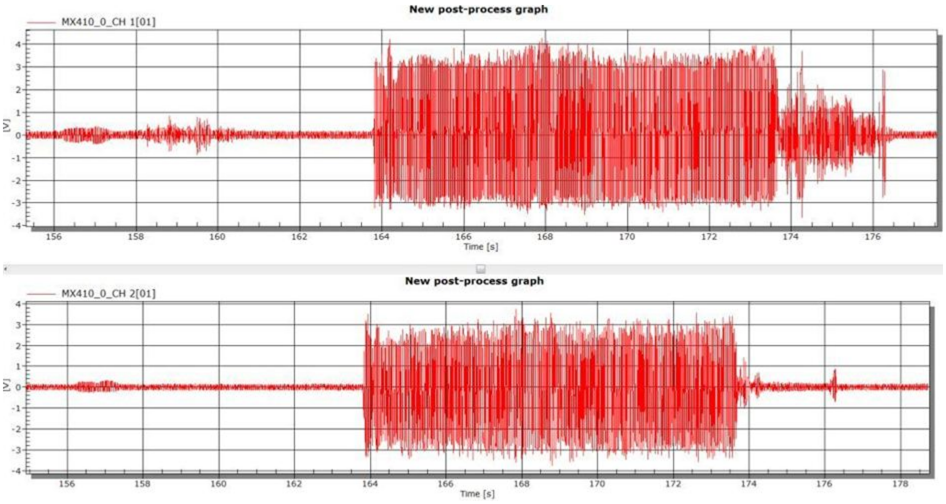
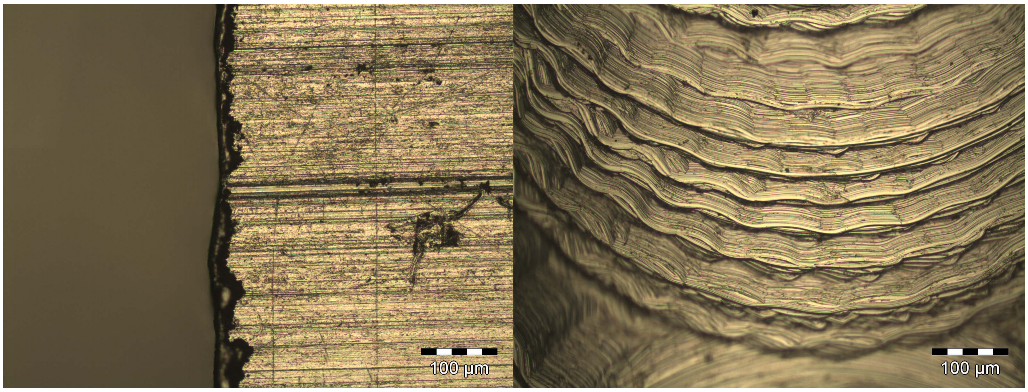


Figure 17.16: The Frequency Measured Whilst Milling Line 5 in the X-Direction using a 1 mm Tool from Left to Right. Information from the Accelerometer on the Y-Axis and on the X-Axis



(a) Milled 1mm Y 01

(b) Milled 1mm Y 02

Figure 17.17: Line 2 Milled in the Y-Direction Using a 1 mm Tool, Milled from Bottom to Top

of the milled slot in the x-direction as can be seen in the optical microscope photo. When considered in the frequency domain, there is again a spike around the 800 Hz mark (half of the calculated tooth passing frequency). This could affect the 742.06 Hz of the second stage. However, apart from this, there are no other spikes that could result in resonance.

396 μm (20X Magnification) Y-Direction Line 1
The quality of the cut in the y-direction when using a 396 μm tool bit appear

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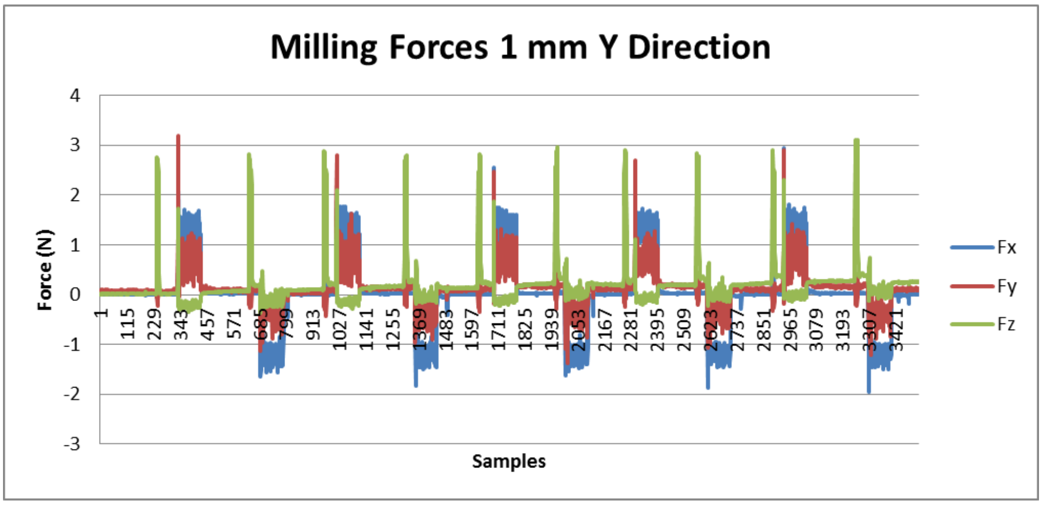

Figure 17.18: The Forces of Milling 10 Lines in the Y-Direction Using a 1 mm Tool

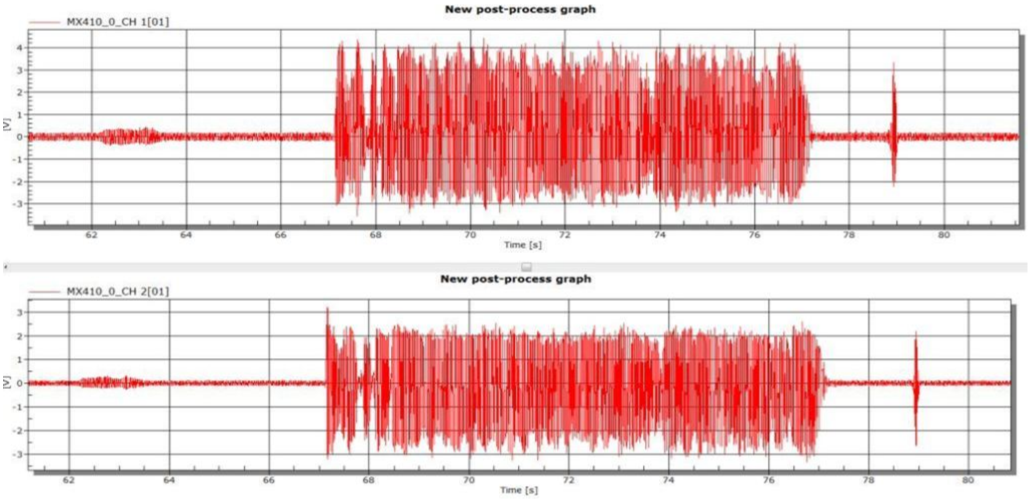

Figure 17.19: The Frequency Measured Whilst Milling Line 2 in the Y-Direction using a 1 mm Tool from Bottom to Top. Information from the Accelerometer on the Y-Axis and on the X-Axis

far less uniform than those when milling in the x-direction. The slots milled appear almost erratic and disfigured, see figure 17.23. In addition to this, the various marks appear to be at varying depths. The sides of the slot appear also to be jagged to a degree.

As mentioned, the milling forces for the 396 μm tool bit are less than those for the 1 mm tool bit. Despite this there is a large amount of variance in the

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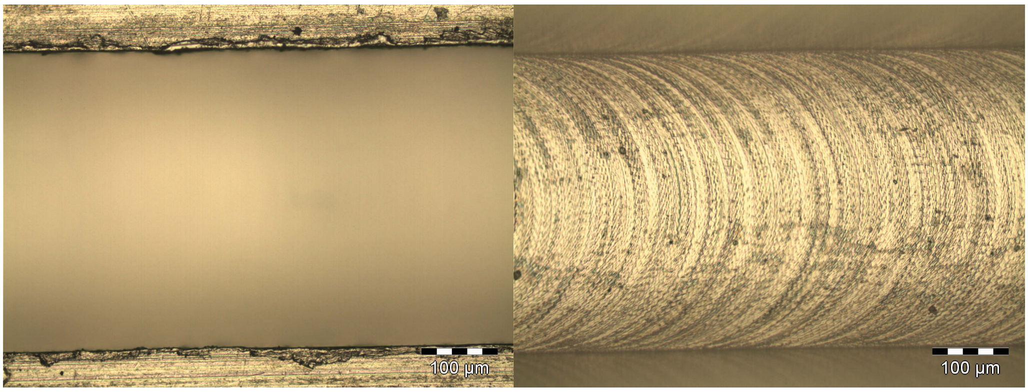

(a) Milled 396mm X 01 (b) Milled 396mm X 02

Figure 17.20: Line 1 Milled in the X-Direction Using a 396 μm Tool, Milled from Left to Right

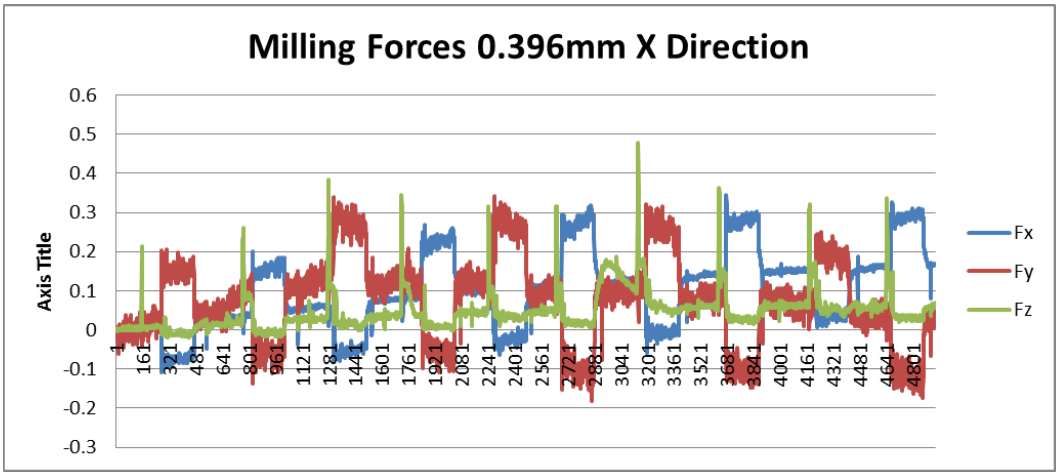

Figure 17.21: The Forces of Milling 10 Lines in the X Direction Using a 396 μm Tool

forces when comparing milling in the x direction with milling in the y direction. The initial spike in forces for the y direction, can be attributed to the jerk experienced when the Motoman's servo's are engaged, see figure 17.24. Even with the spike included the forces did not increase past the 14 N mark. Again no damage would result had the micro-milling spindle been milling with the fine positioning system.

The vibrations measured when performing milling with the 396 μm tool bit in the y-direction appear far less uniform than those of the 396 μm milling in the x-direction, as can be seen in figure 17.25. The almost jagged appearance

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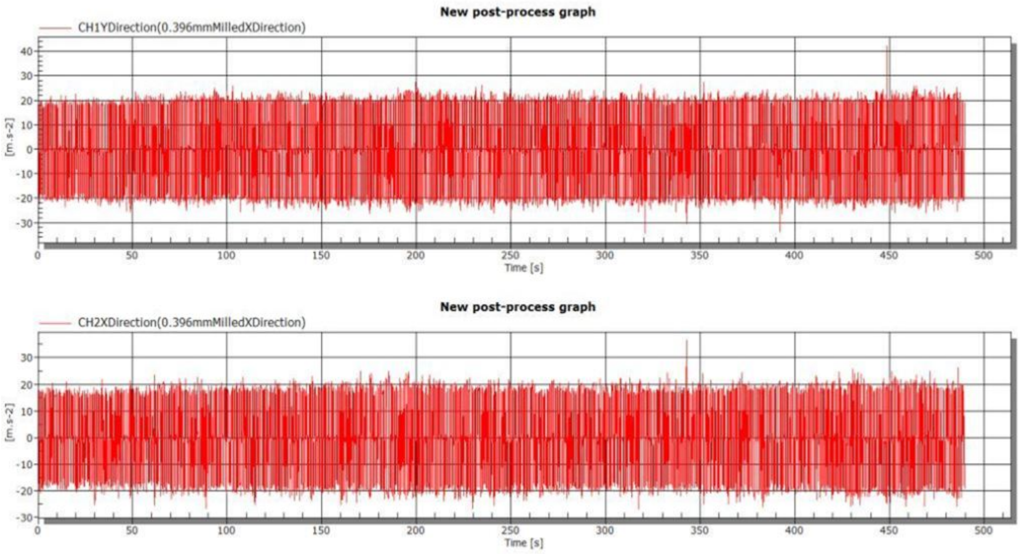
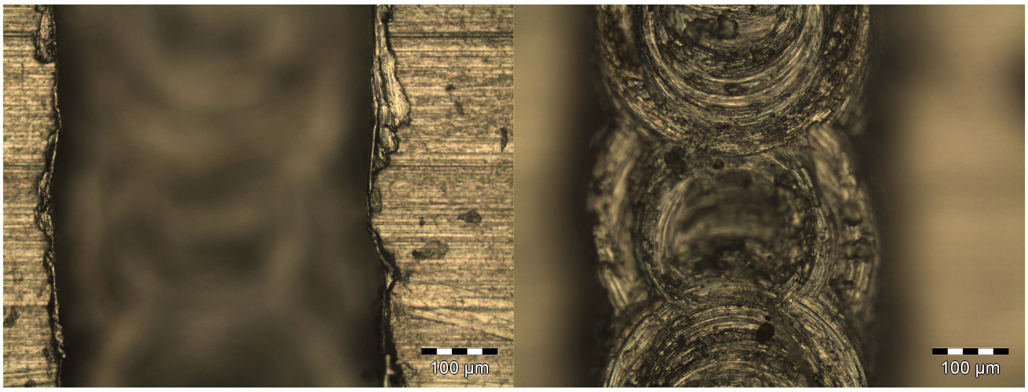


Figure 17.22: The Frequency Measured Whilst Milling in the X Direction using a 396 μm Tool. Information from the Accelerometer on the Y Axis and on the X Axis



(a) Milled 396mm Y 01

(b) Milled 396mm Y 02

Figure 17.23: Line 1 Milled in the Y Direction Using a 396 μm Tool, Milled from Top to Bottom

is clearly reflected in the optical microscope image of the slots as milled in the y-direction. When considered in the frequency domain, there is again a spike around the 800 Hz mark (half of the calculated tooth passing frequency). As stated this, may have a slight influence on the second stage. There are, however, no other spikes to consider.

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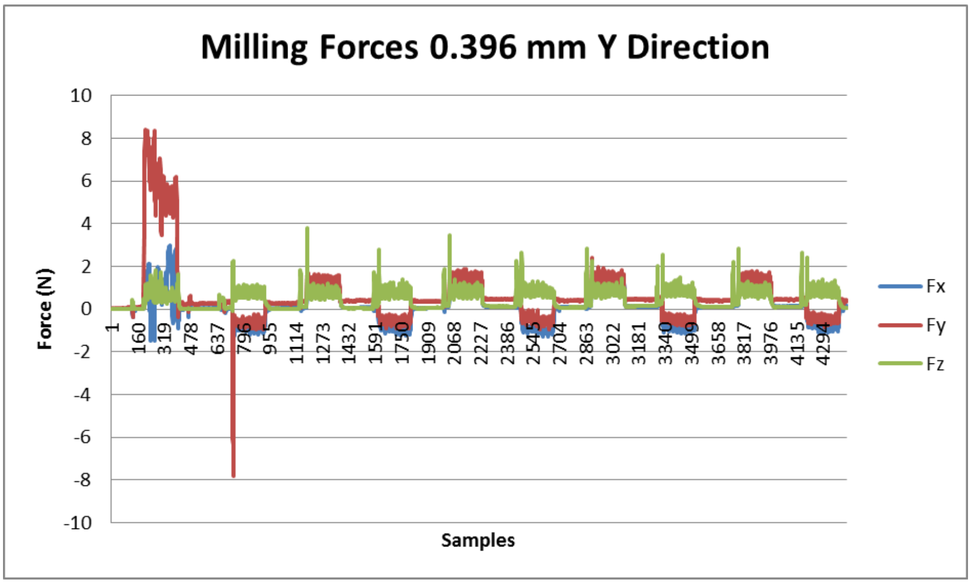

Figure 17.24: The Forces of Milling 10 Lines in the Y Direction Using a 396 μm Tool

Obscure milling pattern (50X magnification) Y-Direction Line 1
What can be observed in figure 17.26 is the changing of the milling pattern. One possibility for this is that the angle at which the micro-milling spindle was cutting was changed. This slight change in angle would cause the bulk of the milling to be shifted, for example, from the front of the tool tip to the back. As can be seen in the red circle, one pattern exists when the spindle could be thought of as being directly above the cutting surface. This angle then changes as the milling process continued.

Chips SEM

An interesting observation on both the chips formed from both the 1 mm milling and the 396 μm milling is that of a series of ridges on one side of the chip. One possibility is that this waviness is due to the chip deformation as it curls away from the cutting surface.

As can be seen in figure 17.27 of the chips obtained from the 1 mm milling, there are large chips and then a number of fragments. These fragments are a positive sign as they indicate the breaking up of the chip. This is important as large chip fragments can get stuck in the milled slot and interfere with the milling process.

What is clear from the above is that the slots were accurately milled. How-

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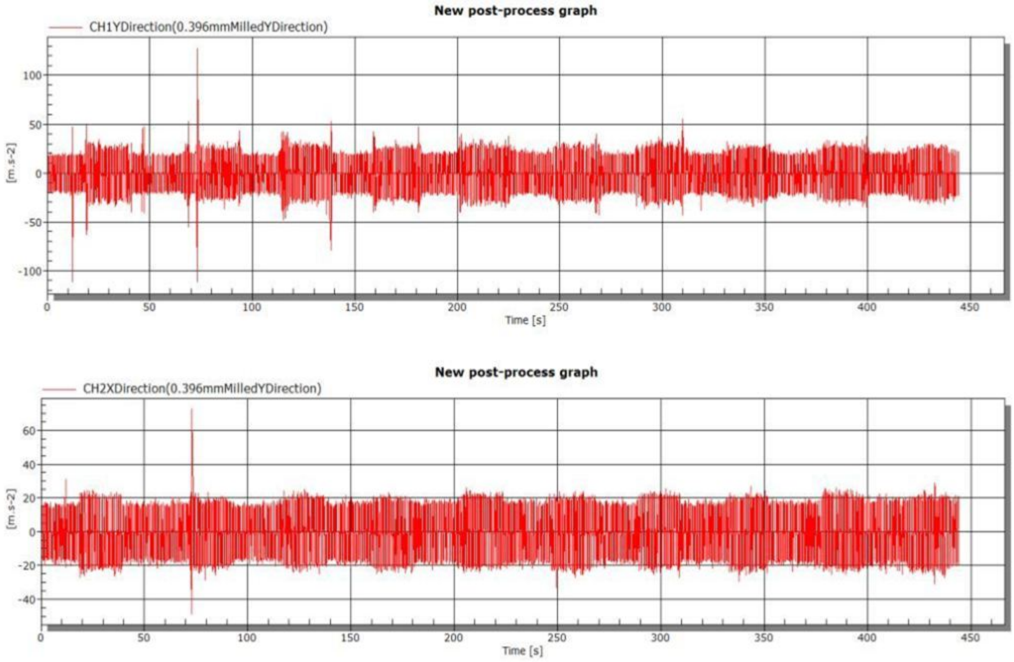


Figure 17.25: The Frequency Measured Whilst Milling in the Y Direction using a 396 μm Tool. Information from the Accelerometer on the Y Axis and on the Y Axis

ever in a similar nature to the drilling methodology, there were obvious forms of deviation. This is particularly the case in the y-direction for the 396 μm tool bit as previously explained. The accurate milling of a 300 μm slot is thus not accurately achievable when using the Motoman SDA 10. There is thus a need for a more accurate coarse-to-fine micro-machining system.

17.4 Results Coarse-to-Fine System and Calibration Function

No vibration or force measurements were taken during this aspect of the testing. This is due to the fact that it has already clearly been shown that the forces and vibrations from the micro-milling and drilling are not significant to cause damage to the Feinmess system, or other components. It is important to determine whether the system as a whole achieved the necessary 5 μm repeatability and 8 μm accuracy. It is also important to determine the quality of the milled slots and then compare this to the previous section of testing.

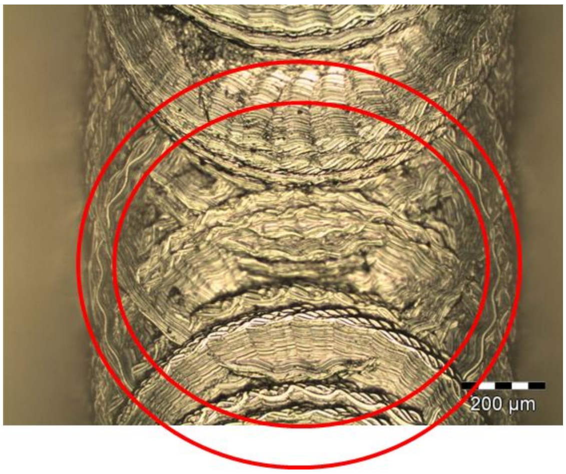
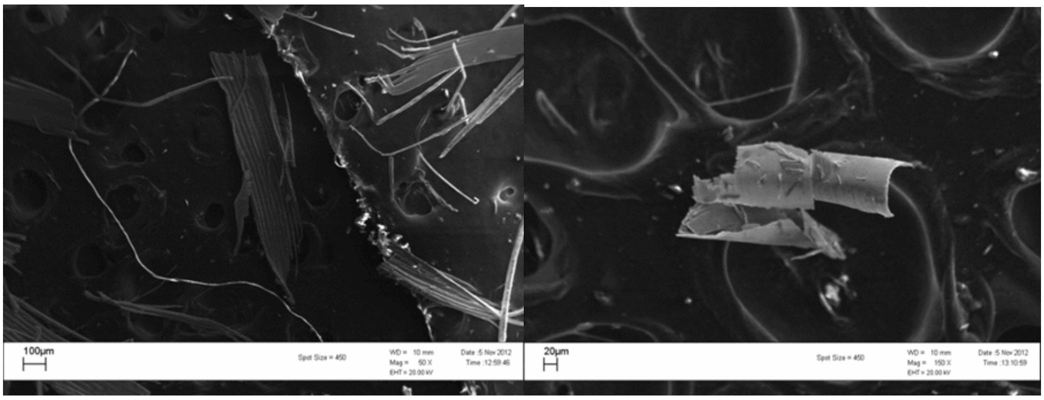


Figure 17.26: Obscure Milling Pattern Line 1 in the Y Direction Viewed at 50 X Magnification



(a) SEM Chip 1mm X

(b) SEM Chip 396mm X

Figure 17.27: Chips Taken from the 1 mm Slots Milled in the X Direction and the 396 μm Slots Milled in the Y Direction

17.4.1 Calibration System

As previously stated, the exact distance between the centre of the image and the centre of the micro-milling tool needs to be determined. To this end the CMM measured a number of points around the lens and around the micro-milling tool, the original and the resultant image can be seen in figure 17.28. In addition to this, it is necessary to determine if the centre of the lens corresponds to the centre of the image captured by the camera.

Measurements taken from both the CAD model and the CMM printout

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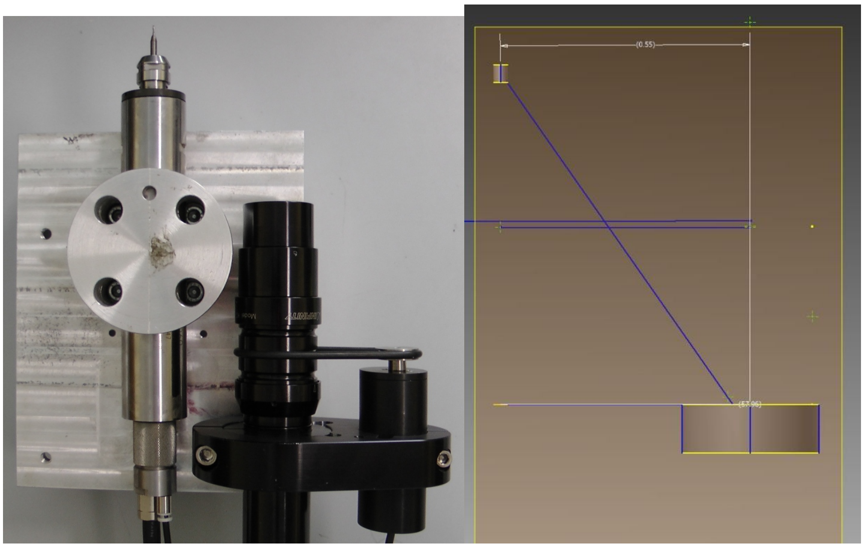

(a) Spindle and Lens (b) Spindle and Lens CMM

Figure 17.28: Actual Image of Lens and Milling Tool and CMM Rendering of Lens (Large Circle) and Milling Tool (Small Circle)

show that there is a 0.55 degree angle misalignment between the centreline of the lens and the centreline of the milling tool. Ideally this angle should be 0 degrees. The angle misalignment results in a deviation of 810 μm when considered at 85 mm (focal distance of the lens).

Having determined the positioning and angle of the lens, the base coordinate system was adjusted to match that of the lens. This allowed the CMM probe tip to be moved 85 mm at a precise perpendicular angle to the surface of the lens. At 85 mm an image was captured with the GigE camera. As can be seen in the figure 17.29, the tip of the probe is not in the centre of the image. This means the camera and lens are not exactly aligned.

By applying the calibration function to the inverted images, it was determined that the centre of the probe (physical centre of the lens) was offset from the centre of the image by -895.5 pixels in the x-direction, and 895.6 pixels in the y-direction. This means the measured distance between the centre of the lens and the centre of the tool should be increase by 895.5 pixels in the x-direction and 895.6 pixels in the y direction. The unit in μm is obtained with the μm per pixel figure as explained in the Control Subsystem chapter.

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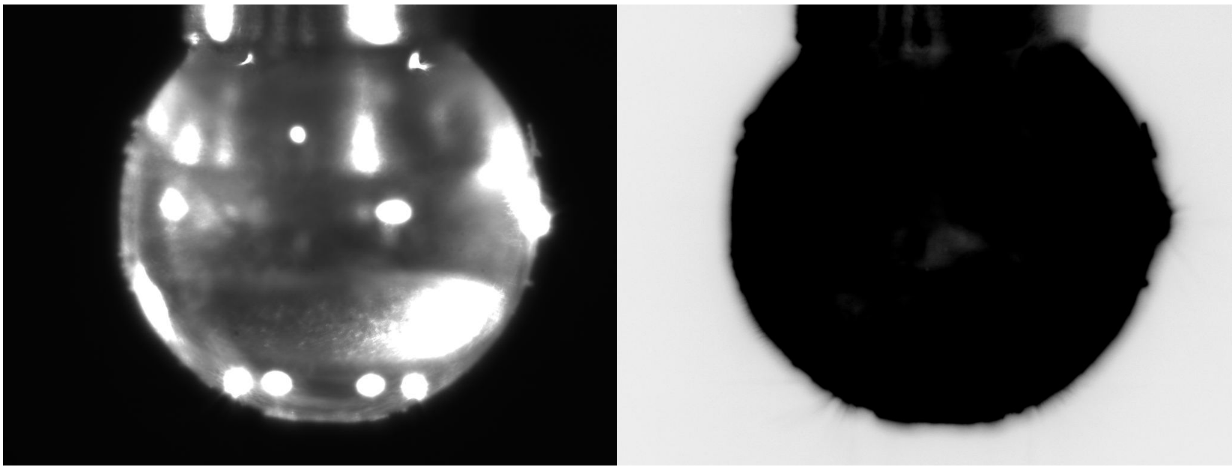

(a) Probe Normal (b) Probe Inverted

Figure 17.29: Image of Probe Taken with GigE Camera and Lens, Image of Probe Inverted

17.4.2 Test Results and Discussion: ISO 9283

What became clear after only drilling one plate of holes, is that the method of zeroing the z-axis was a failure. This was seen in that, the holes varied greatly in depth. The first plate was then scrapped. It was then decided to simply increment towards the surface with the spindle rotating at the correct speed. Once contact between the surface of the plate and the spindle had occurred the z-axis was set to zero. The drilling program was then run. The error is due to the angle of the fine positioning system as it is mounted onto the Motoman SDA 10. In addition to this the surface of the plates is not perfectly flat. What is clear from the failure of this touch-zero method, is that a highly accurate method of determining distance to the surface of the plate must be sought.

Due to time constraints the holes were drilled simply by zeroing the z-axis at the surface of the plate. This obviously results in significant errors in the z-axis. The focus for achieving the needed accuracy and repeatability will thus be fulfilled by examining the x and y positions of the various holes. Plate 7 of the 8 plates drilled can be seen in figure 17.30.

Photos of the surface and bottom of the holes drilled can be seen in figure 17.31. The image of the bottom of the holes shows a relatively good quality cut when compared to the 1 mm holes drilled by the fine positioning system. The surface of the 1 mm hole however appears slightly more jagged than the hole drilled with the Motoman. This shows a decrease in quality.

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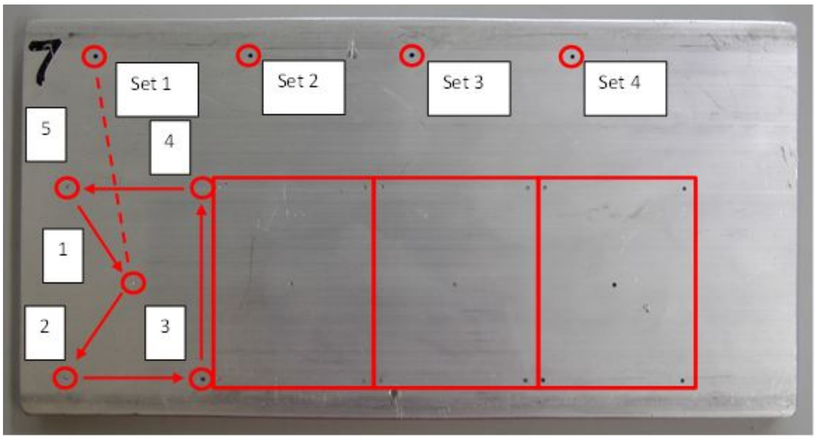
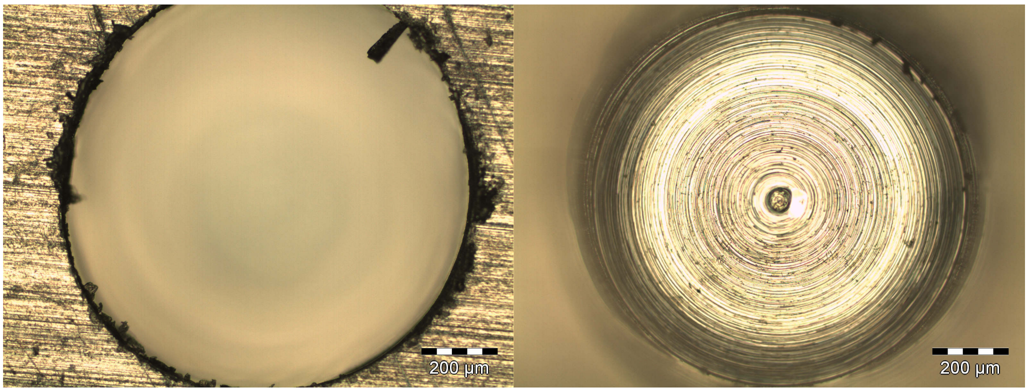


Figure 17.30: Coarse-to-Fine 4 Sets or Cycles on Test Plate 7



(a) Coarse-to-Fine Surface of Drilled Hole (b) Coarse-to-Fine Bottom of Drilled Hole

Figure 17.31: Coarse-to-Fine Comparison of the Surface and Bottom of Hole 3 Set 3 on Plate 7

ISO 9283 Fixed CMM

A sample of plate 7 as drilled and then measured by the CMM can be seen in the CAD representation in figure 17.32. In the picture the 4 calibration symbols can clearly be seen at the top of the image. Apart from the calibration symbols, the exact number of holes was drilled as per the previous set of tests. The average diameter for the 160 holes drilled was 0.993 mm. This is a marked improvement of the 1.091 mm diameter average from the coarse positioning system.

Due to the fact that the calibration system was not designed to compensate for angles, it was decided to initially determine the accuracy and repeatabil-

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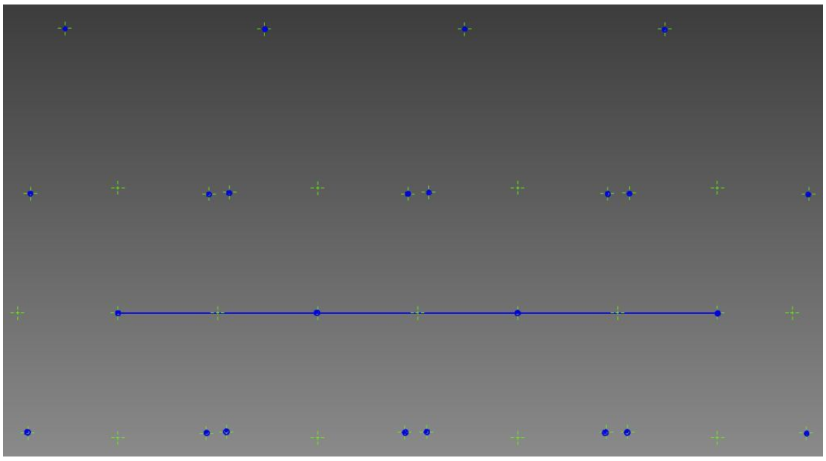

Figure 17.32: Coarse-to-Fine The CAD File Output of Holes Measured on Plate 7

ity of the holes simply using distances. The exact distances were calculated between the points. These we then converted into coordinates that had zero angular error. In addition to this, due to the failure of the z-axis zeroing method, it was decided to put in ideal z-axis values. The calculations for accuracy and repeatability were thus conducted to determine how micro drilling affected the fine positioning system.

Accuracy

The accuracies of the holes drilled, were calculated according to the previously mentioned ISO 9283 formulas and are as follows.

- 0.076 mm for hole 1
- 0.216 mm for hole 2
- 0.249 mm for hole 3
- 0.144 mm for hole 4
- 0 mm for hole 5 (Set as 0 due to distance method)

The overall accuracy was calculated as 0.137 mm. This is a decrease of 1 μm when compared to drilling with the coarse positioning system. The accuracy of drilling with the coarse-to-fine positioning system was predicted to be on the order of the 8 μm. This is a significant variance.

Repeatability

The calculated repeatabilities of the holes are as follows.

- 0.411 mm for hole 1

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- 0.405 mm for hole 2
- 0.415 mm for hole 3
- 0.324 mm for hole 4
- 0 mm for hole 5 (Set to 0)

The overall repeatability was calculated as 0.332 mm. This is a significant variance when considering the predicted 5 μm repeatability of the system specification. The result is worse than the 210 μm repeatability achieved when performing micro drilling with only the coarse positioning system. This result shows that micro drilling significantly degrades repeatability and accuracy of the coarse-to-fine system even after the PID constants of the system had been determined in drilling configuration.

Due to the significant impact of the drilling on repeatability and accuracy, it is meaningless to consider the results of the calibration system (when micro drilling) and even to interpret the raw data (not compensated for angular error). Due to the fact the holes themselves had a diameter of almost 1 mm, it can be surmised that the positioning of the Feinmess system was somehow disrupted by the rotation of the micro milling spindle. This result was impossible to predict without conducting an in depth vibration and force modeling of the system. This type of analysis was not within the scope of the project. Coarse-to-fine micro drilling can thus not be considered a feasible method for determining the accuracy and repeatability of the system. The approach taken should also not be considered for highly accurate and repeatable micro drilling.

17.4.3 Test Results and Discussion: Milling

An unexpected result in milling with the coarse-to-fine system is that it was not possible to achieve milling with a 1 mm tool bit. Due to a combination of a large force, a relatively unsteady working platform, and the vibrations of the robot arm, the system vibrated until the 1 mm tool tip broke. This experiment was repeated, each time however, the tool tips broke. After three tips had been broken, it was concluded that it is not feasible for the system to perform milling with a 1 mm tool bit. This was unforeseen and could not be predicted without advanced modeling (not within the scope of the project). As such there are no 1 mm slots to measure with the fixed CMM or to examine with the microscope.

The forces and vibrations when micro-milling with the 396 μm were far lower and even negligible when compared to those of the 1 mm tool. The result was that the slots, with the 0.396 mm tool, were successfully milled.

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The last two lines when milling in the x-direction were disrupted. This is believed to be the result of tool wear. The tool was replaced and 10 lines in the y-direction were successfully milled. The slots can be seen in figure 17.33.

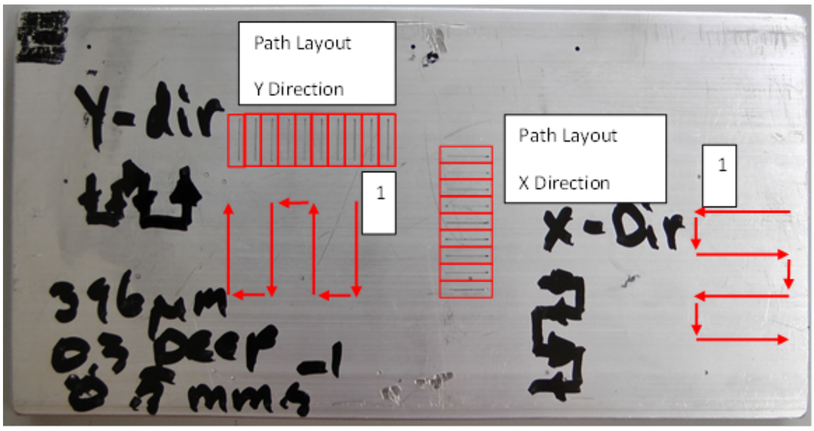

Figure 17.33: Coarse-to-Fine Plate Milled by 396 μm Tool

Optical Microscope

396 μm (20X Magnification) X-Direction Line 1

The lines milled with the 396 μm tool (in the x-direction) have a similar wavy pattern to the slots milled with the 396 μm tool (in the x-direction) when using only the coarse positioning system. In both cases, despite some debris, the edges of the cut are very smooth. The pattern at the bottom of the the slot milled by the coarse-to-fine system appears far smoother, see figure 17.34. The individual cut marks are smaller and almost perfectly distributed. From this, it can be surmised that the coarse-to-fine cut in the x-direction appears smoother and more uniform when compared coarse system cut in the x-direction.

396 μm (20X Magnification) Y-Direction Line 1

The biggest difference in all of the cuts appears when comparing the 396 μm coarse-to-fine cut in y direction with that of the coarse system cut in the y direction. The edges of the 396 μm cut using the coarse-to-fine system are very straight and have almost no irregularities. A similar scenarios is found when examining the pattern at the bottom of the cut. The bottom of the line in the y-direction appears very uniform and smooth, see figure 17.35. It is almost difficult to make a distinction between the x and y cut when examining the bottom of the slots. This is the complete opposite of the cut milled with the coarse positioning system, where the x-direction cut was smooth and the

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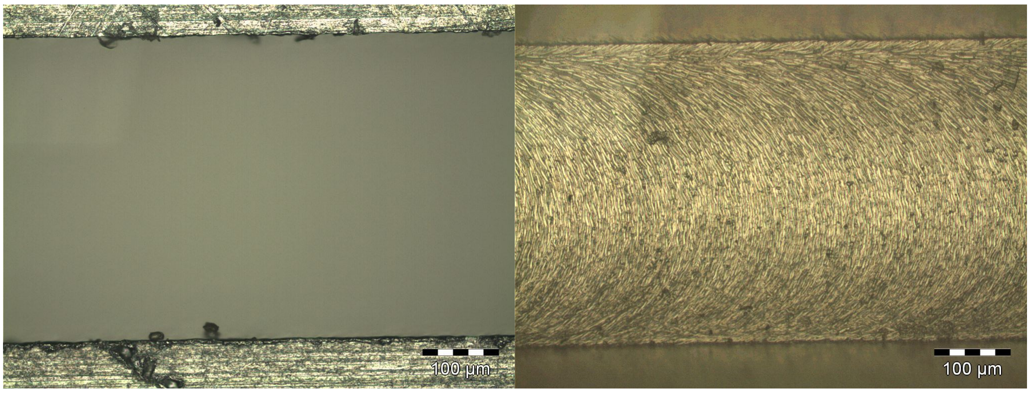
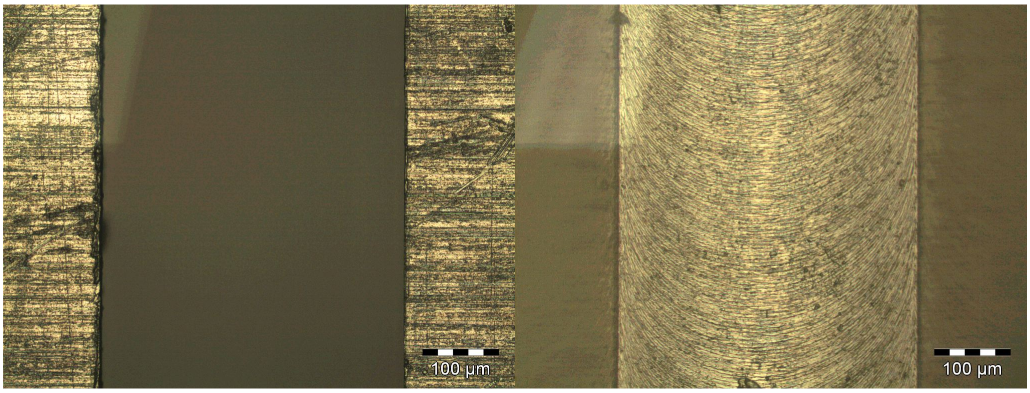


(a) Coarse-to-Fine Milled 0.396mm X 01 (b) Coarse-to-Fine Milled 0.396mm X 02

Figure 17.34: Coarse-to-Fine Line 1 Milled in the X-Direction Using a 0.396 mm Tool, Milled from Left to Right

y-direction cut was very irregular. From this it can be determined that there is a dramatic improvement in the quality and nature of the milled slots in the y-direction when milling with the coarse-to-fine positioning system.



(a) Coarse-to-Fine Milled 0.396mm Y 01 (b) Coarse-to-Fine Milled 0.396mm Y 02

Figure 17.35: Coarse-to-Fine Line 1 Milled in the Y-Direction Using a 0.396 mm Tool, Milled from Top to Bottom

Despite the good quality of the 396 μm slot, the 332 μm and the 137 μm accuracy achieved make it doubtful that the coarse-to-fine positioning system can be effectively used for micro machining, without significant improvement. Another downside of this result it that the accuracy and repeatability of the combined system was not measured. The repeatability of the fine positioning

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system is 1 μm, Feinmess (2011) and the repeatbility of the Motoman is 100 μm, RobotWorx (2011). The combination of the two with calibration system should yield a repeatability on the order of 10 μm. Despite a number of pre-tests and interviews, it was not possible to foresee the spindle affecting accuracy and repeatability in this manner. System functioning was however still intact.

17.5 System Risk

It should be noted that during the course of the testing the fine positioning system stopped working. The ensuing problems were addressed and detailed in the Project Risk report in the Appendix G. Feinmess in Dreseden, Germany was immediately contacted. The result of the discussion was that the system was returned via DHL for repair in Germany on the 14-9-2012. The cause of the failure has not been identified by Feinmess or the project author, but is believed to be due to the unavoidable built up of moisture in the system.

A number steps were taken in order to ensure that no damage would be done to the Feinmess systems during coarse-to-fine drilling, and to ensure that nothing would hinder the system functioning. The entire series of tests revolving around machining with the Motoman SDA 10 were done with the sole purpose of determining potential damaging or hindering factors for coarse-to-fine machining. As previously stated a number of interviews were conducted with various experienced University personnel in order to further identify system risks.

The Feinmess system arrived back from repair on the 5-12-2012. This was 5 days before the deadline. This late delivery was another reason the large number of pre-tests were conducted. In light of this time constraint, with the coarse-to-fine drilling not functioning as expected, there was not enough time to analyse and implement additional testing methods.

17.6 Comparison to Similar Systems Discussion

As part of the innovation management, and systems engineering approaches followed, it is necessary to compare the created system to similar systems.

Sulzer and Kovac (2010) designed a coarse-to-fine material handling system. This system made use of the E2C 351 Epson Scara Robot and the Minirob fine positioning system from Milasys. The Scara robot achieved the macro

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positioning while the Minirob achieve the fine positioning. The precision of the Minirob system allowed nanometre resolution to be achieved, (Sulzer and Kovac, 2010). The major focus of this approach was to develop a highly accurate system and simultaneously and successfully implement image recognition methodologies. The layout of the system can be seen in figure 17.36.

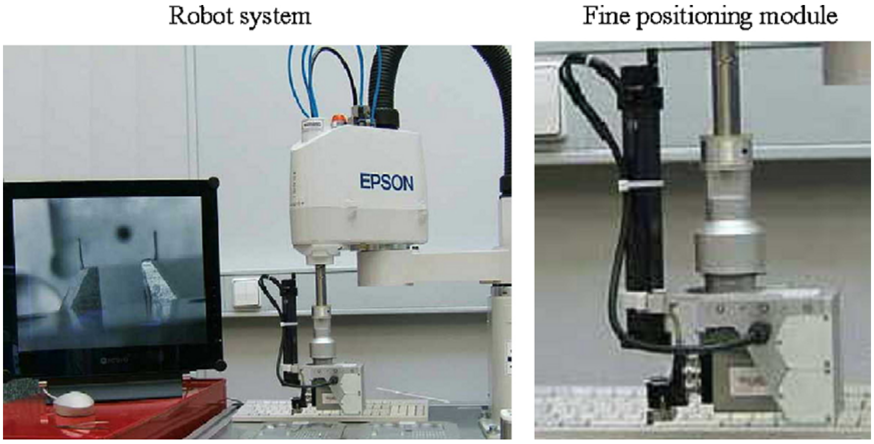

Figure 17.36: Fine Positioning System, (Sulzer and Kovac, 2010)

Freundt *et al.* (2008*b*) also designed a coarse-to-fine positioning system. The aim of his research was, however, to build an assembly head or fine positioning system with the following characteristics. The system should be precise, compact, robust, have six degrees of freedom (d.o.f.) and integrated force sensors for referencing. The sensors would be used to compensate for location or positioning errors.

Freundt *et al.* (2008*b*) focused on further developing this concept for use in a coarse-to-fine positioning system. The focus in his paper was on the design of a friction-free, damped pneumatic design and the concept of a pneumatic sensor.

17.7 System Advantage

No other instances of a Motoman SDA 10 being combined with a Feinmess MP 130 have been found. The only other two similar coarse-to-fine systems identified are those of Sulzer and Kovac (2010) and Freundt *et al.* (2008*b*). As stated the two systems have a distinctly different focus from the designed system. From a haptic dexterous micro-material handling perspective, the system

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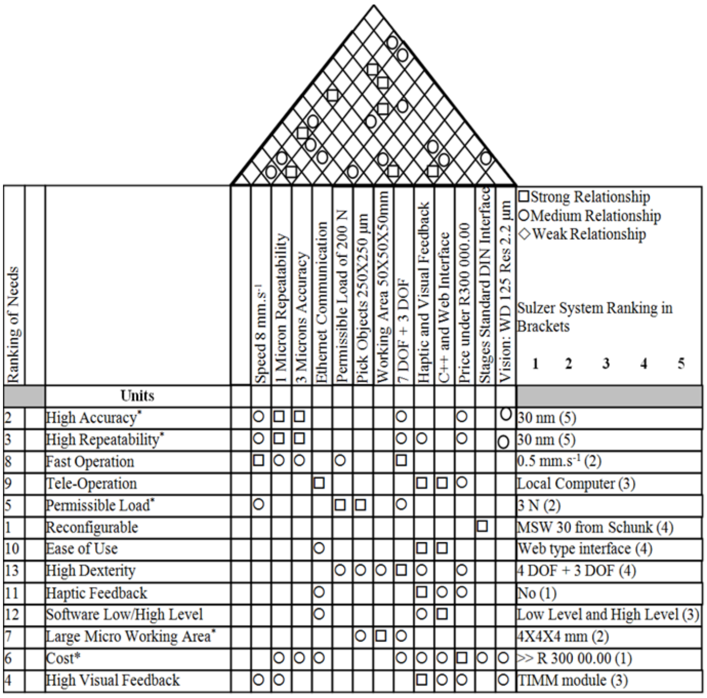
is unique.

A limiting factor in the construction of a coarse-to-fine positioning systems is the fine positioning system. This is due to the fact that there is a direct trade-off between accuracy/resolution and robustness. Either the system has nanometre accuracy but has to be kept in the same orientation Klocke (2011), or the system has only micrometre accuracy and can operate in any orientation with forces applied, (Feinmess, 2011). The second approach was adopted in this design in order to facilitate other applications; such as micro-milling.

The system developed by Sulzer and Kovac (2010) is similar to the created system. In order to differentiate the created system and highlight the system's uniqueness, a Quality Function Deployment (QFD) has been executed according to (Blanchard and Fabrycky, 2006). This can be seen in figure 17.37. It illustrates the relationships between requirements and specifications. The system created by Sulzer and Kovac (2010) is also ranked on how well it fulfils the various requirements. The major differentiating factor in this QFD is the fine positioning system, Feinmess (2011) vs. Milasys (2006).



□Strong Relationship
○Medium Relationship
◇Weak Relationship

Ranking of Needs				Speed 8 mm.s^{-1}	1 Micron Repeatability	3 Microns Accuracy	Ethernet Communication	Permissible Load of 200 N	Pick Objects 250X250 µm	Working Area 50X50X50mm	7 DOF + 3 DOF	Haptic and Visual Feedback	C++ and Web Interface	Price under R300 000.00	Stages Standard DIN Interface	Vision: WD 125 Res 2.2 µm	Sulzer System Ranking in Brackets 1 2 3 4 5
		Units															
2		High Accuracy*		○	□	□					○			○		○	30 nm (5)
3		High Repeatability*		○	□	□					○	○		○		○	30 nm (5)
8		Fast Operation		□	○	○		○			□						0.5 mm.s^{-1} (2)
9		Tele-Operation					□					□	□	○			Local Computer (3)
5		Permissible Load*		○				□	□		○						3 N (2)
1		Reconfigurable													□		MSW 30 from Schunk (4)
10		Ease of Use					○					□	□				Web type interface (4)
13		High Dexterity						○	○	○	□	○		○			4 DOF + 3 DOF (4)
11		Haptic Feedback					○					□	○	○			No (1)
12		Software Low/High Level					○					○	□				Low Level and High Level (3)
7		Large Micro Working Area*							○	□	○						4X4X4 mm (2)
6		Cost*			○	○	○				○	○	○	□	○	○	>> R 300 00.00 (1)
4		High Visual Feedback		○	○							□	○	○		○	TIMM module (3)

Figure 17.37: House of Quality (QFD) Analysis, (Tidd and Bessant, 2009)

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17.8 Chapter Conclusion

To summarise, the four themes of testing were executed and the results documented and explained above. These results include the functioning ability of the Van der Waals gripper, the 2 μm accuracy of the calibration system, the 210 μm repeatability and 136 μm accuracy of the Motoman when drilling, the 300 μm repeatability and 137 μm accuracy of the coarse-to-fine positioning system, and the good quality cut of the 396 μm line. Due to time constraints and technical issues mentioned, the secondary goal of accurate micro drilling and therefore system testing was not achieved. The primary goal of a coarse-to-fine positioning and micro material handling was successfully achieved.

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Chapter 18

Conclusion and Recommendation

When considering the conclusion of the project, it is necessary to re-examine both the Design Methods and Technical Design research objectives. Both of the research objectives were addressed throughout the project as per the figure 18.1. In addition to this, it is necessary to examine the extent to which the system specifications were achieved.

18.1 Research Questions

The design methods questions can only be assessed by qualitative means, while the technical design questions were assessed by the testing methodology and results and discussions chapter.

18.1.1 Design Methods

The design methods research questions were addressed in the Innovation Models chapter, the Systems Engineering Models chapter, the Design Methodology chapter, and the Project Definition chapter.

Innovation Management

As per the Innovation Models chapter, it was determined that an innovation management model could help to structure the project on a broad level. In this regard Ullman's Model of the Development Process was selected as the best innovation model. Following this methodology greatly increased the chances of commercial success.

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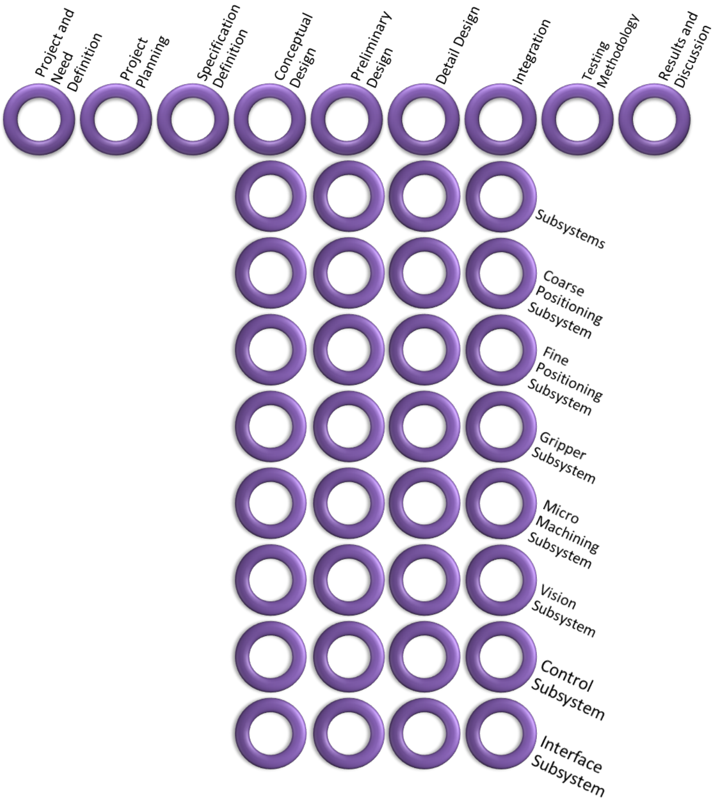

Figure 18.1: Chapter Outline

Systems Engineering

In the chapter Systems Engineering Models the applicability of systems engineering as a technical design method is justified. In addition to this, the Systems Engineering and Analysis model was found to have a clear and logical breakdown of steps. The most applicable systems engineering model for the project due to many tools and its high level of detail.

Design Methodology

A combined methodology of Systems Engineering and Innovation Management was created in order to assist the commercial and technical design of the system. The model combination was effective in creating a successful

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micro-material handling system. The model combination was not effective in predicting or helping to deal with coarse-to-fine micro machining not achieving the necessary specifications. The combination needs to include a continual technical feedback element and better contingency planning. This concurrent engineering will help to deal with problems as they arise.

18.1.2 Technical Design

Having clearly established a means to guide the project on an overall level and on a technical level, it is then necessary to begin the practical project work. This is done according to the chapter layout. The main objective of the project clearly to design develop and test a coarse-to-fine positioning system.

Main Objective: Robotic Coarse-to-Fine Positioning System for Micro-Material Handling and Micro-Machining

1. Define Project (Technically and Commercially)
   The project is needed because of a lack of necessary micro-material handling and micro-machining systems for creating adaptronic materials. Under the Project Definition chapter it was found that the product is an architectural combination. One of the methods to managing the project in light of this is to consider Robert Bosch as a potential client.

2. Understand Specifications
   The specifications were understood in light of their origins.

3. Identify Subsystems
   The subsystems of a coarse positioning subsystem, a fine positioning subsystem, a gripper subsystem, a micro-machining subsystem, a vision subsystem, a control subsystem and an interface subsystem were all selected by examining both specifications and literature.

4. Identify Functioning Concept for Each Subsystem
   This is done by examining the system needs, a variety of other concepts and considering the available resources. This includes the need for accuracy over a 500 mm range and the fact that the University of Stellenbosch currently has a Motoman SDA 10.

5. Identify Components for Each Subsystem
   By determining the correct method to be used and analysing various sources it becomes clear that coarse-to-fine positioning is the most appropriate. By analysing further literature, the various other components needed can be identified. The exact parts such as the Feinmess system are determined through the use of trade-off studies.

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6. Detail Design
   The control and interface subsystems were successfully designed at a detailed level.

7. Integration
   The design of mechanical interfaces can only be achieved while considering a large number interfaces of different parts. The successful integration of parts was demonstrated in this chapter and through the systems functioning.

8. Validation

   a) Micro-Material Handling
      The force teach or force feedback system was developed on top of a haptic control program developed by Pretorius (2011) and improved by A. Smit. This system proved functional enough to perform successful testing with the Van der Waals gripper.

   b) Micro-Machining
      Micro-milling with the 1 mm tool was not achievable with the coarse to fine positioning system. The 396 μm was used to mill a number of good quality lines. Micro drilling with the coarse-to-fine positioning system achieved a repeatability of 332 μm and an accuracy of 137 μm. This is a significant variance from the system specification of 5 μm repeatability and 8 μm accuracy. To this end successful measurement of the systems accuracy and repeatability was not achieved, and it was show that micro drilling cannot be effectively performed with this system. None of the steps taken showed any indication of this level of accuracy and repeatability degradation. Only advanced system modeling (not within the scope of this project) could have led to a meaningful prediction. Due to time constraints it was not feasible to conduct further testing.

18.2 Specifications Definition

The system achieved a large number of stakeholder requirements. The system has the ability to be operated from a remote location as per the specification definition. It can successfully pick and place piezo-ceramic micro components through intuitive force feedback control. The system is also able to record and play back various gripping functions. In addition to this, a calibration system is employed to ensure centring of the system above a calibration mark. As stated the system did not achieve the 5 μm repeatability and 8 μm accuracy when performing micro drilling.

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18.3 Recommendations

In order to increase the accuracy, repeatability and effectiveness of the system, the following should be considered when examining the viability of possible work in the future.

18.3.1 Calibration System

The calibration symbol was used in this project simply to ensure centring of the fine positioning system. Future work is to include the use of a two-shape calibration symbol in order to determine angular errors. These errors should then be compensated for by the program.

18.3.2 Haptic Force Interface

Further work needs to be done in order to ensure that the haptic feedback system functions correctly. At this stage of the project a system was developed to allow for a force teach system. A true realisation of a highly accurate force feedback system at the micro level will require additional programming, and testing.

18.3.3 Gripper

A friction force gripper was designed and used with some success. In order to implement accurate pick-and-placing of the micro components, a Van der Waals gripper was used. A thorough investigation should be conducted into the problems associated with the friction gripper, their solutions and the appropriateness of the friction gripper versus the Van der Waals gripper.

The friction-force gripper served to limit the accuracy of the system. To this end, another conclusion of this is that accuracy throughout the system should be considered when designing. All sources of potential error should be identified and solved.

18.3.4 Micro-Machining

Future work in this section of the project should entail a thorough investigation of the degradation of the accuracy and repeatability when using the coarse-to-fine positioning system for micro drilling. Methods to improve this should be examined. Other feasible methods of testing coarse-to-fine accuracy

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and repeatability should be investigated.

18.4 Conclusion

Using innovation management and systems engineering models and then combining them with research objectives helped the author to think beyond purely technical aspects when designing. An example of this is considering aftermarket service when selecting a camera and lens system. The systems engineering and innovation management combination also assisted the author in looking at the broader context of the technical project. To this end the innovation management definition of the system was created i.e. the system as an architectural innovation. In addition to this, the potential market for this system was examined, and it was found that Robert Bosch would be an appropriate customer.

The design methodology also assisted with project management aspects. This included things such as creating and maintaining a Gantt chart. In addition to this potential risk was identified and reduced. Cost was briefly examined early on.

Another conclusion of the design methodology is that innovation management has a far broader reach when applied to a design project. Systems engineering has far more technical details. When combined with research objectives, the methodologies ensure a well-rounded project that has sufficient technical depth.

Despite this however the combination does not deal well with high risk situations, as was the case with the micro-machining. Concurrent engineering needs to be integrated into this combination methodology. This will make the system more dynamic and responsive as opposed to trying to predict risk outcomes.

When considering the technical development of the system far shorter conclusions are appropriate. The coarse-to-fine positioning system successfully used a force teach system to perform micro-material handling using a Van der Waals gripper. Machining with the coarse-to-fine positioning system resulted in slight increase in the quality of the 396 μm slot, but resulted in degradation of the accuracy and repeatability when drilling.

In conclusion a design methodology incorporating innovation management, systems engineering and research objectives was successfully created and utilised. The system was proven to be unsuitable for accurate and repeatable micro

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drilling. However despite this, the main focus of designing, building and testing a coarse-to-fine positioning system for micro material handling was successfully achieved.

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Appendices

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Appendix A

Comparison of Fine Positioning Systems

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Table A.1: Summary of Micro Manipulator Properties

Model	**By**	**Type**	**DOF**	**REP. ACC (μm)**	**WS (mm)**	**Load (kg)**	**Speed (mm/s)**	**Country**	**Cost (R)**	**Weight (kg)**	**Size (mm)**	**Comm Type**
G1-171	Epson	Scara	4	5	R175 Z100	1	2.63	Germany	133 000.00	8	515×108×411.7	T-Ethernet, USB, I/O
RP-1AH	Mitsubishi	Scara	4	±5	150×105×30	1	800	U.S.A.		**12**	230×260×420	Ethernet
YK-120X	Yamaha	Scara	4	±5	R120 Z30	0.5	1.8	U.S.A		3,4	322×313×50	RS232, Ethernet
YK-150X											307×263×40	
SR4-PLUS	Bosch	Scara	4	**±25**	R400 Z200	2	1600	U.S.A.				
Autoplace 400	Sysmelec	Cart	4	1	450×250×150	5	1.5	Switzerland			640×470×170	
MP63-25DC	Feinmess	Cart	3	5	25×25×25	2	3.5	Germany	±80 000.00	3×0.5	111.5×63×63	Ethernet, RS232
1940	KOPF	Cart	3	1	128×128×128							
MM3A	Kleindiek	RRR (antr)	3	0.005	46×46×46	0.005	10	Germany	363 170.00	0.045	62.1×20.4×25.4	USB, RS232
XYZ Manipulator	Klocke	Cart	3	0.002	70×70×10	0.2	5	Germany	263 986.90	0.3	170×170×76	Ethernet, I/O
Micro Manipulator	Newport	Cart	3	8	25×25×25	1	2.5	South Africa	157 655.00	3×0.59	140×240×140	Ethernet
PCS-6400	Burleigh	Cart	5	1.6	25×25×25		2	Canada	±75 960.00	3.63	165×140×178	USB
Univ. Pipette Manipulator	Semprex	PPPR	6		75×33×25							
MW3R/L	Somapatch	Cart	3	0.25	5×5×5							
Micro Manipulator	Sensapex	PPPR		0.05	22×22×22	0.03		Finland	50 000.00		80×138×39	USB
MiniRob XS	Milasys	Cart	3	0.25	4×4×4	0.3	0.5	Germany	384 150.00		82×48×64	USB TCP/IP
Desktop Delta	Asyril	Delta		2	60×∅350	0.35		Switzerland			680×500×500	Ethernet
M180	PI	Hexapod	6	2	20×20×6.5	5	10	South Africa	±350 000.00	1.7	118 ×88×88	Ethernet RS232

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Table A.2: Micro Manipulators Analysed

Model	**By**	**Type**	**Country**	**Cost (R)**	**Weight (kg)**	**Size (mm^3)**	**Communication Type**
G1-171	Epson	SCARA	Germany	133 000.00	8	515×108×411.7	T-Ethernet, USB, I/O
YK-120X YK-150X	Yamaha	SCARA	U.S.A.		3, 4	322×313×50 307×263×40	RS232, Ethernet
MP63-25DC	Feinmess	CART	Germany	±80 000.00	3×0.5	111.5×63×63	Ethernet, RS232
MM3A	Kleindiek	RRR (antr)	Germany	363 170.00	0.45	62.1×20.4×25.4	USB, RS232
XYZ Manipulator	Klocke	RRR (spher)	Germany	263 986.90		50×26×50	Ethernet, I/O
Micromanipulator	Newport	CART	South Africa	157 655.00	3×0.59	140×240×140	Ethernet
PCS-4100	Burleigh	RPPPR	Canada	75 960.00 (Excluding Controller)	3.63	165.1×139.7×177.8	USB
Micromanipulator	Sensapex	PPPR	Finland	50 000.00		80×138×39	USB
MiniRob XS	Milasys	CART	Germnay	384 150.00		82×48×64	USB TCP/IP
Desktop Delta	Asyril	Delta	Switzerland			680×500×500	Ethernet
M180	PI	Hexapod	South African	350 000.00	1.7	118 × 88 × 88	Ethernet RS232

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Appendix B

Comparison of Gripping Principles

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Table B.1: Comparison of Gripping Principles, (Sanchez-Salmeron *et al.*, 2005)

	Friction	**Pneumatic**	**Magnetic**	**Electrostatic**	**Optical**	**Bernouilli**	**Air-cusion**	**Ultrasonic**
Material	Not Limited	Not too Porous	Magnetic Material	Conductive Materials (Dielectrical Properties Important)	Higher Refractive Index than that of the Surrounding Medium	Not too Porous	Not Limited	Not Limited
Object Example	Resistor	Stents	8-in. Wafer	Metallic Cylinders	Bacteria	Jelly Blocks	Millimetre Sized Polymer Plate	Micro-gears
Force	Not Limited	Not Limited	Not Limited	Not Limited	0.1-10 pN	0.1-10 N		Not Limited
Applicationns	Components Transfer	Components Transfer	Wafers Transfer	Components Transfer	Crystal Manipulation	Food Handling	Components Transfer	Wafer Transfer
Accuracy and Stability	Accurate	Inaccurate	Accurate	Easily Unstable	Easily Unstable	Inaccurate	Easily Unstable	Accurate
Others	Accuracy in Part Release Endangered by Adhesion	External Air Supply Needed	Not Suitable for all Kinds of material Release due to Remnant Force	Sensitive to Humidity	Size Limitation	External Air Supply Needed	External Air Supply Needed	Planar Objects

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Appendix C

Gripper Calculations

C.1 Vertical Orientation

Calculation of weight, and frictional forces needed to pick up piezo-ceramic element as can be seen in the figure C.1 when gripper is in the vertical orientation. In this case the part is being picked from above with minimal contact area.

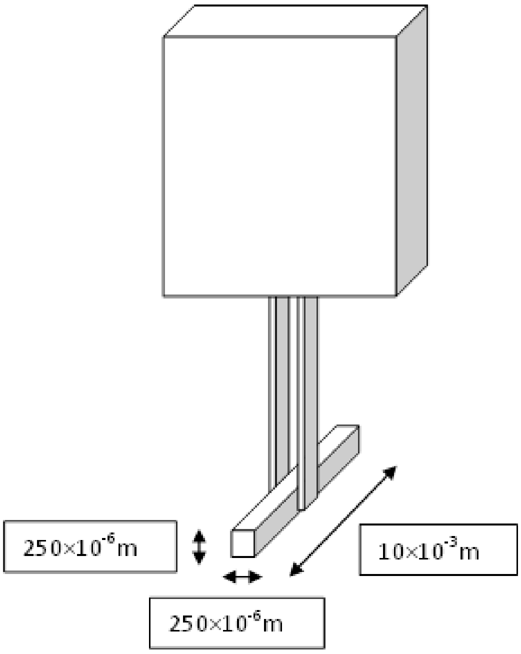

Figure C.1: Gripper Dimensions

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C.1.1 Volume of Piezo-Ceramic PZT Vibrit M1100

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$$L = 10 \times 10^{-3} \tag{C.1.1}$$
$$B = 250 \times 10^{-6} \tag{C.1.2}$$
$$H = 250 \times 10^{-6} \tag{C.1.3}$$
$$V = L \times B \times H \tag{C.1.4}$$
$$V = 625 \times 10^{-12} m^3 \tag{C.1.5}$$

C.1.2 Weight of PZT element

Weight of PZT element as per the force body diagram as seen in figure C.2. The density of the piezo-ceramic PZT 1100 is taken from Matthey (2012) as can be seen in the equations below.

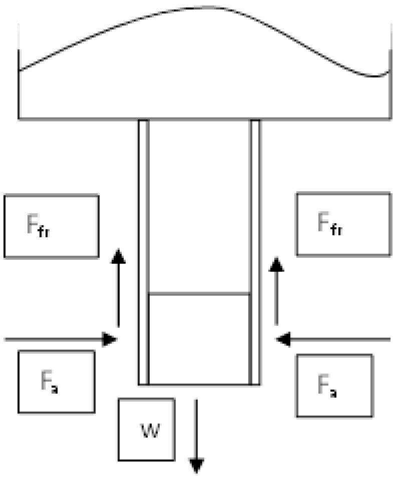

Figure C.2: Gripper Force Diagram

The weight force for the micro parts as calculated per Neugebauer *et al.* (2010*b*) is 56 μN. This is similar to the weight force calculated below.

$$g = 9.81 m.s^{-2} \tag{C.1.6}$$
$$\rho = 8.1 \times 10^3 kg.m^-3 \tag{C.1.7}$$
$$w = \rho V g \tag{C.1.8}$$
$$w = 49.663 \times 10^{-6} N \tag{C.1.9}$$

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C.1.3 Grip Force Needed

The coefficient of friction between the steel gripper tips and the piezo-ceramic is calculated as follows. Slip coefficients for piezo-ceramics are not well documented. However according to Mueller (2011) Al_2O_3 has similar surface characteristics to piezo-ceramic. The coefficient of static friction between Al_2O_3 and steel was obtained from MolTech (2010). This is then used to calculate the minimum gripper force needed to overcome the force of gravity.

$$\mu = 0.15(Steel - Al_2O_3) \tag{C.1.10}$$

$$F_{fr} = \mu F_a \tag{C.1.11}$$

$$2F_{fr} > w \tag{C.1.12}$$

$$2\mu F_a > w \tag{C.1.13}$$

$$F_a > 165.54 \times 10^{-6} N \tag{C.1.14}$$

C.1.4 Maximum Allowable Force

Maximum allowed force is calculated with 2 mm thick gripper tips as can be seen in figure C.3. The maximum allowed pressure according to Matthey (2012) is 30 MPa. This pressure is converted into a force in order to compare it with the force exerted by the Schunk gripper.

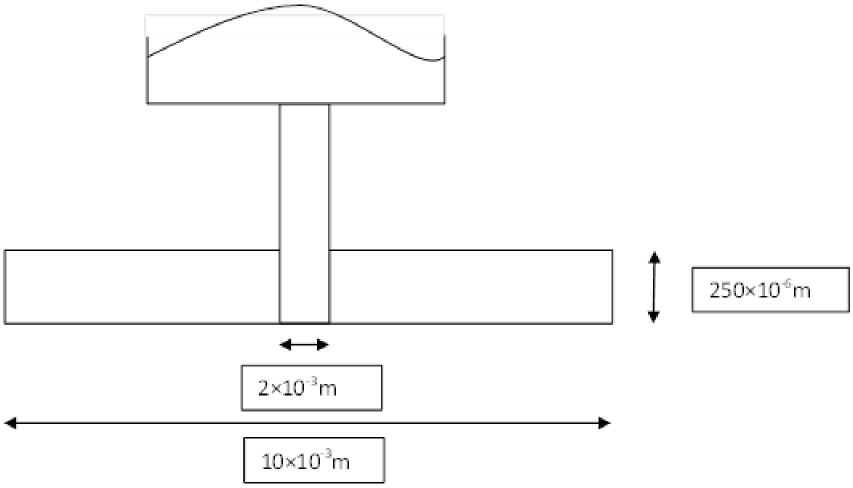

Figure C.3: Gripper Side Dimensions

$$\sigma_{\max} = 30MPa \tag{C.1.15}$$
$$L_c = 250 \times 10^{-6} \tag{C.1.16}$$
$$B_c = 2 \times 10^{-3} \tag{C.1.17}$$
$$A_c = L_c \times B_c \tag{C.1.18}$$
$$F = A_c\sigma_{\max}F = 15N \tag{C.1.19}$$
$$\tag{C.1.20}$$

The maximum closing force that can be exerted by the Schunk MPG 12 gripper is 10 N, (Schunk, 2012).

C.1.5 Schunk Gripper Force

Force exerted by Schunk gripper in Pa as per the source Schunk (2012) is 20 MPa.

$$F_{Schunk} = 10N \tag{C.1.21}$$
$$\sigma = \frac{F_{Schunk}}{A_c} \tag{C.1.22}$$
$$\sigma = 20MPa \tag{C.1.23}$$

C.1.6 Van der Waals Forces

The following calculation is used to determine the Van der Waals forces associated with a gripper finger size of 2 mm. The Hamaker constant for Steel was approximated as per Kuo and Matijevic (1980), as that used for Iron. French (2000) states the Hamaker constant for Al_2O_3 is 145 x 10-21 J. When comparing the Van der Waals forces between two materials Israelachvili (2011) states the Hamaker constants can be combined as in the calculations below.

$$A_{H(PZT)} = 145 \times 10^{-21}J \tag{C.1.24}$$
$$A_{H(Fe)} = 220 \times 10^{-21}J \tag{C.1.25}$$
$$A_{HCombined} = \sqrt{A_{H(PZT)}A_{H(Fe)}} \tag{C.1.26}$$
$$A_{HCombined} = 178.61 \times 10^{-21}J \tag{C.1.27}$$

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The formula Van der Waals force calculated per unit area of contact according to Israelachvili (2011). In the equation below H is the minimum contact distance between the two bodies.

$$H = 100 \times 10^{-9} m \tag{C.1.28}$$

$$per.unit.area = L_{cV} \times B_c V \tag{C.1.29}$$

$$per.unit.area = 500 \times 10^{-9} m \tag{C.1.30}$$

$$f = -\frac{A_{HCombined}}{6\pi H^3} per.unit.area \tag{C.1.31}$$

$$F_V = -4.74 \times 10^{-6} N \tag{C.1.32}$$

The weight force is 10 times larger than the Van der Waals forces. It is therefore safe to assume that for a 2 mm thick gripper, the Van der Waals forces are negligible.

$$w = 49.663 \times 10^{-6} N \tag{C.1.33}$$

C.2 Horizontal Orientation

In this section the various forces associated with gripping when piezo-ceramic element is calculated according to the horizontal orientation gripping orientation, see figure C.4. In this case the weight of object remains the same as in the previous section's calculations.

$$w = 49.663 \times 10^{-6} N \tag{C.2.1}$$

$$F_a > 165.54 \times 10^{-6} N \tag{C.2.2}$$

C.2.1 Maximum Allowable Force

The maximum allowed force when gripped from a horizontal orientation is calculated in the equations below. Figure C.4 illustrates the gripper tip orientation. The maximum force is obtained from Matthey (2012) as 30 MPa.

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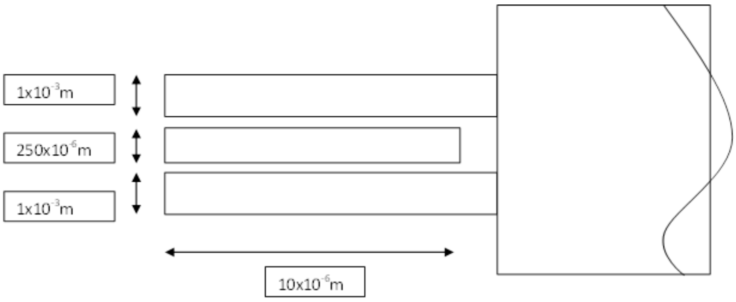

Figure C.4: Gripper Side Dimensions Horizontal Orientation

$$\sigma_{\max} = 30MPa \tag{C.2.3}$$
$$L_{cH} = 250 \times 10^{-6} \tag{C.2.4}$$
$$B_{cH} = 10 \times 10^{-3} \tag{C.2.5}$$
$$A_{cH} = L_c \times B_c \tag{C.2.6}$$
$$F_H = A_c \sigma_{\max} \tag{C.2.7}$$
$$F_H = 75N \tag{C.2.8}$$

C.2.2 Schunk Gripper Force

Considering the surface area calculated above, it is necessary to calculate the pressure that the Schunk gripper exerts. This is done using the gripper force obtained from Schunk (2012).

$$F_{Schunk} = 10N \tag{C.2.9}$$
$$\sigma = \frac{F_{Schunk}}{A_{cH}} \tag{C.2.10}$$
$$\sigma = 4MPa \tag{C.2.11}$$

C.2.3 Van der Waals Forces

In this subsection the Van der Waals forces are calculated as per a gripper finger size of 2 mm when gripped from a horizontal orientation. The Hamaker Constant for PZT (Al_2O_3) and Steel (Iron) remains the same as per Kuo and Matijevic (1980) and French (2000).

$$A_{HCombined} = 178.61 \times 10^{-21} J \tag{C.2.12}$$

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Van der Waals force is calculated per unit area of contact when considering horizontal orientation as per Israelachvili (2011). H is the minimum contact distance.

$$H = 100 \times 10^{-9} m \tag{C.2.13}$$
$$per.unit.area = L_{cH} \times B_{cH} \tag{C.2.14}$$
$$per.unit.area = 2.5 \times 10^{-6} m \tag{C.2.15}$$
$$f = -\frac{A_{HCombined}}{6\pi H^3} per.unit.area \tag{C.2.16}$$
$$F_H = -23.69 \times 10^{-6} N \tag{C.2.17}$$

The weight force is double the Van der Waals force. It is therefore safe to assume that for a 2 mm thick gripper, the Van der Waals forces are negligible.

$$w = 49.663 \times 10^{-6} N \tag{C.2.18}$$
$$\tag{C.2.19}$$

C.3 Piezo-Ceramic Element Bending

The piezo ceramic Elements are themselves not allowed to deflect Matthey (2012). The principal slope and definition for beams with basic loading, (Benham, 1996). If PZT element is gripped in a horizontal manner then the member will not deflect under its own weight. The dimension can be seen in figure C.5.

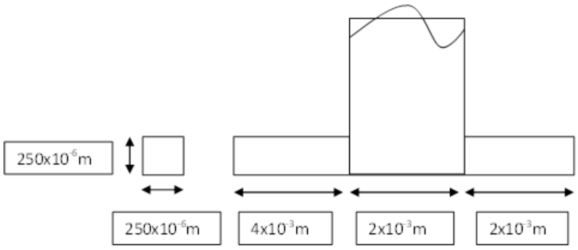

Figure C.5: Gripper PZT Dimensions Vertical Orientation

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C.3.1 Weight per unit Length

The weight of the element is calculated as per the diagram above.

$$w = mg \tag{C.3.1}$$
$$w = \rho V g \tag{C.3.2}$$
$$\tag{C.3.3}$$
$$\rho = 8.1x10^3 kgm^{-3} \tag{C.3.4}$$
$$g = 9.81m.s^{-2} \tag{C.3.5}$$
$$B = 250x10^{-6}m \tag{C.3.6}$$
$$H = 250x10^{-6}m \tag{C.3.7}$$
$$\tag{C.3.8}$$
$$A = BxH \tag{C.3.9}$$
$$A = 62.5x10^{-9}m^2 \tag{C.3.10}$$
$$\tag{C.3.11}$$
$$w_{unitlength} = \rho A g \tag{C.3.12}$$
$$W_{unitlength} = 4.966x10^{-3}Nm^{-1} \tag{C.3.13}$$

C.3.2 Modulus of Elasticity

The modulus of elasticity can be calculated from the inverse of the compliance. This value is obtain from Matthey (2012).

$$Compliance = 20.6x10^{-12} \tag{C.3.14}$$
$$E = \frac{1}{Compliance} \tag{C.3.15}$$
$$E = 48.54x10^9 Pa \tag{C.3.16}$$

C.3.3 Moment of Inertia

The moment of inertia is calculated according to (Benham, 1996).

$$I = \frac{B^4}{12} \tag{C.3.17}$$
$$I = 325.52x10^{-18}m^4 \tag{C.3.18}$$

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C.3.4 Deflection

As can be seen in figure C.6, the piezo-ceramic element has been modeled as a fixed beam with a distributed load, (Benham, 1996). The deflection can thus be calculated.

$$l = 4x10^{-3} \tag{C.3.19}$$

$$v = \frac{W_{unitlength} l^4}{8EI} \tag{C.3.20}$$

$$v = 10.507x10^{-9}m \tag{C.3.21}$$

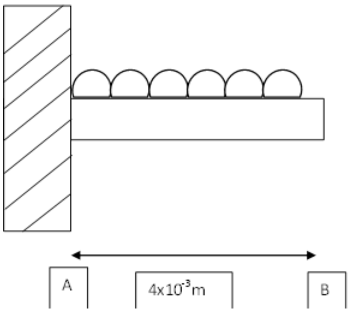

Figure C.6: Gripper PZT Modeled as a fixed beam with a distributed load

The calculated deflection should be in the region of 2.5 nm. Matthey (2012). This is however only a rough guide. If this proves to be a problem the horizontal gripping orientation should be used.

Appendix D

Structure and Housing Calculations

D.1 Coarse Positioning Fine Positioning Mount

The Coarse Positioning Fine Positioning Mount as seen in figure D.1 can be modeled as a plate. In a similar manner to the previous section, this plate can then be used to determine the deflection by using plate deflection calculations, (Benham, 1996).

$$m_{fpcp} = \rho V \tag{D.1.1}$$
$$\rho = 2712 kgm^{-3} \tag{D.1.2}$$
$$V = (130x10^{-3})(130x10^{-3})(10x10^{-3}) \tag{D.1.3}$$
$$V = 169x10^{-6}m^3 \tag{D.1.4}$$
$$m_{fpcp} = \rho V \tag{D.1.5}$$
$$m = 0.458kg \tag{D.1.6}$$

$$a_p = b_p = 55x10^{-3} \tag{D.1.7}$$
$${a_p}^2 + {b_p}^2 = c^2 \tag{D.1.8}$$
$$c = 77.78x10^{-3}m \tag{D.1.9}$$

The total deflection is thus calculated below using the plate calculations in Benham (1996).

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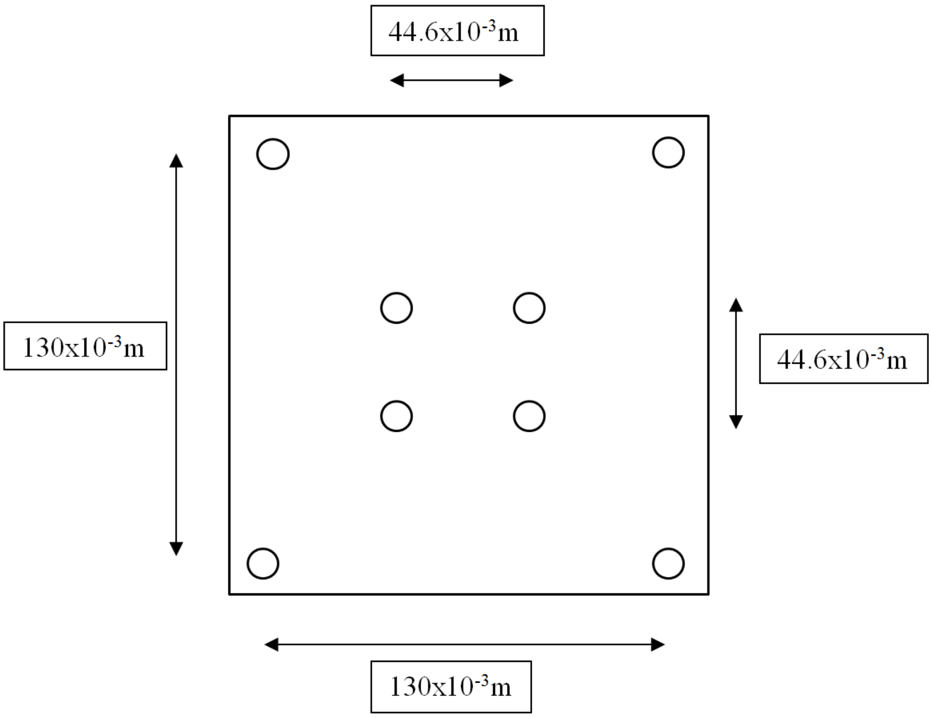

Figure D.1: Fine Positioning Coarse Positioning Mount can be modeled as a plate. This enables plate deflection calculations

$$a_{plate} = 77.78x10^{-3}m \tag{D.1.10}$$

$$b_{plate} = 31.5x10^{-3}m \tag{D.1.11}$$

$$\frac{a_{plate}}{b_{plate}} = 2.469 \tag{D.1.12}$$

$$c'' = 0.405 \tag{D.1.13}$$

$$c' = 0.0237 \tag{D.1.14}$$

$$h = 10x10^{-3}m \tag{D.1.15}$$

$$E = 71.9x10^{9}Pa \tag{D.1.16}$$

$$F_{weighttotal} = \pm 102N \tag{D.1.17}$$

$$w_{\max} = c'\frac{F_{weighttotal}{a_{plate}}^{2}}{Eh^{3}} \tag{D.1.18}$$

$$w_{\max} = 0.204x10^{-6}m \tag{D.1.19}$$

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D.2 Force Sensor Fine Positioning Mount

The force sensor is mounted onto the fine positioning system which is then mounted onto the Motoman SDA 10. The force sensor is highly sensitive. Due to the force sensor's sensitivity the weight of the fine positioning system would bias the force sensor, if the fine positioning system was mounted onto the force sensor. The mounting of the force sensor on the fine positioning system also ensures that the system can be easily integrated with the previously existing teleoperated haptic feedback system.

D.2.1 Weight

The weight of the force sensor fine positioning mount is calculated below.

$$m_{fsfp} = \rho V \tag{D.2.1}$$

$$\rho = 2712 kgm^{-3} \tag{D.2.2}$$

$$V = 140x10^{-3} 86x10^{-3} 176x10^{-3} - 132x10^{-3} 78x10^{-3} 168x10^{-3} \tag{D.2.3}$$

$$V = 389.312x10^{-6} \tag{D.2.4}$$

$$m_{fsfp} = \rho V \tag{D.2.5}$$

$$m = 1.056 kg \tag{D.2.6}$$

D.2.2 Normal Stress

The combination of the force sensor and gripper creates a moment around the face of the Force Sensor Fine Positioning Mount, as per figure D.2. This moment is used to calculate the amount of normal stress applied onto the sides of the Force Sensor Fine Positioning Mount in accordance with Benham (1996). The thickness of this part was calculated as 2 mm. The thickness was later changed to 4 mm to ensure that even the slightest deflection does not occur.

The moment is calculated as per figure D.2. The force sensor's weight is obtained from ATI (2010) as 0.254 kg.

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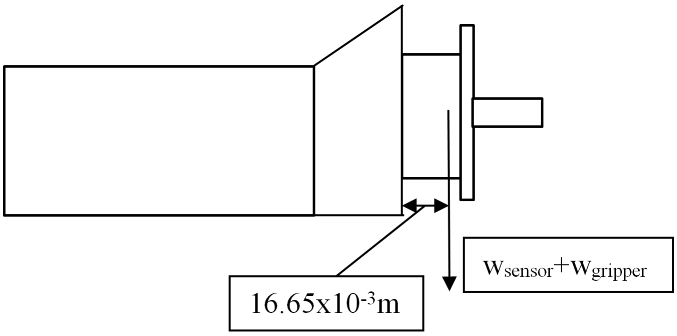

Figure D.2: Force Sensor Fine Positioning Mount diagram with sensor and gripper mount. Arrow shows the centre of gravity of the sensor and gripper combination. These combined weights create a moment around the Force Sensor Fine Positioning Mount

$$m = 0.254kg \tag{D.2.7}$$

$$g = 9.81ms^{-2} \tag{D.2.8}$$

$$d_{sensortomount} = 16.65x10^{-3}m \tag{D.2.9}$$

$$d_{mountthickness} = 2x10^{-3}m \tag{D.2.10}$$

$$d_{total} = d_{sensortomount} + d_{mountthickness} \tag{D.2.11}$$

$$d = 0.01865m \tag{D.2.12}$$

$$M = mgd \tag{D.2.13}$$

$$M = 0.0465Nm \tag{D.2.14}$$

Having calculated the applied moment as per above, the area moment of inertia can be calculated as per Benham (1996). Figure D.3 shows the Force Sensor Fine Positioning Mount without a front plate. This makes it easier to calculate the area moment of inertia of the cross section that will be experiencing the normal force.

In the equations below the moments of each component of the cross section are taken about the top of the structure, i.e. 85 mm. The result of this is that the neutral axis can be calculated for the entire cross section, (Benham, 1996). This axis is represented by the dotted line in figure D.3.

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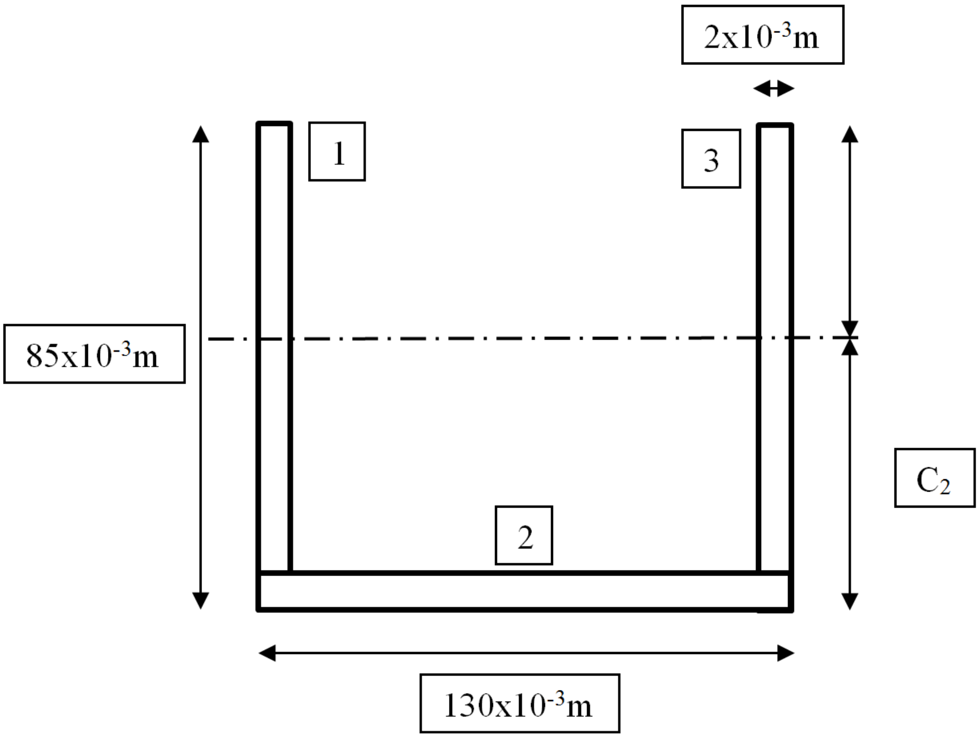

Figure D.3: Force Sensor Fine Positioning Mount diagram without sensor and gripper mount. The force sensor mount plate has been removed in order to help calculate the moment area of inertia experienced by the sides of Force Sensor Fine Positioning Mount

$$A_1 = A_3 = (83x10^{-3})(2x10^{-3}) \tag{D.2.15}$$

$$A_2 = (130x10^{-3})(2x10^{-3}) \tag{D.2.16}$$

$$A_{Total} = 2A_1 + A_2 \tag{D.2.17}$$

$$A_{Total} = 592x10^{-6}m \tag{D.2.18}$$

$$\tag{D.2.19}$$

$$A_{Total}C_1 = 2A_1(41.5x10^{-3}) + A_2(84x10^{-3}) \tag{D.2.20}$$

$$C_1 = 60.166x10^{-3}m \tag{D.2.21}$$

It is then necessary to calculate the moment area of inertia for each component of the cross section. Benham (1996) then states that these individual inertias are calculated around the individual components' centroidal axes. The left most cross section is labelled 1, the bottom is labelled as 2 and the right most area component is labelled as 3, see figure D.3.

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$$b_{13} = 2x10^{-3}m \tag{D.2.22}$$

$$h_{13} = 83x10^{-3}m \tag{D.2.23}$$

$$I_1 = I_3 = \frac{b_{13}{h_{13}}^3}{12} \tag{D.2.24}$$

$$I_1 = I_3 = 9.3x10^{-8}m^4 \tag{D.2.25}$$

$$\tag{D.2.26}$$

$$b_2 = 130x10^{-3}m \tag{D.2.27}$$

$$h_2 = 2x10^{-3}m \tag{D.2.28}$$

$$I_2 = \frac{b_2{h_2}^3}{12} \tag{D.2.29}$$

$$I_2 = 8.67x10^{-11}m^4 \tag{D.2.30}$$

Once the moment areas of inertia have been calculated it is then possible to calculated the total moment area of inertia. This is done using the parallel axis theorem as seen below, (Benham, 1996).

$$I_z = I_{cg} + Ad^2 \tag{D.2.31}$$

$$d_1 = d_3 = 18.67x10^{-3}m \tag{D.2.32}$$

$$d_2 = 23.83x10^{-3}m \tag{D.2.33}$$

$$\tag{D.2.34}$$

$$I_z = 2(I_1 + A_1{d_1}^2) + (I_2 + A_2{d_2}^2) \tag{D.2.35}$$

$$I_z = 12.585x10^{-6}m^4 \tag{D.2.36}$$

The result is that the normal stress exerted by the moment is far less than the yield stress for Aluminium, ToolBox. This form of loading will not cause any deformation.

$$\theta_x = -\frac{My}{I} \tag{D.2.37}$$

$$\theta_x = 222Pa \tag{D.2.38}$$

$$S_y = 70x10^6Pa \tag{D.2.39}$$

$$\theta_x << S_y \tag{D.2.40}$$

D.2.3 Deflection When Modelled as a Plate

One way to determine the deflection of the Force Sensor Fine Positioning Mount is to model the mounting surface as a round plate, see figure D.4. The

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various plate deflection calculations can then be applied in accordance with Benham (1996).

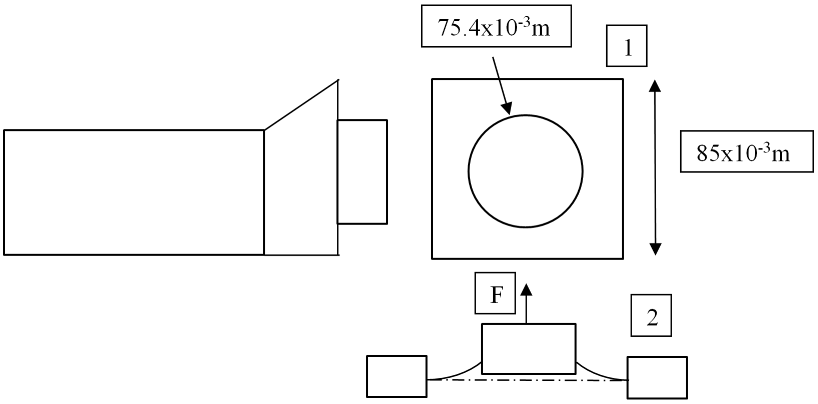

Figure D.4: Force Sensor Fine Positioning Mount can be modeled as a plate. This enables plate deflection calculations

The force experience by the 'plate' is calculated below by adding the weight of the force sensor and gripper system. The force is presumed to be experienced when the full weight of the sensor and gripper is experienced by the plate. This occurs when the fine positioning system is vertical.

$$g = 9.81ms^{-2} \tag{D.2.41}$$

$$m_{sensor} = 0.254kg \tag{D.2.42}$$

$$m_{gripper} = \pm 0.5kg \tag{D.2.43}$$

$$F_{weight} = m_{sensor}g + m_{gripper}g \tag{D.2.44}$$

$$F_{weight} = 12N \tag{D.2.45}$$

As can be seen from the plate deflection calculations the maximum deflection will be smaller than 1 μm, (Benham, 1996).

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$$a_{plate} = 42.5x10^{-3}m \tag{D.2.46}$$
$$b_{plate} = 37.7x10^{-3}m \tag{D.2.47}$$
$$c' = 0.115 \tag{D.2.48}$$
$$c'' = 0.00129 \tag{D.2.49}$$
$$E = 71.9x10^{9}Pa \tag{D.2.50}$$
$$h = 2x10^{-3} \tag{D.2.51}$$
$$w_{\max} = c'\frac{F_{weight}{a_{plate}}^{2}}{Eh^{3}} \tag{D.2.52}$$
$$w_{\max} = 0.0486x10^{-6}m \tag{D.2.53}$$

D.3 Gripper Tips

In designing the gripper tips it is necessary to ensure that the grippers are able to release the 250 μm object when fully open and grip the object when fully closed. Schunk (2012) states that the distance between the mounting tips is 7 mm when fully open and 4.6 mm when fully closed.

Considering the above open and closed distances a gripper thickness of 2.5 mm was needed. Using this thickness on each of the two grippers gives the following characteristics. When the gripper is open, with gripper tips attached, there is a gap of 2.3 mm. The distance that the grippers can travel is however 2.5 mm. The gripper tips will touch after only 2.3 mm of movement. This will ensure that the parts can be firmly gripped. It should also be noted that the maximum finger length as per Schunk (2012), is 12 mm. The lengths of the gripper tips was kept at 10 mm.

D.3.1 Weight/Mass Calculations

The density of the steel gripper tips was taken from ToolBox and was used to calculate the mass of the tips as seen below.

$$\rho_{steel} = 7850kgm^{-3} \tag{D.3.1}$$
$$V_{tip} = 220.48x10^{-9}m^{3} \tag{D.3.2}$$
$$m_{tipstotal} = 2\rho V \tag{D.3.3}$$
$$m_{tipstotal} = 3.46x10^{-3}kg \tag{D.3.4}$$

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Mass of the gripper subsystem, gripper tips, piezo ceramic, bolts and nuts is calculated below and then converted into a weight.

$$m_{piezoceramic} = 5.063x10^{-6}kg \tag{D.3.5}$$

$$m_{bolt} = 0.2x10^{-3}kg \tag{D.3.6}$$

$$m_{nut} = 0.1x10^{-3}kg \tag{D.3.7}$$

$$m_{total} = m_{tipstotal} + m_{piezoceramic} + 2m_{bolt} + 2m_{nut} \tag{D.3.8}$$

$$m_{total} = 4.065x10^{-3}kg \tag{D.3.9}$$

$$w_{total} = 39.87x10^{-3}N \tag{D.3.10}$$

According to Schunk (2012) the maximum mass allowed per finger is 0.01 kg or 10 grams. The total mass allowed is thus 0.02 kg or 20 grams. As can be seen above the total mass of the gripper subsystem is 4.065 grams.

D.3.2 Moment and Deflection

The moments are calculated according to the simplified deflection diagram show in figureD.5.

$$d = 13x10^{-3}m \tag{D.3.11}$$

$$F = 10N \tag{D.3.12}$$

$$M = Fd \tag{D.3.13}$$

$$M = 0.13Nm \tag{D.3.14}$$

The maximum moment allowed according to Schunk (2012) is 0.2 N.m for the three different axes.

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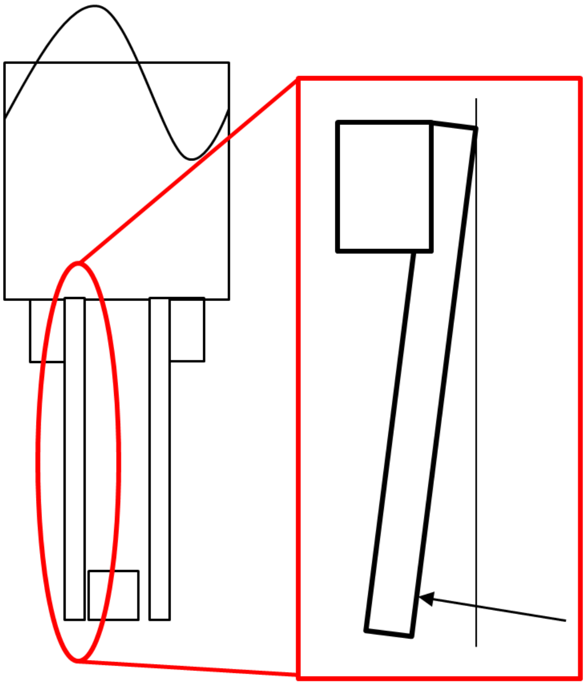

Figure D.5: Simplified gripper tip deflection as a result of force exerted on the piezo ceramic

$$v = -\frac{Ml^2}{2EI} \tag{D.3.15}$$

$$l = 10x10^{-3}m \tag{D.3.16}$$

$$b = 2x10^{-3}m \tag{D.3.17}$$

$$h = 1x10^{-3}m \tag{D.3.18}$$

$$\tag{D.3.19}$$

$$I = \frac{bh^3}{12} \tag{D.3.20}$$

$$I = 1.67x10^{-13}m^4 \tag{D.3.21}$$

$$\tag{D.3.22}$$

$$E = 208x10^9 Nm^{-2} \tag{D.3.23}$$

$$v = 187.126x10^{-6}m \tag{D.3.24}$$

The deflection is large considering the dimension of the part gripped. This is due the large modulus of elasticity associated with steel. This large deflection is intentional as it will prevent the part from being damaged by rigid gripper tips, however a thicker gripper tip will greatly reduce this figure.

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D.4 Vision Mount

First it is necessary to calculate the mass of the vision mount.

$$\rho = 2712kgm^{-3} \tag{D.4.1}$$

$$V = (118x10^{-3})(10x10^{-3})(78x10^{-3}) \tag{D.4.2}$$

$$V = 92.04x10^{-6}m^{3} \tag{D.4.3}$$

$$m_{visionmount} = \rho V \tag{D.4.4}$$

$$m_{visionmount} = 0.2496kg \tag{D.4.5}$$

D.4.1 Normal Stress

The weight of the vision mount is then calculated according to its mass.

$$m_{vision} = 1kg \tag{D.4.6}$$

$$g = 9.81ms^{-2} \tag{D.4.7}$$

$$w = m_{vision}g \tag{D.4.8}$$

$$w = 9.81N \tag{D.4.9}$$

With the afore mentioned weight calculated the pressure exerted on the member can be calculated. This is then compared to the yield strength for Aluminium as per ToolBox.

$$A = 200x10^{-6}m^{2} \tag{D.4.10}$$

$$F = 9.81N \tag{D.4.11}$$

$$\sigma = \frac{F}{A} \tag{D.4.12}$$

$$\sigma = 49.05x10^{-3}Pa \tag{D.4.13}$$

$$S_y = 70x10^{6}Pa \tag{D.4.14}$$

$$\sigma << S_y \tag{D.4.15}$$

The normal stress for the cross section of the vision mount is calculated below. In order to do this the moment area of inertia is used, (Benham, 1996).

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$$d = 5x10^{-3}m \tag{D.4.16}$$
$$M = Fd \tag{D.4.17}$$
$$M = 0.0491Nm \tag{D.4.18}$$
$$\tag{D.4.19}$$
$$b = 20x10^{-3}m \tag{D.4.20}$$
$$h = 10x10^{-3}m \tag{D.4.21}$$
$$I = \frac{bh^3}{12} \tag{D.4.22}$$
$$I = 1.667x10^{-9}m^4 \tag{D.4.23}$$
$$\tag{D.4.24}$$
$$c = 5x10^{-3}m \tag{D.4.25}$$
$$\sigma = \frac{Mc}{I} \tag{D.4.26}$$
$$\sigma = 147.297x10^3Pa \tag{D.4.27}$$

D.4.2 Bending

In order to calculate the bending of the vision mount it is necessary to model it as a beam see figure D.6. The beam deflections can then be used according to Benham (1996).

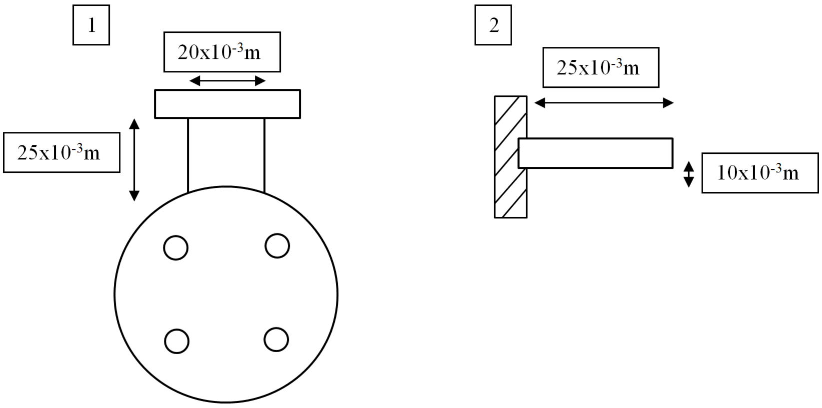

Figure D.6: The Vision System Mount can be modeled as a beam. The deflection can thus be calculated

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$$w = 9.81N \tag{D.4.28}$$
$$l = 25x10^{-3}m \tag{D.4.29}$$
$$E = 71.9x10^{9}Pa \tag{D.4.30}$$
$$I = 1.667x10^{-9}m^{4} \tag{D.4.31}$$
$$v = \frac{wl^{3}}{3EI} \tag{D.4.32}$$
$$v = 0.4264x10^{-6}m \tag{D.4.33}$$

D.5 Total Combined Weight

$$V_{ForcSensorFinePositioningMount}'' = 306.592x10^{-6}m^{3} \tag{D.5.1}$$
$$m_{ForceSensorFinePositioningMount}'' = 0.8315kg \tag{D.5.2}$$

The mass of the combined system is calculated below using individual component volumes and densities obtained from ToolBox.

$$m_{GripperTotal} = 4.065x10^{-3}kg \tag{D.5.3}$$
$$m_{GripperForceSensorMount} = 160.12x10^{-3}kg \tag{D.5.4}$$
$$m_{ForceSensor} = 254x10^{-3}kg \tag{D.5.5}$$
$$m_{ForceSensorFinePositioningMount} = 1.056kg \tag{D.5.6}$$
$$m_{FeinmessPositioningSystem} = 6.510kg \tag{D.5.7}$$
$$m_{CoarsePositiongFinePositioningMount} = 0.458kg \tag{D.5.8}$$
$$m_{VisionSubsystem} = 730x10^{-3}kg \tag{D.5.9}$$
$$m_{SchunkToolChangeSystem} = 600x10^{-3}kg \tag{D.5.10}$$
$$m_{OverallTotal} = 9.772kg \tag{D.5.11}$$

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Appendix E

Micro-Milling Calculations

E.1 Forces

The combined weight of the machined parts, Force Sensor Fine Positioning Mount, the force sensor and the Micro Milling Mount is 1.315 kg. According to Nakanishi (2012) the weight of the EM 3060 milling spindle is 325 grams. This weight is estimated at 0.685 kg when considering cabling etc.

Feinmess (2011) states that the MP 130 system can handle a maximum continuous force of 50 N in all axes. In addition to this the system can withstand 3.4 Nm per axis. In order to determine if it is feasible to perform micro-milling with the Feinmess system all the appropriate forces need to be determined according to figure E.1.

It is first necessary to determine the allowable mass remaining after the force sensor and machined parts have been added.

$$m_{mountings} = 1.315kg \tag{E.1.1}$$

$$m_{spindle} = 0.685kg \tag{E.1.2}$$

$$m_{total} = m_{mountings} + m_{spindle} \tag{E.1.3}$$

$$m_{total} = 2kg \tag{E.1.4}$$

The mass of 2 kg is less than the maximum of 5 kg. The next set of equations is to determine the torque produced by the above mass. The distance is taken as per figure E.1. The torque is then compared to the allowable torque. The result is the torque allowed for the micro-milling.

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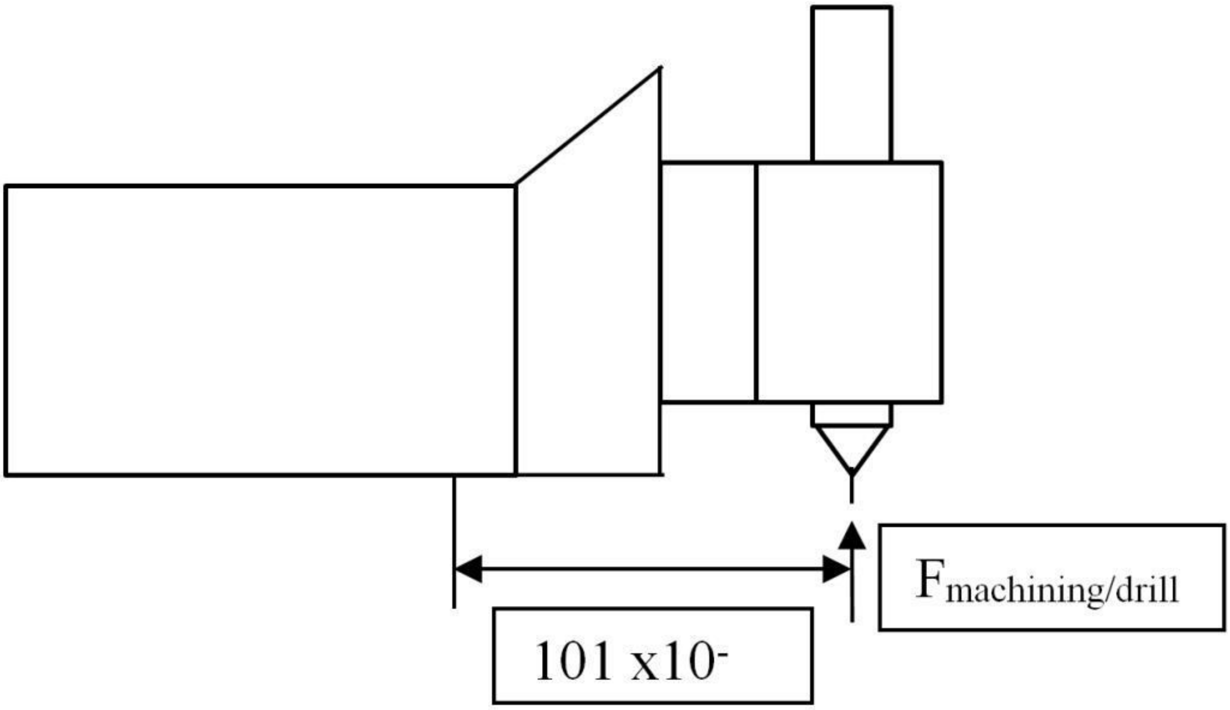

Figure E.1: Micro-Milling Forces and System Interactions

$$d = 101x10^{-3}m \tag{E.1.5}$$
$$g = 9.81ms^{-2} \tag{E.1.6}$$
$$M_{total} = mgd \tag{E.1.7}$$
$$M_{total} = 1.982Nm \tag{E.1.8}$$
$$\tag{E.1.9}$$
$$M_{allowable} = 3.4Nm \tag{E.1.10}$$
$$M_{micromilling} = M_{allowable} - M_{total} \tag{E.1.11}$$
$$M_{micromilling} = 1.418Nm \tag{E.1.12}$$

The torque allowed for the micro-milling is then converted into a force. This force is the maximum force that the micro-milling spindle can exert in the z direction when machining. The remaining axes x,y are limited to 3.4 N of torque as per Feinmess (2011).

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$$M_{micromilling} = Fd \tag{E.1.13}$$
$$F = 14N \tag{E.1.14}$$
$$\tag{E.1.15}$$
$$F_x = F_y \tag{E.1.16}$$
$$M_{micromillingx} = M_{micromillingy} = 3.4Nm \tag{E.1.17}$$
$$M_{micromillingx} = F_x d \tag{E.1.18}$$
$$F_x = 33.66N \tag{E.1.19}$$

E.2 Vibrations

As per Feinmess (2011) the fine positioning system is constructed of three stages. Each stage moves in a single axis. In order to calculate the natural frequency of the not only individual stages but also the system as a whole it is necessary to consider the different masses. The system can be thought of as a serial linked system of stages. The first stage is only affected by its own mass due to the effects of gravity. The second stage is affected by both its weight and the weight of the first stage. Similarly the third stage is affect by its own mass and a combination of the first two masses. In addition to this the third stage is also affected by the weight of an interconnecting structure. The stiffness of each stage both vertically and laterally are given by Feinmess and can be seen below along with the various masses. To confirm the appropriateness of this system for micro-machining, a CNC machine has a roughly 50 N/μm or 50 x 106 N/m, (Pan *et al.*, 2006).

$$k_v = 50x10^6 N.m^{-1} \tag{E.2.1}$$
$$k_l = 25x10^6 N.m^{-1} \tag{E.2.2}$$
$$m_{1stage} = 0.5kg \tag{E.2.3}$$
$$m_{2stage} = 2.3kg \tag{E.2.4}$$
$$m_{3stage} = 6kg \tag{E.2.5}$$
$$\tag{E.2.6}$$
$${\omega_n}^2 = \frac{k}{m} \tag{E.2.7}$$
$$f_n = \frac{\omega_n}{2\pi} \tag{E.2.8}$$
$$\tag{E.2.9}$$

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In order to calculate the natural or resonant frequency of each of the various stages in the vertical orientation it is necessary to the square root their stiffness divided by their masses. This natural frequency in radians per second is then converted to Hertz as seen below. The process is repeated for each of the three stages.

$$\omega_{n1stagev} = \sqrt{\frac{k_v}{m_{1stage}}} \tag{E.2.10}$$

$$\omega_{n1stagev} = 10000 rad.s^{-1} \tag{E.2.11}$$

$$f_{n1stagev} = \frac{\omega_{n1stagev}}{2\pi} \tag{E.2.12}$$

$$f_{n1stagev} = 1591.55 Hz \tag{E.2.13}$$

$$\tag{E.2.14}$$

$$\omega_{n2stagev} = 4662.52 rad.s^{-1} \tag{E.2.15}$$

$$f_{n2stagev} = 742.06 Hz \tag{E.2.16}$$

$$\tag{E.2.17}$$

$$\omega_{n3stagev} = 2886.75 rad.s^{-1} \tag{E.2.18}$$

$$f_{n3stagev} = 459.44 Hz \tag{E.2.19}$$

The process is then repeated for the lateral orientation.

$$\omega_{n1stagel} = \sqrt{\frac{k_l}{m_{1stage}}} \tag{E.2.20}$$

$$\omega_{n1stagel} = 7071.07 rad.s^{-1} \tag{E.2.21}$$

$$f_{n1stagel} = \frac{\omega_{n1stagev}}{2\pi} \tag{E.2.22}$$

$$f_{n1stagel} = 1125.4 Hz \tag{E.2.23}$$

$$\tag{E.2.24}$$

$$\omega_{n2stagel} = 3296.9 rad.s^{-1} \tag{E.2.25}$$

$$f_{n2stagel} = 524.72 Hz \tag{E.2.26}$$

$$\tag{E.2.27}$$

$$\omega_{n3stagel} = 2041.24 rad.s^{-1} \tag{E.2.28}$$

$$f_{n3stagel} = 324.87 Hz \tag{E.2.29}$$

In order to compare the above calculated natural frequencies to the frequency of a machining operation it is necessary to calculate the tooth passing

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frequency. This is calculated for each of the operations i.e. milling with the 1 mm tool and milling with a 0.396 mm tool. According to Nakanishi (2012) the micro-milling spindle can achieve speeds from 5 000 to 60 000 rpm. The maximum speed of 60 000 rpm is 1000 Hz or 1 kHz.

$$N_{1mm} = 24000rpm \tag{E.2.30}$$

$$N_{0.396mm} = 48000rpm \tag{E.2.31}$$

$$n_t = 2 \tag{E.2.32}$$

$$\tag{E.2.33}$$

$$f_t = \frac{n_t N}{60} \tag{E.2.34}$$

$$f_{t1mm} = 800Hz \tag{E.2.35}$$

$$f_{t0.396mm} = 1600Hz \tag{E.2.36}$$

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Appendix F

Technical Drawings

F.1 Overall Assembly Drawings

F.2 Coarse Positioning System

F.3 Fine Positioning System

F.4 Gripper Tips

F.5 Sensor System

F.6 Spacer

F.7 Vision System

F.8 Micro Machining

F.9 CMM Mount

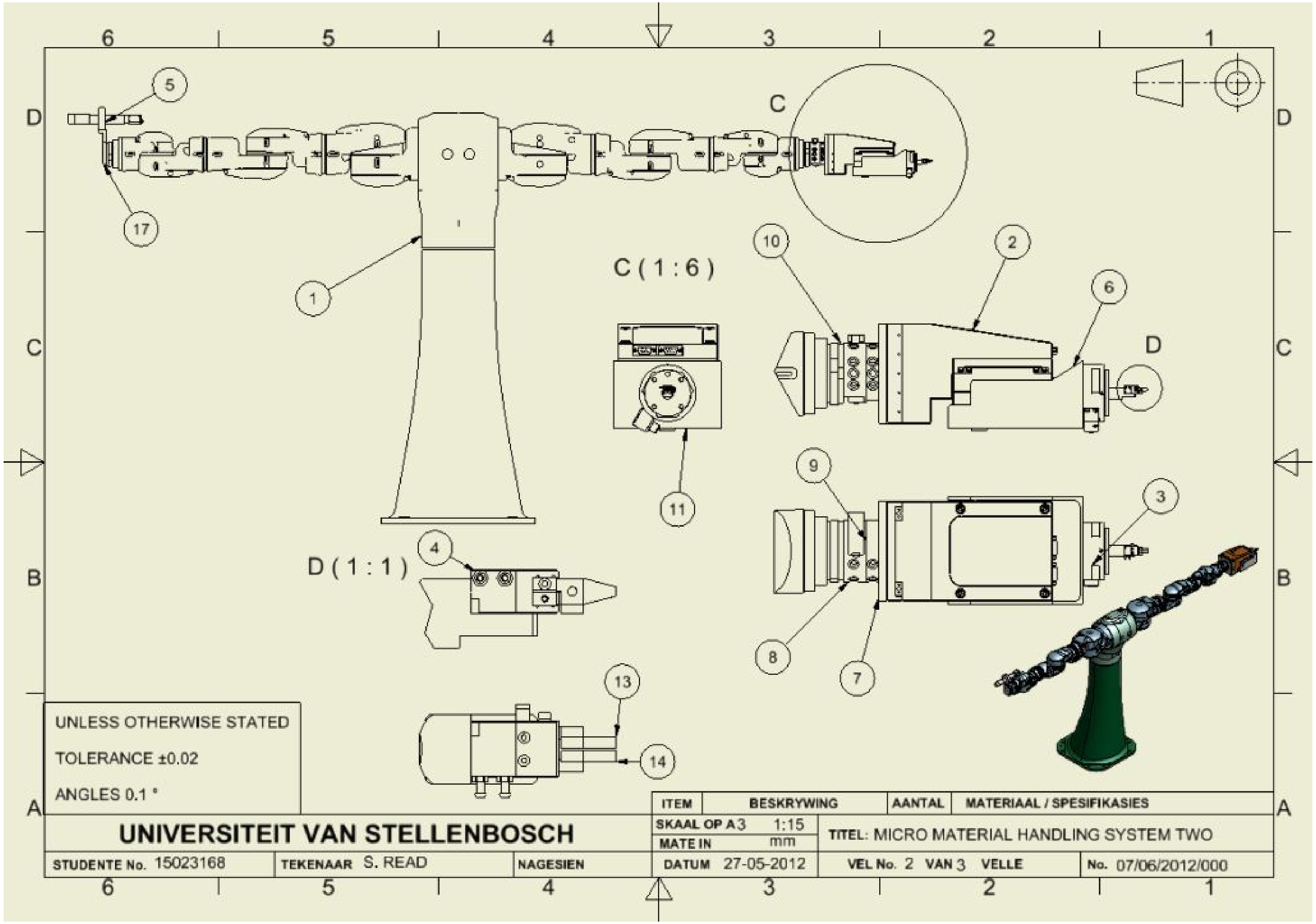

Figure F.1: Force Sensor Fine Positioning Mount One

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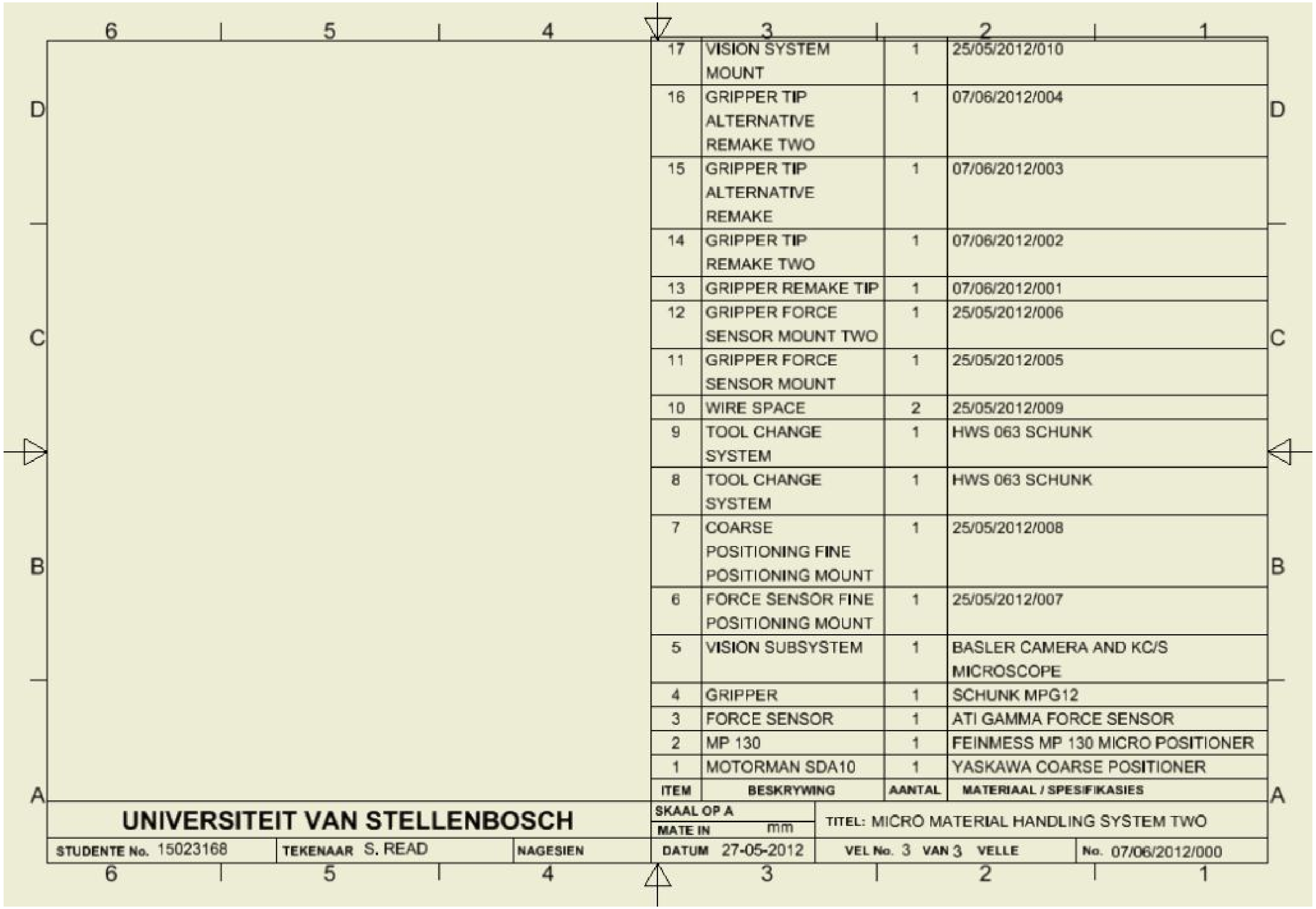

ITEM	BESKRYWING	AANTAL	MATERIAAL / SPESIFIKASIES
17	VISION SYSTEM MOUNT	1	25/05/2012/010
16	GRIPPER TIP ALTERNATIVE REMAKE TWO	1	07/06/2012/004
15	GRIPPER TIP ALTERNATIVE REMAKE	1	07/06/2012/003
14	GRIPPER TIP REMAKE TWO	1	07/06/2012/002
13	GRIPPER REMAKE TIP	1	07/06/2012/001
12	GRIPPER FORCE SENSOR MOUNT TWO	1	25/05/2012/006
11	GRIPPER FORCE SENSOR MOUNT	1	25/05/2012/005
10	WIRE SPACE	2	25/05/2012/009
9	TOOL CHANGE SYSTEM	1	HWS 063 SCHUNK
8	TOOL CHANGE SYSTEM	1	HWS 063 SCHUNK
7	COARSE POSITIONING FINE POSITIONING MOUNT	1	25/05/2012/008
6	FORCE SENSOR FINE POSITIONING MOUNT	1	25/05/2012/007
5	VISION SUBSYSTEM	1	BASLER CAMERA AND KC/S MICROSCOPE
4	GRIPPER	1	SCHUNK MPG12
3	FORCE SENSOR	1	ATI GAMMA FORCE SENSOR
2	MP 130	1	FEINMESS MP 130 MICRO POSITIONER
1	MOTORMAN SDA10	1	YASKAWA COARSE POSITIONER

UNIVERSITEIT VAN STELLENBOSCH
SKAAL OP A
MATE IN mm
TITEL: MICRO MATERIAL HANDLING SYSTEM TWO
STUDENTE No. 15023168
TEKENAAR S. READ
NAGESIEN
DATUM 27-05-2012
VEL No. 3 VAN 3 VELLE
No. 07/06/2012/000

Figure F.2: Force Sensor Fine Positioning Mount Bill of Materials

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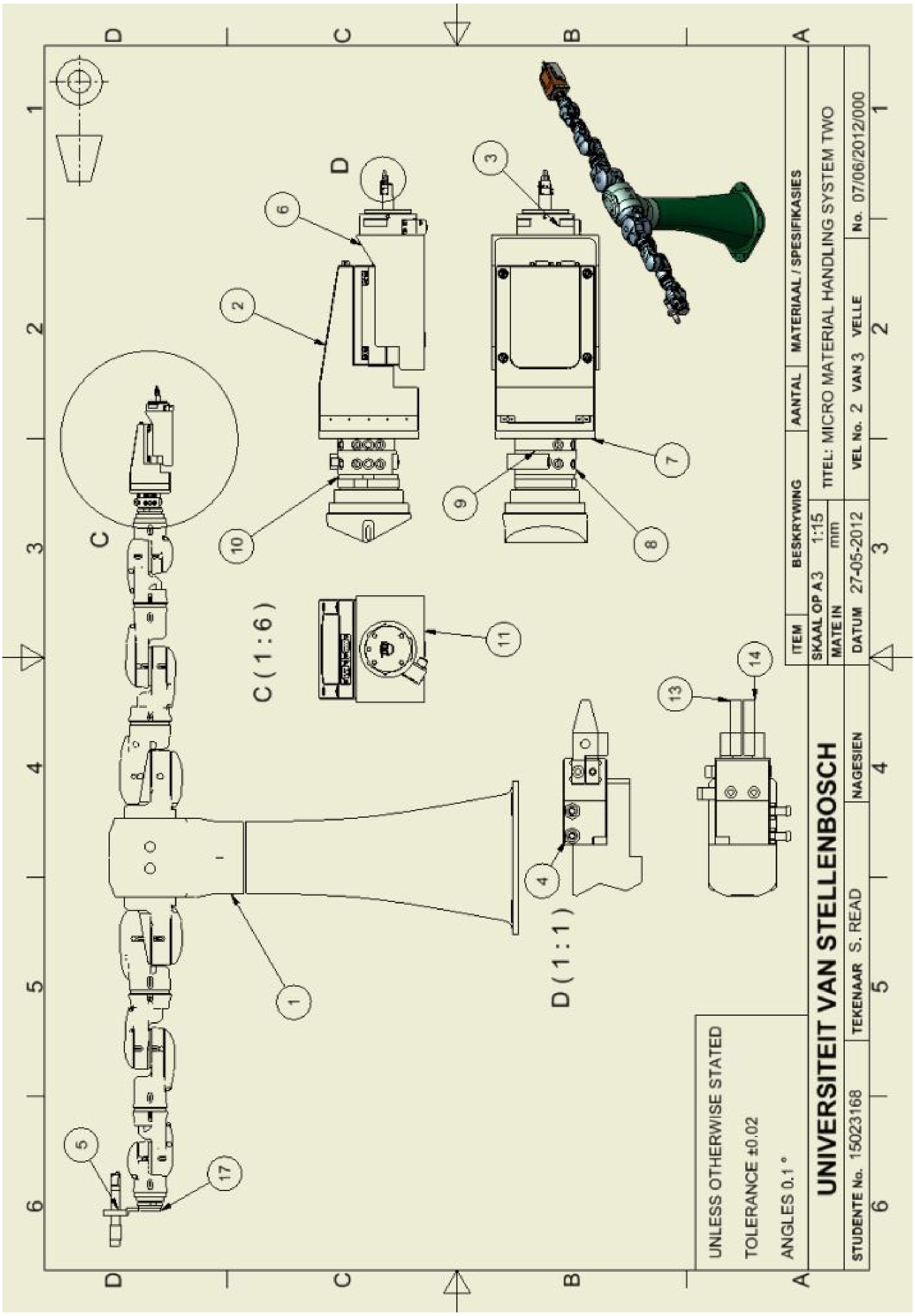

Figure F.3: Force Sensor Fine Positioning Mount Two

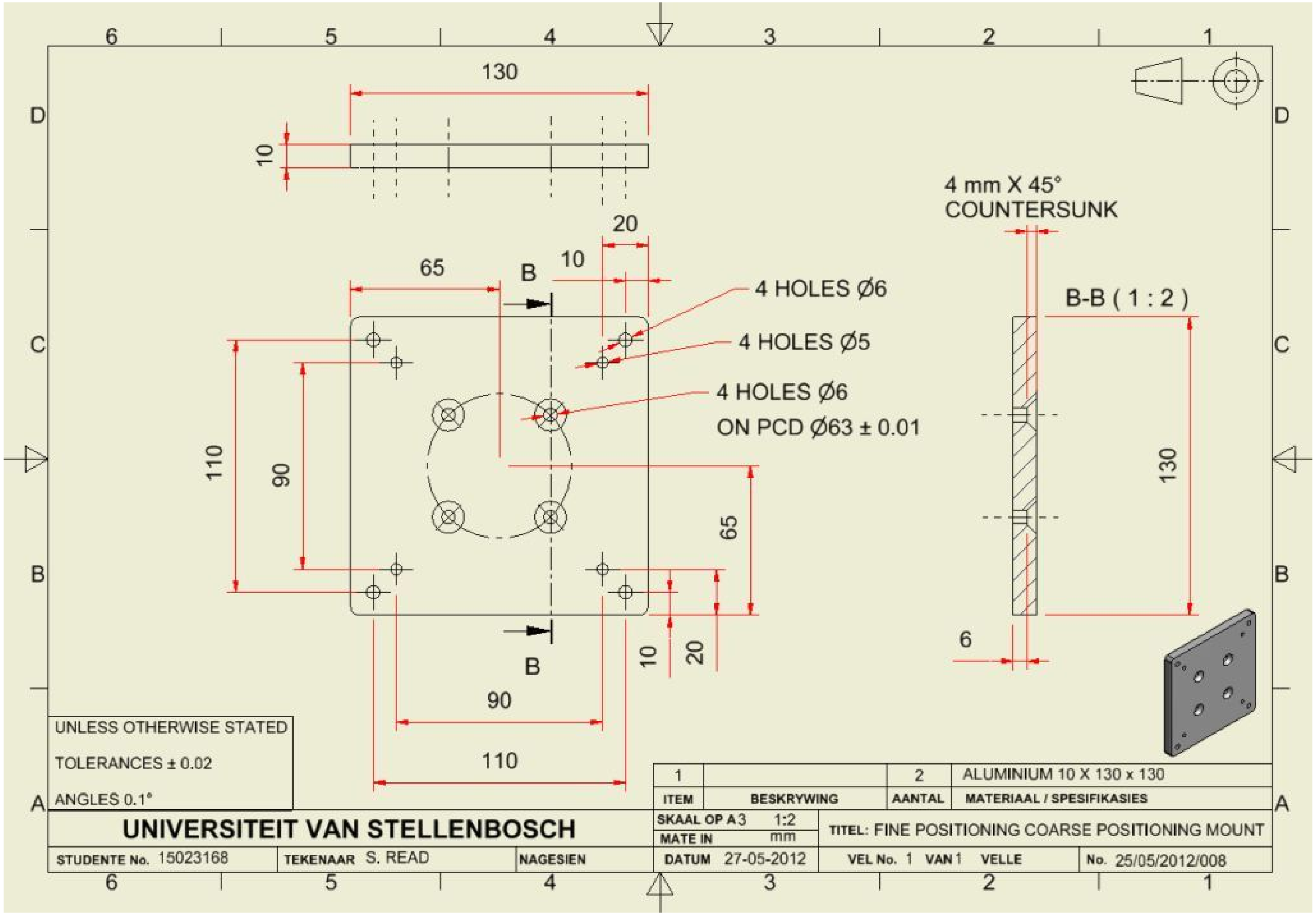

Figure F.4: Fine Positioning Coarse Positioning Mount

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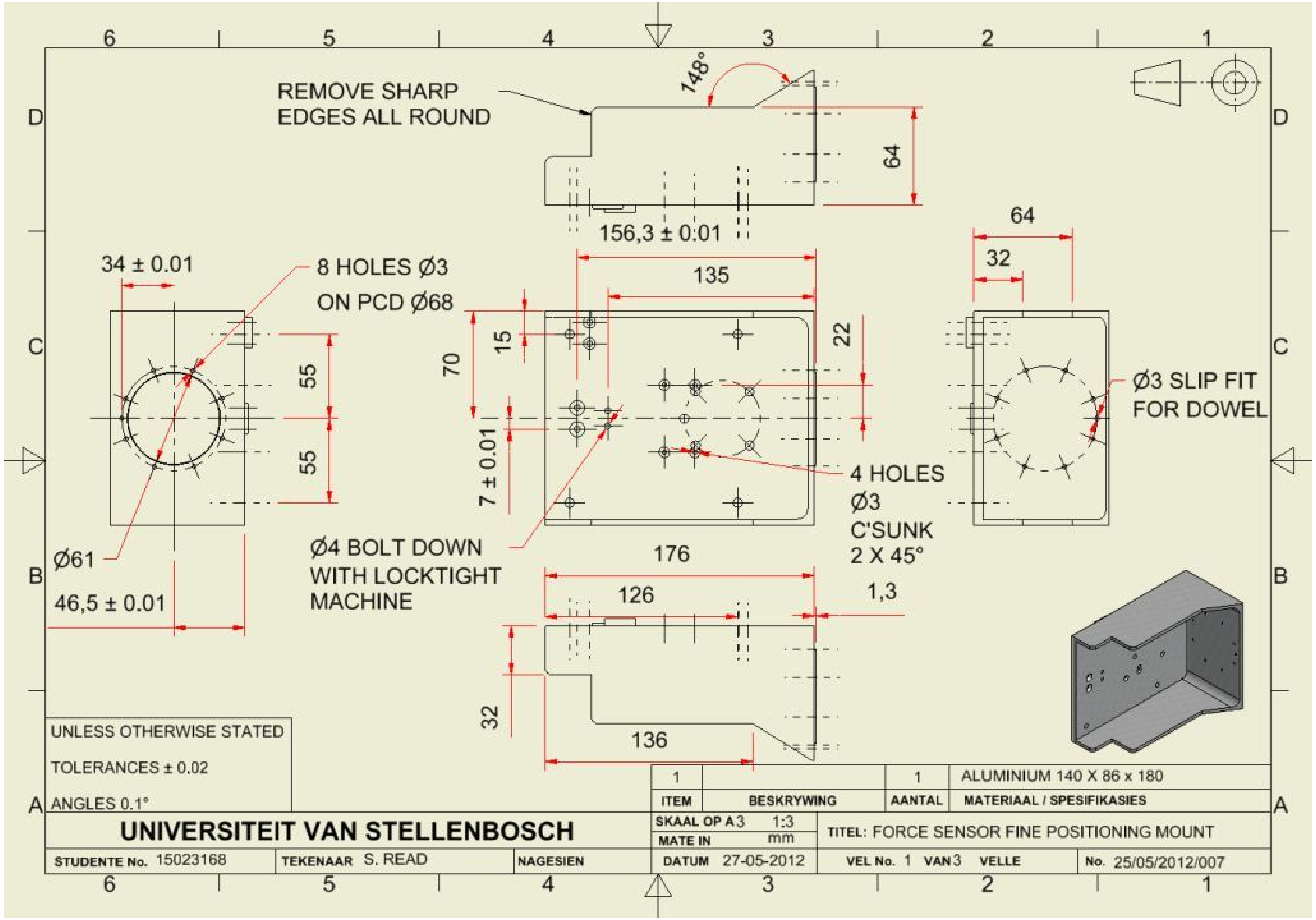

Figure F.5: Force Sensor Fine Positioning Mount One

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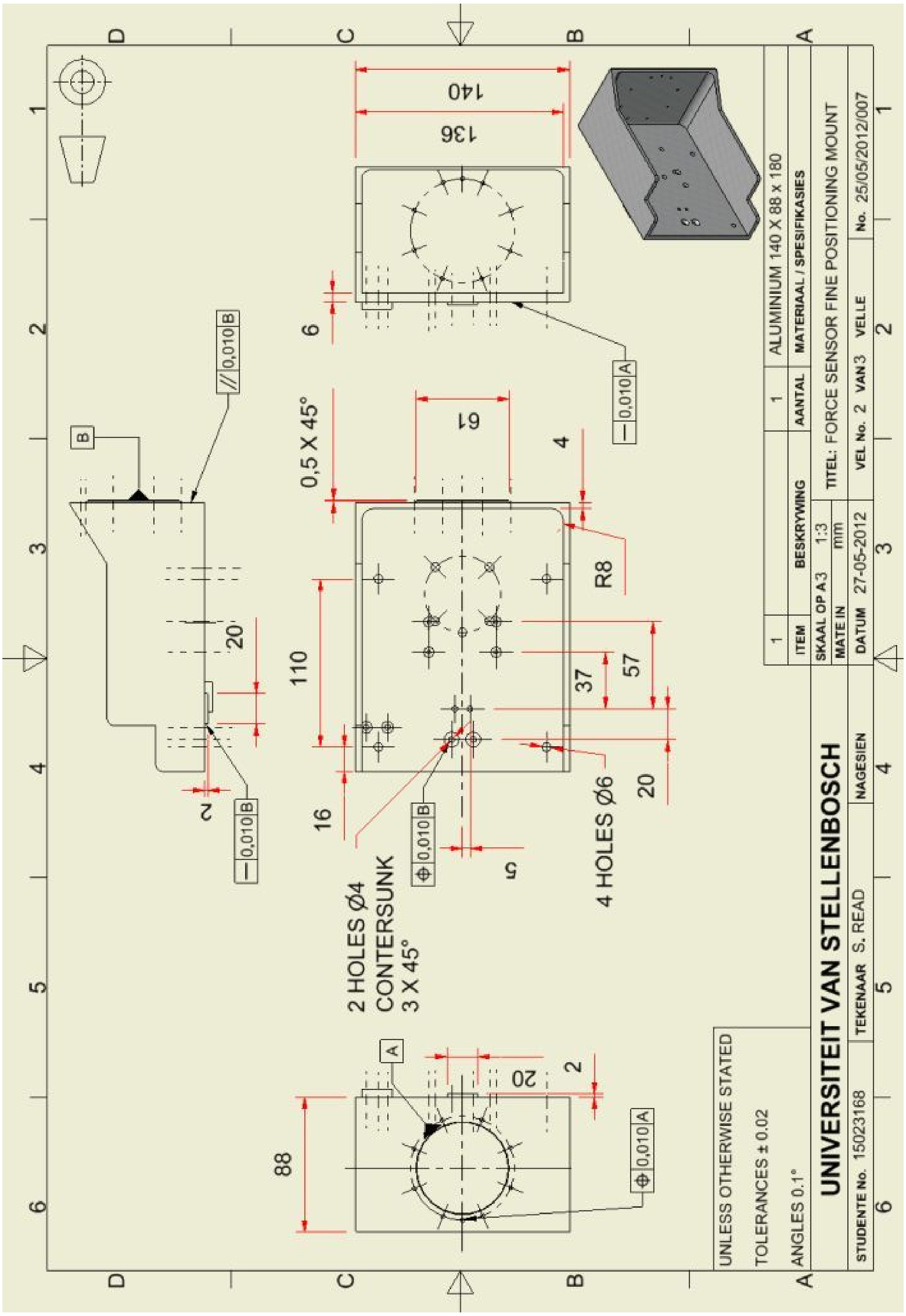

Figure F.6: Force Sensor Fine Positioning Mount Two

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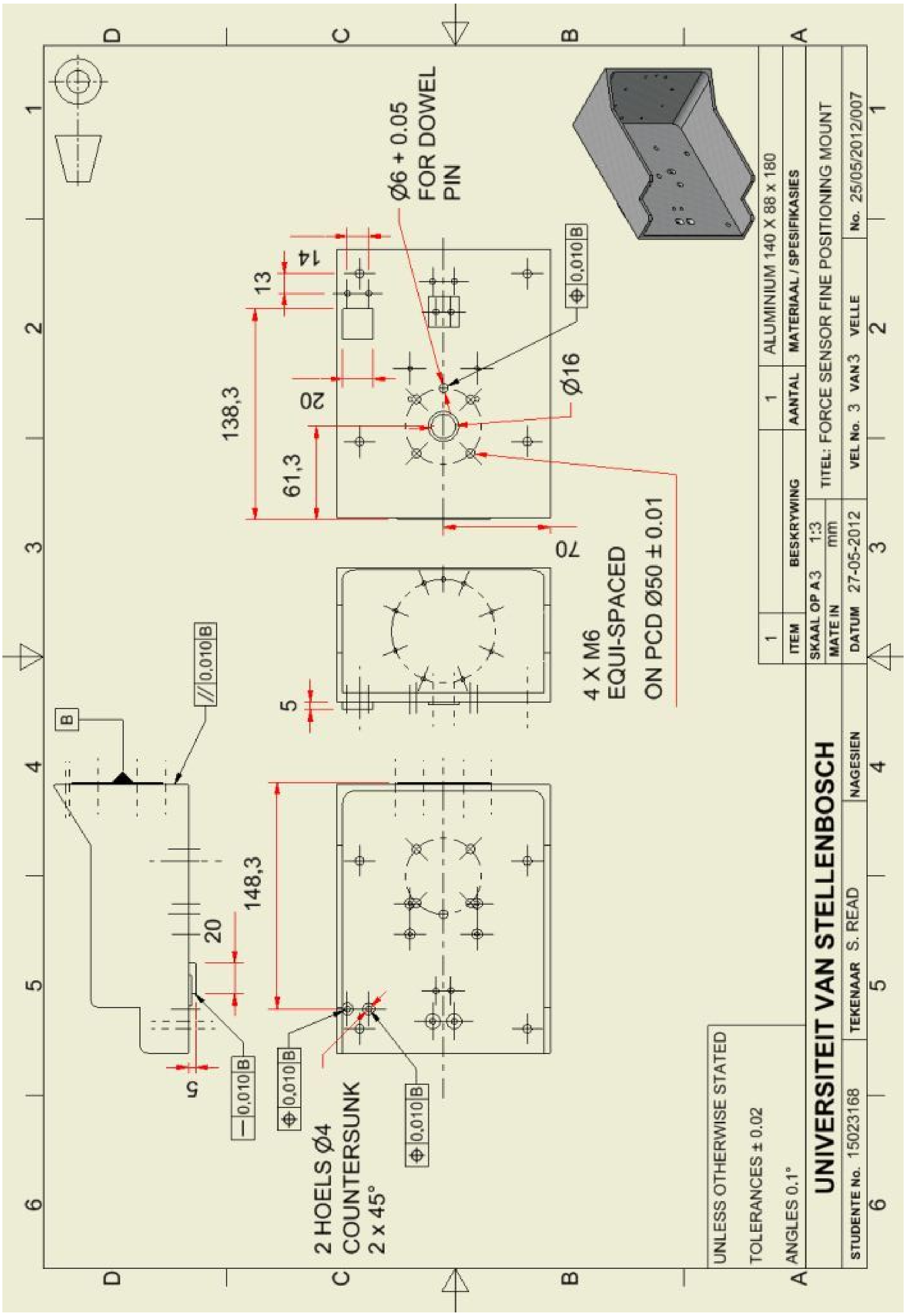

Figure F.7: Force Sensor Fine Positioning Mount Three

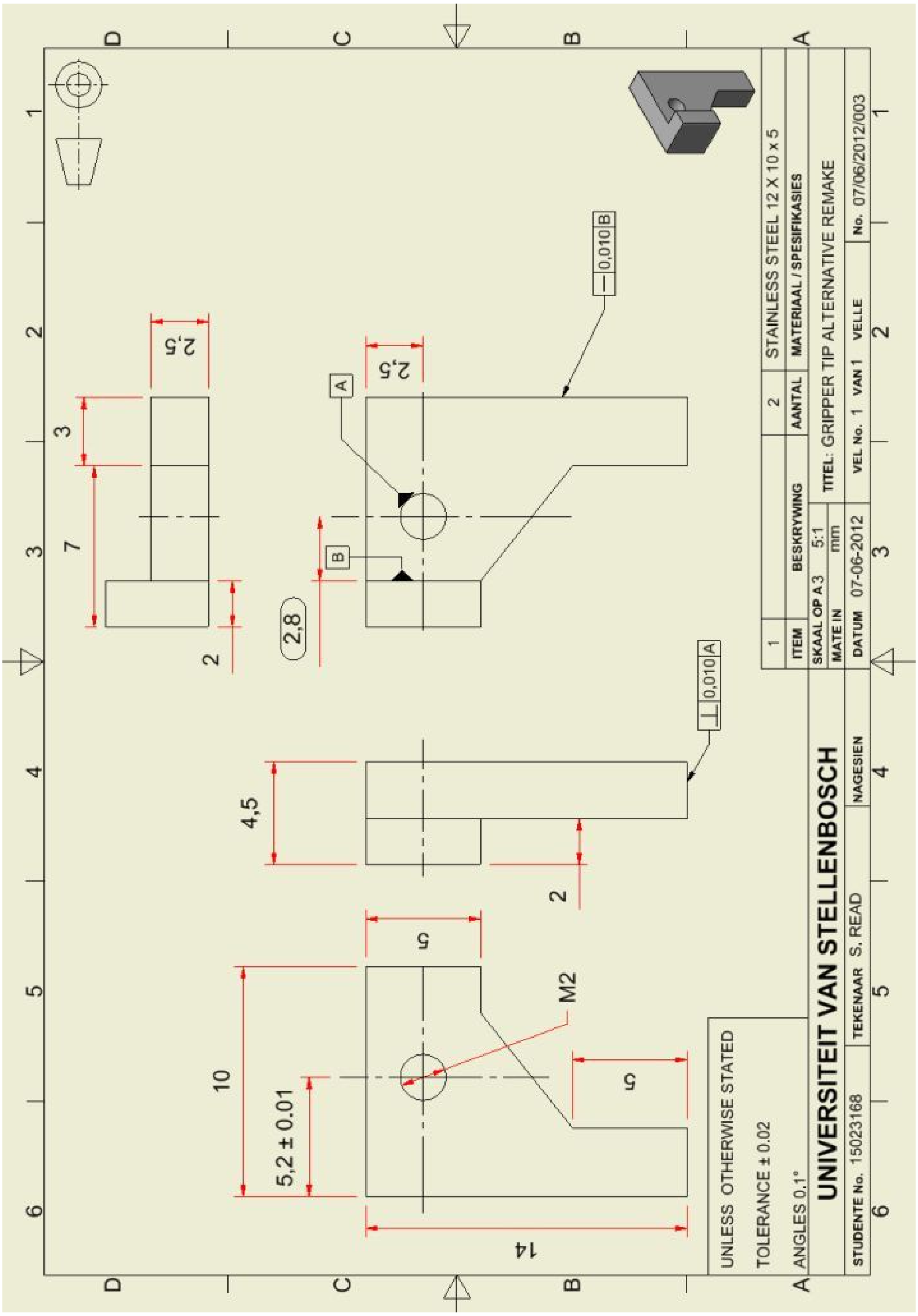

Figure F.8: Gripper Tip Alternative Remake

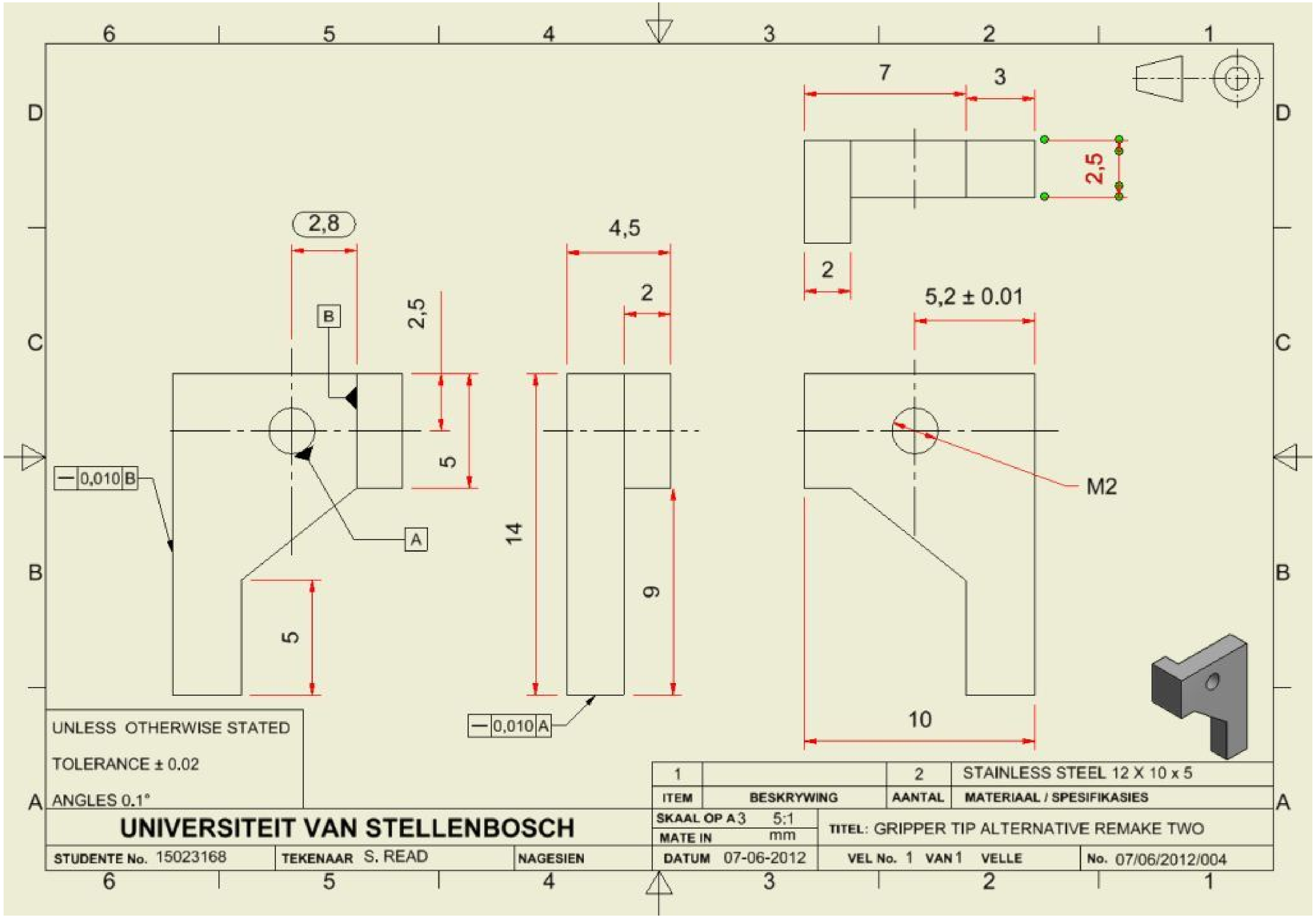

Figure F.9: Gripper Tip Alternative Remake Two

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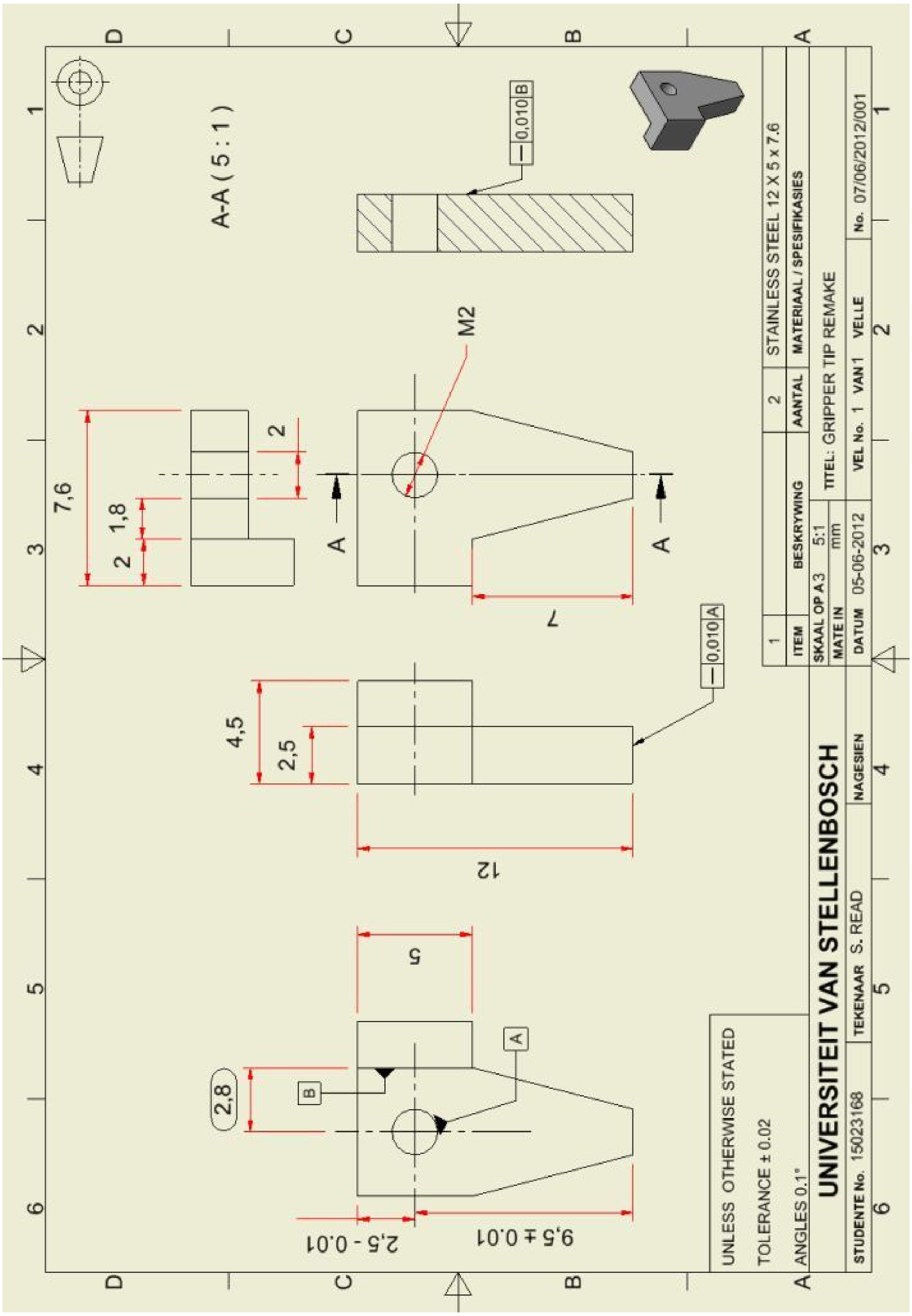

Figure F.10: Gripper Tip Remake

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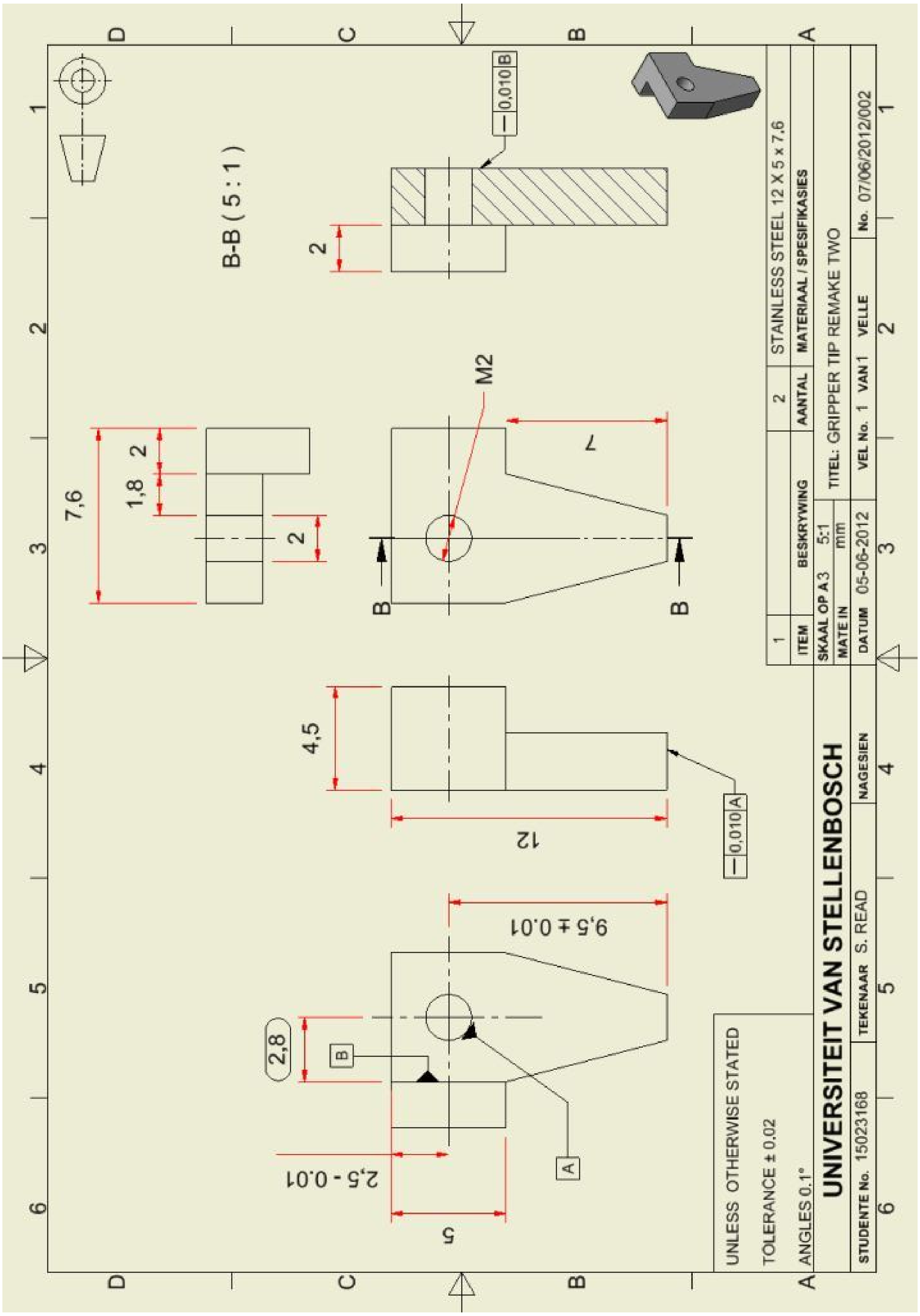

Figure F.11: Gripper Tip Remake Two

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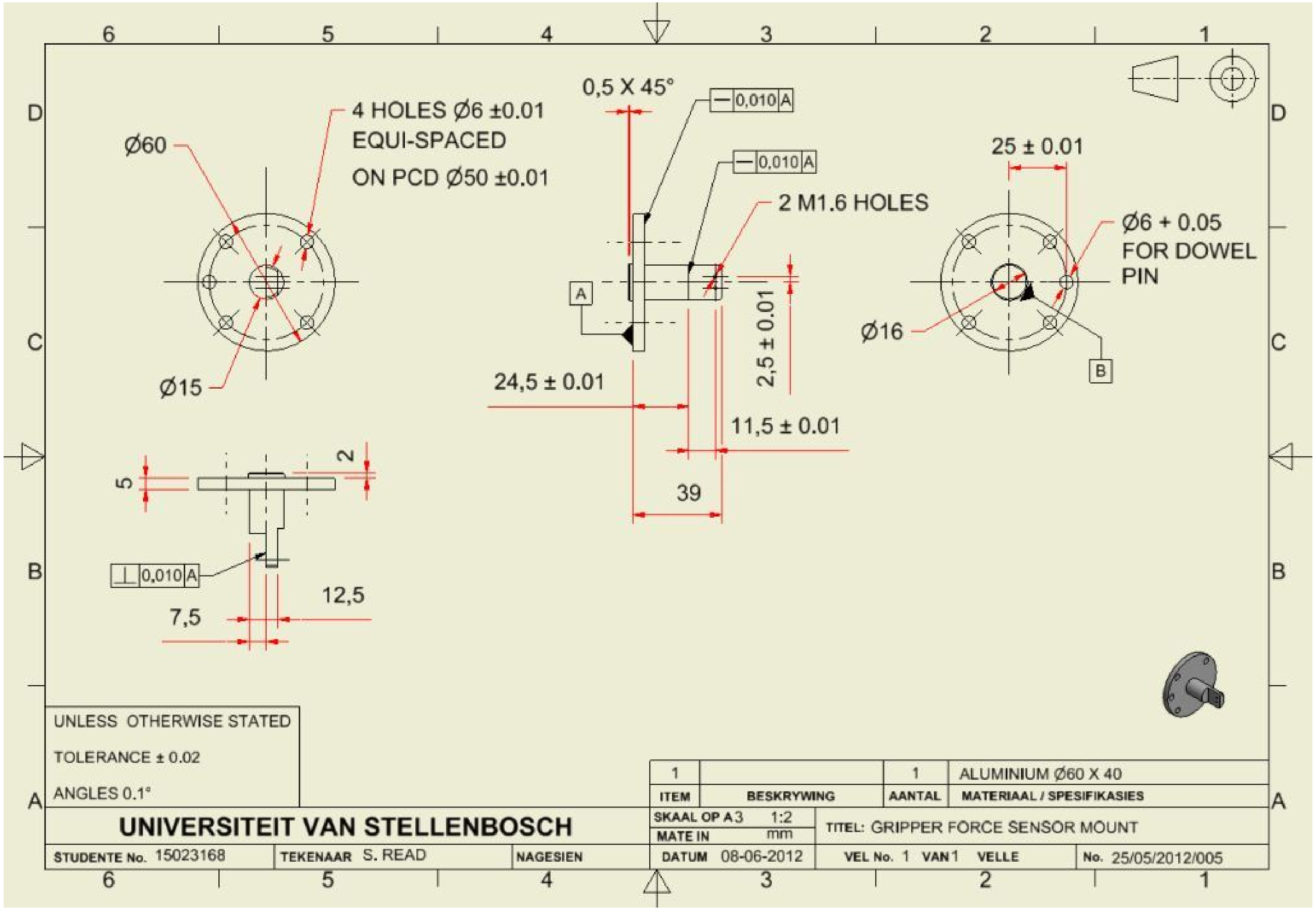

Figure F.12: Gripper Force Sensor Mount One

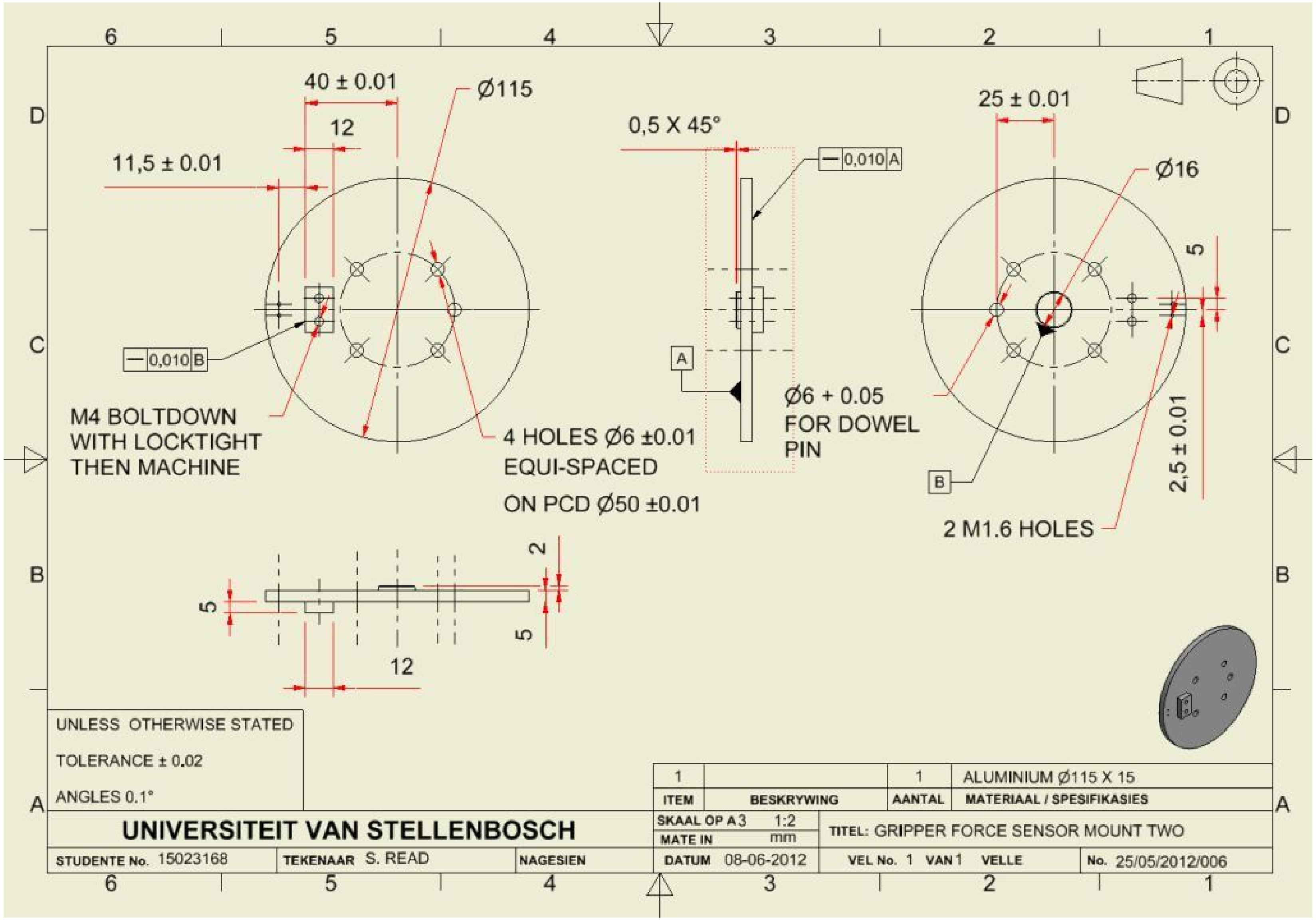

Figure F.13: Gripper Force Sensor Mount Two

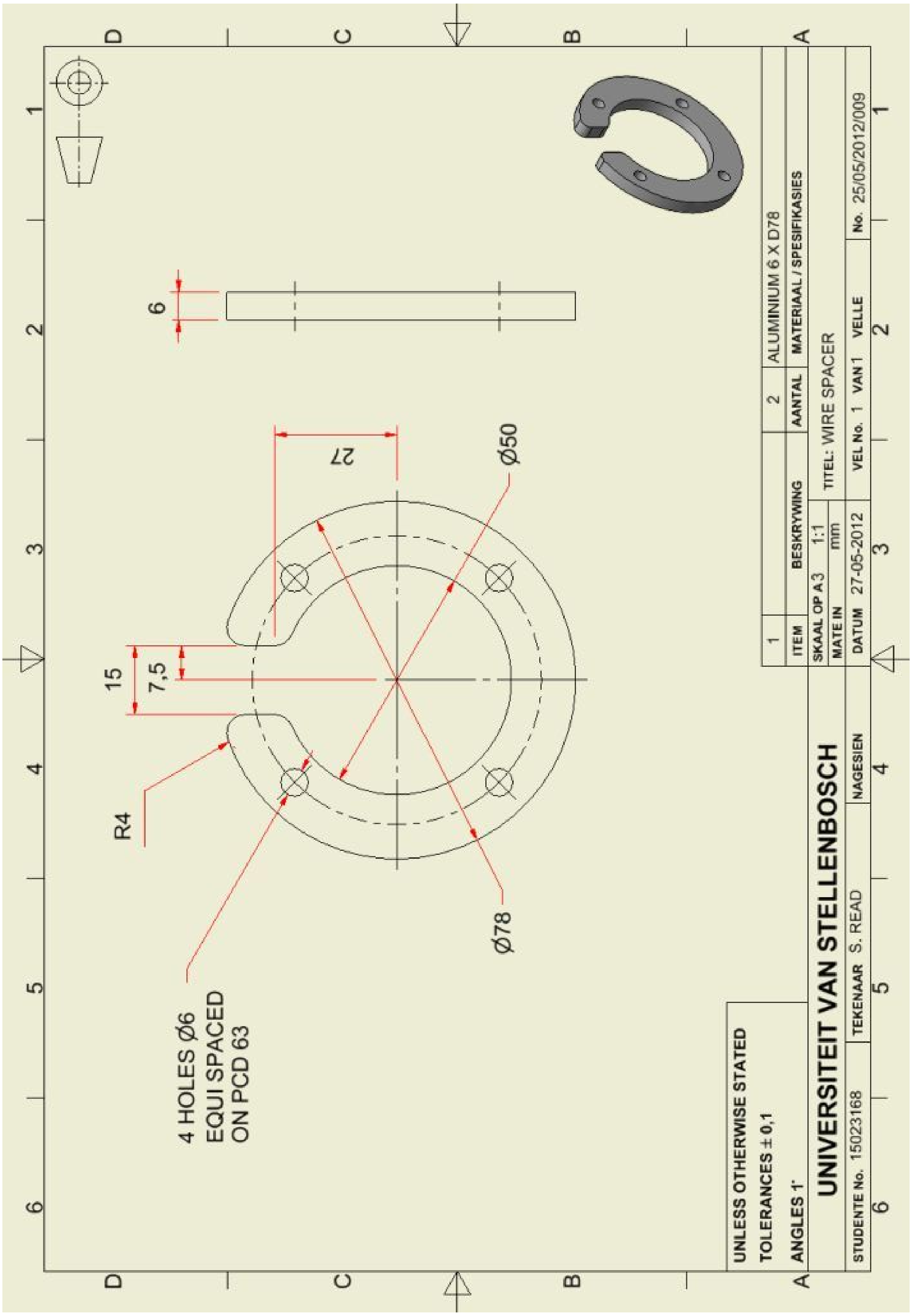

Figure F.14: Wire Spacer

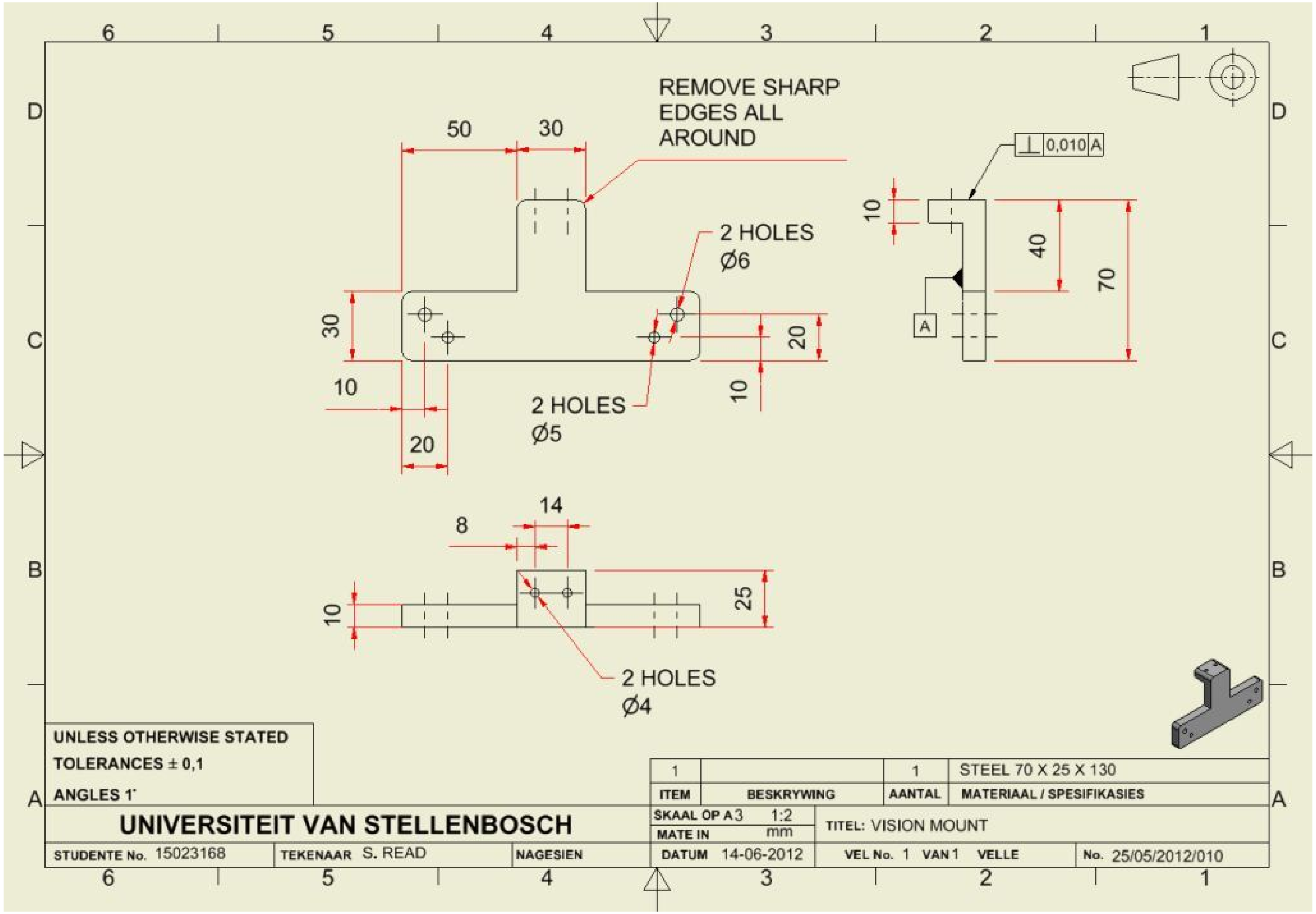

Figure F.15: Vision System Mount

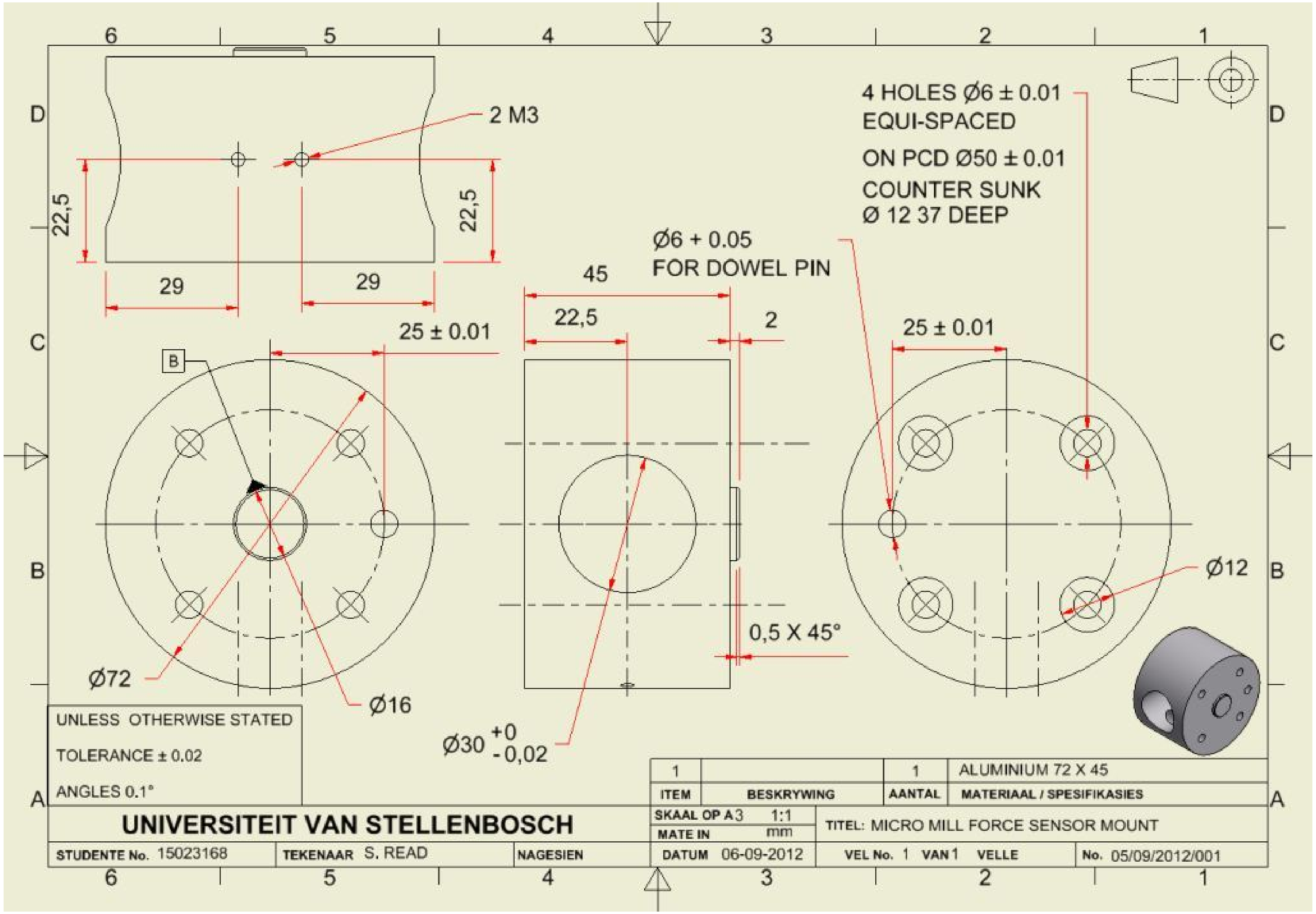

Figure F.16: Micro Machining Spindle Mount

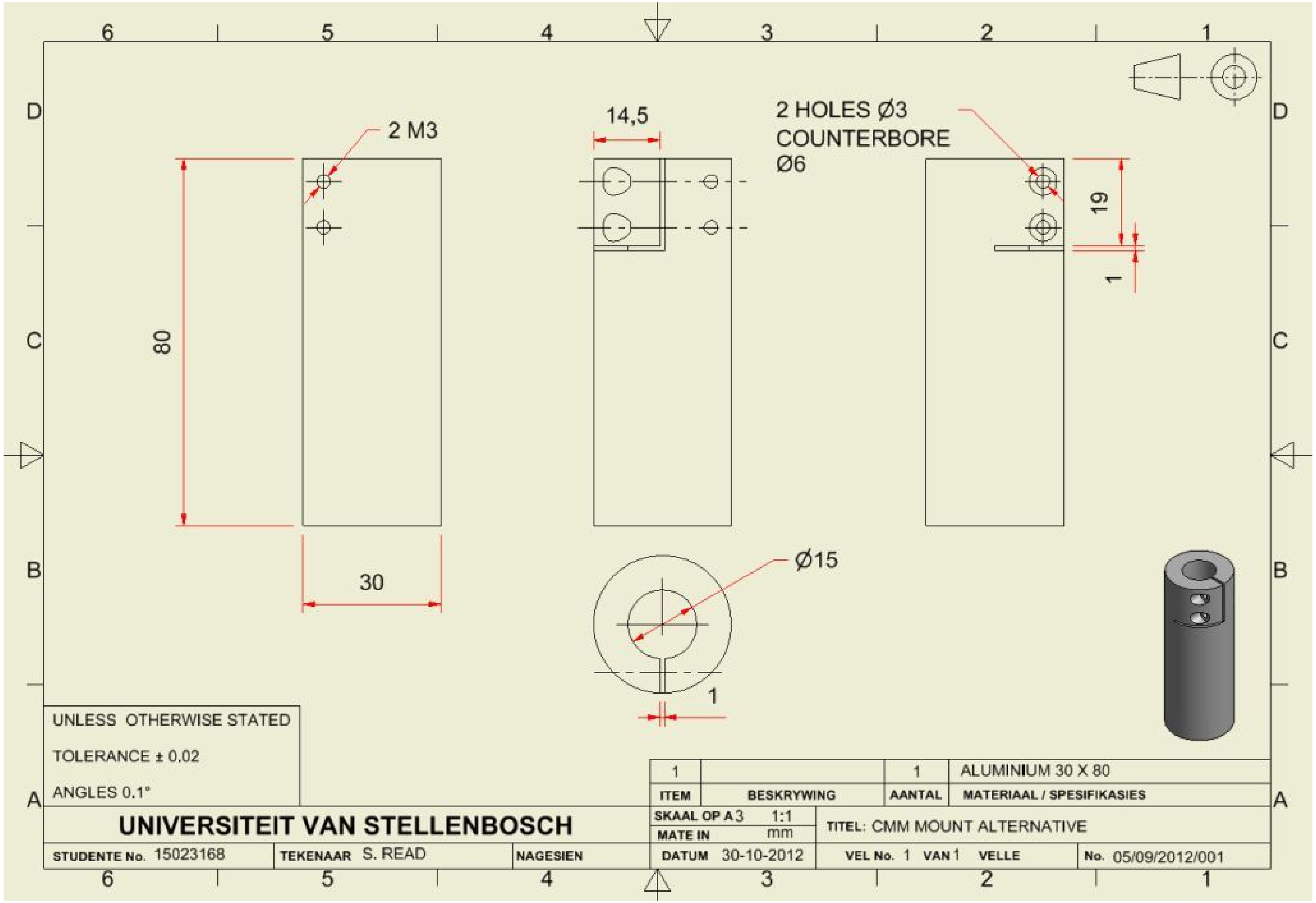

Figure F.17: Portable CMM Mount

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Appendix G

Project Risk

Department of Industrial Engineering
Failure Report - Feinmess Micromanipulation System
Equipment Failure Report

Andre Smit
9/14/2012

Sebastian Read
9/14/2012

G.1 Contents

G.2 Project Description

Project Title: **Development of a Micro Material Handling System**
Responsible Student: **Sebastian Read**
Lab: **SenRob**

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Supervisor: **Dr. A. F. van der Merwe**

Short Project Description:
There is a need for a micro material handling system that operates over a macro range (exceeding 500 mm). The research aims at creating a micro material handling system that is accurate, user friendly and reconfigurable. A pick and place case study in which piezo ceramic rods of 250 μm by 250 μm by 10 mm are placed in 300 μm by 300 μm by 10 mm cavities (to improve base material characteristics) is used to aid this system's development. Using a combination of systems engineering and innovation management techniques the system is designed, built and tested according to the needs of the case study. A Motoman robot fitted with a high precision Feinmess fine positioning system is used. The fine positioning system is in turn fitted with a micro gripper. This set the basis for integrating commercially available components into a micro material handling system which is capable of achieving a 5 μm repeatability in a pick and place case study.

Please Note:
This report is compiled by the **student** under supervision of a **lab assistant**.

G.3 Project Timeline

26-03-2012 Design commences on structure and housing
10-04-2012 System arrives
19-04-2012 System clears Customs/Stellenbosch University clearance
11-06-2012 Extensive Feinmess control software program (GUI) development
20-07-2012 Software development completed
30-07-2012 Structure and housing fabrication and assembly completed
01-09-2012 Implementation of custom control software, Implementing Force Teach
09-09-2012 Spark and Failure of : Z Axis, and Limit Switch on X Axis

G.4 Installation Procedure

The Feinmess MP130 system was attached to the Motoman SDA 10 using the Fine Positioning to Coarse Positioning Mount (Figure 1 (a)). The force sensor, gripper, camera and lens were all attached to the Feinmess system using the Force Sensor Fine Positioning Mount (Figure 1 (b)).

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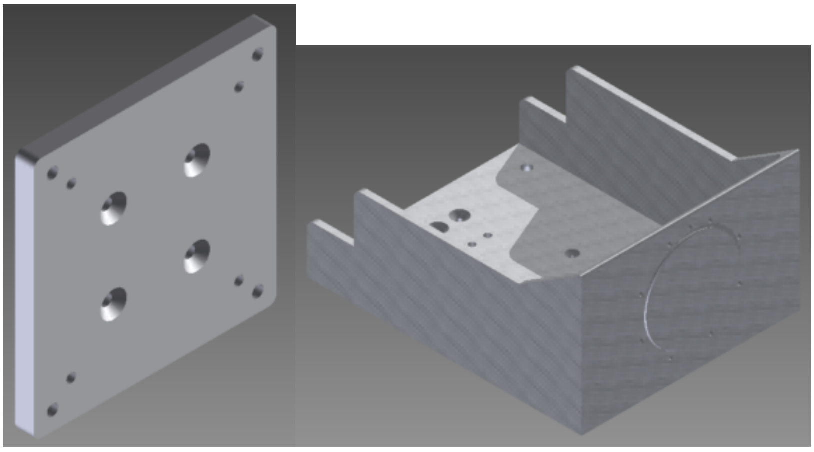
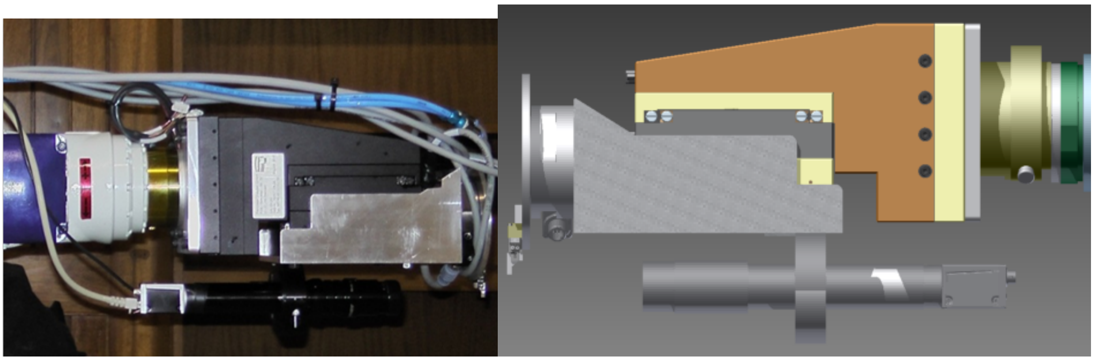


(a) (b)

Figure G.1: Figure 1 - Mounting Fixtures

Once all the manufacturing had been completed, the Feinmess system was assembled as seen below. Only holes specifically provided for mounting were used. No physical or electrical alterations were made to the Feinmess system or controller.



(a) (b)

Figure G.2: Figure 2 - Final Assembly

The assembled system was used in the orientation as seen in Figure 3 (a) and (b).

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(a) (b)

Figure G.3: Figure 3 - Final Position

G.5 Alteration to base system

The metal housing of the x cable was removed at the point of contact to the MP 130 system. This was done in order to increase the range of movement of the system. In addition to this the housing of the y cable was removed. Alwyn Burger a fourth year electrical and electronic engineering student assisted in the re-soldering of the y axis to a 90 degree 15 pin d-sub female. This re-soldering was done using the configuration from the x and z cables (all cables are wired in the same manner, as per the Feinmess hardware manual). This re-soldering was executed around the 20-07-2012. Perfect functioning of the system continued until 09-09-2012.

(a) (b)

Figure G.4: Figure 4 - Connector Re-soldering

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G.6 Failure Identification

G.6.1 How the failure was first suspected

From the beginning of the assembly and usage of the system 30-07-2012, a slight electrical 'sensation' noticed when contact was made with Feinmess Fine Positioning Coarse Positioning Mounting Plate. This sensation was felt continuously throughout operation.

On Sunday 09-09-2012 electrical 'sensation' seemed to be more pronounced than usual. After further use, a spark was seen. System use was immediately stopped. All power was switched off. System was immediately dismounted from Motoman SDA 10. All plates and equipment were removed from system.

G.6.2 Trouble shooting and failure identification:

The initial electrical 'sensation' felt on the 30-07-2012 was initially attributed to a slight short circuit. This minor fault was ignored for a number of reasons. The 'sensation' proved to be without a doubt no risk to the health and safety of any operator. The 'sensation' did not affect function of the Feinmess MP130 system in any way. There were numerous tests to be executed and a thesis to complete. It seemed there was no need to pursue the slight fault correction in light of the deadline of the overall project. The system was operated with the slight fault for 2 months without any incidence.

After the spark incident, as stated the system was completely detached from all mountings and components. The 'naked' system was then visually inspected. Upon closer inspection, a black mark was found on the bottom of the X-Axis (See Figure 4 and Figure 5). Further testing was completed using the provided WSDK as well as the programmed GUI.

G.6.3 Final Failure Identification

After the above testing with the WSDK and the GUI, it was found the Z-Axis of the system was at fault. Any command issued to the Z-Axis would result in it moving at full speed to the end of its axis and then stopping. It was clearly a problem with the encoder of communication hardware.

After uploading and executing the test program provided for by Galil it was noticed that the x axis would not register its' limit switch. Similar information was obtained by testing with the programmed GUI. It was clear the

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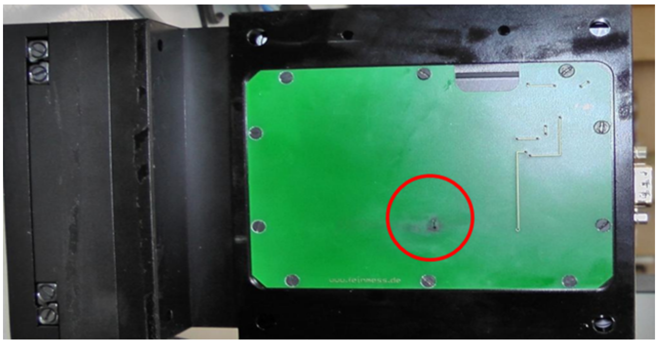

Figure G.5: Figure 5 - Failure Spark Point

Figure G.6: Figure 6 - Failure Spark Burn

limit switch of the X-axis was broken.

G.6.4 Confirmation of Failure with relevant staff:

Failure confirmed with Dr. Andre Van der Merwe on the morning of 10-09-2012. Failure was confirmed with Andre Smit (Lab Assistant) on the morning of 13-09-2012.

Poetschke, Maria (FMD) of Feinmess in Dresden Germany was notified of the failure on the 10-09-2012. Photos and a description of the error were included in an email, forwarded to Dr. Andre Van der Merwe. Further communication ensued.

G.6.5 Failure Reporting Procedure

1. General lab equipment (not pertaining to specific project) failure:
a. Stop all further use:

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i. Notify lab assistant immediately which will assess the situation.
ii. The handling of the failure will be the responsibility of the lab assistant from this point onwards.
b. It is the sole responsibility of the student involved to use the equipment (faulty or operational) in a safe manner, with reasonable care.
2. Specialised (project specific) hardware/ software failure:
a. Stop all use of the equipment immediately:
i. Stop the use of the piece of equipment as soon as possible, this must be conducted in the safest way possible without risk of injury to any person or property.
ii. Notify the person responsible for the equipment asap. For example: Study leader, lab assistant etc.
1. This person will be responsible for arranging fault finding or troubleshooting.
b. Supply the person responsible for the equipment with full documentation:
i. When was the equipment received along with a time line of events that might have contributed to the failure.
ii. What alterations were made to the system, both mechanical and electrical and all software changes.

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Appendix H

Control Code

The square boxes represent actions to be executed. The circles represent choices. The squares that have a corner missing represent a button on the gui.

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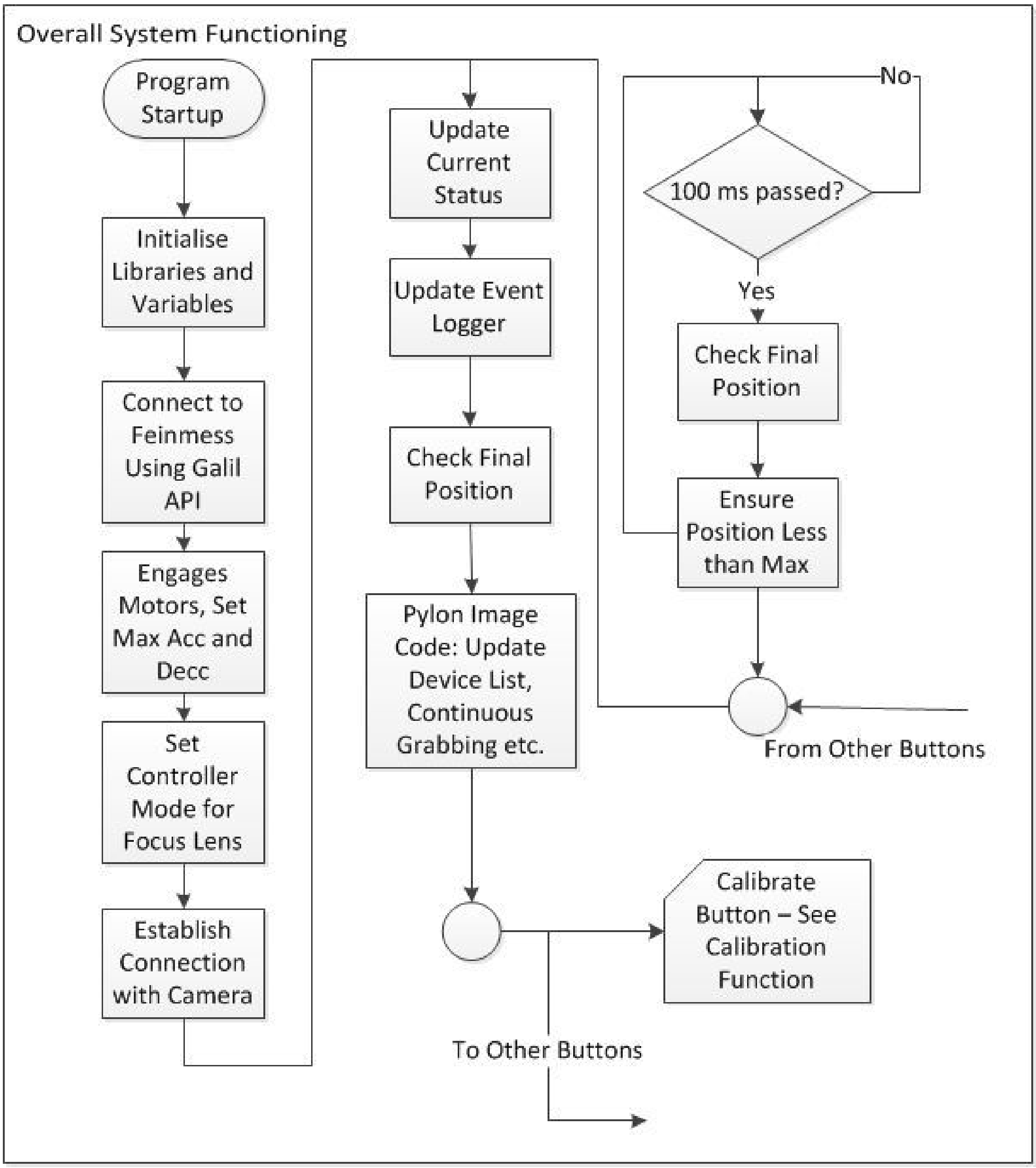

Figure H.1: Overall System Functioning

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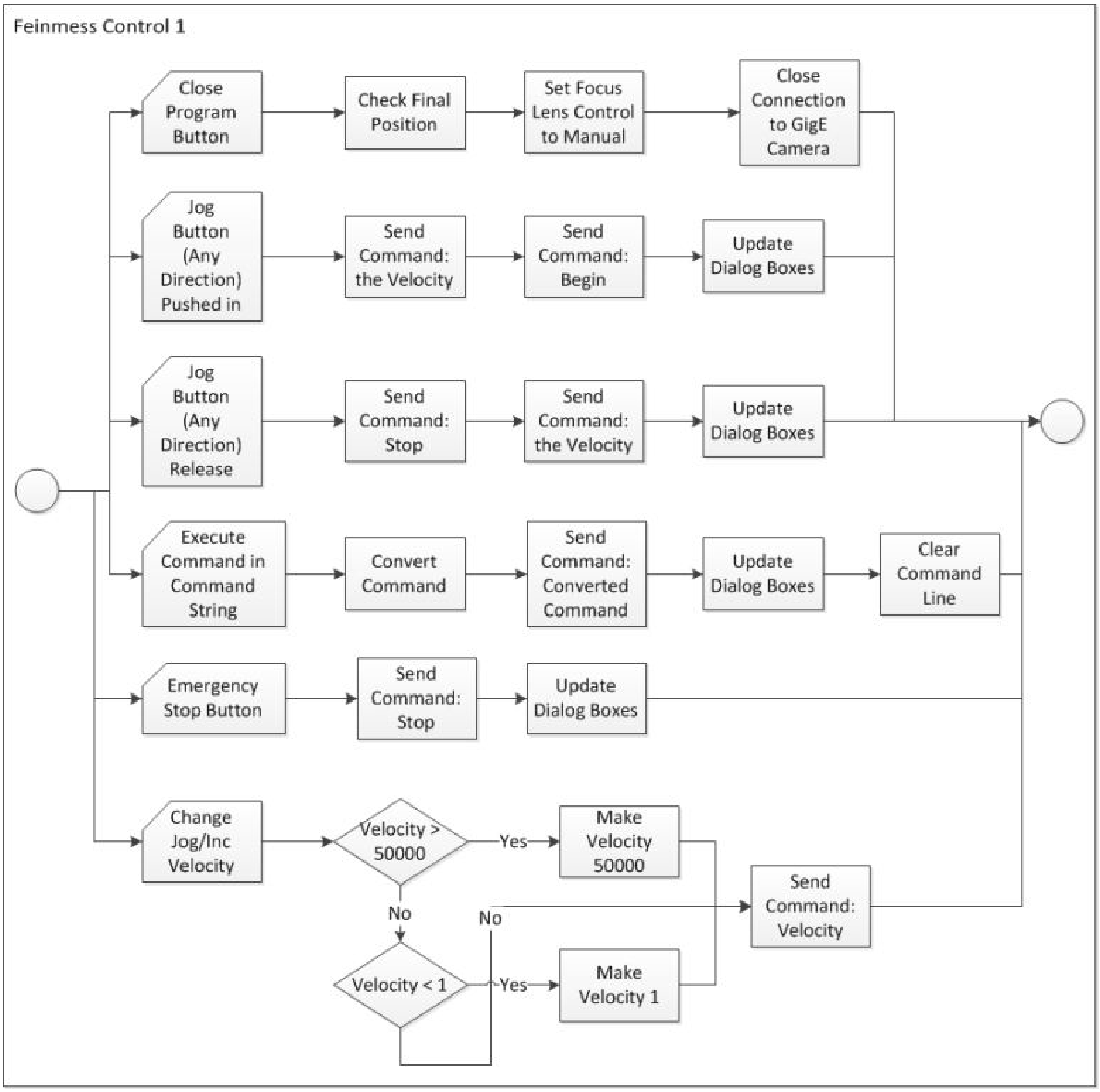

Figure H.2: Feinmess Control Code 1

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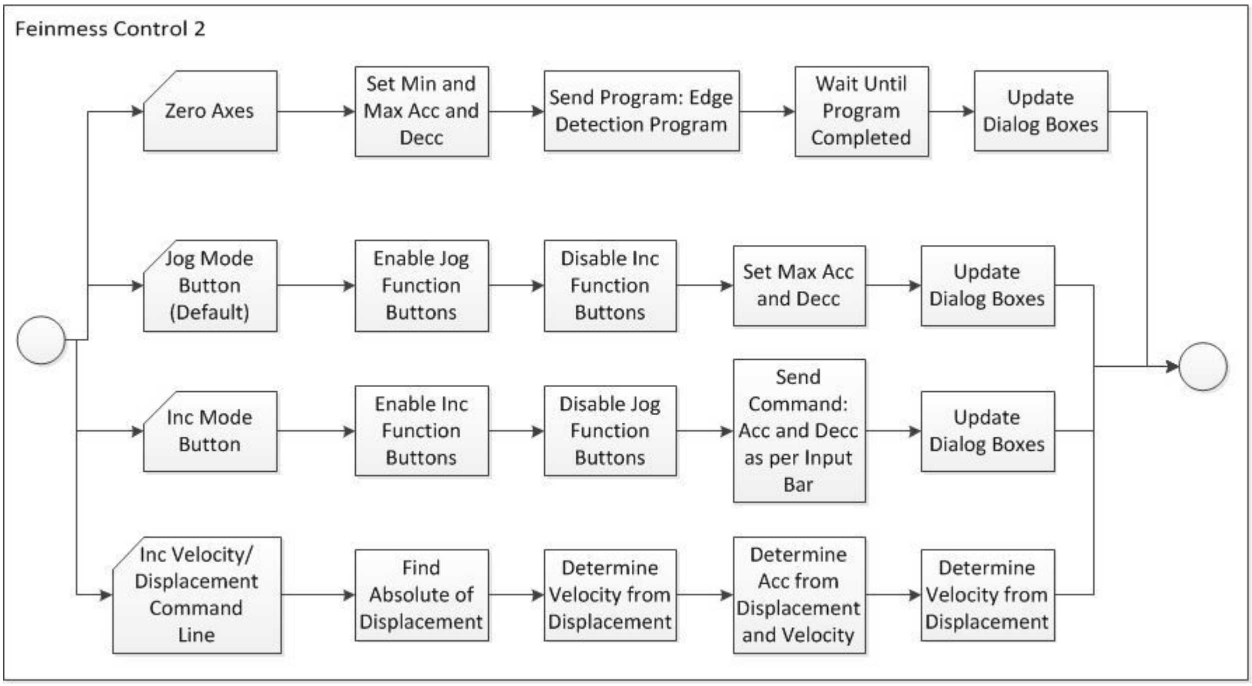

Figure H.3: Feinmess Control Code 2

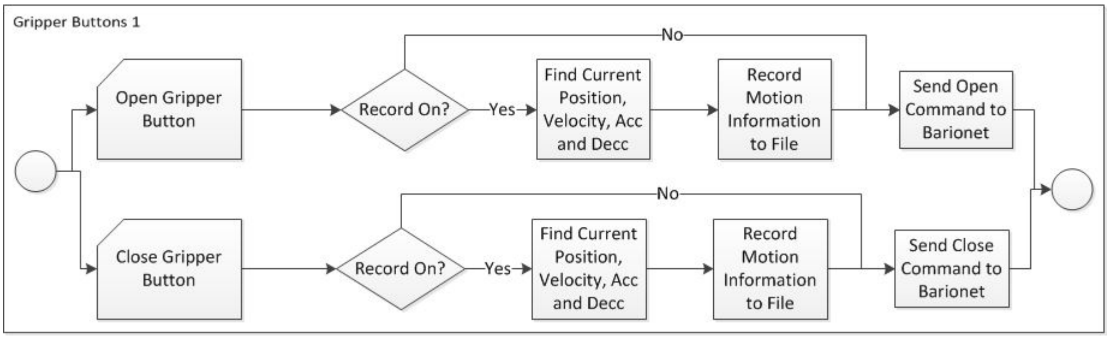

Figure H.4: Gripper Buttons 1

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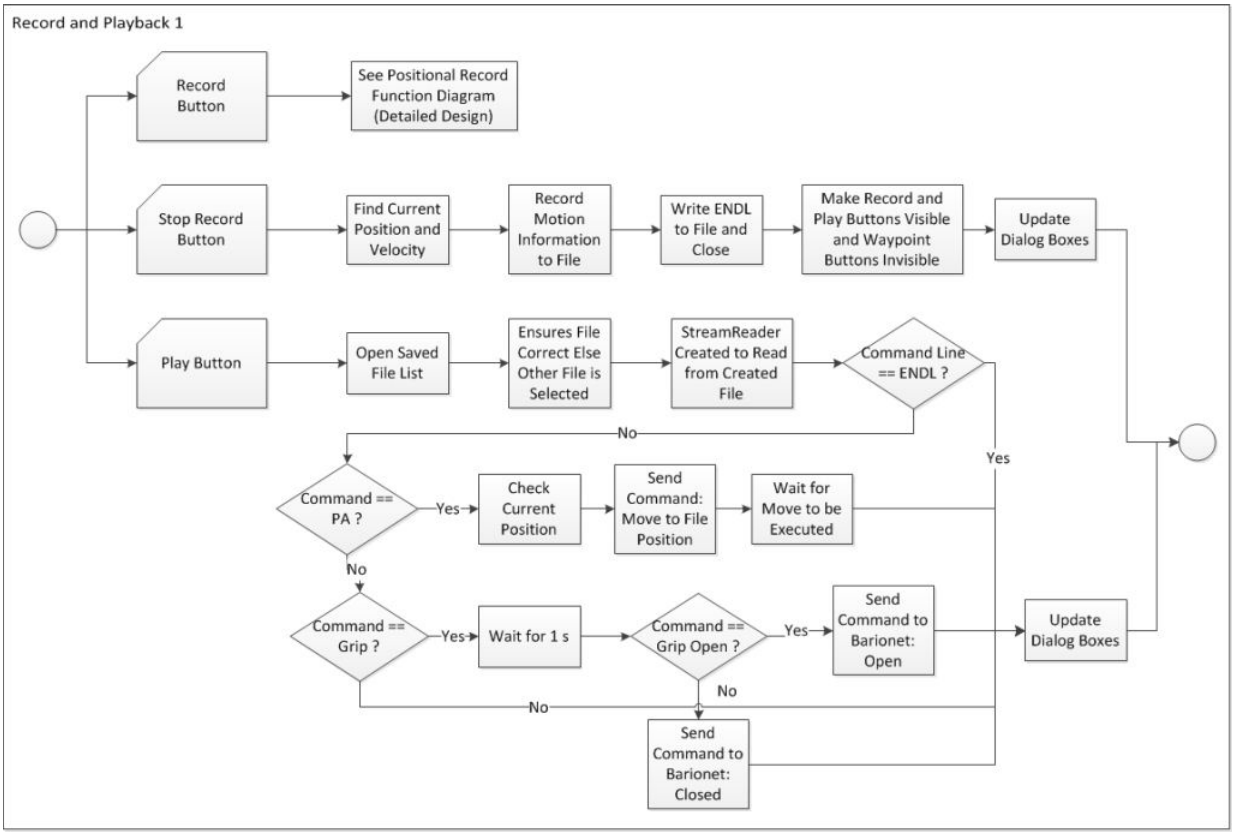

Figure H.5: Record and Playback 1

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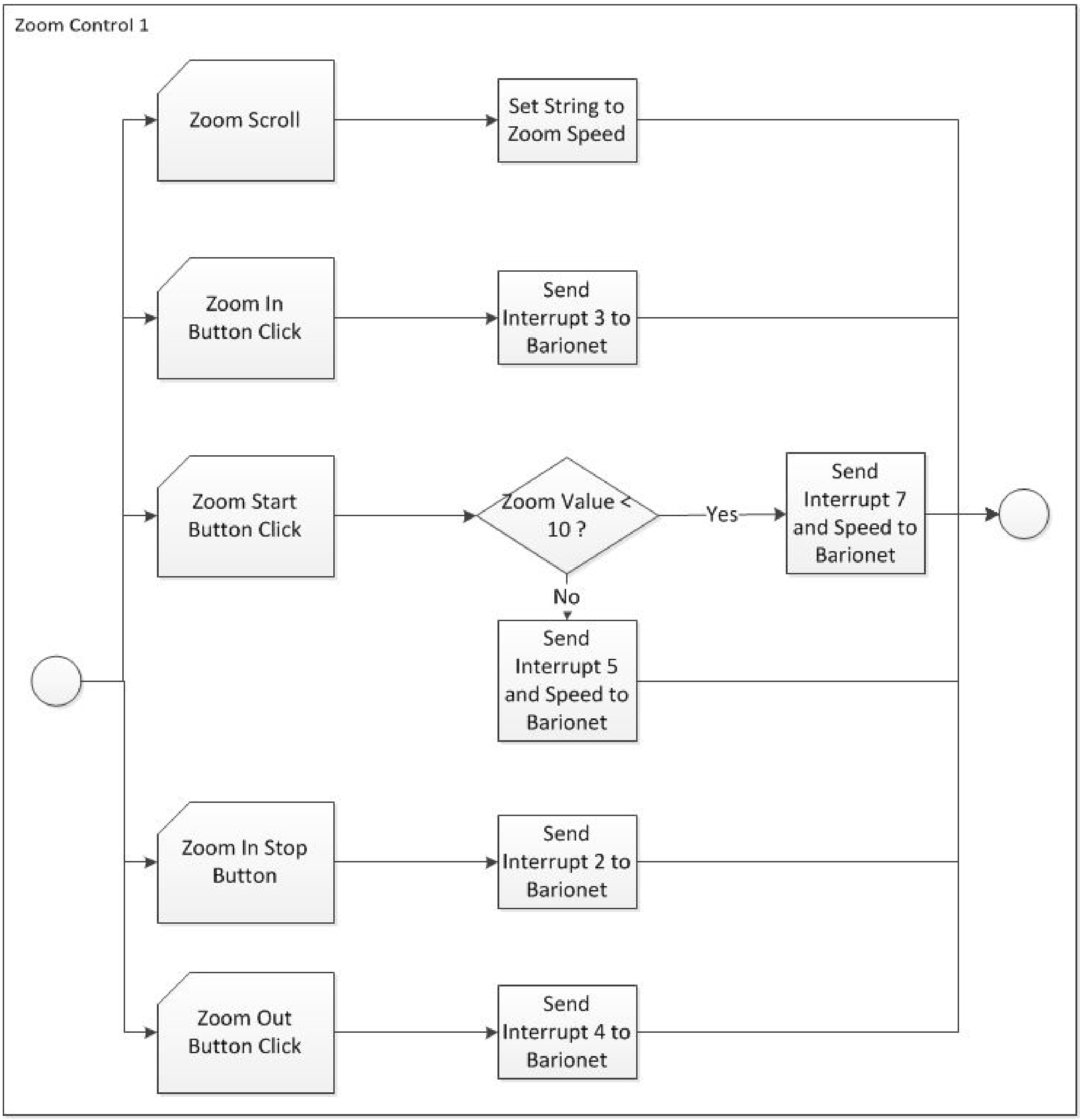

Figure H.6: Zoom Control 1

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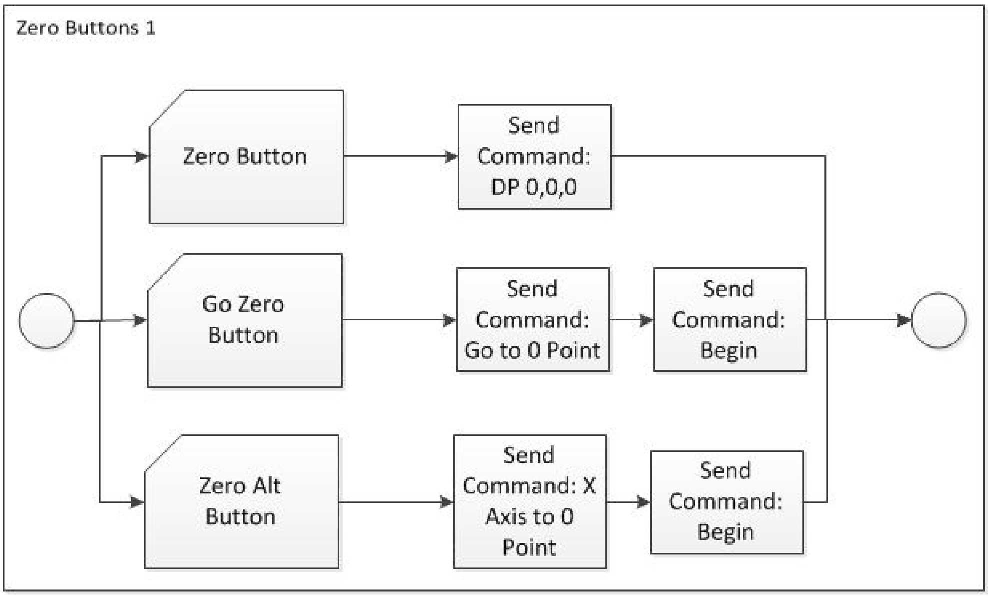

Figure H.7: Zero Buttons 1

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Appendix I

Interviews

①

Sebastian Read
17-09-2012
15023168

Micro Milling Application Interview
Development of a Micro Material Handling System

Interviewer: Sebastian Read
Interviewing: Mike Saxer

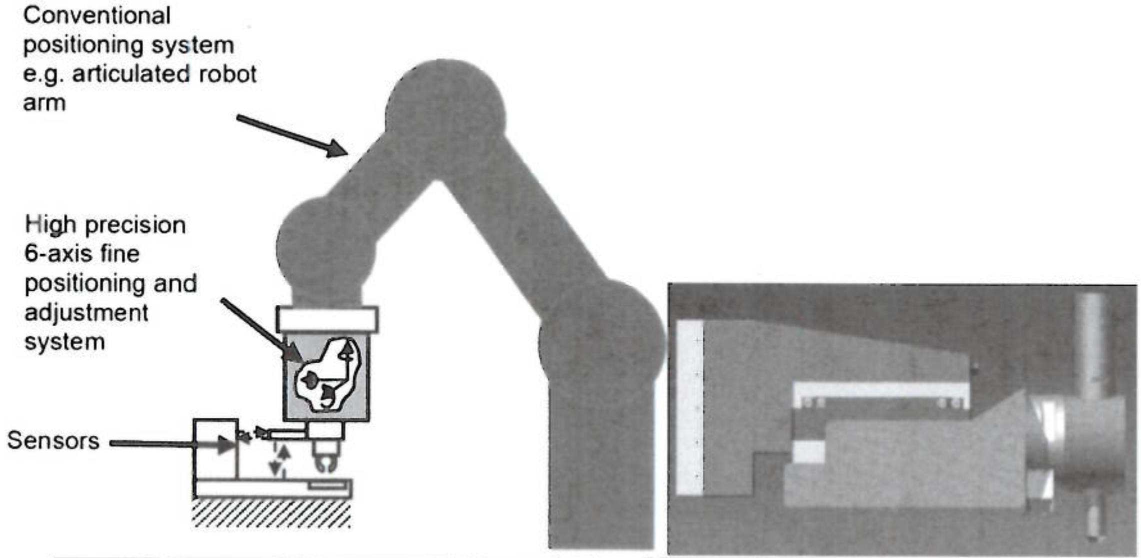
Date: 18-9-2012
Time at Start: 9:42.
Time at Finish: 9:58.

Detail of Person Interviewed

Qualifications:
Diploma Mech Eng (Switzerland).

Experience in Field of Micro Machining and Robotics:
• Years Work Experience as CNC Maching Expert:
>8 - Switerland for studies and for Work Experience, - 2 years in UK.
>4 - Stellenbosch (Prothetics Manufacturing).

Explanation of System



Coarse to Fine Positioning System

Fine Positioning System with Spindle

Micro Milling/Drilling

Feasibility of Micro Drilling as a Test Methodology?
- Vertical Movement
* - 2 mm Drill bit for feasibility; for Stability. Use it as a start
* - Pecking: Peck at hole, on a 2mm drill bit for Al, use 0.5 mm peck depth

①

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Feasibility of Micro Milling as a Test Methodology?

- Cutting; forces and torques all acting on toolbit.
- Might be possible, not likely

✱ - Use 4mm tool bit to start off with.

Accuracy/Repeatability Predicted?

- 0.1 mm, tolerance of shape to be machined

Problems Predicted?

- Slight vibrations / runout will destroy tool bit
- Wobble of tool bit (Run Out).
- Have to ensure tool bit 100% true, no runout.
- Serial Kinematics - large Error

Other Considerations?

- Must have a high speed spindle.
  Smaller tool - larger speed
  Larger tool - slower speed
- Must lubricate process; use tap oil
  Al shavings stick to tool bit.

✱ - Al is best metal, rather start off with high density foam.

- Prove concept on foam, then decrease tool size, then switch to Al with large tool bit.

Signature of Person Interviewed

Signature of Interviewer

②

Sebastian Read
17-09-2012
15023168

Micro Milling Application Interview
Development of a Micro Material Handling System

Interviewer: Sebastian Read
Interviewing: Theuns Van Schalkwyk

Date: 19-9-2012
Time at Start: 11:30
Time at Finish: 11:45

Detail of Person Interviewed

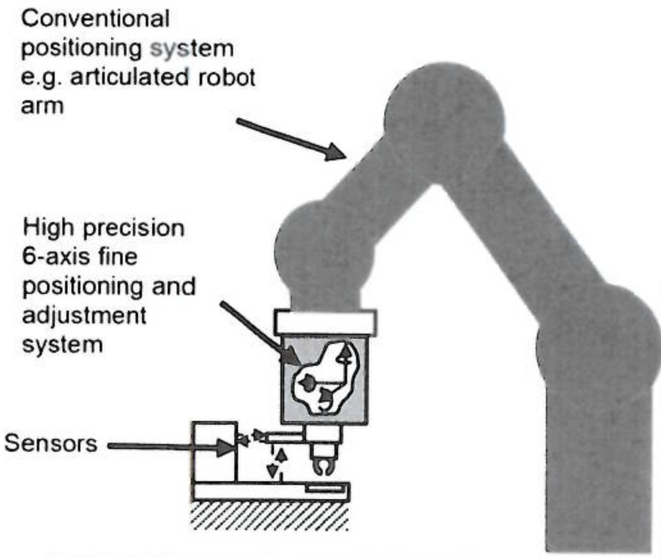
Qualifications:

MEng (Industrial)
BEng (Mechanical)
HBA (Administration)

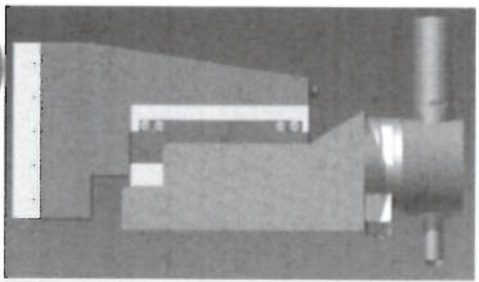
Experience in Field of Micro Machining and Robotics:

- 2 years full time equivalent micro machining experience
- 2 journals, 2 conferences in micro machining

Explanation of System



Coarse to Fine Positioning System



Fine Positioning System with Spindle

Micro Milling/Drilling

Feasibility of Micro Drilling as a Test Methodology?

- Dependent on accuracies of tools involved
- Depth testing might be difficult
- Drilling self centres.

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Feasibility of Micro Milling as a Test Methodology?

- Should work, inertia of Motoman will dampen vibrations of milling spindle.
- Tool tip will break if vibrations occure.

Accuracy/Repeatability Predicted?

- Repeatability of spindle measured at 2 - 3 µm.
- Spindle 5 or 10x more accurate than whole positioning system.

Problems Predicted?

- Once tests completed, accuracy/repeatablity will be of positioning system combined with spindle. (still good enough).
- If too much play in system, tool would break.

Other Considerations?

- Measuring equipment 10x more accurate than actual equipment
- Estimation of accuracy spindle around 10 microns.
- * Attach vibration measurement to Motoman SDA10 in order to determine direct vibrations of settling time etc. - Martin
- Do vibration testing with spindle running.
- * Could perform tests with Theuns micro milling setup.
- 10 mm gap before cutting to ensure proper speed etc.

Signature of Person Interviewed

Signature of Interviewer

③

Sebastian Read
17-09-2012
15023168

Micro Milling Application Interview
Development of a Micro Material Handling System

Interviewer: Sebastian Read
Interviewing: Mnr. Blom.

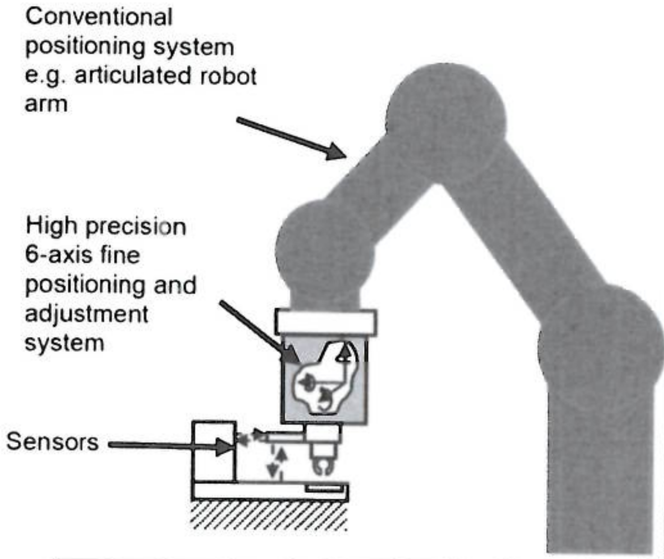
Date: 19-9-2012
Time at Start: 14:10
Time at Finish: 14:30

Detail of Person Interviewed

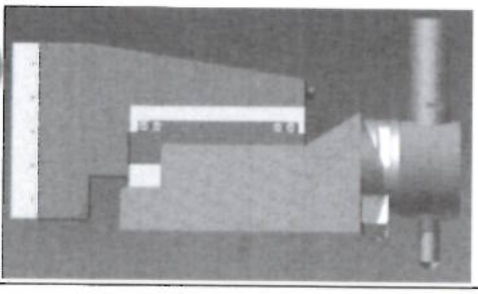
Qualifications:
National Higher Diploma Mech Eng.

Experience in Field of Micro Machining and Robotics:
- 30 Design Manufacture.
- Head of SMD worshop

Explanation of System



Coarse to Fine Positioning System



Fine Positioning System with Spindle

Micro Milling/Drilling

Feasibility of Micro Drilling as a Test Methodology?

- Yes, Micro milling more accurate than other test systems.
- Centering of Drill bit a problem, bit could deflect. Use 2-3mm drill bit.

③

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Feasibility of Micro Milling as a Test Methodology?

- Short length of cutter this will ensure it does not deflect.

Accuracy/Repeatability Predicted?

- 5 - 10μm predicted.

Problems Predicted?

- Vibrations might affect robot / testing.
- Cutter might be forcing material away as opposed to actually cutting. Almost like maching a sponge
- Not to soft.
-

Other Considerations?

* - Use not too soft Aluminium or else material will deform. Use relatively strong Aluminium alloy.
- Direction of Milling and Turning.
  · Climb milling is prefferable.
- Make sure

Signature of Person Interviewed

Signature of Interviewer

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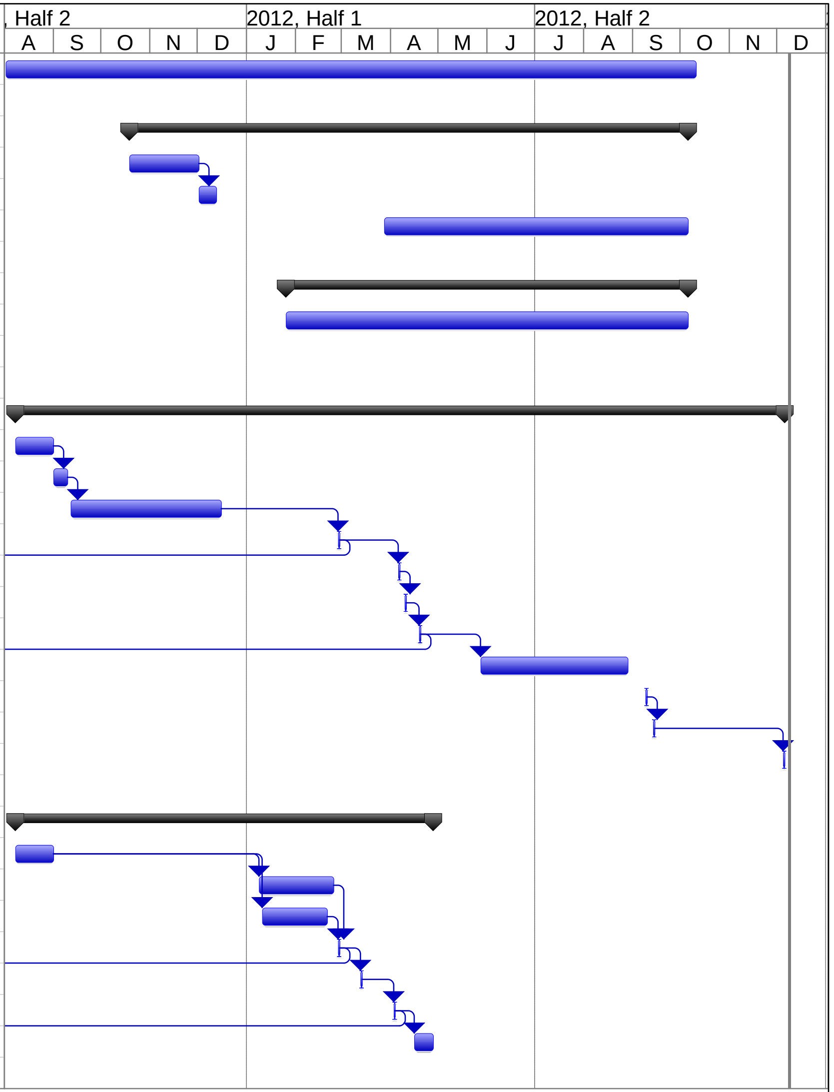
Appendix J

Gantt Chart

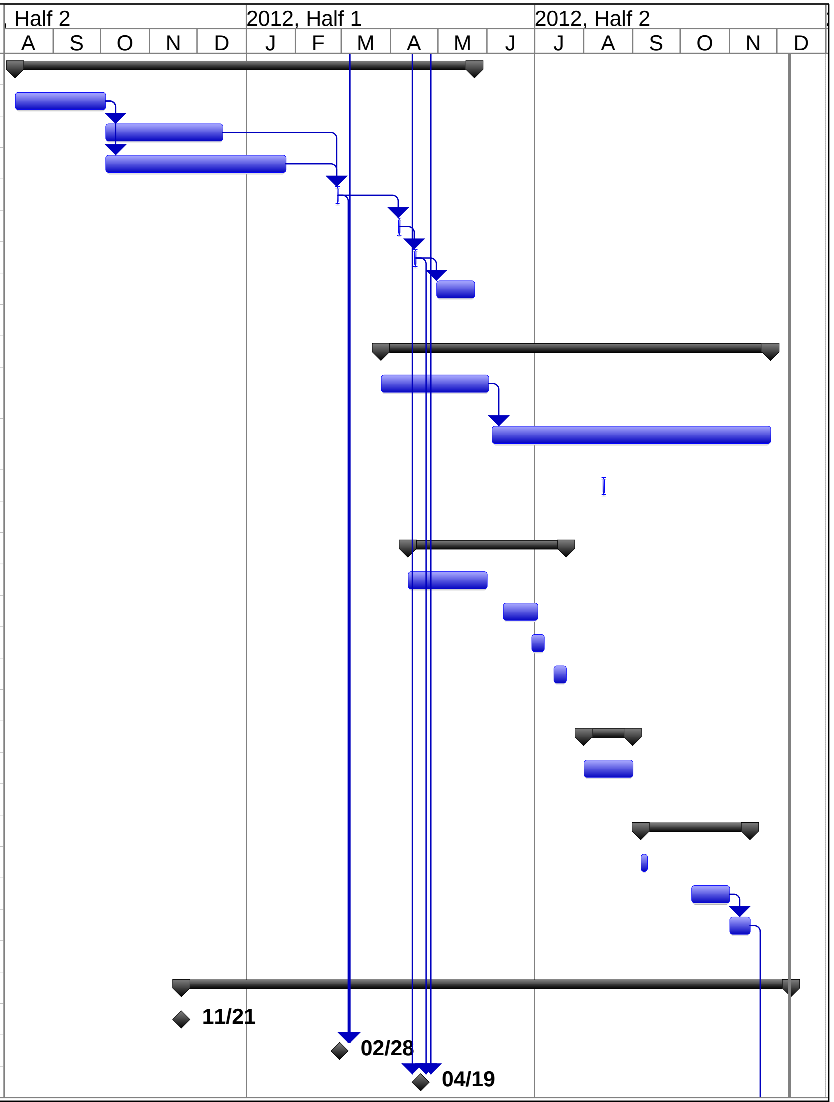
ID	Task Name	Duration	Start	Finish	Predecessors
1	Literature Review	314 days?	Tue 11/08/02	Wed 12/10/10	
2					
3	**Innovation Management**	**255 days?**	**Wed 11/10/19**	**Fri 12/10/05**	
4	Research	32 days?	Wed 11/10/19	Thu 11/12/01	
5	Innovation Management Report	7 days?	Fri 11/12/02	Mon 11/12/12	4
6	Further Innovation Research	139 days?	Wed 12/03/28	Fri 12/10/05	
7					
8	**Systems Engineering Models**	**184 days?**	**Thu 12/01/26**	**Fri 12/10/05**	
9	Research	184 days?	Thu 12/01/26	Fri 12/10/05	
10					
11					
12	**Fine Positioning System**	**350 days?**	**Mon 11/08/08**	**Wed 12/12/05**	
13	Initial Research	18 days?	Mon 11/08/08	Wed 11/08/31	
14	Set Requirements	7 days?	Thu 11/09/01	Fri 11/09/09	13
15	Identify Alternatives	69 days?	Mon 11/09/12	Thu 11/12/15	14
16	Order Fine Positioning System (Payment)	1 day	Tue 12/02/28	Tue 12/02/28	15
17	Fine Positioning Shipping Date	1 day?	Fri 12/04/06	Fri 12/04/06	16
18	Fine Positioning System Arrives	1 day?	Tue 12/04/10	Tue 12/04/10	17
19	Customs Clearance	1 day?	Thu 12/04/19	Thu 12/04/19	18
20	Testing	67 days?	Mon 12/05/28	Tue 12/08/28	19
21	Spark and Failure of Z Axis	1 day?	Sun 12/09/09	Sun 12/09/09	
22	System Given to DHL	1 day?	Fri 12/09/14	Fri 12/09/14	21
23	System Arrives Back from DHL	1 day?	Wed 12/12/05	Wed 12/12/05	22
24					
25	**End Effector System**	**191 days?**	**Mon 11/08/08**	**Fri 12/04/27**	
26	Initial Research	18 days?	Mon 11/08/08	Wed 11/08/31	
27	Set Requirements	35 days?	Mon 12/01/09	Fri 12/02/24	26
28	Identify Alternatives	29 days?	Wed 12/01/11	Mon 12/02/20	26
29	Order End Effector (Payment)	1 day?	Tue 12/02/28	Tue 12/02/28	28,27
30	End Effector Shipping Date	1 day?	Tue 12/03/13	Tue 12/03/13	29
31	End Effector Arrives	1 day?	Tue 12/04/03	Tue 12/04/03	30
32	Testing	10 days?	Mon 12/04/16	Fri 12/04/27	31
33					



Project: Gantt Chart
Date: Sun 12/12/09

Task	▬	External Milestone	◆	Manual Summary Rollup	▬
Split	┆┆┆┆┆┆	Inactive Task	▭	Manual Summary	▬
Milestone	◆	Inactive Milestone	◇	Start-only	[
Summary	▬	Inactive Summary	▭	Finish-only	]
Project Summary	▬	Manual Task	▬	Progress	▬
External Tasks	▬	Duration-only	▬	Deadline	⇩

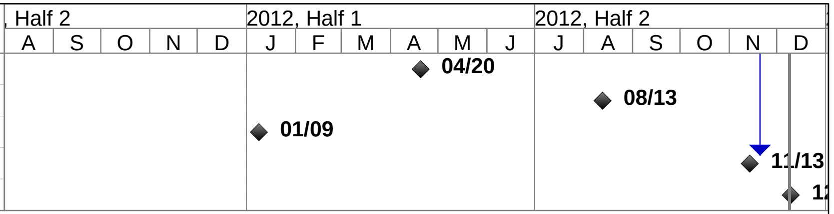
ID	Task Name	Duration	Start	Finish	Predecessors
34	**Vision System**	**209 days?**	**Mon 11/08/08**	**Wed 12/05/23**	
35	Initial Research	41 days?	Mon 11/08/08	Mon 11/10/03	
36	Set Requirements	54 days	Tue 11/10/04	Fri 11/12/16	35
37	Identify Alternatives	82 days	Tue 11/10/04	Wed 12/01/25	35
38	Oder Camera and Lens (Payment)	1 day?	Mon 12/02/27	Mon 12/02/27	37,36
39	Camera and Lens Shipping Date	1 day?	Fri 12/04/06	Fri 12/04/06	38
40	Camera and Lens System Arrives	1 day	Mon 12/04/16	Mon 12/04/16	39
41	Testing	18 days?	Mon 12/04/30	Wed 12/05/23	40
42					
43	**Integration System**	**177 days?**	**Mon 12/03/26**	**Mon 12/11/26**	
44	Design Structure (Drawings and Calculations)	50 days?	Mon 12/03/26	Fri 12/06/01	
45	Manufacture Structure (Time Includes Adjustments)	127 days?	Mon 12/06/04	Mon 12/11/26	44
46	Assemble	1 day	Mon 12/08/13	Mon 12/08/13	
47					
48	**Detailed Design Control**	**72 days?**	**Thu 12/04/12**	**Fri 12/07/20**	
49	Design Software Interface	36 days	Thu 12/04/12	Thu 12/05/31	
50	Marco Phase 1	16 days?	Mon 12/06/11	Mon 12/07/02	
51	Marco Phase 2	6 days?	Fri 12/06/29	Fri 12/07/06	
52	Albie Phase 3	6 days?	Fri 12/07/13	Fri 12/07/20	
53					
54	**Detailed Design Interface**	**23 days?**	**Wed 12/08/01**	**Fri 12/08/31**	
55	Haptics	23 days?	Wed 12/08/01	Fri 12/08/31	
56					
57	**Testing**	**50 days?**	**Thu 12/09/06**	**Tue 12/11/13**	
58	Testing Van der Waals Gripper	3 days?	Thu 12/09/06	Sun 12/09/09	
59	Preliminary Motoman Testing	18 days?	Mon 12/10/08	Wed 12/10/31	
60	Fienmess, Motoman and Calibration Testing	9 days?	Thu 12/11/01	Tue 12/11/13	59
61					
62	**Milestones**	**277 days**	**Mon 11/11/21**	**Mon 12/12/10**	
63	Project Proposal	0 days	Mon 11/11/21	Mon 11/11/21	
64	Parts Ordered	0 days	Tue 12/02/28	Tue 12/02/28	16,29,38
65	Parts Arrive	0 days	Thu 12/04/19	Thu 12/04/19	19,31,40



Project: Gantt Chart
Date: Sun 12/12/09

Task	▬	External Milestone	◆	Manual Summary Rollup	▬
Split	┈	Inactive Task	▭	Manual Summary	▬
Milestone	◆	Inactive Milestone	◇	Start-only	[
Summary	▬	Inactive Summary	▭	Finish-only	]
Project Summary	▬	Manual Task	▬	Progress	▬
External Tasks	▬	Duration-only	▬	Deadline	⇩

ID	Task Name	Duration	Start	Finish	Predecessors
66	Manufacturing	0 days	Fri 12/04/20	Fri 12/04/20	
67	Initial Assembling	0 days	Mon 12/08/13	Mon 12/08/13	
68	Final Assembling	0 days	Mon 12/01/09	Mon 12/01/09	
69	Testing Completed	0 days	Tue 12/11/13	Tue 12/11/13	60
70	Hand In	0 days	Mon 12/12/10	Mon 12/12/10	



Project: Gantt Chart
Date: Sun 12/12/09

Task	▬	External Milestone	◆	Manual Summary Rollup	▬
Split	┈	Inactive Task	▭	Manual Summary	▬
Milestone	◆	Inactive Milestone	◇	Start-only	[
Summary	▬	Inactive Summary	▭	Finish-only	]
Project Summary	▬	Manual Task	▬	Progress	▬
External Tasks	▬	Duration-only	▬	Deadline	⇩

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Appendix K

Costs

Actual costs of components, material, manufacturing and equipment needed for the project.

Feinmess Fine Positioning System

R 144 721.21

Edmund Optics Camera and Lens System

R 46 059.00

Schunk Gripper

R 4 503.00 (Free)

Programming

Graphical User Interface - Marco Smith
R 4 680.00 Marco
Calibration Function - Alwyn Burger
R 1 000.00

Integration Manufacturing

The integration manufacturing is comprise of a number of 5 different jobs.
Total Material Cost
R 2 088.00
Total Labour Hours
67.5 Hours
Total Labour Cost
R 20 775.00

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Total Cost

R 223 826.21 (minus R 4 503.00)
R 219 323.21

(Original estimate was 275 000.00)

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