Design of a Fixtureless Reconfigurable Automated Assembly System

MSc Eng (Mechatronic) Thesis

by

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Declaration

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Abstract

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The conceptual design of a fixtureless reconfigurable automated spot welding system for manufacturing subassemblies for residential circuit breakers was investigated. This research was aimed at developing a possible low cost automation alternative to a South African industrial manufacturer, which is presently heavily dependent on personnel for manual assembly of their core products.

System reconfiguration allows for the assembly of a range of subassemblies with geometric component variation on a given system configuration, as well as the potential for the system to be reconfigured to assemble other ranges of circuit breaker subassemblies.

The subassembly selected as focus consists of six different components, which vary geometrically from one product variant to another. A fixtureless approach was selected, to minimise reconfiguration down time and the need for reconfigurable fixtures since reconfigurable fixtures have not found significant acceptance in industry. This varies from a fixture-based approach, which was considered in related research.

The conceptual assembly system presented here consists of the following modules: a flexible vision based part feeder, twin 6 DOF robotic manipulators each with a multipurpose gripper, and a stationary spot welding station. Critical conceptual design elements were further investigated to refine their selection and confirm feasibility with respect to the target industry application. This process ended with a preliminary cost estimate which served as a basis for comparison between the fixtureless, fixture-based and present manual assembly process. The fixtureless concept was overall more expensive than the fixture-based concept, primarily because of the limits to production throughput. The fixtureless concept was however cheaper than the present manual assembly approach but had a far longer payback period than desired by the industry. The complexity and possible uncertainties of the concept combined with the long payback period indicated that the fixtureless concept is not suitable for the target application.

Uittreksel

Die Ontwerp van 'n Setmaatlose Herkonfigureerbare Outomatiese Samestellingstelsel

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Die konsepsionele ontwerp van 'n setmaatlose herkonfigureerbare outomatiese puntsweisstelsel vir die vervaardiging van subsamestellings van huishoudelike stroombrekers is ondersoek. Hierdie navorsing is gemik op die ontwikkeling van 'n moontlike lae koste outomatiese alternatief vir 'n Suid Afrikaanse industriële vervaardiger, wat tans sterk afhanklik is van werkers wat die montering van hul kern produkte met die handsamestelling doen. Stelsel herkonfigurasie laat die samestelling van 'n reeks subsamestellings, met geometriese komponentvariasies, op 'n gegewe stelsel toe, asook die potensiaal om die stelsel te herkonfigureer om ander reekse van stroombreker-subsamestellings te monteer. Die subsamestelling wat as fokus gekies is, bestaan uit ses verskillende komponente met geometriese verskille van tussen produkvariante. 'n Setmaatlose benadering is gekies ten einde aftyd vir herkonfigurasie en die noodsaaklikheid van herkonfigureerbare setmate te minimeer, omdat laasgenoemde nie noemenswaardig deur die industrie aanvaar word nie. Hierdie benadering verskil van 'n setmaat-gebaseerde benadering wat in verwante navorsing ondersoek is.

Die konsepsionele monteringstelsel wat hier aangebied word, bestaan uit die volgende modules: 'n plooibare, visiegebaseerde voerapparaat; dubbele ses-vryheidsgraad robotiese manipuleerders, elk met 'n veeldoelige gryper; en 'n statiese puntsweisstasie. Kritiese elemente van die konseptuele ontwerp is verder ondersoek om hul keuses te verfyn en uitvoerbaarheid in die teiken industriële toepassing te bevestig. Hierdie proses is afgesluit deur 'n voorlopige kosteraming wat gedien het as 'n basis vir die vergelyking van setmaatlose, setmaat-gebaseerde en die huidige handsamestellingstelsels. Die setmaatlose konsep was oorhoofs duurder as die setmaat-gebaseerde konsep, hoofsaaklik as gevolg van beperkings op die produksie-deurset. Die setmaatlose konsep was egter goedkoper as die huidige handmonteringsproses, maar het 'n veel langer terugbetalingstydperk as wat deur die industrie verlang word. Die kompleksiteit en moontlike onsekerhede van die konsep, gepaard met die lang terugbetalingstydperk, dui daarop dat die setmaatlose konsep nie vir die teiken toepassing geskik is nie.

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1 Introduction

1.1 Background

In today's market assembly is a key process in producing merchandise that can be sold to increase a business' economic wealth. It is therefore desirable to reduce the assembly costs and time to market of all products so that pricing remains competitive and profit is maximised for the business.

To be able to design manufacturing systems of the future, or as they are so called Next Generation Manufacturing (NGM) systems (Hardt 1997), one has to firstly determine or identify the trend of the market demand. The trend in manufacturing system development is directly influenced by the market demand. In today's highly competitive global environment, market demand requires that small production runs are done with short turn-over times. Additionally product variation is increasing to satisfy the unique requirements of the growing global and niche market segments.

To meet these market demands manufacturers are rapidly changing over from large volume dedicated manufacturing systems, that allow minimal production variation, to small volume reconfigurable manufacturing lines, designed for quick turn over and setup times. From the US automotive industries production statistics for 1973 to 1989, it was recorded that an increase of almost 70% in the number of available car models sold and a drop of 34% in the number of units sold per model (MacDuffie et al. 1996). This is an indicator of the automotive market transition from dedicated manufacturing lines to reconfigurable manufacturing lines. The automotive industry is a large portion of the overall manufacturing industry and can be used as an indication of market trends and movements in smaller manufacturing industries. This highlights the importance for the development of Next Generation Manufacturing (NGM) systems and/or methodologies.

The Advanced Manufacturing Technology Strategy (AMTS), which is a national strategy being implemented by the Department of Science and Technology, aims to develop new and improved technologies for implementation in the South African manufacturing industry. The goal is to give the South African manufacturing industries a competitive edge on the global manufacturing market. One of AMTS' project plans entails the conceptual design of reconfigurable manufacturing equipment, with focus on developing low cost machinery for eventual implementation in South African manufacturing industry.

In the African manufacturing industry product assembly is largely performed by personnel as the perception is that labour rates are very attractive. However, due to government legislation and worker unions, labour rates are usually susceptible to large inflation rates. This impact on production cost results in less competitive product pricing both locally and internationally. Due to this undesired increasing production cost and the large expense of mechanisation, South African companies are seeking alternative assembly methods. The need or desire for low cost automated assembly systems with the possibility of reconfiguration, to cater for future manufacturing changes or variants, is becoming more evident within industry. One South African company, Circuit Breaker Industries Low Voltage (CBI), is highly dependent on personnel to assemble their products. CBI is the only African supplier of residual current devices, which are commonly known as circuit breakers. As a result CBI produces a variety of circuit breakers to cater for a majority of the local market. This product variety presents numerous opportunities for automation and NGM system design investigations.

The central focus of this thesis is the design of a reconfigurable automated spot welding system for the main subassembly of a range of residential circuit breakers. Prior to concept development existing assembly automation systems were reviewed. These assembly systems are systematically broken down into industrial identified subsystems which are described and functionally broken down further. Examples of these identified subsystems are presented from industry and literature to allow a broad basis for concept generation. Concept design is focused on the development of a Reconfigurable Assembly System (RAS). The paradigm of reconfigurable manufacturing and assembly focuses on the implementation of low cost automation systems with easily expandable flexibility: Reconfigurable Manufacturing Systems (RMSs) are further described in section 2.1.

1.2 Motivation

By improving manufacturing processes, South African industry can become more competitive in the global market and thus increase its economical wealth. The development of low cost automated assembly systems is a critical step in the evolution of manufacturing. For AMTS and CBI the gains could mean a reduction in long term manufacturing costs, improved product quality, increased production rates and reduced labour dependency.

In the South African manufacturing industry there are a multitude of small businesses that produce a mix of products in small volumes. Typically their product range contains variation that cannot be accommodated in traditional dedicated manufacturing systems and their expected revenue is not sufficient for the purchase of flexible manufacturing systems to perform the automation. RMSs are targeted at these small to medium size manufacturing industries, providing low cost automation systems with customisable flexibility and easy expandability. This limits manufacturing flexibility to what is required for producing the target product range with the opportunity to easily expand these capabilities at a later stage if required, in this way the client does not pay for redundant flexibility initially. This means that South African small to medium size companies are presented with an additional manufacturing alternative to those of the traditional assembly approaches.

The concept design focuses on reducing labour dependencies within industrial manufacturing processes. In South Africa, local industries are highly dependent on manual labour for assembly processes. However labour legislation and worker unions constantly present local industries with fluctuating and generally increasing production costs. For these local industries to remain economically competitive in the global market these production costs need to be reduced. Promoting local industries to globally competitive markets would increase South Africa’s economical wealth.

Formulating a general conceptual design approach for developing a reconfigurable welding assembly system in a logical documented process, would allow other similar industry applications to be investigated with easy adaptation.

1.3 Objectives

This thesis focuses on the conceptual design of a fixtureless reconfigurable automated spot welding system for joining small components of electrical switch gear. This focus is complementary to that of Sequira (2008), who also considered RMSs, but used a fixture-based approach for the same application. The objectives therefore are:

- Evaluate the feasibility of a fixtureless reconfigurable assembly system for a particular industry application as a low cost means to assemble different product families.
- Compare the fixtureless approach to the fixture-based approach presented by Sequira (2008), in terms of cost and reconfigurability.

Certain design aspects of the fixtureless concept were omitted as they would not invalidate the feasibility of the overall concept. These design aspects are:

- The detail design of the central welding unit since specialized welding equipment for this particular application is available from local suppliers.
- Control structure selection, implementation and interfaces were not considered in detail as industry suppliers of the various final hardware subsystems assured that interfacing was indeed possible.

2 Literature review

Prior to and during the concept development research into industrial automation and assembly systems was continually conducted. The research presented describes the meaning and purpose of a Reconfigurable Manufacturing System (RMS) with particular application to automated assembly systems. Furthermore a systematic modular breakdown of the various important subsystems forming a typical Reconfigurable Assembly System (RAS) is presented. This information aided in formulating a broad concept generation and in final design refinement.

2.1 Manufacturing paradigms

Manufacturers typically implement two types of machining systems in today's industry. These types of machines can also be applied to automated assembly systems. These two types are (Koren et al. 1999; Mehrabi et al. 2000):

- Dedicated Machining Systems (DMSs): Machining systems designed for the sole production of a specific product at high volume production rates and uses transfer line technology with fixed tooling and automation.
- Flexible Manufacturing Systems (FMSs): Machining systems capable of producing a variety of products with varying production rates on the same system. Typical hardware configuration uses indexed fixtures and tool changers to provide flexibility for a multitude of manufacturing applications. FMSs use programmable software controllers to automate the production of different products on the same system. Production rates are slower and typically production costs are higher than with DMSs for large volume production products, but lower for small volume production products. FMSs are typically implemented to manufacture a range of products and variants with low production demand, which are too expensive to automate with multiple DMSs.

These two types of manufacturing systems are readily available for implementation in today's industry. However the trend in today's market demand is transitioning from large volume generic products to more customized products with shorter life cycles and of smaller batch sizes. To cater for this future change, research is being conducted, by a multitude of institutions, into new types of manufacturing systems. One paradigm of NGM systems has been defined as Reconfigurable Manufacturing Systems (Koren et al. 1999).

A RMS ideally incorporates modularity, integratability, convertibility, diagnosability and customization. Reconfiguration allows addition, removal or modification to specific modules to increase or alter the system's capabilities. Modules are simplified units which allow for seamless integration into a system. Modules may be added or removed to alter the control, software or mechanical structure of the system, in order to adjust production capacity in response to changing market demands or technologies. This type of system is designed to provide customized flexibility for a particular part family and is designed to allow for system improvement, upgrades and reconfiguration as opposed to complete system replacement (Mehrabi et al. 2000).

RMSs specifications and design philosophies are currently being researched. One such design strategy suggests implementing the Analytical Hierarchical Process to strategically weight all the common design parameters for conventional manufacturing systems with the new requirements of RMS (Abdi & Labib 2003). The requirements of RMS are very broad and complex, which raises the question of possible feasibility. Some identified research issues that may influence the design process are: the structural design of reconfigurable machines, open machine tool controllers, manufacturing process simulation and process-oriented programming systems (Molina et al. 2005). Six design principles for RMS are suggested by Katz (2007). These principles are:

- Design around a specific part family.
- Customized flexibility.
- Easy and rapid convertibility.
- Modular scalability, addition or removal of elements that increase productivity or efficiency.
- Allow reconfiguration so the machine may operate at several locations along the production line performing different tasks at different locations using the same basic structure.
- Should be implemented using a modular approach, common hardware and interfaces.

RMSs are intended to bridge the divide between DMSs and FMSs, by combining slower than DMS throughput rates with limited flexibility of FMS. The design of a RMS should be as such to allow for easy and cost effective expandability for increasing production rates and quick reconfiguration for product family variation and foreseeable future product revisions.

2.2 Reconfigurable Assembly Systems

Reconfigurable Assembly Systems (RASs) or Reconfigurable Assembly Machines (RAMs) applies the design principles of Reconfigurable Machines (RMs) to assembly. One such example of a RAM is presented by Katz (2007). This assembly system for the assembly of the core of automotive heat exchangers was designed to reduce the existing assembly system's cycle time from between 45 to 60 s down to 30 s, by following RASs design principles. A RAS may consist of a multitude of subsystems depending on the assembly process and the level of automation. These subsystems could be DMSs, RMSs or FMSs.

All assembly systems have the same general high level functional breakdown when analyzing the component and material flow through the assembly process. This general functional decomposition is presented below in Figure 1.

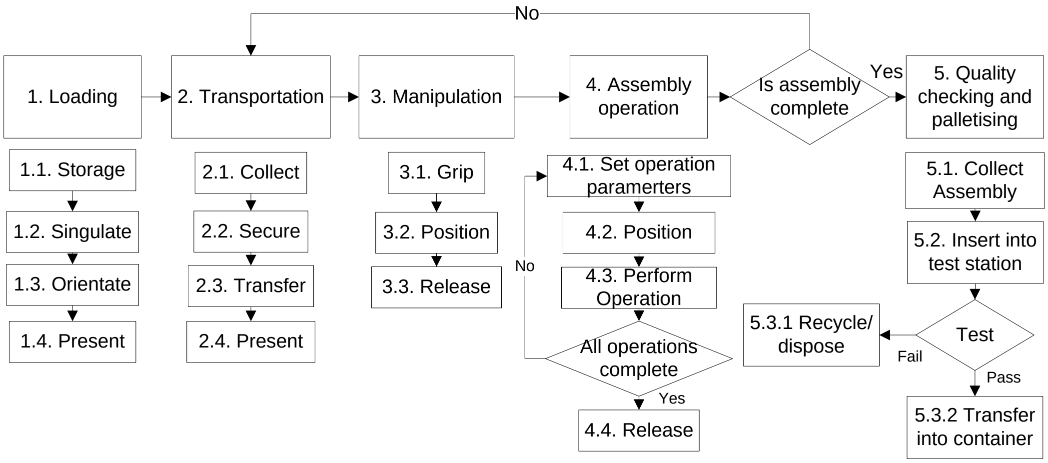


Figure 1 General high level component functional decomposition for assembly systems

These functions are very generic and are incorporated into a vast number of automation subsystems. The focus of this literature review is to provide research into the design of a welding RAS. For this reason functional blocks from the general high level component functional decomposition were grouped to form typical subsystems for a welding automation system. These groupings are shown below in Figure 2.

A technical review of these typical subsystems is presented in the following subsections. The functional breakdown of each subsystem and their interfaces are discussed. Also on a subsystem level, reconfiguration and flexibility criteria are evaluated.

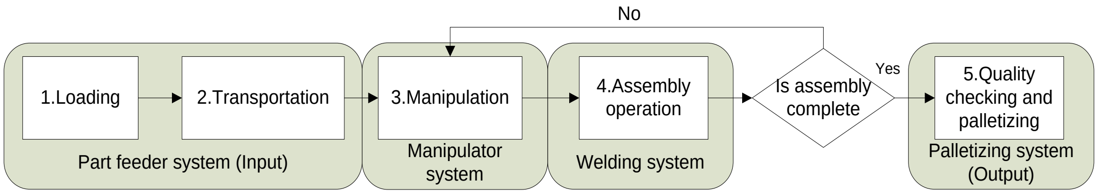


Figure 2 Automation subsystem breakdown

2.2.1 Part feeding

Part feeding becomes necessary in assembly systems where component orientation and positional information is lost in transit from the manufacturing system to the assembly system (Fantoni & Santochi 2005). The function of conventional part feeding systems is to constantly present components to the assembly system in a defined position and orientation. Components are usually presented or inserted into the assembly system via a storage device, in which the parts are either randomly orientated and positioned or palletised. Typically part feeders are designed to feed a specific component (dedicated part feeders) due to the large geometrical and/or mass variation of one assembly component to the next.

Part feeder systems usually are as complex as the parts they are designed to feed, for example components designed with intricate geometries, protruding features and interlocking geometries must be carefully handled to overcome possible tangulation and/or jamming in the feeding process. To overcome this scenario, design collaboration between the product engineers and automation engineers is crucial. This collaboration typically results in informed product design decisions and effective compromise decisions.

However due to the nature of industrial manufacture, some products are initially designed for small scale production and little consideration is given to automating the process when manual labour is more cost effective for the production batch sizes. This becomes a problem when the product becomes commercially successful and production demand increases sufficiently for automation solutions to become feasible and favourable to reduce manufacturing costs. However, often due to the initial design conception, which does not consider automation, the product is difficult to automate for assembly without re-design. The need for quick production transition from manual to automated assembly systems without product re-design favours the usage of complex and flexible feeding systems. In addition flexible feeding systems reduce automation process design time and cost, but flexible feeding systems are more expensive and tend to have a slower feed rate in comparison to dedicated feeders.

Conventional part feeding systems function as follows: Components are buffered in a storage medium. This prevents operational delays in the assembly process and reduces the need for an operator to constantly load components and monitor the feeding system. Needed components are separated (sigulated) from the storage medium for transport and presentation to the assembly system at a specified location, orientation and in a given time. This is conventionally achieved through component manipulation stations along the transfer track between storage and presentation locations. If components along the transfer track are in the incorrect orientation they may either be orientated correctly or recycled back to the bulk storage medium at the beginning of the feeding system for recirculation. A functional breakdown of a typical feeding subsystem is presented below in Figure 3.

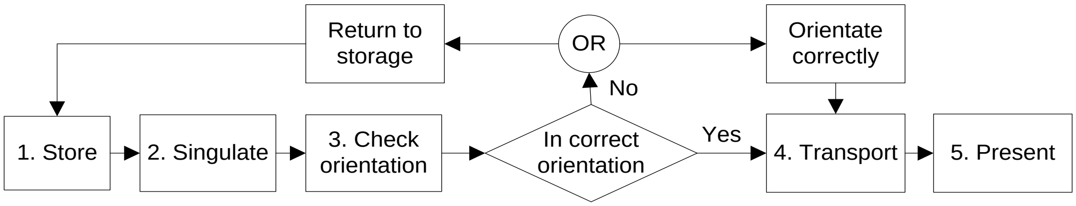


Figure 3 Typical feeding subsystem functional decomposition

Standard part feeding systems have been designed to feed components with basic and standard geometries or features. An overview of such common mechanical feeders is presented by Boothroyd (2005). Feeding small components with non-primitive geometries is extremely challenging and is an area of research which has received a lot of attention over the last few decades.

The most widely implemented and versatile way in industry to feed small components is to use a vibratory bowl feeder. This device consists of a bowl with a helical track which runs around the internal rim. Components are dropped in bulk, either manually or from bulk bins into the centre of the bowl. The components then transition from the centre to the rims and up the helical tracks of the bowl through vibratory motion. Vibration is applied by attaching an electromagnet to the base of the bowl and the support system constrains the movement of the bowl to achieve a torsional and linear vibration about the bowl's vertical axis (Boothroyd 2005; Maul & Thomas 1997). The typical layout of a vibratory bowl feeder is shown below in Figure 4.

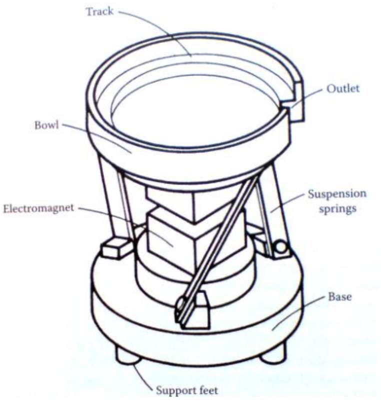


Figure 4 Vibratory bowl feeder (Boothroyd 2005)

Vibratory bowl feeders are conventionally custom designed to feed each individual component. Typically vibratory bowl feeders are designed by experimenting with large quantities of the candidate component to determine the component's suitability and the respective bowl operational parameters, such as frequency and amplitude. This means that vibratory bowl design and development cannot run simultaneously with the product design and assembly process development (Newman et al. 2000). In this regard the scope for reconfiguration is very limited. However, if through testing the vibratory motion achieves a suitable uniform forward transition with a different component, the vibratory bowl may be altered to feed both components, each in separated batches, by changing the operational parameters and the bowl track between component batches.

The design of a programmable vibratory bowl feeder that implements adjustable manipulation and orientation stations along the length of its track (Tay et al. 2005) is one approach towards achieving a more flexible feeding system with shorter changeover cycles. Another approach is to implement modular interchangeable bowl track sections to allow different components to be fed using the same vibratory bowl with minimum change-over time between batches (Joneja & Lee 1998).

In an attempt to achieve a more flexible feeding system that can process a large range of components and meet the flexibility requirements of a RAS, two vision based feeding systems were identified, namely generic bin-picking and vision based manipulation systems. Generic bin-picking feeding systems implement a highly articulated industrial handling robot combined with a 3D sensing system and sophisticated gripping and manipulation subsystem to collect unsorted and randomly orientated components from a storage medium. The complexity of the task due to cluttered recognition scenarios with overlapping parts combined with sophisticated approach and grasp planning with inbuilt intelligence generally results in an expensive, inconsistent and unreliable solution to feeding (Newman et al. 2000).

An example of one such generic bin-picking feeding system is called the PalletPicker-3D (Saldner 2003). The system implements a high precision optical 3D-measuring technique utilizing a video projector and a high resolution camera system, modern image processing techniques and a 6-DOF robotic manipulator. The system is capable of feeding components, which are randomly orientated, from a pallet. The vision system determines which components are at the top most level and are in collectable orientations, if the required collection site for final presentation is unavailable from bin-picking, the component is first transferred using another accessible collection site to a flat surface, where it is dropped in a suitable orientation for recollection at the correct collection site for final presentation. The PalletPicker-3D collecting components for chainsaws with a vacuum gripper from a pallet and a typical re-orientation operation are shown below in Figure 5.

Figure 5 PalletPicker-3D bin picking with suction cup gripper [left] and re-orientation operation using flat surface [right] (Saldner 2003)

The PalletPicker-3D is limited to collecting components which do not tangle or stick together and which do not have diffuse reflecting surfaces. The weight and size of components to be handled is only limited by the size and payload of the robotic manipulator used.

Vision based manipulation feeding systems are a hybrid development utilizing elements from conventional part feeders to singulate and transfer components past a less sophisticated vision system than those implemented in bin-picking feeding systems. Usually a 2D vision system is implemented for the identification of components in collectable static orientations and thereafter their respective collection locations. This information is then transferred to a robotic manipulation system to perform the collection, re-orientation and final presentation.

One such system (Causey et al. 1997) implements a circular system of linked conveyors to singulate components from the bulk in the storage medium and transfers them past the vision window of a static camera. The camera determines which components are in collectable orientations and which are not. If the component is in a collectable position, information of the collection site and orientation of the part is sent to the robotic manipulation system for execution, otherwise the component is rejected back to the bulk bin for later re-circulation. The layout of the feeding system is presented below in Figure 6.

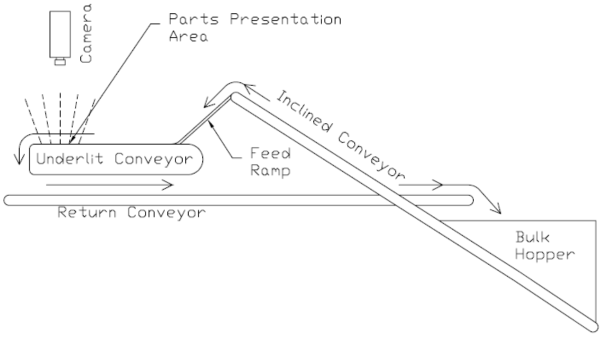


Figure 6 Vision based manipulation feeding system layout (Causey et al. 1997)

This feeding system lacks any specialized orientation hardware for component specific geometry and as a result is able to feed a large range of components. Belt selection can allow for components with various geometries and textures to be fed, even components with no stable orientation such as spherical components may be accommodated by implementing a cleated belt.

However, due to the lack of orientation hardware, components with unique and multiple static orientations would present themselves in numerous orientations on the horizontal collection conveyor which could possibly result in a low chance of collection and thus a slow feeding rate for the system. For this reason a guideline for selecting or designing suitable parts to be fed on the system is suggested, which simply states that components with few static orientations and with a higher number of collectable orientations should be used in this type of feeding system.

2.2.2 Component manipulation

In assembly, components or materials must often be handled and/or manipulated in order to correctly perform the assembly operations. Component manipulation is the skilful process of transferring, orientating, presenting, arranging and/or securing assembly materials or components. Part manipulators may perform a specific manipulation operation or numerous ones. A very general functional decomposition is presented below in Figure 7.

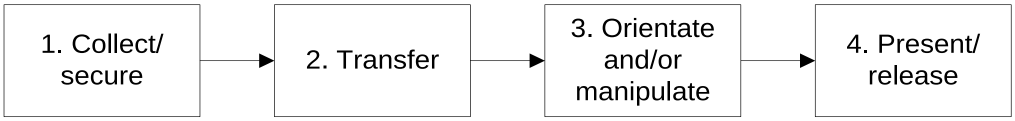


Figure 7 General part manipulator functional decomposition

Part manipulators cover a large base of industrial devices and hardware. In welding automation these divisions usually include industrial robots, grippers and fixtures. All of which are discussed further in the following sections.

2.2.2.1 Industrial robots

Robotic industrial manipulators can be classified as any mechanical frame or linkage that encompasses one or many controllable Degrees Of Freedom (DOFs) to manipulate components, materials or tools. Position of the various DOFs is automatically controlled and can be programmed and reprogrammed via a control interface. There are numerous applications for industrial robots and the main fields of application include packaging, palletizing, welding, spray painting, assembly and product inspection for quality control (Nof 1999). Industrial robots are constantly being researched and developed to perform these types of operations and more within shorter cycle times, with better repeatability and higher endurance.

There are numerous types of industrial robots. The three main classes are articulated robots, Selective Compliance Assembly Robot Arms (SCARA's) and gantry robots. Examples of these three classes are shown below in Figure 8.

Industrial robots are usually designed and modelled to automatically perform functions normally assigned to humans. Industrial robots were initially developed to replace humans in hazardous working environments such as in nuclear power plants, however with the recent advancements in industrial robot design and new technologies they are finding more applications, as they often outperform their human counterparts when it comes to production quality, running costs and/or production rates.

Figure 8 Three common classes of industrial robots: Articulated, SCARA and gantry (EXPO21XX 2008; EXPO21XX 2007) – from left to right

In welding assembly industrial robots in the automotive industry are conventionally equipped with large weld gun end effectors. This allows the weld gun to be positioned and manipulated in a human like manner to reach various often hard to access weld locations. Weld guns are large in size and are typically mounted to heavy payload industrial articulated robots with payloads from 50 kg upwards. Most welding robots in the automotive industry are articulated robots with the exception of some gantry or boom welders. Gantry and boom welders are more commonly found in metal fabrication industries.

Industrial robots are also widely implemented for pick and place manipulation operations. SCARA robots are usually best suited for basic, high speed pick and place operations where operational space is not too constrictive. Usually equipped with a suction cup gripper they excel at handling components or materials with flat 2D geometries.

In small production lines or spatially constrictive scenarios a smaller and simpler pick and place robot becomes more favourable. One such range of robots is the Yamaha YP-X: they are compact in size and easy to operate. These robots have 2-4 DOF designed to handle simple transfers, with fast and precise movements and within operating volumes smaller than 330 mm. The 2, 3 and 4 axis Yamaha YP-X variants are shown below in Figure 9 from left to right respectively.

Figure 9 Yamaha YP-X series pick and place robots: YP220BX (2008a), YP320XR (2008b) and YP340X (2008c) – from left to right

Another new type of pick and place robot that uses a parallel mechanism to achieve higher and more precise handling operations in bigger operational volumes, as large as 1300 mm, has been developed by Adept and is called the Quattro s650H. The lightweight linkage design allows for rapid acceleration and deceleration of the end-effector platform. The robot is mounted on the ceiling to maximise the operating volume. The robot is shown below in Figure 10.

Figure 10 Adept (2009) Quattro s650H robot

Most robotic manufacturing industries now also offer small low payload articulated industrial robots for small and intricate operations, such as handling and manipulation of small delicate components. These robots conventionally have 6 DOFs just like their larger payload counterparts with payloads ranging from 2.5 kg and up.

In terms of reconfiguration, industrial robots are very adaptable and may be reprogrammed to perform different welding or assembly operations via a robot controller. Individual programs can be coded or taught and stored on the robot controller for recall and execution on demand.

New programs are usually taught into the robotic controller by a human operator using a teaching pedestal or with the use of offline simulation software, which is usually obtainable from the robot’s manufacturer. The teaching pedestal is a device that connects to the robot controller and provides a human operator interface for teaching the robot new programs. This is done by allowing the operator to position the robot by manipulating each of its DOFs and setting other operational parameters. The base robot itself is seldom modified on a hardware level, it may however become necessary to mount the robot at a different base location or to a moving platform to increase the operational reach volume accessible to the robot, allowing the robot to perform larger or additional operations.

In assembly automation an operation may be beyond the capability of a single industrial robot. It is then often possible to implement multiple industrial robots to successfully perform the operation. Cooperation between industrial robots with different characteristics such as payload, velocity, repeatability and accuracy usually increases the operationally capability as required. Cooperative robots can perform sophisticated mechanical assembly operations, synchronous or not, with high relative accuracy (Pelagagge et al. 1996). Multiple robots are also capable of performing various large component and/or assembly manipulations cooperatively (Arai et al. 1995). This increased capability can have the additional advantage of reducing the usage of conventional fixtures and increasing the systems reconfigurability.

Cooperative robots sharing the same operational volume also introduce additional operating problems, which include collision, sequencing and synchronization. Therefore careful consideration and investigation should be performed to justify the use of cooperative robots. Robot manufactures like Fanuc and MotoMan sell advanced robotic controllers which are capable of controlling up to four robots simultaneously, allowing for synchronised operation and active collision avoidance between robots. The NX100 robot controller from MotoMan (2007a) is an example of one such controller.

Industrial robots are usually customized to perform different operations by mounting different specialized end-effectors. The end-effector is a device or tool that is mounted to the end of a robot arm. Robots that utilize different end-effectors in succession can make use of tool changing posts for automated and faster changeovers between different tasks or processes, making the robot modularly reconfigurable. Grippers specific to robots are further discussed in the following section.

2.2.2.2 Grippers

Grippers are a specialized form of robotic end-effector for material or component handling and assembly. Grippers function to facilitate easy and efficient collection, locating and securing of components or materials during transfers, final placement and release. A general functional decomposition for a robotic gripper is presented below in Figure 11.

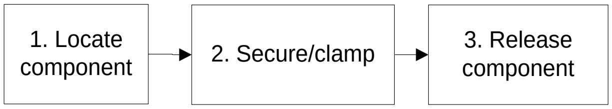


Figure 11 General gripper functional decomposition

Commercially available grippers in industry are fairly simple in function and are designed to handle objects with a limited range of geometries and materials. A gripper consists of two modules namely the actuating base and the contact clasps. The actuating base houses the actuation system which connects to and positions the clasps. Typical actuation systems for gripping use pneumatic, servo-electric and electro-magnetic approaches. Selecting an actuation system is usually dependent on the particular gripper application and what energy sources are readily available in the operating environment.

The contact clasps are conventionally called soft jaws for grippers that use finger like protrusions to grasp components, and suction cups for pneumatic vacuum based grippers. Soft jaw grippers conventionally come in two and three finger configurations with either parallel or pivot acting fingers. Conventionally objects with cylindrical or spherical geometries are handled with 3 finger grippers while objects with 2D extruded geometry and those with parallel flat face features are handled with 2 finger parallel grippers. Then depending on the size, weight, accuracy and gripping force required, a suitably sized gripper is chosen. In industry 2 finger parallel grippers are widely implemented. An overview of typically commercially available configurations for soft jaw grippers is shown below in Figure 12 (Townsend 2000).

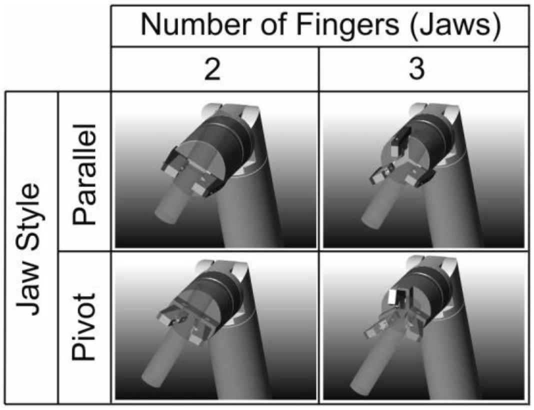


Figure 12 Commercially available configurations for soft jaw grippers (Townsend 2000)

System integrators usually design dedicated grippers which handle a specific component. In the cases where one industrial robot must handle a multitude of components, vendors provide two solutions: a gripper changing post or more flexible grippers.

Use of a gripper changing post (tool changer) allows the industrial robot to quickly and automatically re-fit grippers. The vendor usually supplies an interchangeable gripper mounting bracket or adapter, which is fitted to the end-effector of the industrial robot, to allow for automated gripper refitting. Alternatively a swivel wrist with indexed stations containing different grippers can be used. The swivel wrist is mounted to the industrial robot end-effector and revolves between grippers for faster gripper refitting, however this requires that a large enough operational volume is available, to avoid collisions during operations.

Research into developing flexible grippers that are able to grip a multitude of objects with different geometries and sizes is constantly being pursued. One such gripper implements pneumatically inflatable rubber pockets situated on the soft jaws to expand and grasp objects with varying gripping forces (Choi & Koc 2006). A prototype two finger parallel gripper implementing this gripping technique was designed and built. The prototype was able to grip rigid and non-rigid objects with irregular geometries. The prototype gripper is shown below in Figure 13.

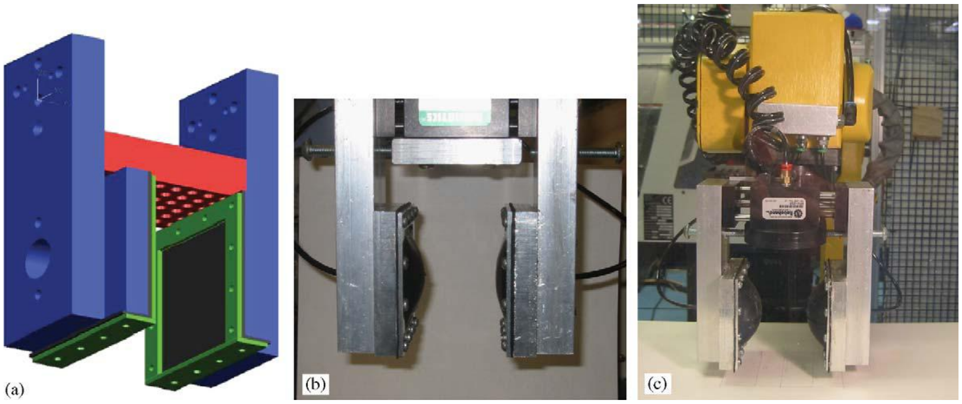


Figure 13 Flexible prototype gripper with inflatable rubber pockets (Choi & Koc 2006)

Another direction into developing more flexible grippers, is to model the gripper more like a humanoid hand i.e. adding additional fingers with additional linkages allowing more degrees of freedom. Commercially these types of intelligent grippers are scarce and very expensive. For example the BarrettHand BH8-250 (Townsend 2000), which is a three finger articulated gripper with 8-DOF, has only been implemented by automotive manufacturers and suppliers in Japan. The BarrettHand BH8-250 is shown below in Figure 14.

Even more sophisticated robotic manipulators are being designed with inbuilt vision and tactile sensors to provide intelligent feedback to the gripper. However with this added flexibility and complexity, these gripper units become expensive, difficult to maintain and calibrate.

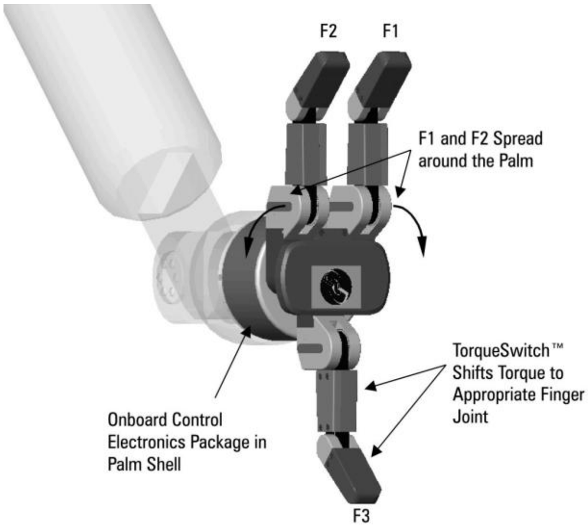


Figure 14 BarrettHand BH8-250 programmable flexible gripper (Townsend 2000)

Reconfigurable grippers follow the reconfigurable manufacturing design philosophy by limiting their application to handling a particular part family instead of attempting to maximise their handling capabilities as with flexible grippers. Part families for reconfigurable grippers are usually determined by grouping objects with similar geometries. For instance assembly components could be divided into circular, square and irregular geometry profile groups. Causey (2003) illustrates this gripper design philosophy in his guidelines for designing flexible grippers. One of his parallel grippers for handling a range of circular objects is presented below in Figure 15.

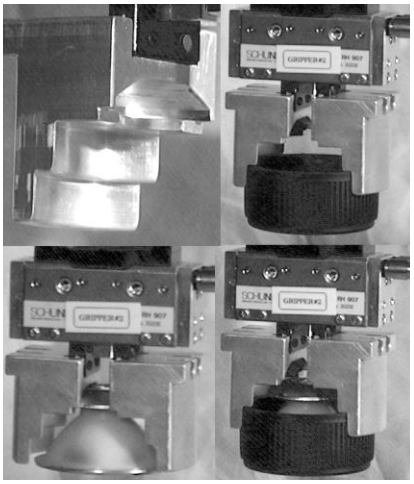


Figure 15 Single gripper designed for handling multiple objects (Causey 2003)

The soft jaws of standard grippers are designed and machined to grasp and handle a particular object. The soft jaw design for reconfigurable grippers are expanded with additional contours and gripping locations to facilitate the collection of more parts with the same gripper.

2.2.2.3 Fixtures

Fixtures are functionally very similar to grippers, but they are not conventionally mounted to the end-effector of a manipulator. Fixtures are primarily used to secure objects prior to and during machining, automation processes and/or inspection. Therefore fixtures are usually larger in size and firmly attached to fixed frames of reference. This allows the fixture to provide increased gripping force to adequately secure the object, with enough force to prevent movement, prior to and during an operation.

Fixtures are most likely the least reconfigurable element in assembly systems as fixtures are designed to conform or mate to existing object geometries to enable tight positioning tolerances and firm grasping. In FMSs fixtures can account from 10 to 20% of the system's costs (Bi & Zhang 2001), which greatly increases manufacturing costs of product ranges with numerous variants and low production quantities.

Flexible Fixture Systems (FFSs) are intended to provide a reusable device or hardware for fixturing numerous different objects or components in an effort to reduce these manufacturing costs. Presently research into FFSs can be divided into two divisions according to their structural design, namely modular structure and single structure (Bi & Zhang 2001). Industry has implemented modular fixtures for decades for manufacture and assembly (Rong & Zhu 1999); however modular fixtures require prior knowledge of the object or component to be clamped and often requires high technical skill, workmanship and experience to manufacture and maintain.

Product revisions or variants usually only differ with slight feature variations. Modular FFSs research is mostly focused on attempting to create interchangeable generic units that may be fitted together in various configurations to conform to new geometries to be secured. These units are usually designed to grasp common and simple geometries and are combined to grasp objects with more sophisticated geometries.

Single structure FFSs have an unchangeable hardware configuration, but contain some form of adjustable range variables, which provide fixturing flexibility. Single structure FFSs are typically divided into two types: adaptive and phase-change FFSs. In adaptive FFSs the adjustable variables are typically locatable fixturing features which are constrained to controllable motions allowing various fixturing configurations. Phase-changing FFSs are made from materials able to change phase or form induced by temperature and/or electrical sources to allow flexible fixturing.

Fixtures are presently very limiting in terms of manufacturing flexibility. Even though some of the discussed modular and single structure FFSs present highly attractive claims, they were not commercially available in the market at the time of writing. This questions the overall reliability of such FFSs in industry. Limiting or eliminating fixtures would be a great approach to increasing the overall manufacturing flexibility of assembly systems.

2.2.2.4 Transportation

In assembly components or incomplete assemblies need to be transferred between various processes in a logical order to complete the assembly process. Additionally the completed assemblies must exit from the system into the next assembly process or for final packaging. Industrial robots are both transfer and manipulation devices and were discussed above in section 2.2.2.1. This section will focus on other transportation system alternatives.

The most common type of transfer medium typically used in industrial environments is the conveyor system or network. Conveyor systems transfer materials or components along horizontal or inclined tracks incorporating belts, rollers or chains. A conveyor network is constructed from linear and curved sections to form a circuit or path which conventionally links the input position to the final destination in a start-to-finish or circulatory configuration. Chained or roller conveyors are able to change direction along the length of their track in a horizontal and/or vertical direction.

Conveyor systems can consist of loops and branches to create routable transfer paths. However conveyors are serial by design meaning all components or materials on a conveyor section will all travel in the same direction and path unless flexible wiper blades or similar flow control hardware stations alter their course. Conveyor tracks can be reconfigured and modified for other applications with the addition and modification of conveyor sections; however the system has to conventionally be taken off-line during the reconfiguration. Components or parts that travel on conveyors conventionally make use of pallets or fixtures if component orientation and position must be maintained during transfer. Examples of flat belt, roller and chain conveyors are shown below in Figure 16.

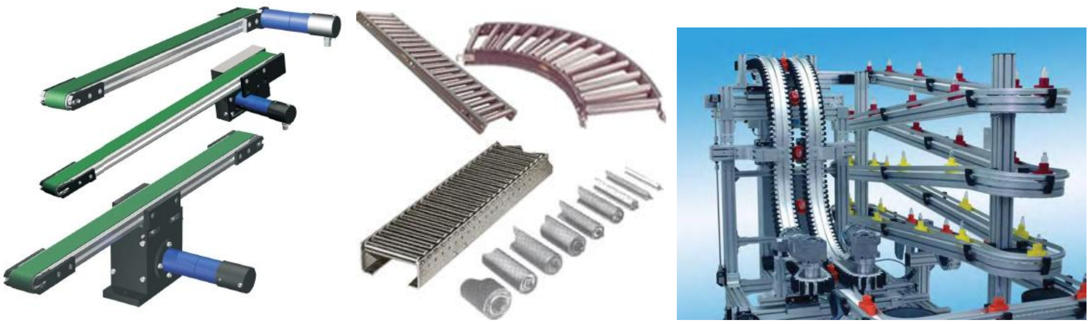


Figure 16 Examples of belt (AS Automation Supplies 2009), roller (Gilmore-kramer 2009) and chain (Bosch Rexroth 2006) conveyors – from left to right

Another variation or alternative to standard conveyor systems are the pallet handling systems. Pallet handling systems implement tracks, rails or guides upon which work surfaces or pallets may move independently from one another. Tracks are formed similarly to those of conventional conveyor systems by adding and removing guide or rail sections. Conventionally pallet handling systems form a closed loop from start-to-finish points and contain a certain number of pallets during operation. The advantages of implementing a pallet system are that small and fragile components may easily be transferred at potentially high speeds without damage or movement relative to the pallet, by using fixtures mounted to the pallet.

Each pallet serves as a movable station potentially able to utilize any workstation hardware situated along its track and may carry an onboard information system such as Radio-Frequency Identification (RFID). The onboard information system allows pallets to potentially store progress and state information about the component or assembly they are couriering.

Some pallet systems, such as the Bosch Rexroth TS 2plus transfer pallet system, are capable of stopping pallets at workstations and taking them off the main track to perform an operation. This prevents interference with the transfer of other pallets in the system. A picture of the Bosch Rexroth TS 2plus pallet transfer system is shown below in Figure 17.

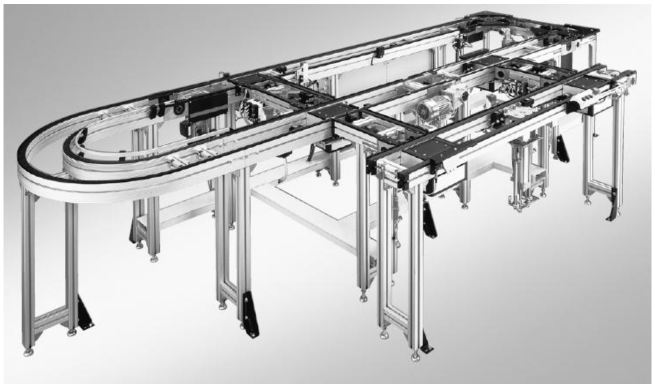


Figure 17 Bosch Rexroth (2008) TS 2plus pallet transfer system

A rudimentary, simple and cost effective transfer system is the rotary table. Rotary tables are usually circular in shape and feature a fixed number of stations. The number of stations is usually directly proportional to the size of the rotating surface. Rotary tables are simple in design but are very inflexible and hard to reconfigure. Also they provide limited operating volume for workstations around their perimeter. As the number of stations is increased, so does the size of the table making the system less and less space efficient.

Rotary tables conventionally rotate in a set sequence. Stations also remain in a fixed order relative to one another. This means that the table may only rotate at the maximum speed of the slowest workstation present along its circumference and no rerouting or flexible sequence of operations is possible in the system. Rotary tables are suited best for processes which have few workstations and require a fixed sequence of operations. A typical rotary table is shown below in Figure 18.

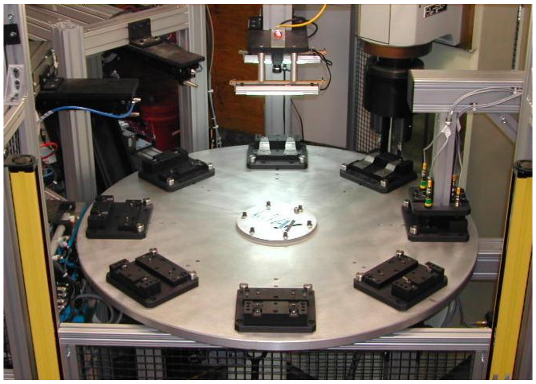


Figure 18 Rotary table transfer system (IMAX Industries 2006)

A promising transportation system for flexible automation is the use of Autonomous Guided Vehicles (AGVs) as couriers to transfer pallets between work stations. AGVs do not need fixed tracks and may simply drive along the shop floor. This means that pallets can be transferred from one work station to another in any sequence or order. However information systems would have to be implemented to track pallets through the process and to ensure each pallet completes the necessary steps required to finish the process before packaging or transfer.

AGVs are very flexible, but they have the highest running costs of the transportation systems discussed thus far and they introduce many operating complexities. Initially the AGVs themselves are expensive, incurring high initial costs, while they are also prone to higher levels of wear and tear requiring a routine maintenance plan. Further in most flexible routing AGV systems, each vehicle has its own power supply making it dependent on a recharging station for continued operation. Additionally sophisticated intelligence is required to perform path planning and collision avoidance with other AGVs within the system (Le-Anh & De Koster 2006). AGV's are potentially highly flexible but expensive to implement.

Transfer systems which feature fixed transfer tracks between stations invariably don't offer the flexibility of easy reconfiguration and usually production must be halted during reconfiguration. Highly flexible AGV systems offer great flexibility in comparison, but at a large cost. A good balance between flexibility and cost is achieved by conveyor and pallet based transport systems.

2.2.3 Resistance spot welding systems

Resistance spot welding assembly operations are relevant to the selected industry design application (Chapter 3) and are therefore discussed below further.

Resistance spot welding joins two metallic components without the use of consumable mediums such as gasses, fluxes or the addition of metals. Instead resistance welding relies on the application of heat induced by electrical resistance when an electrical current is applied across the interfaces of two components to be joined. The electrical current is applied for a certain duration known as the weld time, during which a pool of molten metal is formed between the interfaces, at the point of highest electrical resistance between the two components. This pool of molten material, also known as the nugget, then cools and hardens joining the components. This process is shown below in Figure 19.

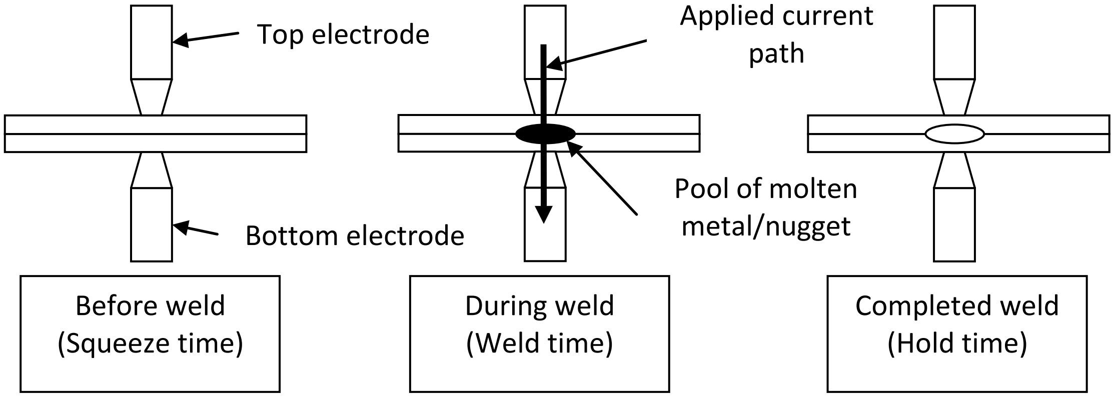


Figure 19 Resistance spot welding process

In addition to the flow of electrical current the electrodes also exert a mechanical clamping force or pressure at the contact interfaces of the components. This force or pressure ensures good contact and thus reduces the electrical resistance between the electrodes and the components to be welded. It also prevents the expulsion of molten metal from the weld nugget and allows the nugget to solidify and set during the hold time before release.

Resistance welding systems and equipment are provided by various manufacturers in various configurations to suit each customer’s requirements. Welding systems are modular in design allowing customers to select the correct transformer, power supply, electrodes and welding frame for their particular application. Resistance welding stations usually consists of the following equipment:

- A rigid frame, housing the transformer which converts high primary voltage and low amperage to low secondary voltage and high secondary amperage.
- Electrodes for contact with the components to localise and complete the current carrying circuit.
- A device for exerting force on the components to be joined through the electrodes.
- A system or method of regulating the applied electrical current.
- A control system which allows the various weld times and pressures to be set and applied.
- A cooling system to remove heat from the electrodes.
- Current carrying conductors which connect the electrodes to the welding transformer.

Clients are able to select from various electrode configurations to best suit their particular application. For instance, due to environmental and volumetric constraints, the preferred opposed electrode configuration may not be possible. In these cases, three other top side electrode configurations are possible according to Miyachi Unitek (2005) namely step, series and parallel gap. These four electrode configurations and their respective welding locations are shown below in Figure 20.

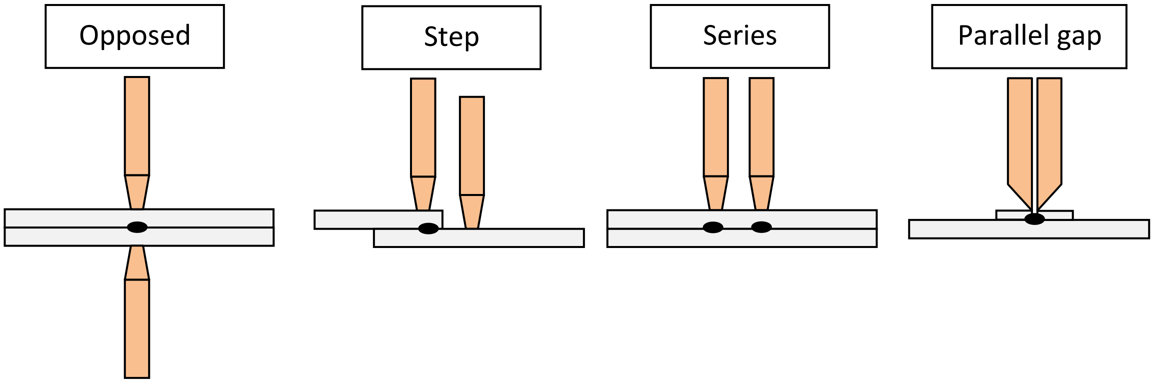


Figure 20 Different resistance spot welding electrode configurations

Welding systems conventionally implement immobile welding heads, such as pedestal and vertical resistance welding systems. These welding systems perform the weld at a set location while the vertical weld height is sometimes adjustable. The components to be joined must therefore be positioned correctly between the welding electrodes before performing the weld. Resistance welding systems with mobile welding heads were first introduced by demand from the automotive manufacturing industry where moving the components or work piece became impractical due to their size and/or mass. Resistance spot welding guns were introduced as result. They typically mount onto the end-effector of articulated industrial robots. This allows the welding head to be positioned to perform multiple welds with different weld orientations without repositioning the work piece. However conventional commercially available weld guns are large in size and are typically fitted to high payload articulated industrial robots. These weld guns range from approximately 50 kg upwards.

To allow different welds to be performed on the same resistance spot welding system, electrodes and programs, that store the weld parameters, usually have to be changed between welds. Programs are changed via the welding system's controller. Automated resistance spot welding systems implement tool changers, which store and index pre-setup electrodes or welding guns. In fixed welding stations tool changer carousel are used, while industrial robots implement tool changing posts or pedestals housing robotic guns. Indexed end-effector tool turrets are not conventionally used with industrial robots due to the large mass of each resistance spot weld gun.

2.3 Control system structures

Control structures or architectures form the basis for control system design. The type of control structure to implement is traditionally determined after the mechanical manufacturing system has been fully designed and implemented. However nowadays to reduce product time to market, reduce development costs and to comply with the flexibility requirements of RMS (Koren et al. 1999), control system design and development should be done in conjunction with the mechanical system design (Bryan et al. 2007). Control systems are broken down into numerous subsystems. In assembly systems these control subsystems are utilized to perform and monitor the necessary assembly operations.

Future control requires constant adaptation and high flexibility to accommodate for manufacturing variation, with minimal configuration and interaction (Van Brussel et al. 1998). As such highly distributed control structures are more favourable, as they consist typically of modular units which autonomously interact with one another to configure themselves to achieve the required manufacturing task. These control units are potentially capable of adapting to changes or modifications made to their operating environment to achieve their manufacturing task. Building the control system structure from modular autonomous units offers greater flexibility, easy modification as opposed to that of traditional hierarchal control structures and improved reliability by using a fault-tolerant approach (Scholz-Reiter & Freitag 2007).

Holonic Manufacturing is a highly distributed control paradigm. Holonic Manufacturing Systems (HMSs) are based on the methodology of cellular functional units (Holons) which are able to perform a specialized function and interact with similar units around them, much like cells that form various tissues/structures in the human body. By coordinating various Holons, each with its individual capabilities, complicated fabrication processes can be achieved. However for this technology to be feasible highly flexible controller designs must be developed which allow for sophisticated communication and planning to be performed amongst Holons. This research is in the preliminary stages of investigation and after a year of investigation, further research has been warranted (University of Hannover undated).

Hierarchal, heterarchical and hybrid control structures are briefly explained in Appendix A, with their respective advantages and disadvantages.

2.4 Machine vision

Industrial automation information subsystems collect operational information about the manufacturing or assembly process, which is then used to monitor, coordinate and execute assembly processes. Information systems in manufacturing are typically divided into various operational levels, from low level information subsystems all the way up to plant wide information subsystems. Information subsystems conventionally collect feedback information using sensors.

Depending on the sensor, small to large amounts of data are obtainable. To maximise manufacturing flexibility it is highly favourable to use sensors that provide a large amount of feedback data for potentially intelligent processing. Vision sensors or cameras are examples of such types of sensors. Vision systems are constantly developing and finding new applications in manufacturing industries. Machine vision can be described as the useful interpretation of the data received from a vision system or camera.

Vision systems come in various hardware configurations suited to different applications and desired registration accuracies. Vision systems may implement from only one camera, for simple 2D registration, to many cameras, for 3D and faster complete component registration. Additionally LED, laser and projector systems may be implemented in conjunction with lighting systems to achieve better registration accuracy for components with dull and dark surface finishes. Vision systems may implement moving camera platforms to achieve better registration results with fewer cameras, such as an industrial robot end-effector or gantry mounted camera. Cameras with various resolutions and optics are also available to optimize the registration accuracy for different camera installation and mounting scenarios. Cameras may also be equipped with filters and/or specialized lenses able to register light data from different spectra such as infrared.

Machine vision often uses machine learning to interpret vision sensor data and convert it into useful information for typically usage in manufacturing instruction generation, decision making operations and quality control inspections. Conventionally a machine learning system is taught using a collection of data from which relevant information is extracted to aid in answering user defined questions on new data (Bradski & Kaehler 2008). How the taught collection of data is interpreted and the type of relevant information or features extracted is determined by the registration method implemented.

Machine vision systems would typically provide the manufacturing system with such information as the presence, or lack thereof, of components or features. Additionally the locations of these components or features may also be estimated if required for typical collection and placement operations. Machine vision systems are also used as measurement and inspection systems in manufacturing lines, typically this would include the quality checking of critical operational geometries and dimensions.

In industrial assembly automation systems object or pattern recognition methods are usually implemented in automated manipulator collection and loading setups. Commercially available vision software often implements published or proprietary machine learning algorithms for pattern or object recognition vision systems. There are two main approaches to machine learning, probabilistic and statistical. Statistical machine learning approaches are more commonly implemented due to their current availability, while probabilistic approaches, such as Bayesian networks and graphical models, are still a new concept undergoing active research and development (Bradski & Kaehler 2008). A few relevant and commonly used machine vision methods or algorithms implemented in automated assembly systems to perform object registration are briefly described below for background:

- Support Vector Machines (SVMs): More specifically, support vector classification is an application of SVMs where input data from two or more known classes or labelled categories are mapped to a higher-dimensional space, known as the feature space, by a suitable choice of kernel function. Projecting data into higher dimensions makes the data likely to be linearly separable (Bradski & Kaehler 2008). The algorithm then separates classes or labelled categories by calculating the optimum separating hyperplanes that maximally separate the classes from one another. New data is then mapped to the feature space and classified according to the region it is located within. This method tends to operate the best when limited training data is available (Cortes & Vapnik 1995). Support Vector Machines have shown promising results in identifying 3D Objects from a single view or aspect of the object subjected to noise and other distortion (Pontil & Verri 1998).

- Boosting: This method relies on a large image database of training images classed into images containing the object and images without the object to be identified. The learning algorithm takes the input images containing the object, extracts features from each image and generates basic classifiers from each extracted feature. The overall classification decision is made from the combined weighted classification decisions of the group of classifiers. During learning, classifiers are initially weighted equally and then re-weighted until overall classification error of the combined classifiers falls below a certain set threshold. Boosting is described in depth by Freund & Schapire (1999). AdaBoosting is a modified implementation of boosting, which improves classification performance resulting in quicker recognition speeds in comparison with other pattern recognition vision algorithms (Viola & Jones 2001).
- Histogram matching: This process involves taking input images of the classed object and formulating a histogram model from all the input image histograms. A histogram is a bar graph distribution that represents the pixel count or frequency of a particular image range variable, such as tone or brightness. Where each bar represents a discrete range of the image variable with its height representing the pixel count or frequency. A histogram model is then formulated by using histogram intersection (Swain & Ballard 1991). New images are tested by running a search window across the image and comparing after each step the search window histogram to the learnt histogram model and if they match within a user defined error tolerance a match is returned. Histogram matching is robust to image rotation.
- Geometric features or contour matching: This image recognition method takes input images of the classed object and identifies prevalent and dominant primitive geometrical features such as lines and circles and creates an object identifier based on the arrangement of these identified features relative to one another. In the case of contour matching, input images are

reduced to binary images from which bodies are identified and their contours traced. The most prevalent contour is stored as the object identifier. New images are taken and run through the same image processing stages and if identified features or contours match the object identifier within a certain error tolerance a match is returned. This method potentially provides the most accurate positional registration result from the above discussed methods or algorithms but is very computationally expensive.

A RAS should use subsystems that require minimal professional expertise when expanding the system's capability or application. A vision recognition subsystem that implements boosting allows for easy and possibly automated teaching processes. The drawback to this recognition method is that it requires a large database of sample images to ensure good operating performance, therefore training times are lengthy. Alternatively vision recognition based on SVMs are able to achieve better performance with fewer images than boosting but teaching is more complex and requires personnel with a higher level of technical ability.

One can therefore conclude that vision systems are used in manufacturing systems which require a high level of flexibility. Vision systems are easily reconfigurable from one application to the next and are capable of performing multiple different operations in succession if required. Minimal hardware reconfiguration is necessary, however occasionally sensor position and/or lens might have to be changed to suite a particular application. In terms of RMSs vision systems provide easily expandable flexibility with minimal hardware modification. Reconfiguration is mainly on a software level, where an operator is required to program or teach the vision system for new or modified tasks.

2.5 Turnkey vision systems

Suppliers of industrial machine vision systems provide a host of solutions tailored for automation, robotic visual guidance, quality inspection and welding. Some industrial robot manufactures and suppliers such as Fanuc and Adept also provide in-house vision systems for their industrial robots. This demonstrates that vision guided robots are indeed commercially feasible. Three of the main international companies, who supply machine vision systems to industrial sectors, are listed and briefly described below.

Intelligent Systems Robotics and Automation (ISRA), with many offices in Europe and USA, specializes in designing and providing vision systems for robotic automation systems. ISRA Vision provides leading automotive manufacturers with a host of vision system solutions for the various stages of production. They offer unique solutions ranging from 2D to 6D systems for robot guidance, e.g positioning, assembly, handling or paint finishing.

Servo-Robot is another vision automation company, with offices in Canada, USA, Japan, Korea, China and India, which specializes in providing leading vision systems for joining processes such as seam finding, seam tracking and weld inspection. Servo-Robot can easily integrate their vision systems with a majority of leading industrial robot manufactures such as Motoman, Kuka and ABB.

Cognex is a vision system provider, with offices situated in North America, Europe, Asia, Latin America and with worldwide distributors including two in South Africa, that provides low cost vision systems for robotic guidance, production line monitoring and ID readers. Cognex provides a host 2D vision systems and allows its customers to purchase a vision system (camera and software) or just their vision software. This allows clients the choice to freely use any supported cameras and/or easily upgrade their existing vision systems. Additionally Cognex allows any potentially interested customer to freely download a limited version of their vision software after registering on their website.

2.6 Quality control

Most manufacturing processes incorporate quality control inspections to reduce the production of defective products. Quality control systems may be integrated into the manufacturing processes, e.g. performing different checks after various stages of product manufacture, or just a final check before packaging. Having multiple quality checking stages helps identify defective products early in the manufacturing process and can save manufacturing time and resources by rejecting them from the production line early in the manufacturing process. Quality control systems also aid in diagnosing system faults in manufacturing processes and determining their origin, such as a faulty machine or tool. Good quality control practises reduce the number of defective products sold, which improves and upholds the production company's image and reputation.

In automated assembly systems, quality control inspections and checks help prevent possible manufacturing line damages and down time due to defective input materials and resources. Sometimes components enter the assembly system that are deformed or out of specification due to poor prior manufacturing/fabrication or handling processes. These components could potentially jam or break assembly equipment which is not designed to handle these component defects. As a result large repair and manufacturing down time costs may be incurred. To prevent these situations from occurring, critical automated assembly lines implement rigorous quality control systems that actively screen input components or materials and monitor the manufacturing equipment stationed along the assembly line.

Quality control systems implement various strategies to determine whether product or manufacturing defects are present. In low cost, low volume assembly lines personnel are usually employed to manually inspect the product during and/or after the assembly process. These personnel may use specialized apparatus and perform various tests to determine whether a product or component is within specification and functions correctly. This can usually be achieved with a visual and/or hands on check. However, if very strict quality control specifications are necessary, the personnel may additionally use specialized equipment to test and inspect the product. In more modern and large scale automated assembly systems, vision inspection systems are becoming more widely implemented. With advancing technologies vision systems are becoming cheaper, quicker, better and easier to integrate within existing assembly lines.

Vision inspection systems are robust and flexible, allowing numerous different inspections to be performed with a single system. Using software, the vision system can be programmed to perform additional or specialized inspection tasks. This allows easy reconfiguration. Vision inspection systems are usually far quicker and more accurate at performing various inspections in comparison to their human counterparts. Vision inspection systems are able to perform a multitude of assembly line operations with great accuracy, in quick succession and with minimal downtime. Also vision systems require minimal running costs, as opposed to personnel. They however are expensive to initially implement.

The trend in the present manufacturing market is more towards high-quality and low volume manufacture, at a low cost (Mehrabi et al. 2000). Quality control mechanisms for RASs need therefore to be selected or designed with RMSs principles in mind.

3 Case study context

It is almost impossible to design a reconfigurable assembly system without a particular initial target application in mind. For this reason and to gain the most from the research done into reconfigurable automated assembly systems, it was decided to select a local South African industry as a case study. CBI-electric: low voltage was chosen as the industry for the focus of this study as they made information on their products available for an academic research investigation.

CBI produces electrical distribution and protection components for low voltage electrical distribution systems. Their product ranges incorporate a variety of custom tailored products. Presently CBI’s major clients are situated in Africa, but the company would like to grow and compete on an international level. Aided by their in-house research and development team, they continually strive to increase production rates, improve product quality and decrease manufacturing costs. Additionally approximately 99% of their products are manufactured in-house making them almost solely based within South Africa.

As a case study, a single subassembly was chosen which incorporates component variation and enough complexity to demonstrate the design approach of a reconfigurable automation assembly system. Later this approach may possibly be adapted for similar assembly applications.

3.1 Implementation focus

CBI produces a range of low voltage products in the field of electrical distribution, such as circuit breakers, surge protectors, electrical meters and motor control electronics. Circuit breakers form a large portion of their production. CBI manufactures a vast range of circuit breakers to accommodate various markets and applications. While these ranges are very diverse in appearance and geometry they consist of the same functional parts. All circuit breakers in the ranges contain a central welded assembly, a load terminal, a line terminal, an arc grid, a moving contact and external housing. The central welded assembly varies for each circuit breaker range to meet the requirements of different customers. The central welded assembly for four different circuit breaker ranges are shown below in Figure 21.

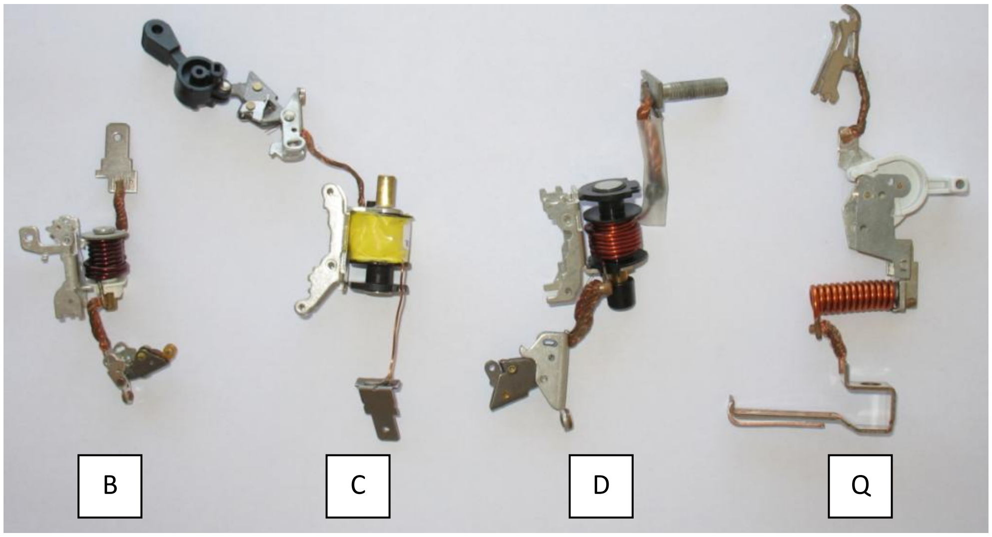


Figure 21 Central welded assembly of B, C, D and Q circuit breaker ranges

The design of an automation system that can assemble the central welded assembly for all the different circuit breaker variations would require a very complex and highly flexible system, if such a system is at all possible. This would mainly be due to the vast variations in geometry, as can be seen in the above figure. As an alternative, the design of a RAS able to assemble one of these central welded assemblies with the potential to quickly and easily be reconfigured to assemble a different one, was chosen as a more feasible automation approach for further investigation.

Next the primary central welded assembly, to form the target part family for the design of the RAS, had to be selected. The Q-frame circuit breaker range makes up, at the time of writing, a large proportion of CBI's production. For this reason automation focus within the Q-Frame would more favourably be received and endorsed by the company. The layout of a typical Q-Frame circuit breaker with the top cover removed from an off the shelf model, is shown below in Figure 22.

The Q-Frame assembly consists of many components and subassemblies that vary throughout the product range. These variants were introduced to meet specialized customer requirements, such as operating current and tripping characteristics.

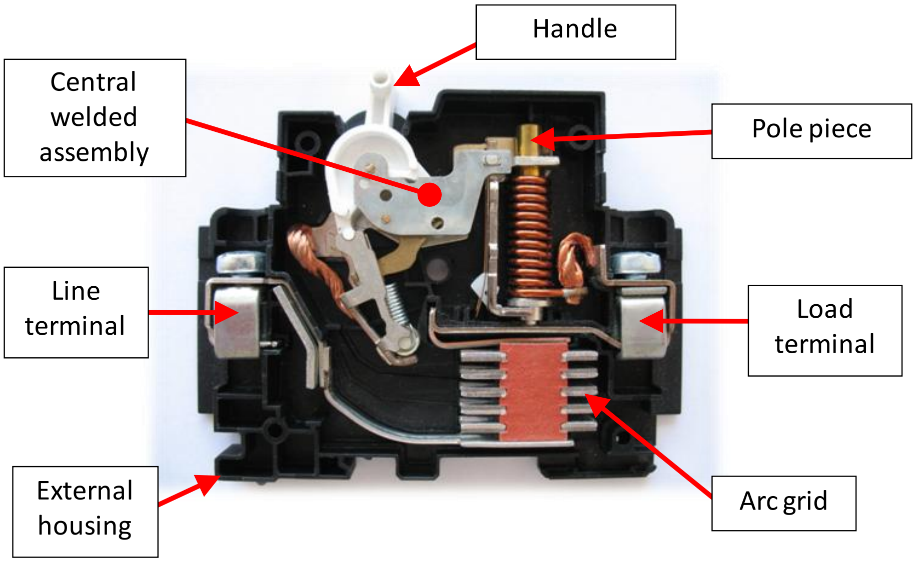


Figure 22 Typical Q-Frame circuit breaker with top cover removed

3.2 Target resistance spot welded subassembly

A Q-Frame circuit breaker assembly consists of roughly a hundred components which form multiple subassemblies that are combined to form the final product. A majority of the assembly processes are performed manually, while one or two subassembly processes have already been automated.

To refine the focus of this thesis a single central resistance spot welded subassembly (which will be referred to as the target subassembly) was carefully selected from the various assembly and subassembly candidates. The target subassembly contains six different components that can vary to meet specialized customer requirements. These variations incorporate a distinct set of component permutations, which must be provided for in the automation design. Therefore the initial target part family was selected to include all these variations of the target subassembly. The subassembly selection allowed for reconfiguration design to be investigated, but was not overly complex to avoid overcomplicating the design process. A schematic layout of the target subassembly is presented below in Figure 23 which shows the various components with their respective names.

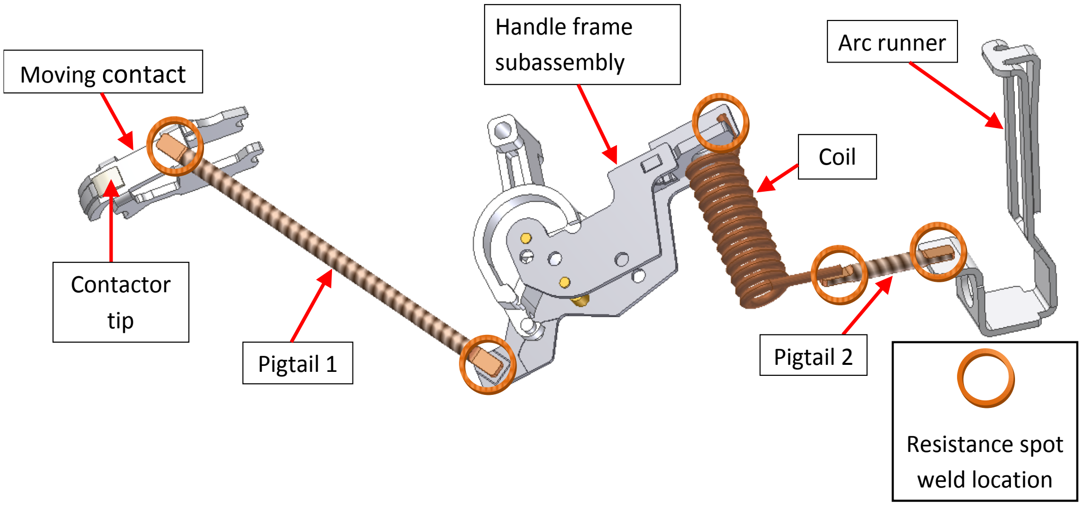


Figure 23 Layout of target subassembly

The target subassembly was studied to determine the range of variation and number of assembled variants present. A tabulated breakdown of the variations for each component of the target subassembly is attached in Appendix B. A summary of these variations is given below in Table 1.

Table 1 Assembly component variations

	Variation	
Component	**Geometrical**	**Material**
Moving contact	Presence of contactor tip	Copper for low ratings or pre tin plated copper
Pigtails	Length and diameter of braided wire	N/A
Coil	Number of turns, wire diameter and cross-sectional wire profile	Wire material and coating

At the time of writing about 21 different components existed within the target part family. These different components combined in specified configurations, resulted in a total of 10 different products. The target subassembly is formed through joining six components by five different resistance spot welding operations. The locations of these welds are circled above in Figure 23. The present manual assembly process for the target subassembly is documented and described in the section that follows.

3.3 Present target subassembly production process

The target subassembly was designed to be manually assembled. Therefore component geometries are very sophisticated and there is an absence of assembly location features for easy insertion and placement operations. Presently all the components, except for the pigtails, are manufactured at the company's central office situated in Johannesburg. Each component is manufactured in bulk and transported in cardboard boxes for assembly to Lesotho. The components within the cardboard boxes are jumbled and are not palletised or loaded in magazines.

The handle frame subassembly is assembled in a prior assembly process in the assembly plants. The pigtails are produced with wire cutting machines, also located within the assembly plants, which cut and fuse the ends of the braided copper wire to form the pigtails.

In the assembly plants rows of vertical resistance spot welding machines are configured to perform a particular weld in the target subassembly. Components or incomplete target subassemblies are welded at one station then transferred on trays to the next to complete the following weld operation. This process continues until all the components of the target assembly are welded together. Between batches of product variants of the target subassembly the welding machines are set and retooled by trained machine setters, if necessary, for the new welding operation. The layout of a welding row is shown below in Figure 24.

Figure 24 Welding row [Left] and station close-up [right]

All present welding systems in operation are vertical pedestal welders with an opposed electrode configuration. Component quality control is also performed by the welding station operators, as they are trained to recognise notable component defects and to discard these components.

Fixtures, which also function as the electrodes for the welding station, are used for critical welds only to ensure higher production standards. Other welds were positioned by the two hands of the operator between the flat surfaces of opposed electrodes before pushing the foot pedal to perform the weld, which is referred to as a fixtureless welding operation. For some welds where copper on copper interfaces were present, a flux or weld paste is applied for better joining between the two components when welding.

After the components of the target subassembly has been successfully joined together with the various welding operations, the target subassembly is placed within the Q-Frame circuit breaker external housing, as shown in Figure 22, with other components and subassemblies to form the final product. Lastly the mating external housing is attached and secured, holding all the internal components in place.

Finally each finished circuit breaker is manually inserted into a quality testing apparatus which ensures that the circuit breaker trips at the rated current within the rated tripping time. This ensures the circuit breaker is within design specifications before packaging and shipping.

4 Concept design

The mechanical design process outlined by Ullman (2003) was used as a guideline to aid the logical development of the design of an automated resistance spot welding system (which will be further referred to as the concept assembly system). The design process documented in this chapter serves to discuss a range of different concept possibilities. This provides an overview of all the considered concepts and the choice to focus the design approach on a fixtureless reconfigurable assembly system as stated in the objectives.

After background information on the target subassembly was obtained and the existing manual assembly process studied, the design process could begin. Customer requirements were formulated based on the product information, existing automation systems, quality control and additional input obtained from CBI automation engineers and personnel.

With this information it was possible to refine the general assembly functional decomposition, shown in Figure 1, for the target application. Using this functional breakdown it was possible to list various types of equipment for each required sub-function or subsystem. Equipment and subsystem combinations were formulated to generate concept layouts with different attributes. These layout concepts were then briefly evaluated in terms of the customer requirements, as weighted by the relevant personnel. A single layout concept was then selected for further development in the concept refinement chapter.

4.1 Specification development

Customer requirements were derived to determine what was required from the concept assembly system by the company (CBI). These requirements were formulated by examining the usage of existing automation machinery and considering the personnel who would use the machinery and those that would influence their purchase. A list of parameters which distinguished one automation system from another was formulated by considering how these personnel hypothetically would examine and evaluate automation systems. These customer requirements are listed below and shortly described in context.

- Reconfigurability: The ease with which the system can be reused/configured to manufacture variations of products.

- Maintainability: The technical skill and knowledge required to perform routine maintenance and repair to the system. Also, from a technical perspective, the complexity of performing maintenance on various parts of the system.
- Low cost: Estimation of the initial and running costs required.
- Automation level: Indication of the level of interaction required to supervise and operate the system and the number of workers required.
- Physical size of system: The volumetric size occupied by the system.
- Robust: The level of failure tolerance achievable by the system in question.
- Lean manufacture: Does the system minimise work in progress and utilize machinery intelligently without wasting material or implementing buffers.
- Product traceability: how easy is it to determine the product progress and position during manufacture.
- Safety: How safe is the machinery to operate, what is the risk of injury to surrounding workers.

Scrap rate would normally also be considered as an import customer requirement, but due to the conceptual stage of the designs, it would not have been possible to make a comparison between the concepts on this basis. Scrap rate was therefore not further considered here.

The next stage in the specification development process (Ullman 2003, p 68) is to investigate what competitor products are available, evaluate them in terms of the generated customer requirements and then to determine whether further product development should be pursued. However due to the intended specialized application of the concept assembly system, it was not possible to find an off the shelf commercial product for evaluation. Therefore instead an initial feasibility study was performed to determine whether sufficient technologies were available to implement such an assembly system. Various industry consultants and system integrators were also approached to gain insight into automation systems. After the initial literature study, it seemed that the necessary technologies and subsystems were available to warrant further investigation.

Quantitative engineering specifications were then derived for final evaluation of the concept assembly system. The engineering specifications were determined from the existing manual assembly process' production rates and running costs. For the target subassembly the engineering requirements were determined to be:

- A production rate of 30 000 assemblies of the target part family per day.
- Payback period less than two years.

The payback period was difficult to allocate a quantitative amount as this specification is highly dependent upon the size of the industry, the lifetime of the produced product and the company's available funds for research and development. Also the degree of investment risk that the company is willing to pursue influences this value. This measure was determined after consulting with one of the managers at the company who recommended that any system to be considered by them should have a payback period of less than two years. It was not possible to formulate engineering specifications for the remaining customer requirements as the client had no specified values. However these requirements would be used for relative concept comparison and in final concept selection after concept generation.

4.2 Concept generation

Before concepts are generated a clear understanding of the function of the assembly system is required. First the main function to assemble the target subassembly has to be broken down into its sub-functions which do not explicitly specify or favour a particular manner or approach of assembly. A functional decomposition is generated by listing all the functions to be performed.

A functional decomposition was generated following this procedure and by considering typically what distinguishable assembly modules are necessary to transform input components into the target subassembly. When examining the functional decomposition for each component within the target subassembly, it was apparent that they shared the same functional blocks and process flows. Therefore a general functional decomposition was formulated that is applicable to each component within the target subassembly. This general component functional decomposition is presented below in Figure 25.

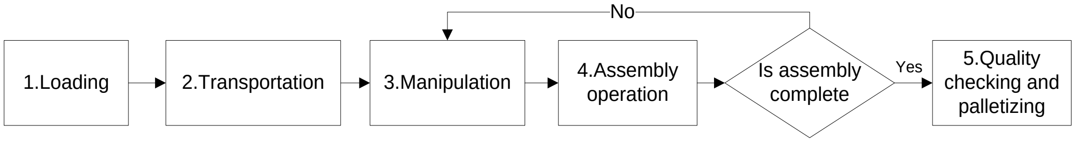


Figure 25 General component functional decomposition

In order to favour a greater concept generation basis, the general component functional decomposition was left at this level, so that the system did not become over specified. Functions were grouped into typical sub-systems present in assembly systems. These groupings are presented below in Figure 26.

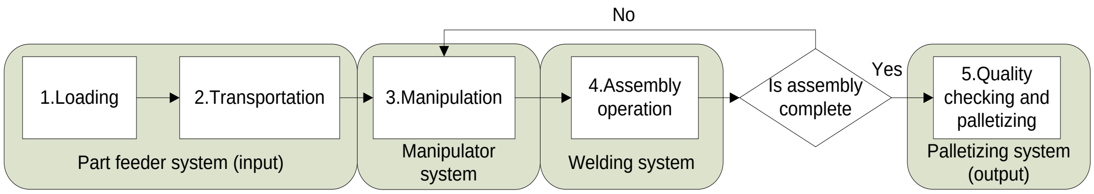


Figure 26 Function module allocation for concept assembly system

To generate as many layout design concepts as possible, a large base of hardware modules were reviewed and concepts researched for each module. Five different concept layouts were generated; they are presented and discussed below.

4.3 Layout concepts

Concept 1 was based on the idea of imitating the existing manual assembly process by simply replacing the operator at the welding station with two articulated industrial robots. Part bins would be placed within reach of the respective industrial robot to supply the industrial robots with different components of the target subassembly. A transfer conveyor would courier finished assemblies from the assembly system. These industrial robots would be equipped with end of tool machine vision systems to perform autonomous part collection and manipulation. Additionally a bird's eye view camera would be used to coordinate the operation of the two robots. These sensors would allow the industrial robots to collect components from an unsorted bulk bin and manipulate them for the weld operations. The layout is presented below in Figure 27.

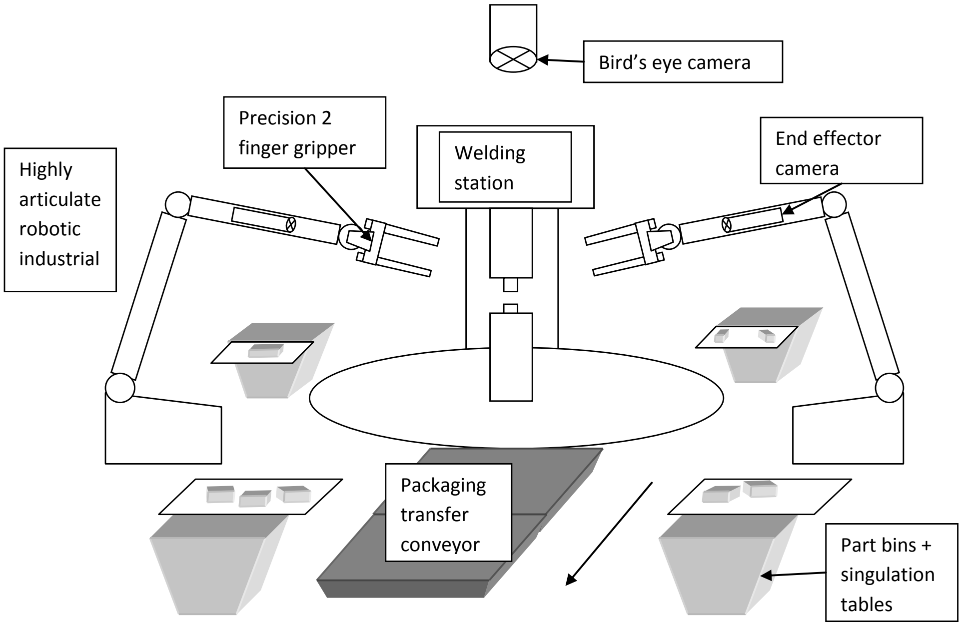


Figure 27 Concept 1: Twin robotic manipulator concept with end of tool vision systems layout

This concept maximises the usage of the existing hardware for simple integration and replacement of the existing manual assembly process. The sophistication of control and hardware implemented means that this concept has the possibility of being highly flexible, however prone to operating complexities. The feeding system relies on a bin picking approach with a singulation table if additional re-orientation operations are required to correctly grasp the component for final presentation to the welding station. The concept relies heavily on the flexibility of the industrial robot grippers. The assembly welding operations would be performed in a fixtureless manner, as the grippers would be used to collect, position and hold/secure the components before and during the weld operations.

Concept 2 was based on a modular idea, where each component in the assembly has its own independent dedicated modular feeding and manipulation subsystem and each weld is performed by a dedicated welding gun. These modules would be able to move relative to one another with enough degrees of freedom to position the component relative to its welding gun or guns. This would also allow the modules to retract so that the completed target subassembly could fall on a lower conveyor and be couriered away on completion of the welds. All assembly manipulation operations are done in parallel by each module, all the components are positioned correctly relative to one another and the welding guns before simultaneously performing all the welds to complete the assembly process. The positioning head or end-effector for each module would be of a dedicated design, with geometry to conform to a particular component. This head would secure the component in a set position and orientation during transfer motions and welding operations. The layout for this concept is shown below in Figure 28.

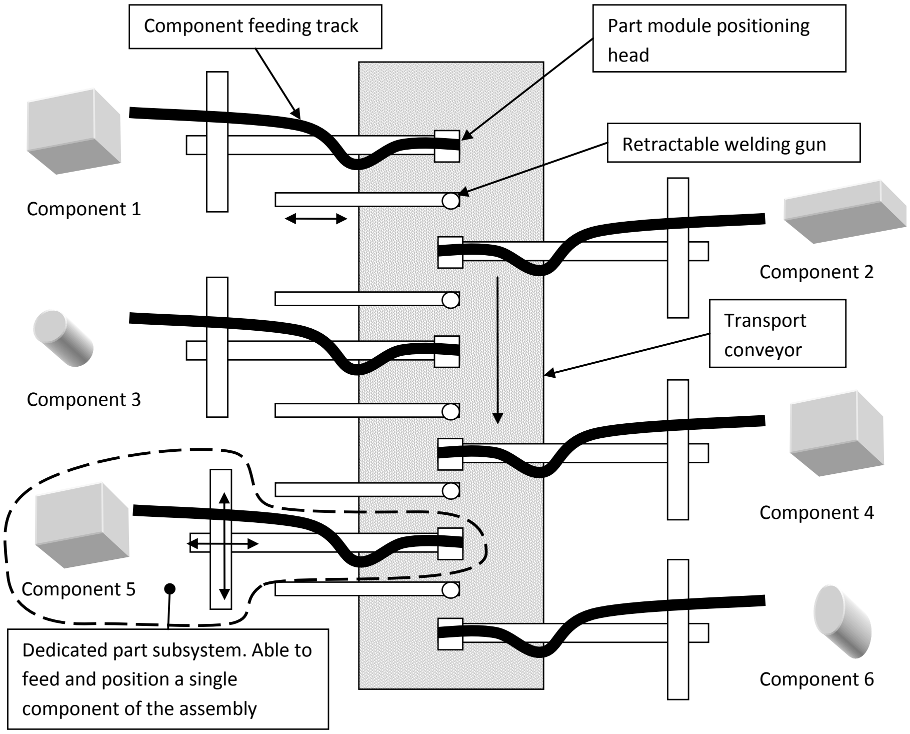


Figure 28 Concept 2: Combined feeder and manipulator modular layout

The design of these modules would be done to conform to the requirements defined by RMSs. This would allow for easy reconfiguration of each module from one component to the next, for all the components of the target assembly. This system may then be implemented to automate other similar assemblies by adding or removing modules depending on the number of components in the assembly and retooled accordingly. Unfortunately on a low level the concept utilizes a lot of dedicated hardware and incorporates a larger number of welding stations.

Concept 3 was derived to minimise the amount of hardware required and make use of less articulated manipulation systems for component positioning and transport. The feeding system would provide the assembly manipulators with parts in their final orientation required for the welding operation and the manipulators would simply collect, transfer and position the components at a central welding station for welding. The welding operations would be done in a fixtureless manner with the grippers of the manipulators positioning and securing the components prior to and during each successive weld. Components would be joined to the assembly without releasing the incomplete assembly. The completed assembly is dropped onto a transfer conveyor to be transported from the assembly system. The layout for this concept is shown below in Figure 29.

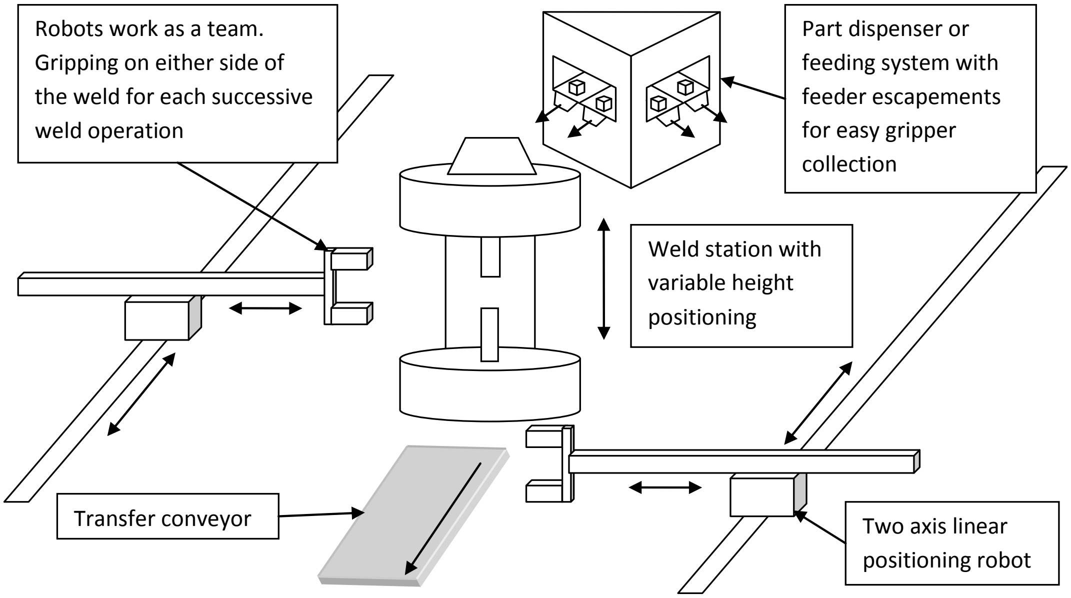


Figure 29 Concept 3: Part dispenser feeder with twin two axis linear positioning robots layout

In this concept the parts dispenser or feeding system would have to be very sophisticated to handle all the components in the assembly and present them in the final desired orientation for collection by the grippers. The parts dispenser would be modular in design and would then be changed between target-subassembly variants.

Concept 4 was based on the traditional assembly process, which is commonly used in industry. This concept implements a central fixture based approach to assembly. Components are transported and fed into the system for placement within a fixture. The fixture locates and secures the components for all the welding operations to be performed. This method is proven to work in industry and some of the existing welding processes of the target subassembly presently use this approach during the manual assembly process. In this concept the fixture would either be modular, allowing different fixtures to be used for different assembly variants or reconfigurable.

The concept operates as follows: components are transferred and placed into the fixture where they are secured; a gantry welding station with step electrodes moves from one welding site to the next performing the necessary welds; the completed assembly is then flipped over and ejected by fixture ejection pins into a collection bin. The layout for the concept is shown below in Figure 30.

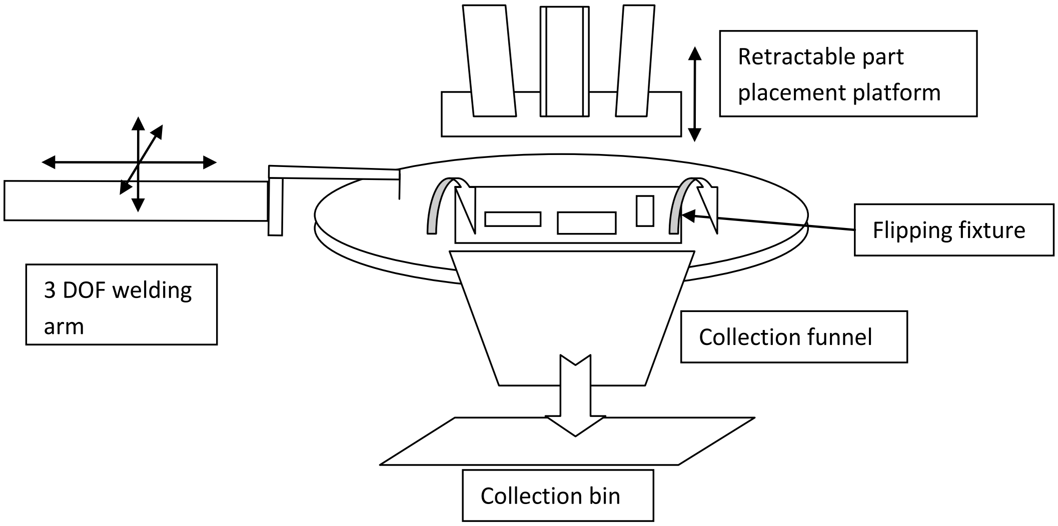


Figure 30 Concept 4: Central fixture layout

The fixture design for this concept would be very complex in order to allow accurate placement of assembly components for correct welding with top side electrodes, also the fixture would have to be modular or reconfigurable to accommodate component variations within the target subassembly.

Concept 5 was generated by combining elements from concepts 1 and 3. This concept utilises an intelligent feeding system to actively provide components that are in collectable orientations to the robotic manipulators. The layout for this concept is shown below in Figure 31.

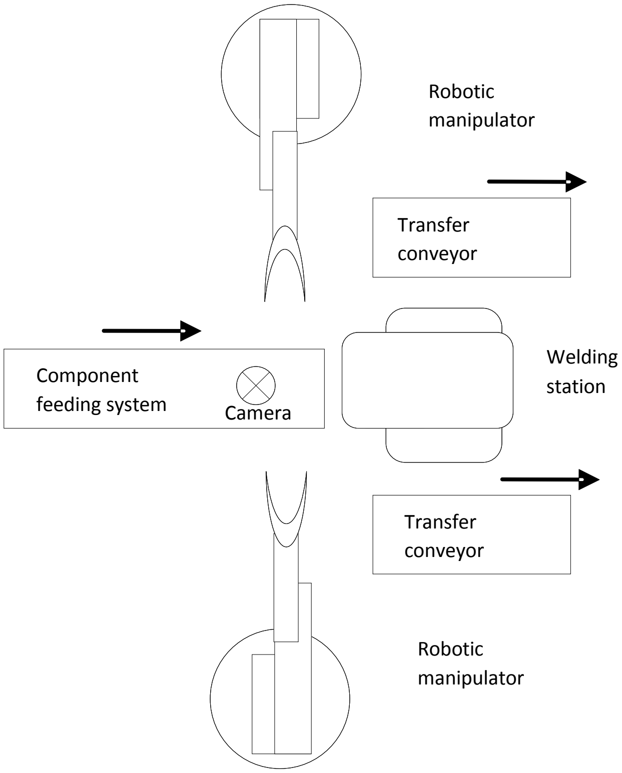


Figure 31 Concept 5: Twin robotic manipulator with intelligent feeding system layout

A vision system is implemented to provide information on all the components entering the assembly system via the flexible part feeder. The vision system determines whether the components being fed are in collectable orientations or not. If the component is collectable, this information plus the location of the collection site are transferred to the robotic manipulation system. If the component is not in a collectable orientation it is simply rejected back to its respective storage medium and jumbled for later re-circulation by the feeding system. This process would be repeated until the component enters the system in a collectable orientation. This concept was conceived to overcome foreseen design complexity of the vision systems and sensors proposed in concept 1 and the overly complex part feeder design of concept 3.

4.4 Layout concept evaluation

It was not possible to develop all the concepts further due to time limitations. Therefore it was decided to select a single layout concept for further development and evaluation. This was done by scoring each concept according to the derived requirements and selecting from the highest scoring concepts overall.

A modified decision making matrix (Appendix C) was formulated to determine the weighted importance of each design requirement. This was done by estimating how the relevant personnel from the company would rate the importance of each requirement. Using these ratings, a weighted average for each requirement was calculated, according to the perceived respective importance of each personal's influence on the final implementation decision.

The concepts were then rated on a scale of one to ten, where one was the worst and ten was the best, for each design requirement. Then these ratings were scaled using the derived weighted importance for each design requirement. The scaled scores were summed for each concept to form an overall concept score. From the evaluation two concepts were favoured; they were concepts 4 and 5. This evaluation was however based on estimated concept scoring values, which all had a degree uncertainty associated with them. The overall score differences between concepts were not conclusive of which concept was the best.

The concepts were therefore reviewed again, keeping the evaluation results in mind. Concept 4 featured lower cost in comparison with the other concepts, hardly any concept feasibility concerns and followed traditional methods of automated welding assembly, making this concept most likely the client's favourite choice. However the concept made little allowance for reconfiguration and manufacturing flexibility. Concept 5 featured a great degree of flexibility at a low cost in comparison with the other concepts, making it a favourable candidate for a low cost RAS design investigation. It was therefore decided to select concept 5 for further development and to determine its feasibility for the target application. Concept 4 was further developed and investigated by Sequira (2008) to determine its feasibility for automating the assembly of the target subassembly and its variants. Concept 5 will be referred to as the robotic fixtureless assembly concept throughout the remainder of the thesis.

5 Robotic fixtureless assembly concept refinement

The various subsystems of the robotic fixtureless assembly concept are functionally further developed and different subsystem configurations suggested and evaluated to determine the best configuration in terms of feasibility, flexibility and cost. The modified general component functional decomposition with subsystem module divisions for the robotic fixtureless assembly concept is presented below in Figure 32.

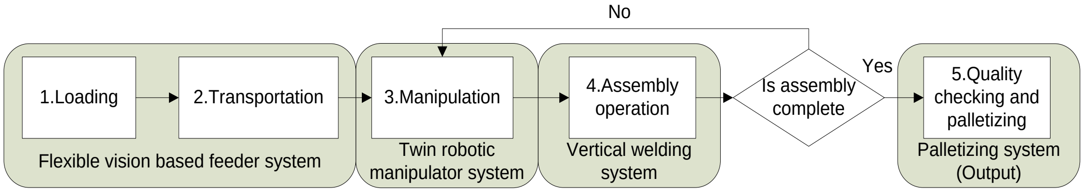


Figure 32 Robotic fixtureless assembly concept functional decomposition

The various subsystems are further developed and refined from the generalised layout conceptual idea in the following subsections. Additionally quality control integration and implementation for the concept is overviewed.

5.1 Part feeder

To automate the assembly process the components which make up the assembly must be presented on demand to the robotic manipulation subsystem.

The function of the feeder in the robotic fixtureless assembly concept is slightly different from that of conventional industrial feeding systems. The feeder design is intended to utilize the flexibility of the robotic manipulation system to minimise component specific orientation and manipulation hardware within the system. The feeding system must however provide the robotic manipulation system with information regarding the position, orientation and collection site of the fed components. The modified functional decomposition for this feeding system is presented below in Figure 33.

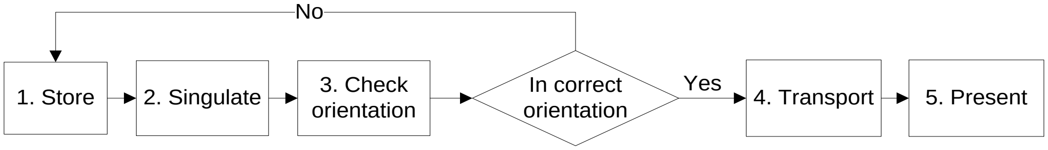


Figure 33 Robotic feeder functional decomposition

The components of the target subassembly would arrive at the assembly site in separated bulk bins. The components would be jumbled within these bins. These bins would be unloaded into a particular storage medium of the feeding system by a human operator for automated on demand feeding without human interaction until the storage medium has to be re-filled.

Concepts were generated for each functional block of the functional decomposition to allow various feeder designs to be generated. Three robotic based feeding subsystem concepts were generated based on the above functional decomposition.

All concepts use a bulk hopper to store components entering into the feeding system where possible. Mechanical and vibratory bowl feeders were also considered, but these feeders are mostly component specific and require retooling and parameter adjustment to feed different components. It was thus favourable to use a bulk hopper where possible and only to implement mechanical and/or vibratory bowl feeders for complicated components that might jam or tangle during feeding.

For instance, components such as the arc runner from the target subassembly would most likely tangle. These components would therefore have to be fed using a different feeding mechanism. To determine the feasibility of using vibratory bowl feeders for feeding such components from the target subassembly, a local industry specialist from Ayelsbury Engineering and Automation (Ramdeo 2008) was contacted. He confirmed that these components and others from the target subassembly, excluding the handle frame assembly, could be fed using vibratory feed bowls. Using vibratory feed bowels for components that could not be fed using bulk hoppers, would however limit feeding flexibility.

All the concepts generated and discussed below implement a vision system to determine whether the fed components are in collectable orientations or not. The vision system design and selection is discussed in section 5.5.

In the first concept components are dropped from the hopper onto a rectangular vibratory flat surface, where the components are singulated with shake operations. The vibratory surface is constantly monitored by a camera, which collects orientation and positional data of each component on the surface for collection by the robotic manipulation system. Each feeding module would be dedicated to feed a particular component of the assembly meaning the number of feeding modules required is equal to the number of assembly components. The feeder modules are placed close together and within reach of the robotic manipulation system. The module and cell layout are shown below in Figure 34.

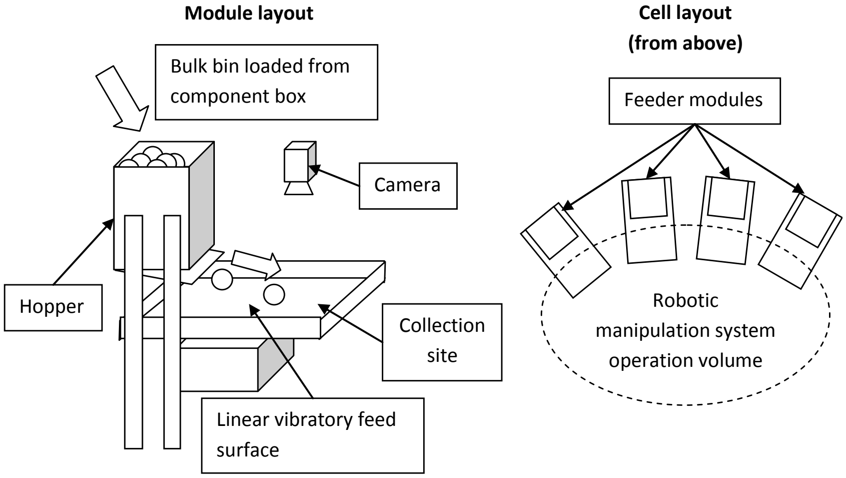


Figure 34 Vibratory surface feeder concept

The second concept implements three independent conveyor belts to transfer and singulate components from the bulk bin or hopper. Singulation is achieved by varying the conveyor speeds relative to one another. After singulation the components are then transferred past a vision system window for inspection and then either presented for collection at the end of the conveyor or circulated back to the bulk bin and jumbled for another circulation attempt. The modular feeder design allows multiple modules to be placed in parallel for each particular component of the target subassembly. The module and cell layout are shown below in Figure 35.

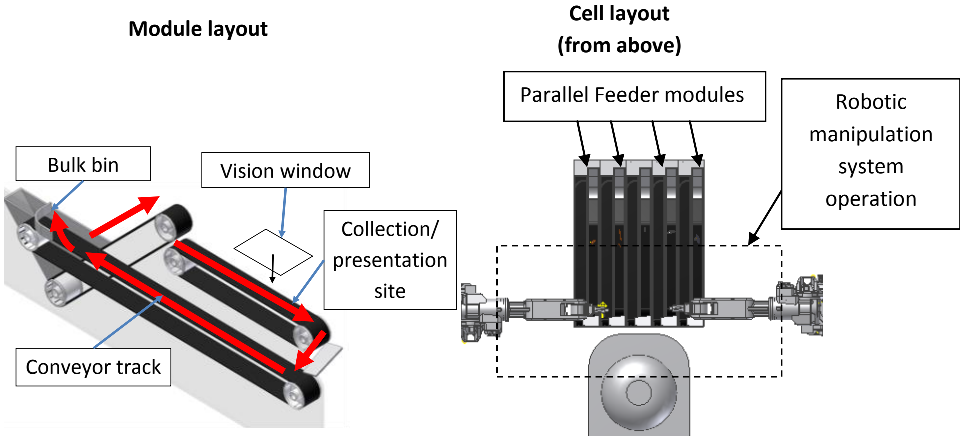


Figure 35 Re-circulating modular conveyor belt feeder concept

The last concept is similar in design to the second concept, but it consists of a simpler modular layout, which simply transfers components to a communal central conveyor for presentation or circulation back to the bulk bin. The module and cell layout showing the conveyor network are shown below in Figure 36. This concept operates as follows:

1. When a particular component is required for the assembly process, the bulk bin containing this type of component starts feeding these components onto the central conveyor via the module’s transfer conveyor in a stream. The central conveyor singulates components by running at a higher speed than that of the module’s transfer conveyor.
2. These components are transported along the central conveyor and under a camera. When a component passes under the camera, the vision system determines its presence and stops all conveyors, before photographing the component. This insures accurate component recognition.
3. The vision system then determines whether the component is in a collectable orientation. If the component is not in a collectable orientation:
    a. The conveyors are started and component feeding resumes.
    b. A pneumatic piston corresponding to the correct incline return conveyor transfers the component onto the incline return conveyor.
    c. The component travels up the incline return conveyor and then along a horizontal return conveyor that passes above the bulk bins. It is then deposited into its source bin by an adjustable wiper blade situated along the conveyor.
    d. This process (from a-c) continues until the vision system identifies a collectable component.
4. If the component is identified by the vision system to be in a collectable orientation, component feeding from the bulk bin ceases and the collectable component is transferred to the collection site. At the same time, the rest of the components along the central conveyor track are cleared by rejecting them back via the return conveyors to the source bulk bin, as described in steps a to c above.
5. When the collectable component reaches the collection site at the end of the central conveyor, all the conveyors are stopped and the component is collected by a robotic manipulator.
6. After the component has been collected, steps 1 to 5 are repeated.

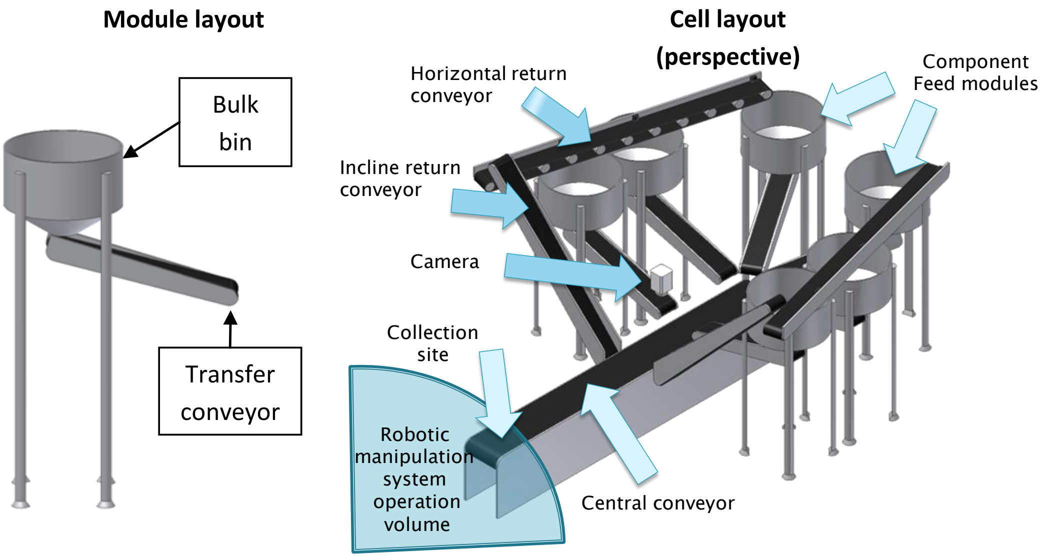


Figure 36 Re-circulating network conveyor feeding concept

The operation of this concept when feeding components of a particular type is illustrated below in Figure 37. The two operational pathways, as viewed from above, for components successfully identified for collection (1) and for components either in the incorrect collection orientation or not properly identified (2) are shown in the figure.

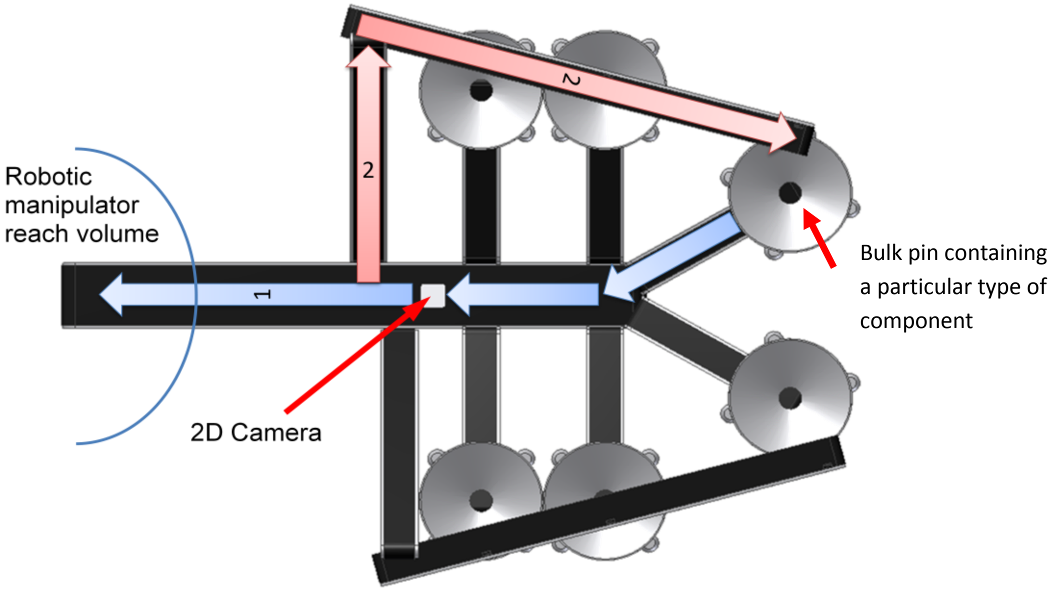


Figure 37 Flexible feeding concept operation and component pathways when feeding a particular type of component

Modules are placed on either side of the central conveyor to minimize distance from the furthest away module to the camera and collection position, to reduce feeding lead times.

These concepts were evaluated by rating them according to the following main subsystem specifications:

- Estimated cost.
- Reconfigurability.
- Minimizing the robotic manipulation collection volume.
- Scalability: Ability to accommodate assemblies which consist of few or numerous different components.

It was not possible to clearly evaluate the better concept in terms of cost without considering a particular application. However a trend was determined, using initial quotations for industrial cameras and conveyor belt sections. It was evident that any modular feeding system that implemented a camera or vision system for each dedicated component feeding module in the assembly would become very costly in assemblies consisting of numerous different components. However for assemblies consisting of a few different components, for instance two or three components, the dedicated independent feeding modular design would become more feasible and additionally would provide a faster throughput rate opposed to larger networked feeding systems.

The concepts were then compared in terms of minimizing the collection volume required by the robotic manipulation system and to allow for faster collection. Minimizing the size of the operational volume reduces the size of the industrial robots required. This is important as the components to be manipulated are small in size and must be manipulated within a congested operating volume around the welding station. Additionally smaller industrial robots are cheaper compared to their larger counterparts. With assemblies that consist of numerous different components, modular independent feeding systems may require the implementation of larger industrial robots or attached robots to movable platforms so that all the components would be within reach, which is less desirable.

Overall the conveyor network concept was favourable for assemblies consisting of some to many components as it has fewer expensive vision systems, and it also presents all the components at a single location for collection. This reduces the required operational volume of the robots. Additionally by extending or shortening the length of the central conveyor the number of feeding modules accommodated can be increased or decreased. This means that any assembly, regardless of the number of components it consists of, may be accommodated with minimal hardware modification or revision also the collection site would remain unchanged. However in very large assemblies the conveyor length from the furthest feeding modules to the vision system and presentation site becomes increasingly longer which would result in longer feeding lead times due to the increased transfer distance.

The conveyor network feeding concept was evaluated in terms of the selected target application. The target subassembly consists of 6 different parts, which is a large assembly size for automation. Therefore 6 different feeding modules would be required. For this application the cost of expensive vision systems is minimised in comparison to the other presented concepts. Also the collection volume size and location remains constant, as opposed to the other concepts where the collection volume size would increase proportionally to the number of different assembly components present, making them less feasible or favourable for these types of assemblies. Lastly reconfiguration in terms of cheap expandability is possible. Therefore the conveyor network feeding concept was chosen from the available concepts.

5.2 Robotic manipulator selection

A suitable robotic manipulation system which is capable of adequately re-orientating and transferring the assembly components from the collection location, at the feeding system, to the weld presentation position, at the welding station, is required. Before investigating the specialized design of a robotic manipulator, commercially available industrial robots were reviewed to determine if a particular model and configuration would be suited for this handling and transfer application.

As discussed in the literature review three common classes of robots could be selected from. The SCARA robots, which are conventionally 4 DOF robots, are used to position and orientate objects which usually only present themselves with one upwards orientation. These robots are typically designed to transfer objects or components in three translational directions and revolving it about its vertical axis. Gantry robots are usually also configured as 4 DOF robots with additional axes conventionally attached to the end-effector, if additional articulation is required. However gantry robots are unable to share their operational volumes with one another. Lastly there are articulated robots, which are typically modelled to mimic the motion of a humanoid arm and thus perform monotonous tasks usually assigned to human personnel. Articulated robots conventionally have 6 DOF providing them with great dexterity within their operational volume.

Robotic manipulators are usually selected by determining the manipulation requirements needed for the application, examining the spatial envelope within the work cell layout and the materials to be handled. The feeding subsystem provides the target subassembly components in various collectable orientations to the manipulation system at a common collection position. Therefore the components making up the target subassembly were examined to determine all the stable orientations present. Then a list of required spatial transformations could be determined by examining the target subassembly layout to determine the desirable presentation orientations for the components at the vertically opposed weld station, so that the welds could correctly be performed. A table was formulated which presents the worst possible collection orientation, the proposed presentation orientation at the welding station and the various Cartesian spatial transformations necessary between these two orientations for each component of the target subassembly (Appendix D). From this table it was evident that if all the components must be transported and orientated by the same manipulator, it would require at least 6 degrees of manipulation. It was therefore decided to investigate the range of commercially available industrial articulated robots for a suitable model.

Articulated industrial robots range from small low payload robots to large high payload robots that are commercially available from robot suppliers such as Kuka, ABB, Motoman, Staubli Fanuc and Adept, to list a few. These suppliers typically group their robotic manipulators by the maximum payload they are able to handle. The payload simply refers to the additional mass the robotic manipulator is able to support at its end-effector. As discussed in section 5.3, the selected Festo HGP-16-A-B pneumatic actuating gripper base (197 g) with specialized soft jaws (150 g) carrying the entire load of the completed target subassembly (23 g) amounted to a total payload requirement of approximately 0.5 kg.

The smallest articulated robotic manipulators commercially available, at the time of writing, ranged from 2 to 5 kg with a reach ranging from 0.5 to 0.8 m. However, when examining the limited available operational volume of these industrial robots in a virtual CAD layout of the work cell, the possible collection surface was small in size. Additionally there would be a large overlap in operational volumes of the two robotic manipulators. This would obstruct the operation of the robots by limiting their flexibility due to interference. Therefore the range of robotic manipulators slightly larger than that of the smallest was considered.

These industrial robots typically support a payload of 6 kg and have a horizontal reach of 1.3 m. When placing this sized robotic manipulator into the CAD work cell layout, the operational volume congestion was greatly reduced and the overlap of operational volumes between the two robotic manipulators was minimized. Additionally the usage of the collection surface was maximized allowing additional collection flexibility if required. For these reasons robotic manipulators from within this range were selected. A list of commercially available and potentially suitable models of robotic manipulators from ABB, Motoman and Fanuc were identified.

In terms of the target assembly application a suitable model of robotic manipulator needed to be selected and verified. The Motoman HP6 industrial robot model was selected and its assembly application simulated with components from the target subassembly in section 6.3. This industrial robot featured a repeatability accuracy within 0.08 mm (Motoman 2007b), which is relatively very small in comparison to the tightest target assembly tolerances. It should be noted that other industrial robots from other suppliers could possibly also have been used. Although representatives from Motoman insisted that the accuracy is achievable, this value is much better than what is commonly experienced in industry. The accuracy should therefore be verified.

5.3 Gripper design

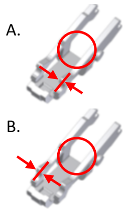
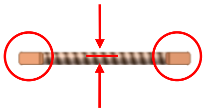
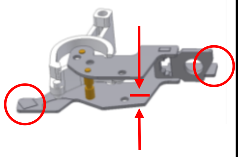
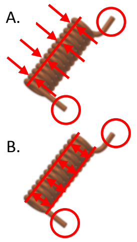
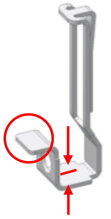
While flexible grippers are available for industrial robots, they are not small in size, are not typically designed to collect small components and are neither designed for fixtureless assembly. Additionally, flexible grippers are very expensive and sophisticated which would require additional maintenance and therefore increase the chances of operational faults. Flexible grippers with multiple DOF, which are often shaped like humanoid hands, are rare in industry and are seldom sold commercially. These flexible grippers are usually custom designed as academic or research prototypes.

The concept uses two robotic manipulators to perform the assembly operations; it was therefore possible to assign different components to each robotic manipulator for handling. This would possibly allow for the design of two specialized but less sophisticated grippers for each respective robot. When analysing the assembly operations and their sequence of execution however, it was determined that each gripper would still have to handle components with both cylindrical and flat geometrical features. Additionally the components handled by each robotic manipulator would change from cycle to cycle to minimize idle time. It thus becomes favourable to first attempt to design a single reconfigurable gripper able to collect, manipulate, secure and release all the components of the target subassembly. Therefore the design part family was chosen to include all the components of the target subassembly. The gripper design guidelines proposed by Causey (2003) were used and are referenced throughout the design process.

After the target part family to be handled by the gripper was selected, it was necessary to determine desirable final collection sites on each of the components. These sites were carefully selected to ensure that there was no obstruction of the welding site locations for each component. Also they were selected in such a way as to minimise deformation exerted on the components during the welding process. Critical assembly constraints and existing component variations were carefully considered during the design process. The best identified final collection sites for all the components of the target subassembly are presented below in Table 2.

When examining the desired final collection sites and their locations, it is deducible that a pincer or two finger parallel closing gripper should be sufficient in handling all of the components. All components have opposed identified collection surfaces allowing them to be secured between two parallel acting fingers, but collection surfaces are either flat or round in cross section. This problem could be overcome by designing specialized soft jaws to collect both geometries. Alternatively multiple grippers could be used to handle each type of geometry. However this would result in undesired extended cycle times due to tool/end-effector changes.

Table 2 Target subassembly component collection site information

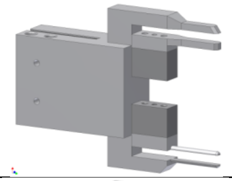
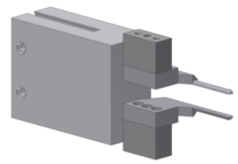
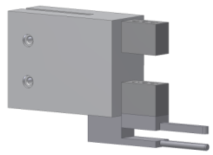
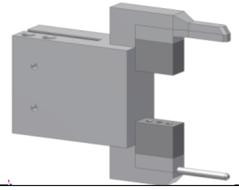
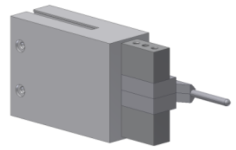
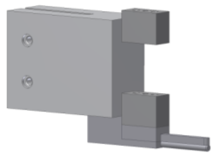
Assembly Component	**Moving contact**	**Pigtail**	**Handle frame subassembly**	**Coil**	**Arc runner**
Picture of collection point(s) and welding sites (circled)					
Description	Opposed, flat and parrallel gripping surfaces on either side of the moving contact	Contact surface is cylindrical, secured by clamping on either side of cylindrical body	Gripped on either side of bottom plate, surfaces are opposed, flat and parallel	Gripping surface is the interior and exterior cylindrical faces.	Gripping surfaces are opposed, flat and parallel.
Gripping thickness and acting direction	A – 0.8 mm closing B – 0.8 mm closing	1.382 – 2.26 mm closing	0.8 mm closing	A - (circumference) 0.8 – 4 mm closing B - (Insertion) 4.8 mm opening	0.8 mm closing

Next a suitable commercially available gripper actuation base was selected. The function of the two parallel finger gripper actuating base is to provide sufficient force to secure and hold the components during transfer and welding operations and offer sufficient finger stroke and length to grip all components of the target subassembly. Therefore a pneumatic gripper was favoured as fine force control was not necessary and pneumatic air supplies were already available at the assembly site. The components are also light in weight and only require minimal force to secure; this meant that a small predetermined force could be applied for all the components to adequately secure them without causing damage. The size of the gripper would be determined by the required stroke of the actuator fingers. From Table 2 above, the largest gripping width required was determined to be 5 mm, offering 0.2 mm of extra allowance. The Festo HGP range of pneumatic grippers was selected as a suitable platform to design the gripper soft jaws around. This gripper provided sufficient gripping force in a compact size with double acting fingers for internal and external gripping capabilities. The size of the gripper from the HGP range to use could only be determined after the specialised soft jaw concept was selected and refined, as finger strokes and soft jaw lengths would be needed for the final selection.

It was noted that the selected HGP actuating base is not designed for welding applications and welding splatter, however resistance spot welding does not conventionally produce weld splatter and the soft jaws would be mounted to the HGP gripper base via insulation spacers to isolate the soft jaws from the actuating base preventing welding current and heating from potentially causing damage to the HGP actuator or the robotic manipulator. These precautions seemed adequate to justify their selection and implementation.

The soft jaws had to be specially designed to effectively collect, secure, hold and release all the components of the target subassembly. Three soft jaw gripper concepts were developed for the HGP actuator base, which are shown and described below in Table 3.

Table 3 Gripper soft jaw concepts

Gripper concept	Dedicated soft jaw sets	Central combined soft jaw	Combined L-shaped soft jaw
Open			
Closed			
Description	Separate soft jaw sets, one set dedicated to handling components with flat collection surfaces and the other set for components with cylindrical internal features. Each soft jaw set implements a stationary finger which is simply mounted to the base of the gripper in an unconventional manner.	Symmetric soft jaws are shaped with flat internal mating surfaces for collection of components with flat surfaces and have a cylindrical outside finger contour for insertion and collection of components with cylindrical internal features. Soft jaws are central acting (both move and close at a central location)	Two different soft jaw fingers. Upper soft jaw has flat inner face for collecting components with flat collection surfaces. Lower soft jaw has flat inner mating surface and cylindrical finger outer contour for insertion and gripping of components with cylindrical shell features. The lower soft jaw is stationary and is mounted to the base of the gripper in an unconventional manner.

In all the above concepts, components with flat adjacent gripping surfaces at their collection sites and the pigtail are gripped between the soft jaws, as shown in A of Figure 38 below. The dedicated soft jaw sets and central combined soft jaw concepts grip the coil by inserting the soft jaws along the centre line of the coil and opening them to exert force on the internal circular surfaces, as shown in B of Figure 38 below. The combined L-shaped soft jaw concept, however, grips the coil on its circumference by inserting the lower soft jaw along the coil’s centre line and clamping the coil between it and an external soft jaw as shown in C of Figure 38 below.

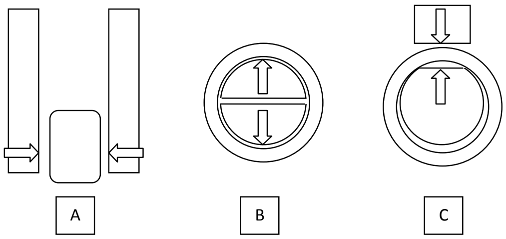


Figure 38 Gripping methods for gripper concepts

With three different concepts, evaluation criteria were formulated to determine which concept to further develop and implement. The evaluation criteria were defined as follows:

- Effective use of confined operating volume around welding station (minimally intrusive)
- Complexity of proposed design
- Effective design maximising component collection possibilities

The combined L-shaped soft jaw concept favoured all the above evaluation criteria in comparison to the other two concepts. The combined jaw design meant that only one set of soft jaws would be required to handle components with flat and curved contours, reducing the spatial volume occupied by the gripper. The dedicated and L-shaped soft jaw concepts allow additional collection scenarios for each component as it allows collection in both parallel and perpendicular approach directions to the collection surface. Traditional soft jaw designs usually only accommodates collection in either parallel or perpendicular directions to the collection surface. These collection scenarios are presented below in Figure 39 as demonstrated with the L-shaped soft jaw concept.

The combined L-shaped soft jaw concept, featured a stationary lower finger, which resulted in gripping being performed by moving the upper finger towards the lower finger and then away from the lower finger for release. The parallel collection scenario, depicted in Figure 39 below, meant that the collection surface would have to provide minimal displacement allowance during collection to prevent damage to the gripper or collection surface. The collection surface for the concept was a rubber conveyor belt, which would most likely provide enough displacement allowance during collection, otherwise a spring loaded collection surface could be implemented.

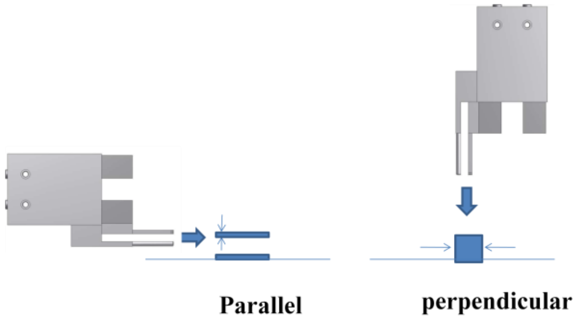


Figure 39 L-shaped gripper collection scenarios

After evaluation, the combined L-shaped soft jaw emerged from the above concepts and was selected for the target subassembly. Next the gripper soft jaw design had to be refined and the target application verified. This was done by selecting a model of Festo HGP grippers with sufficient finger stroke length and then determining whether it exerted sufficient gripping force to secure the components during transfer, while not being excessively large to deform the specialized soft jaw fingers. Also the induced maximum stresses within the designed soft jaws had to be checked to determine whether they would not lead to static and/or fatigue failure. Gripper verification is discussed further in section 6.2.

5.4 Welding station

The welding operations are central to the target subassembly. Three different concepts for the welding station were generated in context of the proposed fixtureless assembly concept. The first concept simply integrates the existing vertically opposed electrode resistance spot welding station, which is presently being used in the manual assembly process (discussed in section 3.3), into the assembly system. The second concept is the use of new off the shelf specialized welding equipment for automated resistance spot welding of small electrical switch gear components. The last concept involves implementing a third robotic manipulator with a mounted welding gun to provide possibly additional flexibility and reduce transfer distances of the twin robotic manipulators.

When these three concepts were compared, the third concept was discarded since, as was reported in the literature review, a high payload robot of 50 kg or above would be required to mount the smallest of resistance spot welding guns on. An industrial robot with this payload is large in size and not accurate enough. Additionally the cost of implementing a third high payload robot was relatively very expensive.

The second concept of purchasing new specialized equipment to perform the welding operations presented few advantages over the existing equipment used. One manufacturer, Miyachi Unitek, produces a range of fine spot welding equipment for joining small electrical switch gear components and has local suppliers in South Africa. However when examining the advantages of a quoted welding system recommended by the supplier to perform the various welds forming the target subassembly, a minimal gain was noticed. Overall the welding station size was drastically reduced, welding performance and quality was slightly better than the existing welding stations, but not justifiable in terms of large additional system cost.

For these reasons the initial concept of integrating the vertically opposed electrode resistance spot welding stations used in the present manual assembly process into the new assembly system, was favoured and would additionally reduce the overall assembly system cost.

5.5 Vision system

The vision system is part of the proposed flexible feeding system and interprets visual information captured from a 2D camera system. Only horizontal positional information is required from the vision system since the height of collection for components travelling along the central conveyor would remain constant, making it possible for the collection point height for all the components poses to be pre-programmed from part designs. The type of information required from the system would include the presence, orientation and 2D collection location (if applicable) of components on the central feed conveyor. The proposed functional decomposition for the vision system is presented below in Figure 40.

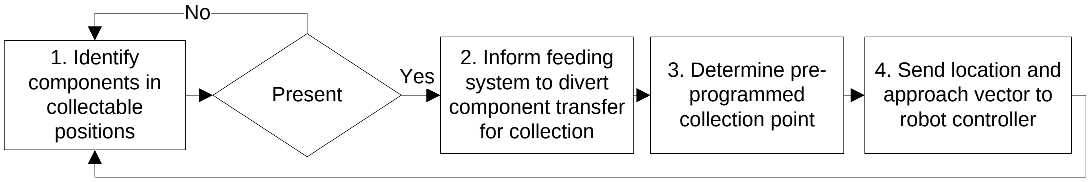


Figure 40 Vision system functional decomposition

The vision system controls the operation of the flexible feeding system so that only components in desirable or collectable orientations are presented to the robotic manipulators. When a component is required for assembly, it is fed from its feeding entry point, past the camera of the vision system. The vision system then determines whether the component is in a collectable orientation for gripper collection by the robotic manipulators. If so, it is transferred to the end of central conveyor and to within the collection volume of the robotic manipulation system, otherwise it is cycled back to its bulk bin for later recirculation.

Industry suppliers of commercial vision systems were approached, as listed in section 2.5, to determine what products and solutions were available for this particular vision inspection configuration. Cognex, which had two distributors in South Africa, was chosen as they provided a free limited trial version of their commercially available software, Cognex VisoinPro, and for their quick and reliable correspondence. Three different commercial vision systems were suggested: a low or high resolution standalone DVT vision system or a PC software based vision solution including camera, software and licensing, machine vision light and panel PC.

The vision system for the concept assembly system should be easily reconfigurable on both a software and hardware level allowing the system to be easily adapted from one automation application to another. The standalone high and low resolution DVT vision systems made little allowance for hardware modification and accessories. These vision systems were designed as self contained units, featuring inbuilt software and input/output ports for limited interfacing. This ensures that these vision systems perform a set task easily and reliably. In terms of reconfiguration, however, these systems allow little flexibility for expandability or adjustment. The number of input/output ports, per device, is limited and the software, while flexible, is limited by the number and types of industrial robots and/or hardware it is able to control.

The computer based vision system allows a modular architecture for easy hardware reconfiguration and expandability. The camera is not restricted to any particular brand or type of camera. This allows the system integrator to select a suitable camera for his particular application and allows easy refitting or upgrading for alternative or future applications. The PC vision system operates by using a licence based software package that runs in the Windows® environment of an ordinary PC. So additional hardware such as input/output, network interfaces and data-acquisition expansion cards can easily be added to or removed from the system. The PC may also be custom configured by a system integrator to decrease processing times, by installing a faster CPU for instance. The PC based vision system would, however, compromise stability in sophisticated system configurations and possibly also suffer from slower processing times in comparison to the DVT systems.

The PC based vision system provided the most flexible platform for the development of a potentially reconfigurable vision system. Additionally the PC based vision system, incorporating a low cost industrial camera, was less expensive than the cheapest standalone DVT vision based system. The PC based vision system was selected for application with the target subassembly, as the software, VisionPro by Cognex®, was freely available from their website for download and trial purposes. This would allow for easy feasibility testing without incurring extra design costs. The feasibility of a PC based vision system is further investigated with components from the target subassembly in section 6.4.

5.6 Palletizing system

Completed target subassemblies in general must be transferred from the design assembly system to either the next assembly process or for final packaging. However the interface at the output of the design assembly system is left undefined as there presently is no existing automation machinery to interface with. When the welding has been completed, the subassemblies are still gripped by the robotic manipulator so final placement on a conveyor or pallet is possible. Therefore this aspect of the design is left open, with numerous possibilities available for any particular output requirement. This allows the system integrator to customise the system output for his particular need.

5.7 Quality control system

Quality control inspections reduce production defects of the manufactured product and ensure correct operation of the designed assembly system. To prevent operational crashes and damage to the assembly subsystems, inspection should be performed on components prior to entry into the assembly system. For this reason a visual inspection by the assembly system's machine operator prior to or during loading of the various components into their respective bulk hoppers within the feeding system should be performed. Additionally the vision system used to identify component pose and position may be used as an additional visual inspection and measurement tool to ensure component quality, effectively using a single camera to inspect all the components on the central conveyor and only allowing components within design specifications to pass along to the robotic manipulators and rejecting the others.

Next a quality control inspection should be performed on the final assembly after the target subassembly has been completed and placed within the external housing of the circuit breaker and sealed. This process would be performed as in the present manual production system (section 3.3) using their existing specialized quality testing apparatus, to check if the completed circuit breaker's tripping current and tripping time are within specification.

5.8 Refined concept overview

An overview of the robotic fixtureless assembly concept consisting of the selected subsystems for the intended target application is presented below. The concept refinement chapter demonstrates how the initial concept was developed and refined for manufacture of the target subassembly. This process could just as well be applied to other similar target applications for automation, such as the manufacture of different central welded subassemblies for other circuit breaker ranges (section

3.1). Some selection and design decisions may be changed to accommodate these new applications. This would most likely involve the design of new grippers and welding electrodes. The layout for the final robotic fixtureless assembly concept is presented below in Figure 41. Layout drawings are given in Appendix E.

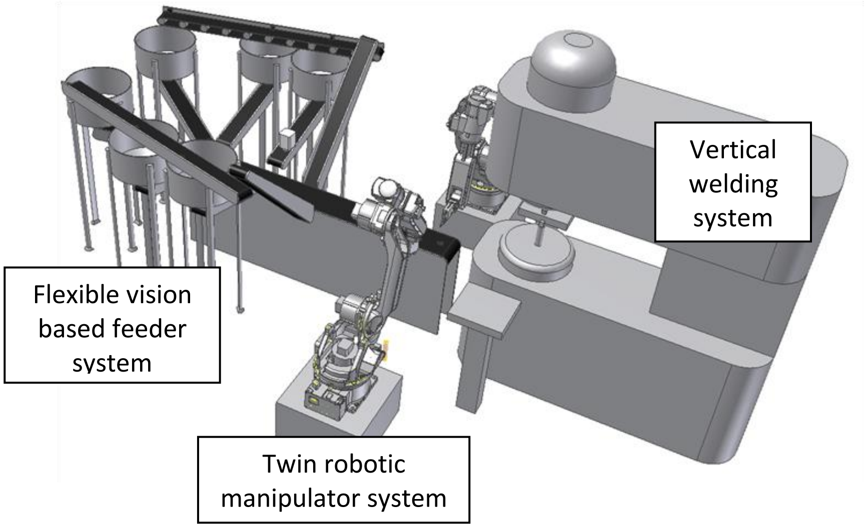


Figure 41 Final robotic fixtureless assembly layout for target subassembly manufacture

Subsystems within the robotic fixtureless assembly concept are chained together in a serial manner, which means that the overall system flexibility is determined by the least flexible subsystem or module within the system.

The subsystem which greatly restricts the flexibility of the designed assembly system is that of the gripper or robotic end-effector. Due to the strict handling requirements identified when designing the gripper for particular application with components of the target subassembly, no commercial flexible gripper was available. The design of a flexible gripper, capable of handling a variety of components similar to and including those of the target subassembly, would be highly sophisticated and incur large development, and possibly running, costs. The gripper was therefore simplified in form and designed to handle a certain variation of components using the same set of soft jaws.

When reviewing the proposed layout for the robotic fixtureless assembly system, it was not apparent whether such a configuration would be indeed feasible. The next stage in the development process was to determine which aspects or subsystems were critical to the successful operation of the concept assembly system and then whether further testing, experimentation or calculations would be warranted to determine whether they would operate as intended.

6 Feasibility investigation

The focus of this section is to identify the various elements or subsystems that are critical to the operation of the robotic fixtureless assembly concept assembly system and that would warrant further investigation, in the form of calculations, simulations and/or experiments to determine if they would indeed operate as required for the selected case study.

Four main elements within the flexible feeding system and robotic manipulation subsystems were identified as possible operational concerns that would require further investigation i.e. whether:

- The drop probability of components presenting themselves in final collectable poses from the feeding system for collection by the robotic manipulation system was high enough to avoid feeding delays.
- The soft jaw design of the gripper was suitable for gripping and securing components from the target subassembly without structurally failing due to static or fatigue loads.
- The dexterity of the selected robotic manipulators and designed grippers was enough to collect and manipulate components of the target subassembly as required for all the necessary assembly operations without violating axis limits and avoiding collisions.
- The vision system would be able to identify and distinguish between different component orientations and determine their collection sites.

These four elements are further described and investigated in the following sections and afterwards the case study costing estimation and evaluation is presented.

6.1 Feeder collection probability

The custom designed flexible feeding system presented some uncertainties in its operation with components from the target subassembly. The main concern was whether the drop probability of components presenting themselves in final collectable poses would be sufficient to achieve a fast production rate. A pose is a static stable orientation of a component which results after the component comes to rest after dropping on a flat surface. The final collection pose is an identified component pose that allows the robotic manipulator to collect and present the component to the welding station directly.

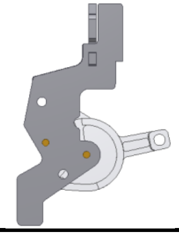
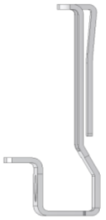
Without active and passive orientation features, the feeding system would have to rely on the fact that each component had a higher probability of presenting itself in one of the final collectable poses, as opposed to other static poses not suitable for collection, after they are dropped from their respective feeding modules onto the central feed conveyor. Ideally it is desirable to always present components in their final collectable poses; this could also be achieved through clever component design, but this was not considered in the work presented here.

The most logical method of determining the probability that components of the target subassembly would present themselves in their final collection poses was to perform a series of drop tests with each of the components from the target subassembly under similar conditions as those proposed by the conceptual feeder design. This was deemed the best method since the components had sophisticated geometries and are light in weight (heaviest component had a mass of 8 gram). This meant that their centre of gravity would have little influence in determining the static pose probabilities analytically. The collision between the component and the collection surface, and the geometrical design of the components, were expected to have a larger influence on the resulting static pose. Only components that would sometimes present in an undesirable pose were tested, since the others would only present themselves in desired collection poses e.g. the coil and pigtail.

From performing a series of drop tests, a drop distribution for the various static poses of each component was generated. From this distribution it is possible to approximate the probability that a component of the target subassembly would present itself in a final collectable pose. The tabulated results for each component are presented in Appendix F and the summarised results are presented below in Table 4.

The drop test results show that the handle frame subassembly and the moving contact had less than favourable chances of presenting themselves in a final collectable pose. These statistics could be used to estimate each component’s feed rate, however excessive testing on the full scaled system or using sophisticated simulation software would be required to obtain a significantly more accurate prediction. The desire to achieve maximum throughput rates from the designed assembly system for the target subassembly meant that a delay imposed by component feeding was undesirable.

Table 4 Probability for tested components of the target subassembly to present in a final collectable pose

Assembly component	Moving contact	Handle frame subassembly	Arc runner
Picture of a desired final collection pose (as viewed from above)			
Probability of final collectable pose presentation	65%	55%	92.5%

Two solutions were suggested to possibly increase feeding rates. The first idea was to implement a flipping manipulation station along the central feed conveyor to re-orientate components to a final collectable pose from one of its other poses, effectively increasing the occurrence of final collectable pose presentations. This would however require the implementation of an additional camera and additional conveyor segments and stations.

The second solution was simply to use the robotic manipulators to re-orientate the components into final collectable poses. This would be done by first collecting the component from a collectable pose and then placing the component on a work surface in a different pose that would allow for final collection by the gripper. This solution would only require the addition of a work surface for each robotic manipulator for re-orientation placement and re-collection operations. All the components of the target assembly also always present themselves in a collectable pose so that collection by the gripper is always possible. However cycle times may lengthen due to the potentially increased number of assembly manipulation operations required. Potentially this would be faster than waiting for a component to arrive from the feeding system in a final collectable pose. This implies that production cycle time would be dependent on the operating speed of the robotic manipulators.

6.2 Gripper design

The robotic gripper was conceptually designed to handle components from the target subassembly. Following the conceptual design of the gripper in section 5.3, it was not evident whether or not the gripper soft jaw design would be able to withstand the forces encountered during clamping and securing components for the numerous operations required in the assembly. Also it was not clear whether the gripper was able to exert sufficient force to prevent slippage during transfer motions. It was also determined that the gripper would be clamping and releasing components with rapid succession to reduce cycle times. When the Motoman HP6 robotic manipulators operate at full feed speed, cycle times between clamping and releasing could be as short as half a second. With all these design concerns, which were not easily deducible, an in-depth feasibility calculation was warranted.

Firstly a 3D CAD model was made using Autodesk Inventor 2009 to refine and better determine the final geometry and dimensions of the soft jaws. An assembly drawing of the robotic gripper is given in Appendix G. With this information, combined with the Motoman HP6 robotic manipulator specifications from the supplier, it was possible to perform the following calculations and selections:

- Determining the basic gripping force required to preventing slippage of handled components during transfer motions, by roughly calculating the required static frictional force using coulomb friction.
- Selecting an appropriate sized Festo HGP pneumatic actuating base and then determining the actual gripping forces.
- Calculating the deflection of the gripper fingers to determine whether it was within an acceptable operating range.
- Selecting a suitable material for the soft jaws of the gripper. The geometry and material selection were then used to perform static and fatigue failure calculations to verify this selection.

From the calculations given in Appendix H, it was found that the Festo HGP-16-A-B would be a suitable actuating base selection for handling components of the target subassembly. It would exert sufficient clamping force to prevent slippage during transfer motions and not excessively deform the components or soft jaws. It was noted in the datasheet that Festo does not recommend using these gripper actuating bases for welding applications as they are not designed to handle weld splatter and excessive heat. Resistance spot welding however does not produce the kind of weld splatter and constant heat that other welding methods do. The soft jaws would therefore be mounted to the HGP actuating base with insulted screws and mounting spacers to isolate the high welding current and heat from the gripper's actuator base.

Another calculation in Appendix H determined to what extent the lower soft jaw finger would deflect. For this calculation an extreme loading case was selected, where the full force of the gripper is exerted at the tip of the lower soft jaw finger. The loading forces encountered during welding were neglected as they would probably be small, due to the selected vertically opposed electrode configuration of the welding system (section 5.4). The potential problem of components sticking to the electrodes and inducing additional handling forces is avoidable by redressing the electrodes at set intervals. The deflection for this case was calculated to be 0.188 mm, which was within tolerable manufacturing allowances for the target subassembly.

Through iterative calculations, 826M40 (En26) steel was selected as a suitable material to manufacture the soft jaws from. This steel could withstand higher yield and ultimate stresses than conventional mild steel and yet was not difficult to machine. This selection of material, combined with the proposed geometry of the soft jaws, resulted in static and fatigue safety factors of 12 and 3, respectively. These safety factors were within operational limits and made allowance for some real world uncertainties. All the calculations are given in Appendix H.

In summary, from the calculations it was found that the Festo HGP-16-A-B mounted with the proposed soft jaw geometries would perform the required assembly operations within acceptable operating parameters. For this application it was possible to use only one specialised gripper design to minimised cycle times. However, for other applications where a single specialised gripper design would not be feasible, multiple grippers and a gripper changer may be used.

6.3 Concept simulation

The assembly system was first modelled in 3D using Autodesk Inventor 2009 for basic spatial verification. The assembly process for the target subassembly involves numerous operations, which were difficult and time consuming to verify using this 3D model. It was therefore decided that a simulation would be necessary. The objectives for creating a simulation of the designed assembly system were:

- To serve as a developmental platform upon which the operation of the selected robotic manipulators and gripper design could be verified within a 3D virtual environment.
- Verifying placement of the robotic manipulators relative to the flexible feeding system and welding station and potentially optimising placement.
- Verifying the complete assembly process of the target subassembly by checking for collisions, obstructions and/or axis movement violations of both the robotic manipulators and grippers during the transfer motions.
- Determine a rough estimate of the minimum assembly cycle time.

- Provide a visual demonstration of the proposed assembly process.

A Motoman software package, called MotoSimEG, allowed all their commercially available industrial robots, including the HP6, to be simulated in a virtual environment for offline programming and verification. It was therefore selected to create the simulation with.

The operation of the flexible feeding system was not implemented in the simulation due to programming and interfacing complexities. This meant that re-orientation operations were avoided in the simulation and components were placed statically within the feeding system collection site in their final collection pose. Additionally the potential flexibility of the handled components or incomplete assemblies was not modelled, as this was not possible with the software. This simulation would represent the ideal scenario neglecting all feeding system induced orientation adjustments on components and delays. Geometries of the target subassembly components, vertical welding station and flexible feeding system were closely approximated with basic geometries to save computational resources and reduce modelling complexity. A picture of the simulation is shown below in Figure 42.

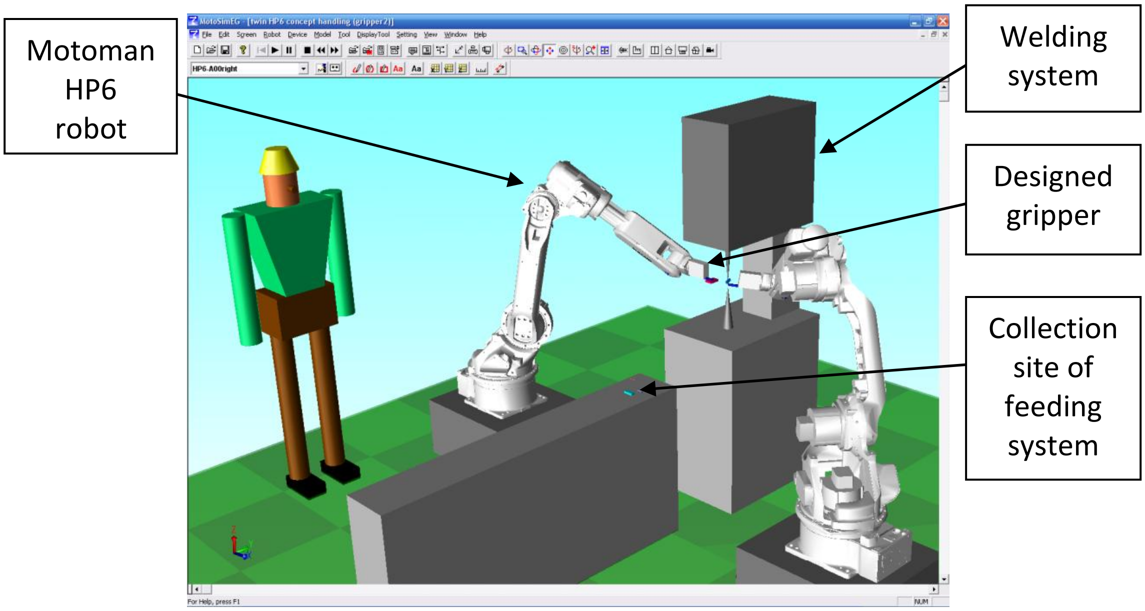


Figure 42 MotosimEG simulation of operational concept

Videos of the complete simulation, at 20% and 100% of the intended operational speed, clearly demonstrate the intended assembly process of the target subassembly from its components. These videos can be located on the included DVD

(\Process simulation 20%.avi, \Process simulation 100%.avi). Images showing the components of the target subassembly being handled by the gripper, as well as the welding process are given in Appendix I.

The simulation demonstrates the successful assembly process of the target subassembly for the ideal scenario. Information gained from generating the simulation aided in verifying the defined objectives. From the simulation it was possible to determine that the selected robotic manipulators (twin Motoman HP6s) combined with the grippers were able to reach the various collection and presentation points required during the assembly. This was possible without encountering any collisions and without exceeding axis limits of the selected robotic manipulators. Additionally from the simulation, a minimal cycle time of 21.45 second was calculated at maximum robotic manipulator feed rates. This cycle time factored in gripper closing and opening times, and estimated welding times.

This simulation shows that the selection of robotic manipulator model combined with the gripper design is capable of assembling the target subassembly. The simulation only demonstrates a single ideal scenario and therefore additional component placement scenarios (orientation, position and pose) were also considered. When examining the tool accessibility volume at the collection location it was noted that a limited range of collection approaches was not possible due to axis movement limits on the Motoman HP6 manipulator. These limited scenarios could be overcome however, by performing re-orientation operations with the robotic manipulator, similar to what was described in section 6.1.

The operational complexity of this solution meant that the logic, which created the robotic code for collecting and handling the components of the subassembly, would probably be sophisticated. The feasibility of this aspect in the design would require great expertise in interfacing between the vision system and robotic manipulators and would only be determinable through the cooperation of specialists from both these fields. The assembly system design was not far enough developed to warrant such an investigation yet and incur additional design costs. This would only therefore be investigated after the initial feasibility investigation was completed.

6.4 Commercial vision system

The vision system is vital to automating the robotic fixtureless assembly concept. It is potentially capable of registering component information for any assembly component. A single camera may also be used to register any number of pre-taught assembly components making it highly flexible. Conventionally the vision system is taught to recognise a component and which information to determine and what to do with that information. This is usually done with software programs and tools provided as part of a commercial vision system. This process of teaching can be performed offline without interrupting present production progress.

For the flexible feeding system to function properly the vision system must be capable of identifying each component's static poses, orientation and position on the central feeding conveyor. This information is required for the robotic manipulation system to collect the component. The complexity of obtaining this information is highly dependent on the component geometries and materials that make up the assembly under investigation. The vision system must then determine the corresponding collection site and approach vector for the correctly identified component pose. This information would then be relayed to the robotic manipulator's controller for robotic code generation and execution when the component arrives at the feeder's presentation position.

To determine the feasibility of the suggested vision system with specific application to components from the target subassembly, an experiment was conducted. The main aim of this experiment was to determine whether a commercial vision software package would be able to distinguish between various component static poses and determine their respective collection sites. Cognex's VisionPro commercial software was selected over in-house or self developed software as it would provide vital professional support and teaching services for technical personnel. The vision system integration with the selected Motoman HP6 robots was also supported. The experimental procedure and results are documented in the following sections.

6.4.1 Objectives

The Cognex VisionPro software was used to achieve the following objectives:

- To determine the static pose and its respective collection site of a known component from the target subassembly could be identified without false or missed detections.
- To assess the capabilities and technical skills required to train and use such a vision system for actual automated manufacture.
- To determine an estimate of the recognition times required using a standard computer.
- To visually evaluate the collection site registration accuracy on a computer screen.

6.4.2 Apparatus

A list of equipment and software used for the experiment are presented below with a short description of their function:

- A free downloaded 60 day limited trail version of Cognex VisionPro software from their official website (Cognex undated) to perform the image processing and recognition.
- Due to limitations in the demo software for acquiring images, an adapted image capturing framework from previous work was programmed to automate image capture and pre-processing to create the image databases (Dymond 2006).
- Pentium 4 3.0 GHz computer with 1 GB ram and an 80 GB hard drive running Windows XP was used to run the software.
- 7.1 MP Canon Power Shot A620 to acquire the images.
- Tripod to mount the camera for top down image capture, as conceived in the conceptual feeder design.
- Top down light to eliminate cast shadows and better ensure environmental lighting consistency.
- Overhead projector, with a smooth glass surface to represent the collection surface.
- A black marked capture pattern for component placement, measuring applications and to simulate the colour of the belt surface of the actual feeding conveyor.

All the above listed equipment was assembled to approximate the real vision system layout for the robotic fixtureless assembly concept. Pictures of the experiment setup are shown below in Figure 43.

Figure 43 Vision system experimental layout

6.4.3 Method

To evaluate the objectives stated, the following method was followed:

1. An image database for each component of the target subassembly was constructed. Ten to seventeen images of each component's static poses were photographed and combined to form a single component image database. All the images were taken with the component in the centre of the camera's field of view. Each image within a pose image set was photographed with the component pose in a different rotation. This would simulate typical images captured of components moving past the camera vision window on the central feed conveyor of the feeding system. Images were captured at 640x480 resolution to represent the typical captured image of a low cost industrial vision camera.
2. A single image of a component pose was extracted from the database and used to train the pattern recognition component in the VisionPro software (CogPMAlignTool). During training an origin was defined to determine registration accuracy.
3. The trained pattern recognition tool was then tested on all the images from the component database, which includes all static poses, to determine its identification and registration accuracy.
4. If false or missed registration errors were obtained, various thresholding and other parameters were adjusted.
5. Steps 3 and 4 were repeated until 100% registration accuracy was obtained, which was possible, with no false or missed registration errors from images within the component image database.
6. Steps 2 to 5 were repeated for each static component pose.

7. Steps 2 to 6 were repeated for each component in the target subassembly.
8. Information relevant to each component's processed static poses was recorded and tabulated. These tables are given in Appendix I.

6.4.4 Observations

During image database construction it was observed that certain static orientations presented by some components of the target subassembly were not very stable and tended to rock or move during placement. These poses are: both static poses of the tested coil and the moving contact pose with the dimple facing downwards. This could be overcome by using a dampening surface material in the experimental setup. The design assembly system would utilize a carefully selected belt with dampening and low reflective surface properties to alleviate this stability concern.

During training the selection of component pose unique features was highly important. Features were carefully selected for components which contained moving parts and for components with similar looking poses. The moving contact contained two static poses which looked very similar when viewed from above, namely the upside down and right side up poses. These poses were correctly distinguished and identified from one another with careful training parameter adjustment. The pigtail presented potential registration problems due to its flexibility. It would undergo minor deformations during the experiment when handling. This resulted in minor offset registration errors in the trained system. However in the manufacturing environment far less deformation and variation is expected. Otherwise a different feeding approach for the pigtail could be considered, such as feeding it directly to the robotic manipulator at a fixed collection position for gripping.

The registration accuracy was visually examined on the computer screen of the test computer and was found to vary slightly from one image to another within a component pose image set. All components from the target subassembly have 3D geometry, which is not ideal for 2D vision system registration. This possibly resulted in the slightly offset collection site registrations observed. The impact of these registration offsets on overall manufacturing accuracy was not determined and would warrant further investigation in a later feasibility study.

6.4.5 Findings

It was possible to achieve 100% pose identification results for all the components of the target subassembly from images in the database. An attempt was made to obtain a generic set of pattern recognition parameters for all the poses of all the components of the target subassembly, but was unsuccessful and various poses required specialized parameter adjustments. The coil, pigtail and moving contact proved hard to train properly to avoid false identifications. This process was time consuming.

The software package VisionPro from Cognex was easy to learn and use. To obtain good results however, a lot of training and experience is required. The teaching process required a lot of time due to the complexity of the components of the target subassembly. This potentially means that automating other similar assemblies in industry could incur large costs and lengthy software training periods. Qualified personnel would most likely be required to perform these training operations.

Processing times were almost negligible and were roughly proportional to the number of static poses each component had. The longest processing time was estimated to be 161 ms for the arc runner using the above stated computer.

This experiment concludes that such a vision system using a low resolution industrial camera is capable of successfully distinguishing between various component poses for each component of the target subassembly. The length of training time is highly dependent on the complexity of the component being trained. Of the components from the target subassembly, the moving contact proved the hardest to train and consumed the most time. This experiment did not include component variation, due to manufacturing variances, on the registration results, as sufficient components were not available. This should warrant further investigation. Lastly a few registration results showed slightly offset collection sites, as observed on the computer screen. It was notably worse for component poses that had long protruding geometries. This is believed to be mainly due to the 2D vision system's perspective error and should be further investigated.

6.5 Costing estimation

After refining the various subsystems of the design assembly system and with positive basic verification results, an initial costing estimation was appropriate. The cost estimate would serve as a basis for economic evaluation, which would allow the proposed fixtureless assembly concept to be evaluated in comparison with the existing manufacturing process, as documented in the case study, and that of the fixture based concept presented by Sequira (2008).

Without a detailed final design which includes all system elements it was not possible to determine what the system would exactly cost. However with most of the major subsystem hardware selections made and designed, a good initial cost estimate could be formulated. From the process simulation demonstrated in the concept simulation section (6.3), an optimum cycle time for the manufacture of the target subassembly was determined to be approximately 21.45 second. This cycle time represented the minimal possible cycle time, which was very optimistic. Therefore after carefully considered feeding delays and/or component re-orientation operations possibly required, a cycle time of 30 second was selected as a better estimate.

Reconfiguration time was not required for the various known geometrical and material variations of the components within the target subassembly's part family, as the gripper was able to collect all known component variations due to the clever selection of collection sites and the vision system would have been pre-trained with all the variants in a database. The robotic manipulator controller would contain all the variant assembly processes in different programs, which could be easily switched between, to avoid delays. The bulk hoppers would carefully have to be monitored however, to feed the correct component from the correct part family at the correct time. The welding system may require tool changing or electrode re-dressing, which could also result in manufacturing delays. Due to the lack of information regarding the welding system, it was not possible to include its influences in terms of manufacturing delays. It was further assumed that a single set of well designed electrodes would be able to perform all the required welds with only automatic welding parameter adjustments performed by the welding system controller.

Using this approximate cycle time and with the known daily production rate requirement of 30 000 target subassemblies obtained from the design specifications, it was possible to determine approximately how many robotic fixtureless assembly cells would be required. To meet this production rate target a total of 11 cells operating 23 hours a day would be required. Next an initial cost estimate for the designed assembly system was determined from obtaining quotations from various local suppliers for hardware costs of the various subsystems. Costing for the flexible feeding system and gripper were closely approximated with aid from industry consultants.

The derived cost per robotic cell and total for all the robotic cells required are presented in Table 5 below. For comparison, the costing of the fixture based assembly model 1 system by Sequira (2008), which was found to be the most cost effective of his concepts for this application, is also included in the table. The model 1 assembly concept is based on a single closed loop pallet system incorporating the TS 2plus Transfer System from Bosch Rexroth (2008). In this concept fixtures are mounted on moving pallets within the system. These fixtures are filled with components by pick and place robots along the track, then transported to a gantry welding station for joining and finally to a removal station, before recirculation.

Table 5 Initial assembly system cost comparison

	Robotic fixtureless assembly concept	**Fixture based assembly model 1 concept** (Sequeira 2008)
Single system cost	R 1 416 735.35	R 1 634 449
Total number required	11	4
Total cost	R 15 584 088.89	R 6 537 796

From the cost comparison it is noticeable that the single system cost of the robotic fixtureless assembly concept is slightly cheaper than the fixture based assembly model 1 presented by Sequira (2008). However due to the fact that the fixture based assembly model 1 concept has such a short cycle time in comparison, far fewer systems are required overall to produce the required daily production amount. Therefore the total system cost of the fixture based assembly model 1 concept is 57% cheaper than that of the robotic fixtureless assembly concept. A breakdown of the initial cost estimate for the robotic fixtureless assembly concept is attached in Appendix K.

To determine the running costs of the proposed overall system, various maintenance and service intervals were obtained for the various subsystems of the designed assembly system. However labour costs were hard to determine for the required personnel to operate such a conceptual system. Also the running cost of the welding system was neglected as enough information was not available. This running cost should be minimal in comparison to the other running costs. Therefore a rough running cost was made. This running cost estimate, combined with the initial cost, would allow a payback period to be calculated, when compared to the existing manufacturing costs of the present manual assembly process. A payback period of 4.22 years was calculated, which was far longer than the design specification of two years. This would conclude that the robotic fixtureless assembly concept would most likely have a far too long payback period than desired. Additionally the actual running cost would be slightly more expensive than the estimate when considering all the running costs. The running cost estimate is attached in Appendix K.

6.6 Case study evaluation

The robotic fixtureless assembly concept, along with the fixture based assembly concept, were presented to a panel of employees from CBI. The panel included engineers, production managers and technicians. The costing comparison was however not presented due to incomplete results at the time. The employees responded positively to both proposed concepts but, did however state that the designs were still very conceptual and would required more research and experimentation to determine their feasibility. No concept was selected over the other. Instead, manufacturing assembly variants and detailed hardware design aspects of both concepts were questioned. Pertaining to the robotic fixtureless concept, the unique and complex robotic gripper design was questioned in terms of overall feasibility. Also the accuracy obtainable for the joining operations at the welding station without a vision monitoring system was questioned. The gripper design and operation was therefore subsequently discussed with an industrial expert (Grau 2009), who advised that prototype testing and experimentation should be conducted in addition to the calculations and simulations already performed. This was not however possible at the present stage of design. This feasibility concern was therefore identified as a possible design risk. If the proposed single gripper design was found unsuitable through testing, multiple specialised grippers with a tool changer could be used instead. Prototype testing would also show whether an additional vision monitoring system would be required at the welding station to meet joining accuracy requirements. The disadvantage of the additional vision system is its additional purchase cost and reconfiguration time.

The overall achievable accuracy of robotic fixtureless assembly system at this stage appears to be within the limit required to correctly assembly the target subassembly. This accuracy is determinable from the cumulative accuracies of the vision, robotic manipulator and gripper subsystems. The selected Motoman HP6 industrial robot has a rated repeatability accuracy within 0.08 mm (although this is questioned by industry experts), and the Festo HGP-16-A-B gripper, a repeatability accuracy within 0.04 mm, which are small relative to the required target assembly tolerances (which cannot be disclosed due to confidentiality). The soft jaw deflection would also cause a small accuracy error, calculated to be within 0.188 mm, relative to the required accuracy. The vision system would most likely account for the largest inaccuracy of all the subsystems due to registration inaccuracies as noted in the experimental findings (section 6.4.5). This accuracy was not confirmed, but it would be unlikely that this inaccuracy would be large enough to invalidate the operational feasibility of the concept, and image recognition tools are available to overcome or reduce this inaccuracy.

The robotic fixtureless assembly concept was evaluated in section 6.5 using the limited economical specifications. It was concluded that even though the proposed system would most likely be cost effective in comparison to the existing manual assembly process, the determined payback period would not justify such a risky investment. When comparing the robotic fixtureless assembly concept with that of the fixture based assembly model 1 concept presented by Sequira (2008) it is clear that the conventional fixture based system is far more economical in terms of initial cost, when the full daily production quantity was considered. The running costs of the two systems would likely be very similar, meaning that the fixture based system should be cheaper overall. The fixtureless assembly system would, however become feasible for applications where part families contain vastly different and numerous component variations, as numerous fixture designs would most likely be higher in cost than that of specialized robotic gripper designs.

In terms of reconfigurability the fixtureless concept features fewer subsystems and maximises the usage of the most flexible elements in the system. This reduces the overall system cost, but eliminates parallel production capabilities. Hardware reconfiguration required between manufacture of different product families is limited only by the robotic manipulator grippers and welding station electrodes. On a software level, however, component image recognition may require long programming periods and the new assembly process has to be programmed into the robotic manipulators controller. These software reconfiguration processes may be time consuming but would only have to be done once for every newly automated product and may also be done offline. Once programmed these programs are stored and may be switched between as required for each production batch in negligible time.

The fixture based system featuring a flexible transport pallet system is capable of easy production parallelisation as documented and researched by Sequira (2008) to determine an optimum production layout. This design features dedicated feeding modules and multiple welding stations. The increased amount of hardware and subsystems present in each system would require more reconfiguration operations to set up for different product families and each pallet within the system might have to be re-fitted with a different fixture every time a different product batch was to be manufactured. For the selected target application only a small quantity of the daily production quantity consisted of product family variants. With this information reconfiguration cycles and down times were limited by only using a single system to manufacture the product family variants, while the other systems operated as dedicated assembly lines producing the mass required product variant.

7 Conclusions

A fixtureless reconfigurable automated spot welding assembly system was designed in an attempt to provide a low cost automation approach to assembling resistance spot welded subassemblies for residential circuit breakers. This process is presently being done manually, which is becoming expensive. The design process focused on a selected part family, while keeping in mind similar products from the industrial manufacturer. In this way concept generation and subsystem selection was performed with the focus on easy and quick design revision of a few assembly subsystems for manufacture of similar products. The refined conceptual design had a minimal number of subsystems to reduce system cost.

The final concept featured minimal hardware reconfiguration elements for changing between product part families, however relied on once off software reconfiguration for every new part family to be automated. In terms of system reconfigurability, direct component handling elements were reduced to two hardware subsystems, the robotic grippers and the welding station electrodes. These hardware modules are designed with tool changing capabilities in mind, allowing different tools to be fitted as required. These tool changes may be manually performed or automated using hardware such as tool changing posts or turrets, allowing easy modular production capability expansion. Overall the designed assembly system's flexibility is limited by its least flexible subsystem, as assembly processes are chained together. The greatest flexibility constraints within the assembly system are those imposed by the robotic grippers and, potentially, the welding station.

To determine whether the refined concept was capable of successfully performing the assembly processes required to manufacture the selected target subassembly, a feasibility study was performed. Four main elements in the design, which required additional calculations and/or experiments in order to verify their successful operation, were investigated. The two subsystems investigated were the flexible vision based feeding and the robotic manipulation subsystems. The feasibility study concluded that the refined concept would most likely be able to perform the assembly application. However additional areas of research and investigation were identified and recommend for firmly supporting this deduction.

The refined designed concept was evaluated by comparing its initial cost estimate to that of the fixture based concept (Sequeira 2008) and the present manual assembly process. It was found that the single system cost, while cheaper than that of the fixture based concept, was overall approximately 57% more expensive when considering the entire system cost to meet daily production quantities of the target product. A rough running cost estimate was formulated to determine a payback period for the refined designed concept. The running cost was estimated to be less than that of the present manual assembly process. It was however calculated that the payback period, of just over four years, would be approximately double the time desired by the client. This increased time frame combined with the operating uncertainty or risk of the proposed concept concluded that it was most likely not suited for this target application.

When comparing the fixtureless to the fixture based concept (Sequeira 2008) in terms of reconfigurability, the fixtureless concept implements more flexible subsystems, but compromises in production throughput in an attempt to reduce initial system cost. In contrast the fixture based system relies on numerous subsystems with limited flexibility, which however allows for easier production parallelisation and expandability. The fixture based system is therefore highly suited for production lines with minimal number of product family variants and large quantities of a main product family model, such as in the selected case study. The fixtureless concept, on the other hand, would excel in production lines featuring product families containing numerous variants in small production quantities. In these types of production lines the assembly system presented in this thesis would most likely feature reduced running costs and faster production rates, in comparison to the fixture based concept and traditional dedicated assembly lines.

From an industrial automation perspective, reconfigurable assembly systems provide a balance between manufacturing flexibility and automation cost, bridging the divide between dedicated and highly flexible manufacturing systems.

In terms of the objectives and characteristics defined for reconfigurable systems, the robotic fixtureless assembly concept makes allowance for quick and easy reconfiguration between different part families. An emphasis on a low cost assembly system throughout the design process produced a potentially highly flexible assembly system at a reasonable initial cost. Unfortunately this cost component leads to a compromise in throughput rate for flexibility, making it unsuitable for large production batches, such as was the case for the chosen application.

8 Future word and recommendations

The research and design process presented in this thesis serves as a broad overview of the design and application of a robotic fixtureless reconfigurable automated spot welding system. Only critically identified design aspects, that would determine the overall successful operation of the concept, were identified and investigated using various tools to determine their feasibility. Recommendations are made where further research and investigations can be performed to further prove or disprove the concept in terms of the target application.

- Due to the complex geometry of the components making up the target subassembly, research and experimentation should be performed to determine if these components could be fed into the assembly system with some specialized machinery which prevents tangulation and jamming of the components with such sophisticated geometries.
- The selected 2D vision system registration accuracy was only visually inspected on a computer screen. While 2D vision systems are conventionally used to register components or objects with 2D flat geometry, it was proven to work for all the components from the target subassembly which all had 3D geometry. However, it was noted that registration accuracy of the collection sites varied sometimes. The impact on the registration accuracy should be thoroughly investigated to determine the range of inaccuracy, the causes and possible solutions.
- The welding system design presented was limited due to the lack of information available, both on the manual welding process and resistance spot welding of small electrical switch gear in general. In the industry technicians conventionally experiment with different welding parameters and electrode designs to determine a suitable setup. Little scientific information is available on the process. For this reason research into welding technologies should be pursued to better understand and formulate a design approach for such industry applications.
- The collection accuracy of the robotic handling system when collecting components from the target subassembly should be determined through experimentation or calculation. The accuracies of the robotic manipulators, robotic gripper, conveyor system and vision system would have to be taken into consideration. This would help to determine whether additional vision systems would need to be incorporated into the design as questioned by the client (section 6.6).

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Appendix A Control structures

A.1 Hierarchal

Due to the modularity of RAS, implementing traditional centralized hierarchal control becomes very sophisticated. Hierarchal control systems are typically designed from the top-down with multiple levels of control. Control levels are formed from functional breakdowns or logical deduction. Each level of control has a master-slave relationship (Anosike and Zhang, 2007), with the higher level typically being the master.

This design methodology greatly restricts the application of the control system beyond the initial design intention. Modification is also difficult and the complexity of the modification is directly proportional to the number of the level on which it is performed and size of the entire control structure. Additionally modifying the control structure can only be done while the system is offline (Van Brussel et al. 1998). Conventionally all scheduling and planning are done at the highest level of the control structure, which is often referred to as the central planner.

Instructions or commands are initiated by the central planner and propagate downward to the lowest level to be executed. Feedback travels in reverse, i.e bottom-up. This means that at the highest level feedback has to be quickly processed for the appropriate response commands to be generated to achieve near real-time operation and reduce possible manufacturing delay faults.

When expanding the control structure to include more child nodes, representing resources or processes, dedicated real-time control becomes nearly impossible with present hardware (Cheng et al. 2004; Monostori et al. 2006) and a time scheduling system is usually implemented. This means parallel process execution without faults cannot be assured. Hierarchal control is effective and low cost when minimal hardware needs to be controlled and minimal process alteration is required.

A.2 Heterarchical

Heterarchical control is forming the platform for RMS and RAS control system design research. Heterarchical control consists of independent entities which form the building blocks of the flat control structure. These entities are usually termed agents (Monostori et al. 2006). They cooperate with each other, unlike the master-slave relationship in hierarchal control, to achieve control of the entire system in a Multi-Agent System (MAS). Defining how these entities share and interpret information and what an agent encapsulates, distinguishes typically one methodology or design approach from another.

Cooperation between agents in a MAS is vital to achieving the desired product from the system. The selection of the most appropriate structure can optimize the performance of the system by utilizing the resources of the system intelligently (Van Brussel et al. 1998). There are numerous approaches to coordinating the efforts of agents to achieve the set outcome. These approaches have developed from artificial intelligence research into human and insect societies (Xiang & Lee 2008) and from biological structures (Jarvis et al. 2005).

Heterarchical control structures tend to reduce overall control software complexity in large scale control systems. Heterachical control also introduces modularity by implementing decentralized intelligent control on a low level, with no central planner, potentially allowing a MAS to have a high level of fault and failure tolerance without execution interruption (Heragu et al. 2002). The independence of agents and modularity of the control structure also allows for so called plug and produce capabilities, where additional resources can be added into a manufacturing system, without halting the system, to reduce bottlenecks and increase productivity where necessary. As an example, Yusuke et al. (2007) successfully integrated an additional manipulator into an agent based assembly system.

However, due to the independence of the agents of the control structure, information of the entire system is not instantaneously available. This means that throughput rates of the system are difficult to determine and would fluctuate according to the present production quantity and their progress through the system (Van Brussel et al. 1998). Also prediction of product process flows through the system can be complex and maybe impossible to determine.

A.3 Hybrid

Hybrid control structures are developed to combine the advantages of both hierarchal and heterarchical substructures. Typically the overall system coherence and objectivity of hierarchal structures is combined with the adaptability and fault allowance of heterarchical substructures (Leitão in press).

One such hybrid structure presented by Van Brussel et al. (1998) is based on the methodology of a Holonic Manufacturing System (HMS) (Valckenaers 2001). He proposes that agents or holons are categorized into four types namely: product, resource, organization and staff holons. Resource holons typically represent the machinery and tools available in the manufacturing system. They also incorporate the knowledge required to operate them and provide information of their present state. Product holons represent all the necessary manufacturing information of a particular product. Typically this information would include the correct manufacturing steps to follow in order to ensure successful production of the product. Order holons represent instances of the product in the manufacturing system and contain all the current state information of that particular product instance.

The relationship between the three basic building blocks of this product-resource-order-staff architecture (PROSA) is shown below in Figure A-1**.**

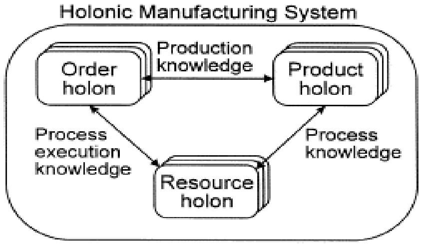

Figure A-1 Basic building blocks of a HMS and their relations (Van Brussel et al. 1998)

Lastly the optional staff holons represent expert experience in the system and allow for the possible formation of centralized solutions by imposing global rules on the MAS or Holorchy. This allows legacy hierarchal manufacturing systems to be retrofitted with holonic manufacturing controls.

In terms of RMSs, heterarchical and hybrid control structures would provide easier flexibility, adaptability and expandability than conventional hierarchal control structures. Hybrid control structures assign agents within the system with specialized functions as opposed to that of generalized all-round knowledge agents in heterarchical control structures. Therefore agents of hybrid control structures are less complex to design opposed to those of heterarchical control structures. Hybrid control structures are therefore well suited for RMSs, providing flexibility without a large level of complexity.

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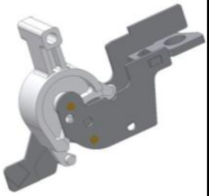
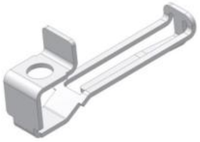
Appendix B Resistance welded subassembly

The components which make up the target resistance spot welded subassembly of the Q-Frame circuit breaker are listed in Table B-1 below. This table provides information regarding the geometry, parameter variation range, material and other component specific information.

Table B-1 Resistance welded subassembly component information

Component name	Picture	Spatial envelop (major dimensions)	Quantity per assembly	Parameter variations (within part family)	Material	Present number of component variants	Weight
Pigtail		CA: 2.5-4mm^2 L: 1.5-4mm	2	Cross sectional area and length	Braided copper wire	5	1,3765g
Moving contact		L: 27 mm H: 11.7 mm W: 7.9 mm	1	Contactor tip presence and material type (copper or steel)	Tin plated copper	3	2,7601g
Handle frame subassembly		L: 48.525 mm H: 33 mm W: 9.45 mm	1	Plastic rocker colour and frame material (copper or steel)	Brass, Plastic, steel	2	7,9625g
Arc runner		L: 42.629 mm H: 18.4 mm W: 9.8 mm	1	None	Tin plated copper	1	4,6705g
Coil		L: 30.47 mm H: 14.755 mm W: 8 mm Ø: 1-2 mm	1	Windings, material, wire diameter and type	Enameled copper wire	10	5,1099g

The components, as depicted above, are joined with five resistance spot welding operations to produce the completed welded subassembly. The layout of the completed subassembly and the location of the welds are shown below in Figure B-1.

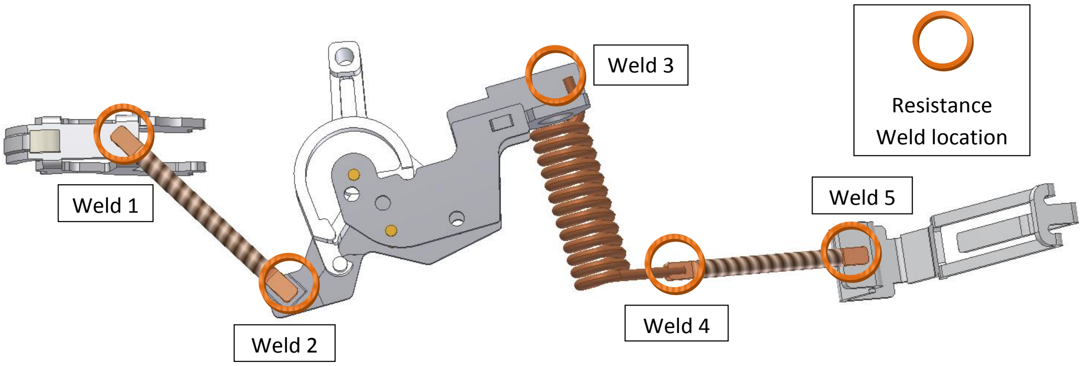


Figure B-1 Subassembly layout

The welded subassembly is subject to the following assembly constraints for final product assembly and operation.

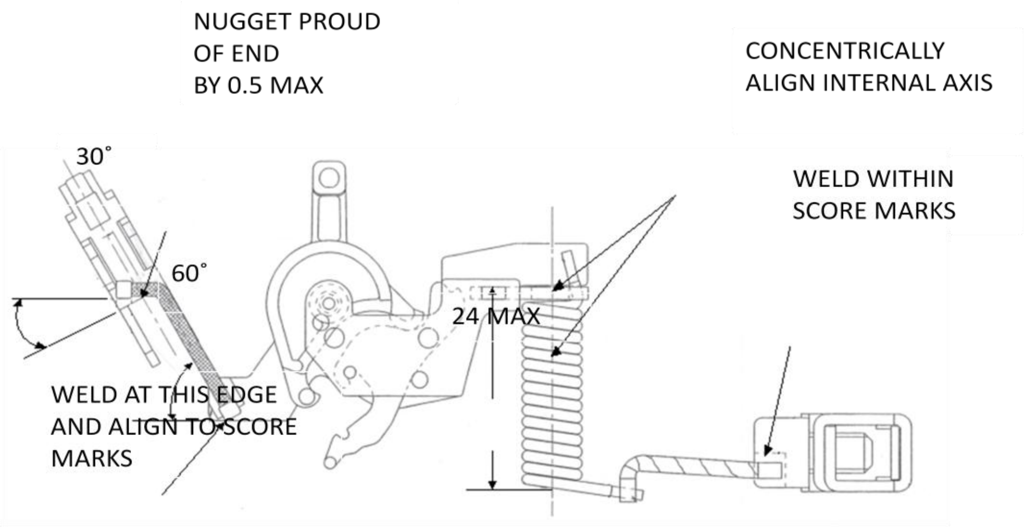


Figure B-2 Subassembly assembly constraints and instructions

Appendix C Layout concept evaluation

The company’s decision to invest in the proposed concept is the desired outcome from the design process and determines whether the design process was successful. Therefore to understand what the company wants and requires is critical to the design process. A weighted decision matrix was constructed to approximate the overall importance of each derived design requirement. This was done by approximating how relevant personnel from the company would weigh the requirements and then formulating a weighted average using the respective personnel’s deduced importance in making the final decision.

Table C-1 Decision matrix with personnel requirement ratings and weights

	Importance (% out of 100)			
	50	**20**	**10**	
Requirement	Manager	Product designer	Factory workers	Weighted importance (0 - lowest 10 - highest)
Reconfigurability	8	9	6	8.00
Maintainability	7	6	7	6.75
Low cost	10	7	4	8.50
Automation level	7	5	4	6.13
Physical size of system	1	3	2	1.63
Integration	7	8	8	7.38
Robust	6	6	7	6.13
Lean manufacture	3	4	5	3.50
Product traceability	5	5	3	4.75
Ease of diagnosis	7	8	7	7.25
Safety	8	8	10	8.25
Product Quality	7	8	6	7.13

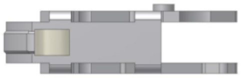
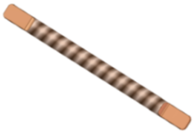
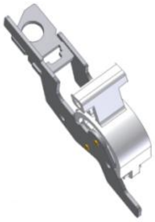
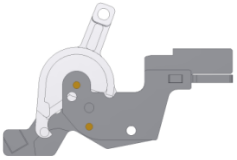
Table C-2 Weighted concept scoring

Requirement	Weighted importance (0 - lowest 10 - highest)	Concept scoring					Importance scaled result				
		1	2	3	4	5	1	2	3	4	5
Reconfigurability	8.00	9	6	5	4	8	0.96	0.64	0.53	0.42	0.85
Maintainability	6.75	4	5	6	7	6	0.36	0.45	0.54	0.63	0.54
Low cost	8.50	3	4	6	7	4	0.34	0.45	0.68	0.79	0.45
Automation level	6.13	9	5	7	6	8	0.73	0.41	0.57	0.49	0.65
Physical size of system	1.63	6	3	5	6	5	0.13	0.06	0.11	0.13	0.11
Integration	7.38	6	2	4	3	5	0.59	0.20	0.39	0.29	0.49
Robust	6.13	4	5	6	6	6	0.33	0.41	0.49	0.49	0.49
Lean manufacture	3.50	4	3	4	7	5	0.19	0.14	0.19	0.33	0.23
Product traceability	4.75	7	6	6	8	7	0.44	0.38	0.38	0.50	0.44
Ease of diagnosis	7.25	3	4	4	4	4	0.29	0.38	0.38	0.38	0.38
Safety	8.25	4	6	5	6	4	0.44	0.66	0.55	0.66	0.44
Product Quality	7.13	7	6	6	8	6	0.66	0.57	0.57	0.76	0.57
					Overall concept score		5.4	4.7	5.4	**5.9**	**5.6**

Appendix D Robotic manipulator selection

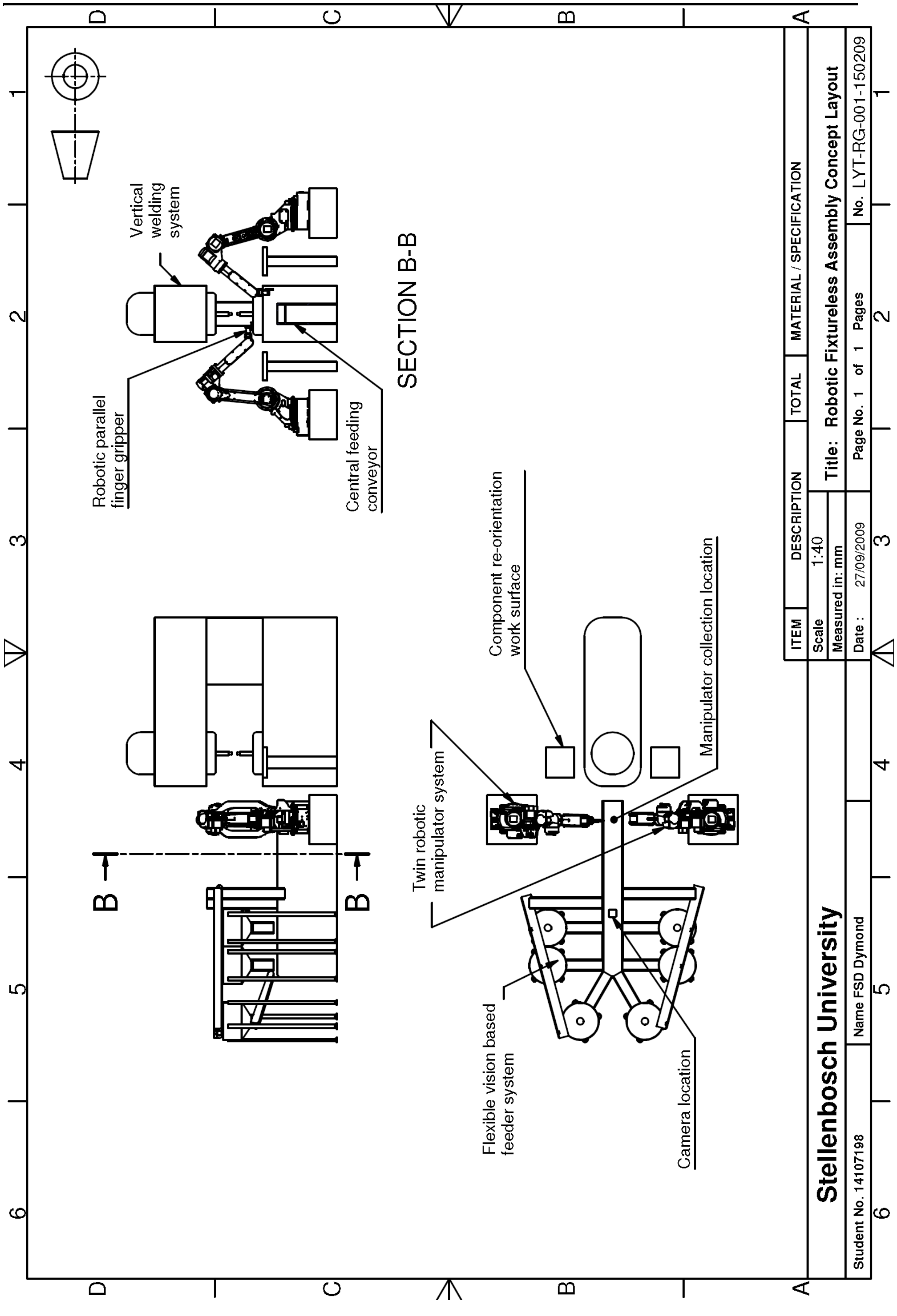
The components of the target subassembly were individual analysed to determine which orientations were presented upwards on a flat surface after various drop tests. The orientation which required the most re-orientation operations from the collection surface to the proposed presentation orientation for welding were tabulated for each component of the target subassembly. Then all the required Cartesian spatial transformations required from the collection orientation to the presentation orientation were listed and the total number of spatial transformations summed. This information is presented below in Table D-1.

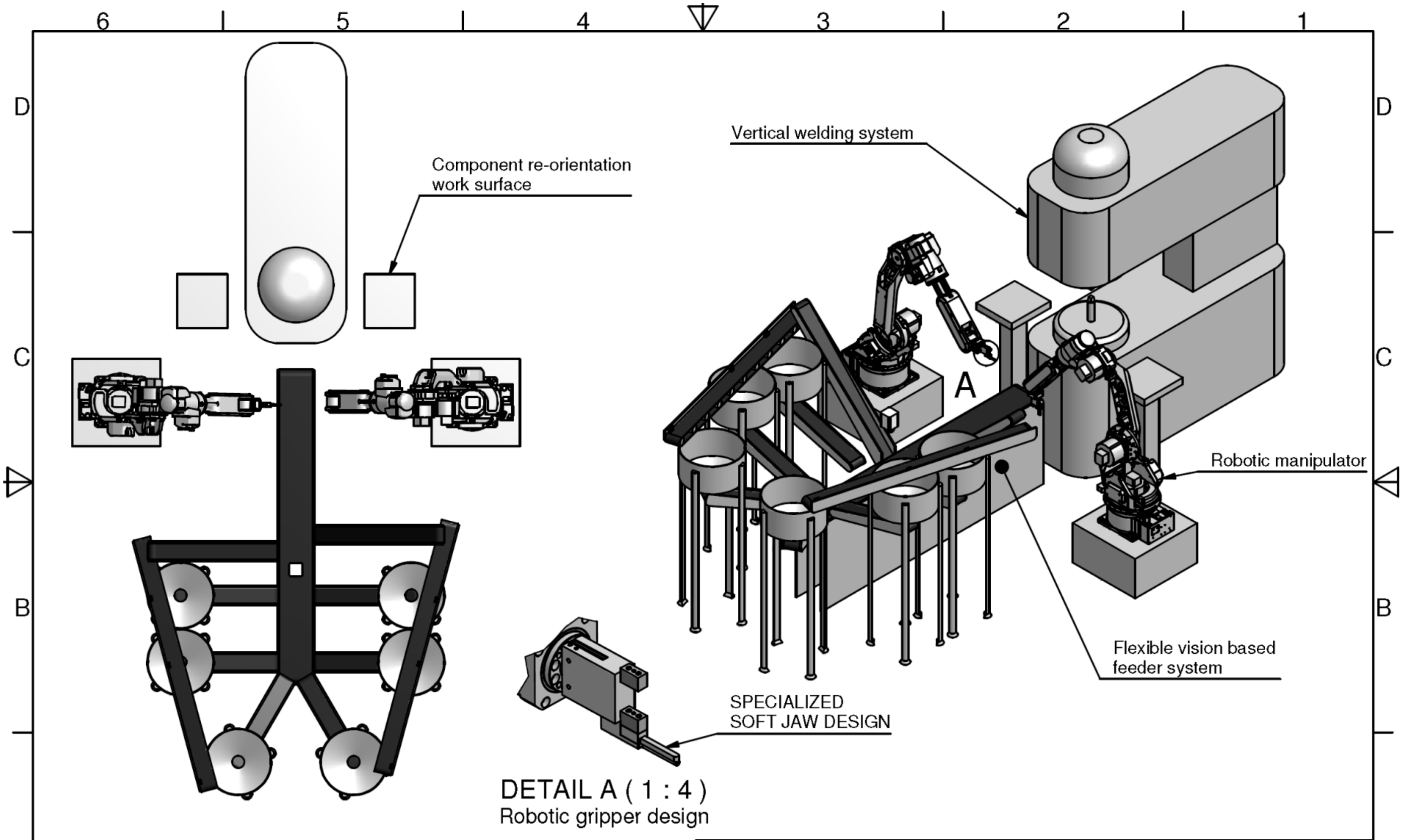
Table D-1 Target subassembly component spatial transformations

Assembly component	Worst collection position (Viewed from top)	Presentation position (Viewed from top)	Spatial transformations required						
			Translation			Rotation			Total
			X	Y	Z	X	Y	Z	
Moving contact			✓	✓	✓	✓	✓	✓	6
Pigtail (between Moving contact and Handle frame subassembly)			✓	✓	✓			✓	4
Handle frame subassembly			✓	✓	✓	✓	✓	✓	6

Coil			✓	✓	✓	✓		✓	5
Pigtail (between coil and Arc Runner)			✓	✓	✓	✓		✓	5
Arc runner			✓	✓	✓	✓		✓	5

Appendix E Robotic fixtureless assembly concept





ITEM	DESCRIPTION	TOTAL	MATERIAL / SPECIFICATION

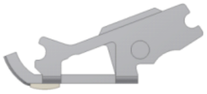
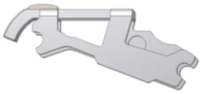
Stellenbosch University

Scale	1:25	**Title: Robotic Fixtureless Assembly Concept Layout**		
Measured in: mm				
Student No. 14107198	Name FSD Dymond	Date : 28/09/2009	Page No. 1 of 1 Pages	No. LYT-RG-002-150209

Appendix F Drop testing results

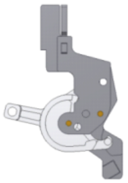
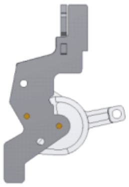
Testing involved dropping each component of the target subassembly 40 times. Components were dropped onto a flat surface from a height of 140 mm in a random orientation. Component variations were not tested as they were unattainable for testing. The results from the performed drop testing for each component are presented below.

Table F-1 Moving contact pose drop probability

Picture of static pose (top view)				
Static pose name	Bottom up	Top up	Dimple up	Flat side up
Final collection	TRUE	FALSE	TRUE	TRUE
Re-orientable	N/A	TRUE	N/A	N/A
Count	4	14	11	11
Probability	10%	35%	28%	28%

Final collection pose probability	**65%**
Notes	No tip present on test specimen, very bouncy response

Table F-2 Handle frame subassembly pose drop probability

Picture of static pose (top view)				
Static pose name	Collectable plate down	Collectable plate up	Collection insertion	Balancing on rocker
Final collection	FALSE	TRUE	TRUE	FALSE
Re-orientable	TRUE	N/A	TRUE	TRUE
Count	18	20	2	0
Probability	45%	50%	5%	0%

Final collection pose probability	**55%**
Notes	Handle frame assembly is fragile and susceptible to breaking after numerous drops

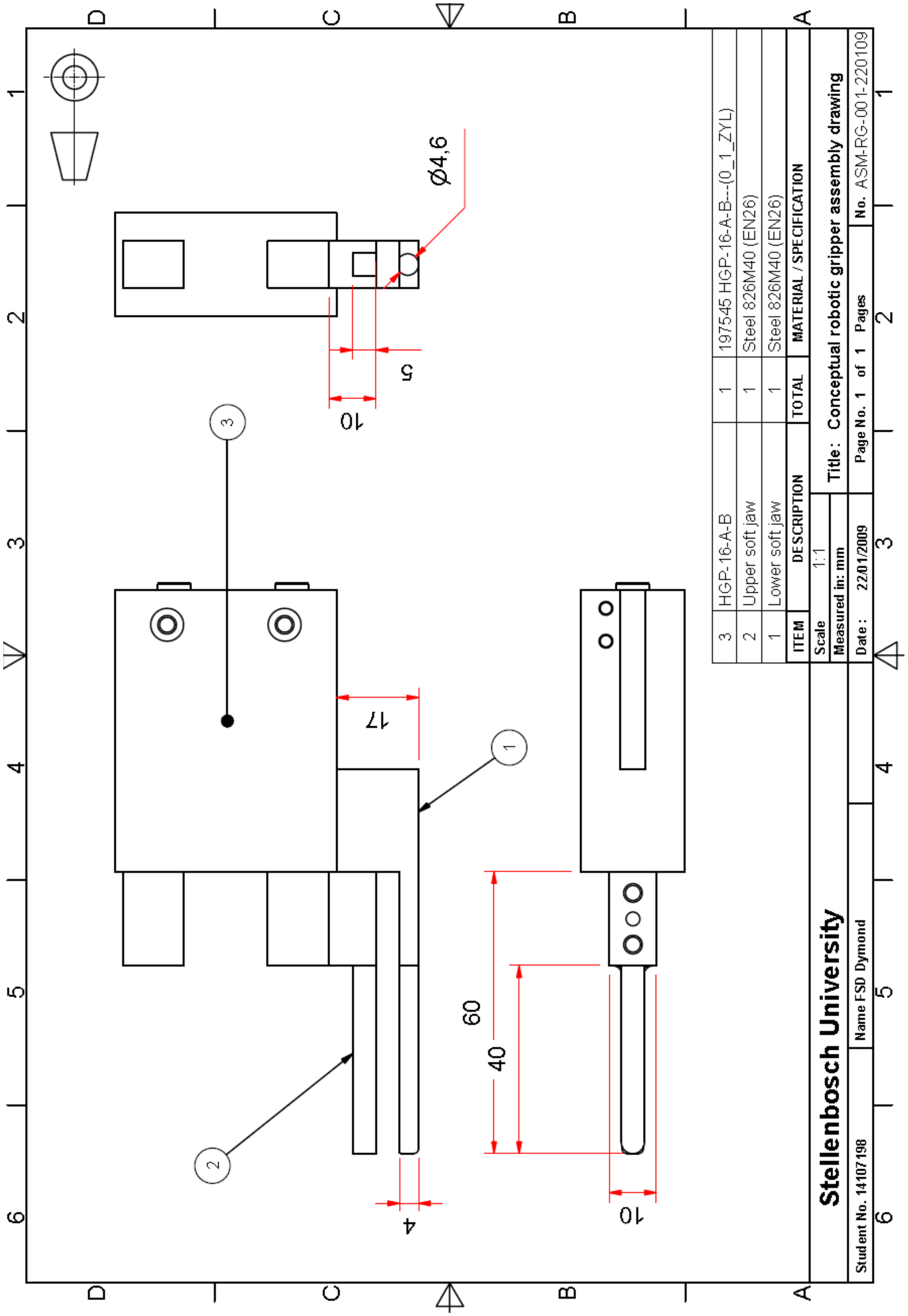
Table F-3 Arc runner pose drop probability

Picture of static pose (top view)					
Static pose name	Side 1	Top up	Side 2	Standing	Upside down
Final collection	TRUE	FALSE	TRUE	FALSE	TRUE
Re-orientable	N/A	TRUE	N/A	TRUE	N/A
Count	19	3	18	0	0
Probability	48%	8%	45%	0%	0%

Final collection pose probability **92.5%**

Notes

Appendix G Assembly drawing of robotic gripper



Appendix H Gripper soft jaw verification calculations

Deflection and failure analysis of soft jaw gripper design

Gripping force calculation

Assumptions and background

The maximum frictional force required during transfer motions of the robotic manipulator system to prevent load slippage has to be determined. With this force know the minimum required normal exerted gripping force can be calculated.

Due to the multitude of different transfer motions possible, it was hard to determine which transfer motion would require the greatest frictional force, therefore possibly the worst case scenario was considered. The manipulator would be considered to be extended to its maximum horizontal reach and the base swivel axis would be decelerating at its maximum rate, while at its maximum angular velocity. This should represent the worst case as the length of the other linkages are much smaller in comparison even though some linkage joints have faster acceleration rates.

Parameters

$g = 9.807\,\frac{m}{s^2}$ (Gravitational constant)

The various contact surface sets for all the components to be handled of the target subassembly where examined to determine the contact surface set which had the lowest static frictional coefficient. The static frictional coefficient for copper on steel was used as it was less than that of steel on steel ($\mu_s = 0.6$ - ref [2] - pg 695)

$\mu_s := 0.53$ (Copper on mild steel (dry) - ref [8])

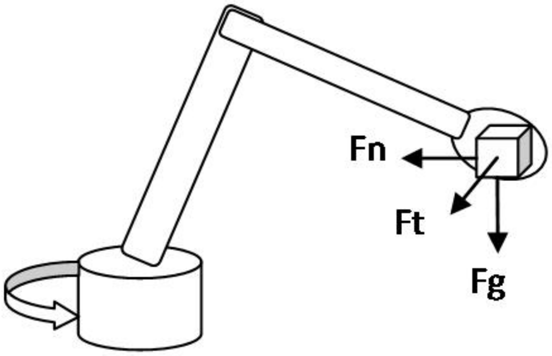
Selected robotic manipulator: Motorman HP6

$r_{max} := 1378mm$ (Maximum horizontal reach - ref [9])

$\omega_{max} := \frac{150}{180}\cdot\pi\,\frac{rad}{s}$ (Maximum rotational velocity of S-axis (base swivel axis - joint 1) - ref [9])

$m_{max} := 0.023kg$ (Maximum mass of components handled by robotic manipulator - mass of entire target subassembly was used)

$\alpha_{max} := \frac{1250}{180}\cdot\pi\cdot\frac{1}{s^2} = 21.817\cdot\frac{1}{s^2}$ (Value obtained from IGRIP software from Motorman Johannesburg sales director Kurt Rosenberg)



Force calculations

Vector forces:

$F_g := m_{max} \cdot g$	$F_g = 0.226\,N$	(Maximum gravitational acceleration of load)
$A_t := \alpha_{max} \cdot r_{max}$	$A_t = 30.063\,\frac{m}{s^2}$	(Maximum tangential acceleration of load)
$A_n := \omega_{max}{}^2 \cdot r_{max}$	$A_n = 9.445\,\frac{m}{s^2}$	(Maximum normal acceleration of load)
$A_p := \sqrt{A_t{}^2 + A_n{}^2}$	$A_p = 31.512\,\frac{m}{s^2}$	(transfer plane combined acceleration magnitude - force is applied parallel to gripper collection surfaces)
$F_p := m_{max} \cdot A_p$	$F_p = 0.725\,N$	(Planar force magnitude due to load mass, this represents the required static friction force to prevent the load mass from slipping)

With the max required friction force determined the required gripping force can be calculated

$$F_{max} = \mu_s \cdot N$$ (ref [3] Eq. (6/1) -pg 330)

$$N = \frac{F_{max}}{\mu_s}$$

The static friction coefficient for dry steel on steel was used.

$$F_N := \frac{F_p}{\mu_s}$$

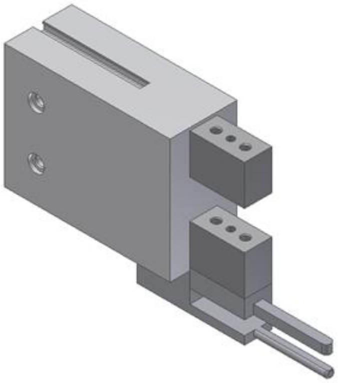
$F_N = 1.368\,N$ (Required normal acting gripping force to prevent load slippage)

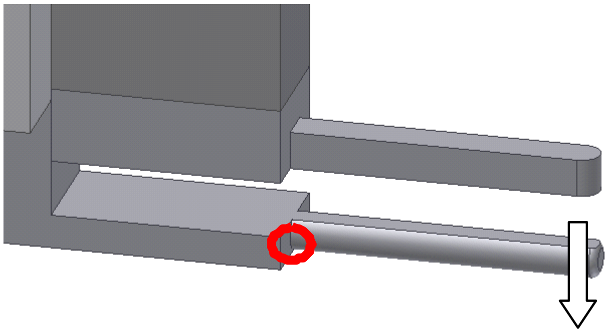
The required normal force is very small, however due to unknown influences in the actual operating environment such as: surface finishes from component to component varying and the chance of more vigorous transfer motions being executed, a lager force should be used. It was decided that a gripping force greater than 2.5 N should be sufficient. When selecting the best suited HGP pneumatic actuating gripper from Festo for the application the HGP-16-A-B was selected as it had a large enough stroke to be able to grip all the components of the target subassembly. It was however found that the lowest operating pressure for the gripper was 2 bar and at this operating pressure a gripping force of 10 N would be exerted on the load at the end of the gripper finger (ref [10] - pg 7) Therefore the gripping force to use would then be 10 N and will be used in the deflection, static and fatigue failure calculations.

$F_N := 10N$

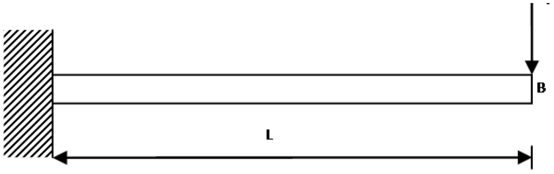
Deflection and stress calculations

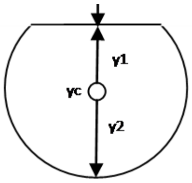
The soft jaws are to be made from steel. First failure is expected to occur somewhere along the length of the lower slender finger protrusion. It was assumed that failure would most lightly occur at the region circled in the figure below. As the highest principal stress would most likely be induced by bending moment at the bottom edge furthest from the cross section centroid. To simplify the calculation only the lower soft jaw finger protrusion was modeled as it would most lightly fail first as opposed to the studier designed upper soft jaw. The extreme loading case, where the full extend of the force is exerted on the tip of the gripper finger as a point load, will be examined.

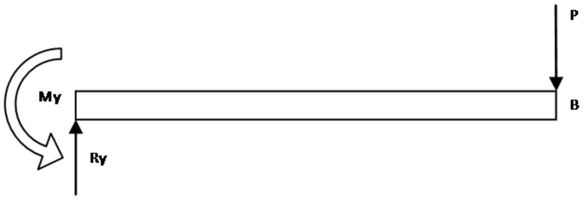




The lower finger was modeled as a cylindrical cantilever beam with a slight flat on the upper side.







Geometry and loading parameters

$P := F_N$ (Force applied is equal gripper force required to prevent load slippage)

$L := 60\text{mm}$ (Total Length of the protrusion of the lower gripper soft jaw)

$r := 2.3\text{mm}$ (Radius of circular protrusion of gripper)

$lf := 3\text{mm}$ (Length of flat on the circular protrusion of the finger)

Material selection and characteristics

For this application a high carbon steel was selected with a high yield and tensile stress. This steel is conventionally used to fabricate shafts, gears and pinions and lifting equipment. The selected steel is:
826M40 (En26) or 40NiMoCr10 5 (Din specification)

(ref [7])

(ref [6])

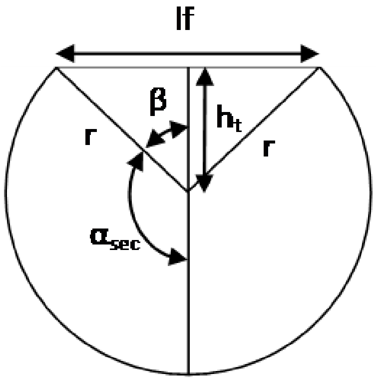
$\sigma_{yt} := 865\text{MPa}$

$\sigma_{ut} := 960\text{MPa}$

$S_{ut} := \sigma_{ut}$

$E := 210\text{GPa}$

Cross-sectional calculations



$$lf^2 = 2\cdot r^2 - 2\cdot r^2\cdot\cos(2\beta)$$

(Law of cosines)

$$\beta := \frac{\operatorname{acos}\left(\frac{2\cdot r^2 - lf^2}{2\cdot r^2}\right)}{2}$$

$$\beta = 0.71\cdot rad$$

$$\alpha_{sec} := \frac{2\cdot\pi - 2\beta}{2}$$

$$\alpha_{sec} = 2.431$$

(segment angle for section)

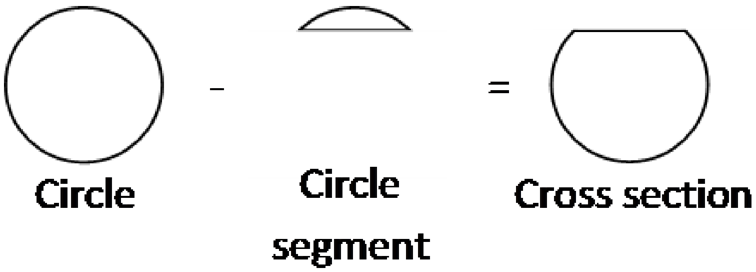
$$h_t := \sqrt{r^2 - \left(\frac{lf}{2}\right)^2}$$

$$h_t = 1.744\cdot mm$$

(height from center to flat edge)

Centroid and second moment of inertia calculations

The section can be broken into a circular segment and a circle. Adding the parameters of these two sections will provide the parameters for the chosen sectional geometry



For the circle segment

$$\beta = 40.706\cdot deg$$

(Less than 45 deg)

$$y_{seg} := r - r\cdot\left[1 - \frac{2\cdot\sin(\beta)^3}{3(\beta - \sin(\beta)\cdot\cos(\beta))}\right]$$

$$y_{seg} = 1.969\cdot mm$$

(ref [4] [17] - less than 45 deg)

$$A_{seg} := -r^2(\beta - \sin(\beta)\cdot\cos(\beta))$$

$$A_{seg} = -1.143\cdot mm^2$$

(Negative area)

$$I_{seg} := \frac{r^4}{4}\left[\beta - \sin(\beta)\cdot\cos(\beta) + 2\cdot\sin(\beta)^3\cdot\cos(\beta) - \frac{16\cdot\sin(\beta)^6}{9(\beta - \sin(\beta)\,\cos(\beta))}\right]$$

$$I_{seg} = 0.024\cdot mm^4$$

(Second moment of Inertia for circle segment)

For the circle

$A_{cir} := \pi\, r^2$ $\quad A_{cir} = 16.619\,mm^2$

$y_{cir} := 0$

$I_{cir} := \frac{\pi}{4} r^4$ $\quad I_{cir} = 21.979\,mm^4$ (Second moment of Inertia for circle)

Centroid calculation

$A_t \cdot y_c = A_{seg} \cdot y_{seg} + A_{cir} \cdot y_{cir}$ (ref [5] - Eq.A.1 - pg 598)

$$y_c = \frac{A_{seg} \cdot y_{seg} + A_{cir} \cdot y_{cir}}{A_{tot}}$$

$A_{tot} := A_{cir} + A_{seg}$ $\quad A_{tot} = 15.476\,mm^2$

$$y_c := \frac{A_{seg} \cdot y_{seg} + A_{cir} \cdot y_{cir}}{A_{tot}} \qquad y_c = -0.145\,mm$$

Iyy around section centroid

$I_{cirp} := I_{cir} + y_c^{\,2} \cdot A_{cir}$ $\quad I_{cirp} = 22.33\,mm^4$

$I_{segp} := I_{seg} + \left(h_t + |y_c|\right)^2 \cdot A_{seg}$ $\quad I_{segp} = -4.054\,mm^4$

$I_{yy} := I_{cirp} + I_{segp}$ $\quad I_{yy} = 18.276\,mm^4$ (Second moment of Inertia for chosen section)

Deflection calculation

$$\delta_b = \frac{P \cdot L^3}{3 \cdot E \cdot I_{yy}}$$

(ref [1] case 1 - pg 969, cantilever - end load)

$$\delta_b := \frac{P \cdot L^3}{3 \cdot E \cdot I_{yy}} \qquad \delta_b = 0.188\,mm$$

(Maximum deflection - At point B)

The deflection due to loading of the lower soft jaw is negligible.

Bending stress calculation

$R_y := P$	$R_y = 10\,N$	(Reaction force in y-direction)
$M_y := L \cdot P$	$M_y = 0.6 \cdot N \cdot m$	(Resultant moment at wall)
$y_1 := h_t + y_c$	$y_1 = 1.889 \cdot mm$	(Distance from section centroid to top surface of section)
$y_2 := r + y_c$	$y_2 = 2.155 \cdot mm$	(Distance from the section centroid to the bottom of the surface section)
$A_b := A_{tot}$	$A_b = 15.476 \cdot mm^2$	(Cross sectional area)

Stress due to bending:

$\sigma_{b1} := \frac{M_y \cdot y_1}{I_{yy}}$	$\sigma_{b1} = 62.013 \cdot MPa$	(Tension)
$\sigma_{b2} := \frac{M_y \cdot -y_2}{I_{yy}}$	$\sigma_{b2} = -70.735 \cdot MPa$	(Compression)

Shear forces:

$\tau_y := \frac{R_y}{A_b}$	$\tau_y = 0.646 \cdot MPa$	(Negligible)

Stress induced by shear force is negligible, so the maximum stress is present at σ_{b2} in compression. Next the safety factor is calculated

$S_y := \sigma_{yt}$

$\sigma_{max} := \sigma_{b2}$	$\sigma_{max} = 70.735 \cdot MPa$	(von Mises failure criteria maximum equivalent stress ref [1] Eq 6-15 - pg 262)
$S_f := \frac{S_y}{\sigma_{max}}$	$S_f = 12.229$	(Design safety factor, greater than 1. failure will not occur during loading)

The safety factor is greater than 2 and is well within acceptable operating stresses. There is no need to examine the upper soft jaw as it is thicker and larger in cross-sectional area. Required holding forces during welding were hard to determine however they should be negligible if components did not stick to the electrodes.

Fatigue calculation

The loading and unloading of the gripper finger occurs in repetitive short cycles. This therefore means that cyclic loading becomes a concern and failure due to fatigue could be of concern. For this reason the endurance limit (S_e) is calculated and used to determine if failure due to fatigue occurs and if not, what the safety factor is?

$$S_e = k_a \cdot k_b \cdot k_c \cdot k_d \cdot k_e \cdot k_f \cdot S_{ep}$$

(ref [1] Eq 7-17 - pg 328 was used to determine all limit modifying factors)

$$S_{ep} := 0.5 \cdot S_{ut}$$

(ref [1] Eq 7-8 - pg 325)

Determining limit modifying factors for case application:

Surface factor (k_a)

$$k_a = a \cdot S_{ut}^{\,b}$$

$a := 4.51$

$b := -0.265$

(Gripper finger has a machined surface finish, ref [1] table 7-4 pg 329

$$k_a := a \cdot \left(\frac{S_{ut}}{MPa}\right)^{b}$$

$k_a = 0.731$

Size factor (k_b)

$d_e := 0.37 \times 2 \cdot r$

$d_e = 1.702 \cdot mm$

(Cross section is approximately circular in shape ref [1] Table 7-5 - pg 331)

$$k_b := 1.24 \cdot \left(\frac{d_e}{mm}\right)^{-0.107}$$

$k_b = 1.171$

($d < 51$ mm, ref [1] Eq 7-19 - pg 329)

Loading factor (k_c)

$k_c := 1$

(Bending loading is prevalent ref [1] Eq 7-25 - pg 331)

Temperature factor (k_d)

$k_d := 1$

(Operating temperature of the environment is not known, therefore room temperature of the 20 degrees Celsius was selected. ref [1] Table 7-6 - pg 332)

Reliability factor (k_e)

$z_a := 3.091$

(A reliability of 99.9 % was selected from ref [1] Table 7-7 pg 334)

$k_e := 1 - 0.08 \cdot z_a$ $\qquad k_e = 0.753$

Miscellaneous-effects factor (k_f)

$k_f = 1 + q \cdot (k_t - 1)$

$r_f := 3mm \qquad D := 10mm \qquad d := 4.6mm \qquad \frac{D}{d} = 2.174 \qquad \frac{r_f}{d} = 0.652$

$K_t := 1.5$

(Stress concentration factor was deduced by selecting the highest K_t factor found between ref [1] Figure A-15-5 pg 983 and ref [1] Fig A-15-9 pg 984 with interpellation, as no figure which accurately represents the geometry of the finger was found.)

$q := 0.88$

(Determined from ref [1] fig 7-20 (bending and axial loading) pg 336 with notch radius of 3 mm and a S_{ut} just under 1 GPa)

$K_f := 1 + q \cdot (K_t - 1)$ $\qquad K_f = 1.44$ $\qquad$ (ref [1] Eq 7-31 - pg 336)

$k_f := \frac{1}{K_f}$ $\qquad k_f = 0.694$

Calculating the endurance limit

$S_e := k_a \cdot k_b \cdot k_c \cdot k_d \cdot k_e \cdot k_f \cdot S_{ep}$ $\qquad S_e = 214.83 \cdot MPa$ $\qquad$ (ref [1] Eq 7-17 pg 328)

Determine fatigue safety factor

$s_{ff} := \frac{S_e}{\sigma_{max}}$ $\qquad s_{ff} = 3.037$

The fatigue safety factor is larger than 2 and not close to one. This eliminates most uncertainties that fatigue failure would occur. However the Size factor (k_b), operating temperature (k_d) and miscellaneous-effects factor (k_f) were chosen with careful consideration, but these values cant firmly be supported. As with any fatigue calculation results are not always conclusive and experimental testing of the part should be also performed.

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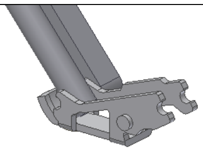
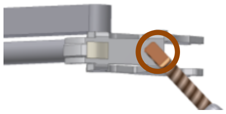
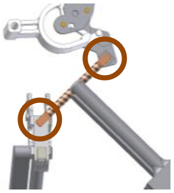
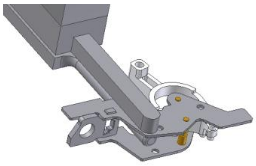
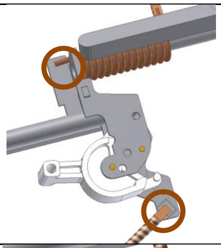
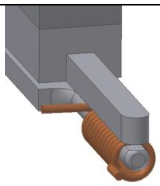
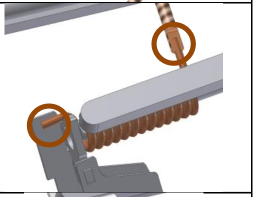
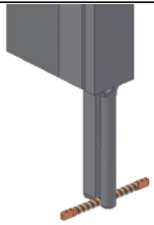
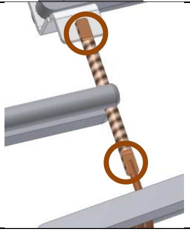
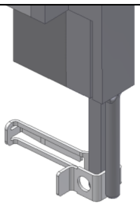
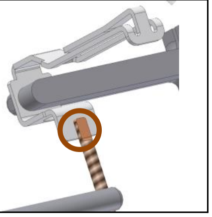
[9] Motoman, Industrial robot Motoman-HP6, Datasheet, Available at: http://www.motoman.com/motomedia/datasheets/HP6.pdf [Accessed Feb 15, 2008]

[10] Festo, *Parallel grippers HGP*, Datasheet, Available at: https://xdki.festo.com/xdki/data/doc_engb/PDF/EN/HGP_EN.PDF [Accessed April 10, 2008]

Appendix I Component handling for assembly

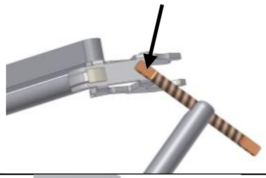
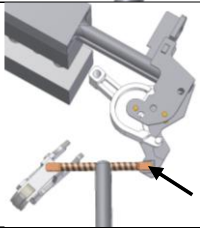
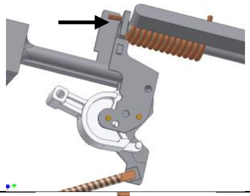
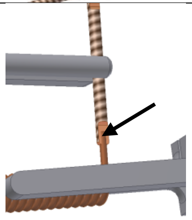
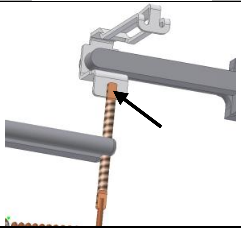
The final collection and presentation for all the respective components making up the target subassembly by the designed gripper soft jaws are shown in Table I-1 below.

Table I-1 Target subassembly gripper component handling

Component name	Picture of final collection	Picture of presentation (welding sites circled)
Moving contact		
Pigtail 1		
Handle frame subassembly		
Coil		
Pigtail 2		
Arc runner		

The sequence of welding operations to complete the assembly is presented in Table I-2 below, with an accompanying image of each operation.

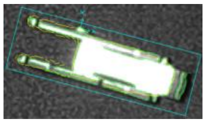
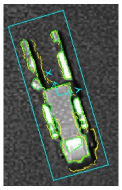
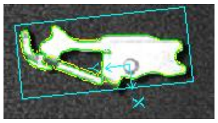
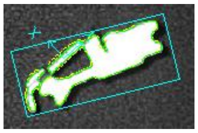
Table I-2 Welding process for target subassembly

Assembly operation	Picture of operation layout (weld indicated with arrow)
Weld 1	
Weld 2	
Weld 3	
Weld 4	
Weld 5	

Appendix J Vision system recognition testing results

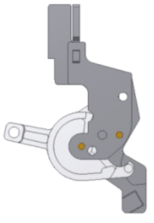
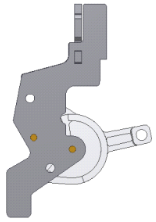
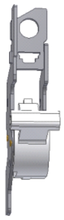
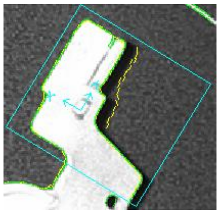
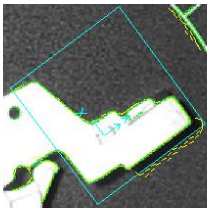
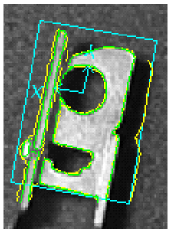
The vision training results obtained using Cognex VisionPro are presented below. Each table presents all the applicable static poses of a particular component of the target subassembly and the various training and recognition results obtain for that particular pose.

Table J-1 Moving contact pose registrations

Picture of trained region				
Number of images of pose in database	15	14	16	15
Percent correctly identified	100.00%	100.00%	100.00%	100.00%
Percent of identification error	0.00%	0.00%	0.00%	0.00%
Level of training difficulty using software	Hard	Hard	easy	easy
Approximate processing time per image - searching for single pose. (in ms)	28.65	23.55	25.21	28.26
Notes and remarks	Difficult to train recognition to distinguish between top-up and bottum-up poses. Fine adjustment of contrast and thresholding values was needed	Difficult to train recognition to distinguish between top-up and bottum-up poses. Fine adjustment of contrast and thresholding values was needed		Some false detections, parameters finely adjusted. Perspective error becomes prevalent due to high protruding geometry.

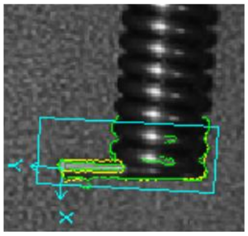
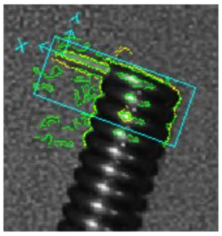
Total of 60 images in database
Estimated total processing time 105.67 ms

Table J-2 Handle frame subassembly pose registrations

Picture of static pose			
Static pose name	Small plate on top	Large plate on top	Upright
Picture of trained region			
Number of images of pose in database	14	13	14
Percent correctly identified	100.00%	100.00%	100.00%
Percent of identification error	0.00%	0.00%	0.00%
Level of training difficulty using software	medium	medium	easy
Approximate processing time per image - searching for single pose. (in ms)	20.98	51.56	25.26
Notes and remarks	Fixed feature of pose was chosen so that the moving rocker would not interfere with the registration.	Fixed feature of pose was chosen so that the moving rocker would not interfere with the registration.	Insertion hole provided a distinguishable feature for training

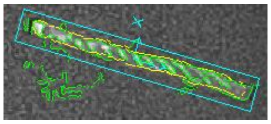
Total of 41 images in database
Estimated total processing time 97.8 ms

Table J-3 Coil pose registrations

Picture of static pose		
Static pose name	side 1	side 2
Picture of trained region		
Number of images of pose in database	13	16
Percent correctly identified	100.00%	100.00%
Percent of identification error	0.00%	0.00%
Level of training difficulty using software	medium	medium
Approximate processing time per image - searching for single pose. (in ms)	17.43	18
Notes and remarks	To limit feature weighting of the central wound coils, only the bottom protuding wire and a few windings were selected for the training region	To limit feature weighting of the central wound coils, only the bottom protuding wire and a few windings were selected for the training region

Total of 29 images in database
Estimated total processing time 18 ms

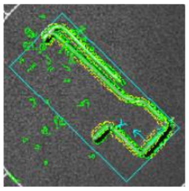
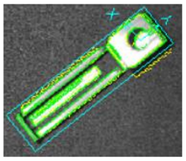
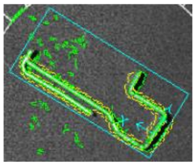
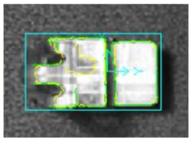
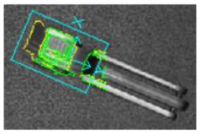
Table J-4 Pigtail pose registrations

Picture of static pose	
Static pose name	flat
Picture of trained region	
Number of images of pose in database	17
Percent correctly identified	100.00%
Percent of identification error	0.00%
Level of training difficulty using software	Hard
Approximate processing time per image - searching for single pose. (in ms)	16.82
Notes and remarks	Training parameters had to be finely adjusted to allow for skew and deformation variation. Shifted collection sites were however observed.

Total of 17 images in database

Estimated total processing time 16.82 ms

Table J-5 Arc runner pose registrations

Picture of static pose					
Static pose name	**Side 1**	**Top up**	**Side 2**	**Standing**	**Upside down**
Picture of trained region					
Number of images of pose in database	14	14	15	13	16
Percent correctly identified	100.00%	100.00%	100.00%	100.00%	100.00%
Percent of identification error	0.00%	0.00%	0.00%	0.00%	0.00%
Level of training difficulty using software	easy	easy	easy	medium	medium
Approximate processing time per image - searching for single pose. (in ms)	35.15	22.25	44.94	31.43	26.76
Notes and remarks				Some false detections, parameters tweaked. Perspective error becomes prevalent due to high protruding geometry.	Carefully had to select training region. protruding geometry causes shadows and different reflections, was initially confused with top up pose. Therefore feature at the back was chosen

Estimated total processing time 160.53 ms
Total of 72 images in database

Appendix K Cost estimation

The initial cost estimate for the robotic fixtureless assembly concept is presented below in Table K-1. This cost estimate was generated by making a breakdown of the various hardware subsystems forming the robotic fixtureless assembly concept and contacting local South African industry suppliers for quotations, advice and estimates.

Table K-1 Initial cost estimate

Item No	Description	Unit cost inc VAT	Quantity	Total inc VAT
1	**Twin robotic manipulation system**	R 545 077.67		R 545 077.67
2	**MotoMan SSF2000 6 Axis, 6Kg Payload 1378mm reach robot**		2	
3	NX100 Controller, with teach box		1	
4	8m connecting cables		2	
5	600mm high robot base		2	
6	5 kVa Transformer		1	
7	**Grippers**			
8	HGP-16-AB Gripper base	R 6 347.52	2	R 12 695.04
9	Tubing and values (estimate)	R 1 938.00	3	R 5 814.00
10	Gripper interfacing with robot (estimate)	R 11 400.00	2	R 22 800.00
11	Soft Jaw set manufacture (estimate)	R 4 560.00	2	R 9 120.00
12	**Feeding system**			
13	11 Conveyor network (estimate)	R 232 560.00	1	R 232 560.00
14	Pneumatic flow control piston	R 880.08	8	R 7 040.64
15	Push plate and piston housing (estimate)	R 2 280.00	8	R 18 240.00
16	PLC intelligent control system (estimate)	R 91 200.00	1	R 91 200.00
17	PC plugin expansion cards wiring and accessories (estimate)	R 34 200.00	1	R 34 200.00
18	bulk hoppers (estimate)	R 35 340.00	6	R 212 040.00
19	Metal frame work (estimate)	R 22 800.00	1	R 22 800.00
20	Onsite setup and commissioning (estimate)	R 13 680.00	1	R 13 680.00
21	**Vision system**			
22	Camera	R 45 600.00	1	R 45 600.00
23	VisionPro Software (1 licence)	R 24 624.00	1	R 24 624.00
24	Machine Vision Light	R 11 514.00	1	R 11 514.00
25	Panel PC	R 22 230.00	1	R 22 230.00
26	Installation and setup	R 17 100.00	1	R 17 100.00
27	Programming (estimate)	R 22 800.00	1	R 22 800.00
28	Interfacing (estimate)	R 34 200.00	1	R 34 200.00
29	**Labour and installation**			
30	Installation cost	R 11 400.00	1	R 11 400.00

Total (single cell)	**R 1 416 735.35**
Total (11 Cells)	**R 15 584 088.89**

Next the running cost for the entire system was estimated, in order to determine what the payback period of the proposed robotic fixtureless assembly system would approximately be. The running and maintenance costs for the welding system were neglected and should be added, if a better future approximation is required. This meant that the presented cost estimate would most likely be less than the actual running cost. It was decided that only 3 part time engineers would be needed to run all the 11 robotic cells and that 1 fulltime operator per cell would be sufficient. The estimated running costs are presented below in Table K-2.

Table K-2 Entire system running cost estimate

Hardware replacement and maintenance

Item no	Description	Quantity	cost inc VAT	Life in hours	Days	Cost per day
1	**MotoMan SSF2000 6 Axis robot service**	22	R 110 000.00	20000	833.333	R 132.00
2	**Grippers**					
3	HGP-16-AB Gripper base replacement	22	R 142 076.00	20000	833.333	R 170.49
4	Soft jaw set replacement	22	R 10 000.00	20000	833.333	R 12.00
5	**Feeding system (*note 1)**					
6	Conveyor newtork monthly service (estimate)	22	R 25 080.00	720	30	R 836.00

Subtotal R 1 150.49

Personnel

Item no	Description	Quantity	Working hours per day	Cost per hour	Cost per day
1	Operator (*note 2) (estimate)	11	23	R 35.00	R 8 855.00
2	Engineer (estimate)	3	2	R 125.00	R 750.00

Subtotal R 9 605.00

Total system daily running cost R 10 755.49

Personnel running costs are determined as cost to company, without considering overheads

Notes

1. Contacted conveyor consults (Conveyco) received a quotation for hourly maintenance rate of R250 exc vat.
Monthly maintenance of 4 hours per conveyor network was recommended.
2. Operator hourly cost was based on searching online for machine operator positions
Using hourly salaries researched for laundry machine operators and professionally experienced
artisans a figure between these two amounts was estimated
Turret Lathe Operator/Turner R40 per hour (http://www.careerjet.co.za/job/17c18eb5d406fb03c96d5cb1074e050b.html)
Laundry minimum wage rates R13.71 per hour (http://www.laundrybc.co.za/wages.htm)

It is notable that the personnel running costs are far larger than that of the system's hardware running costs. Therefore reducing the number of required personnel would greatly aid in decreasing the overall system running cost.