Smart Dock for Bicycle Protection in Theft-Prone Urban Areas

by

Mardu Christof Swanepoel

Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering (Research) in the Faculty of Engineering at Stellenbosch University

Department of Electrical and Electronic Engineering,
University of Stellenbosch,
Private Bag X1, Matieland 7602, South Africa.

Supervisors:
Prof. M.J. Booysen
Dr. W.J. Smit

December 2017

Plagiarism Declaration

UNIVERSITEIT·STELLENBOSCH·UNIVERSITY
jou kennisvennoot • your knowledge partner

1. Plagiaat is die oorneem en gebruik van die idees, materiaal en ander intellektuele eiendom van ander persone asof dit jou eie werk is.
   Plagiarism is the use of ideas, material and other intellectual property of another's work and to present is as my own.

2. Ek erken dat die pleeg van plagiaat 'n strafbare oortreding is aangesien dit 'n vorm van diefstal is.
   I agree that plagiarism is a punishable offence because it constitutes theft.

3. Ek verstaan ook dat direkte vertalings plagiaat is.
   I also understand that direct translations are plagiarism.

4. Dienooreenkomstig is alle aanhalings en bydraes vanuit enige bron (ingesluit die internet) volledig verwys (erken). Ek erken dat die woordelikse aanhaal van teks sonder aanhalingstekens (selfs al word die bron volledig erken) plagiaat is.
   Accordingly all quotations and contributions from any source whatsoever (including the internet) have been cited fully. I understand that the reproduction of text without quotation marks (even when the source is cited) is plagiarism.

5. Ek verklaar dat die werk in hierdie skryfstuk vervat, behalwe waar anders aangedui, my eie oorspronklike werk is en dat ek dit nie vantevore in die geheel of gedeeltelik ingehandig het vir bepunting in hierdie module/werkstuk of 'n ander module/werkstuk nie.
   I declare that the work contained in this assignment, except where otherwise stated, is my original work and that I have not previously (in its entirety or in part) submitted it for grading in this module/assignment or another module/assignment.

	Signature
M.C. Swanepoel ***Initials & Surname***	December 2017 ***Date***

Abstract

Cycling, when utilised as a form of transport in an urban environment, holds valuable benefits and sustainable advantages for a wide variety of stakeholders. Various barriers exist that contribute to a low user adoption of cycling in an urban area, despite a high and growing user adoption of recreational cycling. Bicycle theft and inadequate bicycle storage facilities for on-street urban bicycle storage are amongst these barriers identified. In theft-prone urban areas, urban cyclists are hampered by the prevalence of theft when bicycles are temporarily secured during urban commuting trips. This can negatively affect an individual's attitude towards urban cycling, and thereby increase the difficulty for regional authorities to draw from the advantages accompanying a high urban-cycling prevalence. This study proposes an on-street smart bicycle dock that is capable of adequately protecting a bicycle during an urban commuting stop-over, thereby aiding in the removal of the related barriers weighing against a higher user adoption of urban cycling.

To ensure a successful and sustainable solution, three important stakeholders were considered in order to incorporate their requirements and behaviour into the solution. Bicycle thieves were interviewed and studied to understand the methods and motives involved in urban bicycle theft, active cyclists were investigated through questionnaires to understand their requirements and attitude towards a potential solution, while a local municipal and academic institution involved in the potential implementation of the solution were engaged with to understand and incorporate their needs and requirements.

A conceptual solution that serves as the research model was produced by turning the relevant insights obtained from the research activities into product design specifications that served as a quantitative template to guide the development of the conceptual solution. The resulting solution was broken up into four functional areas that were developed separately but dependent on each other, after which they were combined to collectively form the final solution.

The first solution area sees the development of a mechanical steel frame that secures a bicycle docked in the system, by physically locking its wheels and frame using a novel locking method. This frame protects the bicycle's critical components against the majority of tools and methods commonly used in bicycle theft, and was found to provide better protection than existing solutions, accept against theft using a hacksaw where only 71% of the required protection was provided. The second area sees the development of a sensing system that uses force transducers situated below the bicycle, to convert any disturbance on the bicycle into a digital time-discrete signal that is processed by a signal processing algorithm developed, in order to detect any attempt of theft performed on the docked bicycle. The sensing system obtained a false-negative rate of 8%, a detection duration of 8.6 seconds, and a false-positive rate of 15%. The third area sees the development of a locking mechanism that engages and disengages the mechanical frame's protection in 1.4 seconds, in a way that is universally accessible to different users without them requiring a physical method of access. The lock obtained a locking reliability of 96%. The fourth area sees the development and implementation of system elements that are responsible for the system's integration and general control, including a system state machine, user interface, cloud platform, and communication capabilities with accompanying communication protocol for the various system elements.

The resulting solution's performance was measured through five tests aimed at addressing different performance areas of the solution. The overall performance of the model is determined as satisfactory, with it meeting the majority of the initial requirements and specifications defined, and thereby successfully addressing the problem statement relevant to this research.

Uittreksel

Fietsry, as 'n vorm van vervoer in 'n stedelike gebied, hou waardevolle en volhoubare voordele vir 'n wye verskeidenheid belanghebbendes in. Daar is verskeie faktore wat kan veroorsaak dat die gebruikers-syfer van fietsryers in 'n stedelike gebied afneem, ten spyte van 'n moontlike hoë en groeiende gebruikers-syfer van ontspannings-fietsryers. Fietsdiefstal, asook onvoldoende stedelike fietsbergingsfasiliteite, is twee van hierdie faktore. In stedelike gebiede met baie gevalle van fietsdiefstal, word fietse gewoonilik geteiken wat in fietsbergingsfasiliteite gelaat word. Dit kan 'n individu se houding teenoor stedelike fietsry negatief beïnvloed, en dit ook vir plaaslike owerhede moeilik maak om die baie voordele wat stedelike fietsry bring, te kan geniet.
Hierdie stel `n straat-vaste slim-fiets-bergingsfasiliteit voor, wat dit moonlik maak om ` n fiets te beveilig en dus ook poog om die negatiewe houding teenoor fietsry in stedelike areas te oorbrug.

Om 'n suksesvolle en volhoubare oplossing te vind, is drie belanghebbende groepe oorweeg en hul vereistes en gedrag in gedagte gehou tydens die ontwikkeling van die oplossing. Hierdie sluit in onderhoude wat gevoer is met fietsdiewe om die metodes en motiewe wat betrokke is by stedelike fietsdiefstal te verstaan. Aktiewe fietsryers se behoeftes en houding teenoor 'n moontlike oplossing is ondersoek met vraelyste wat aan hulle gegee is, terwyl 'n plaaslike munisipaliteit en `n akademiese instansie wat betrokke sal wees by die moontlike implementering van die oplossing, se behoeftes en vereistes ook ondersoek was. Deur die relevante insigte wat verkry is vanuit die navorsingsaktiwiteite, in produkontwerpspesifikasies te verander, kon `n konseptuele oplossing gevind word wat dus as navorsingsmodel dien. Hierdie produkontwerpspesifikasies het as 'n kwantitatiewe sjabloon gedien tydens die ontwikkeling van die konseptuele oplossing.

Die voorgestelde oplossing was opgedeel in vier funksionele oplossings-areas, wat afsonderlik, maar interafhanklik van mekaar ontwikkel is. Die eerste oplossings-area behels die ontwikkeling van 'n meganiese staalraam, wat 'n fiets beskerm deur sy wiele en raam fisies te sluit deur die gebruik van 'n nuut ontwikkelde sluitmetode. Hierdie raam beskerm die kritiese komponente van die fiets teen die gereedskap en metodes wat die meeste gebruik word vir fietsdiefstal, en dit is gevind dat die raam ‘n fiets beter as bestaande beveiligingsmeganismes beskerm. Wanneer `n staalsaag egter gebruik is, het die meganisme slegs 71% van die vereiste beskerming gebied. Die tweede area behels die ontwikkeling van 'n sensor-stelsel wat enige steuring wat op die fiets uitgeoefen word, in ‘n digitale, tyd-diskrete sein verander. Die sein word dan verwerk deur 'n seinverwerkingsalgoritme, wat so ontwikkel is dat dit pogings van diefstal op die fiets kan identifiseer. Die sensor-stelsel het 'n vals-negatiewe koers van 8%, 'n syn opsporings-tydperk van 8,6 sekondes, en 'n vals-positiewe koers van 15%. Die derde area behels die ontwikkeling van 'n sluitmeganisme wat die meganiese-raam se beveiliging in 1.4 sekondes kan koppel, op 'n manier wat universeel toeganklik is vir verskillende gebruikers, sonder dat hulle 'n fisiese metode van toegang benodig. Die slot het 'n sluitingsbetroubaarheid van 96%. Die vierde area behels die ontwikkeling en implementeering van stelselelemente wat verantwoordelik is vir die stelsel se integrasie en algemene beheer, insluitend 'n stelselstaatmasjien, gebruikerskoppelvlak, wolkplatform en kommunikasievermoëns, met gepaardgaande kommunikasieprotokol vir die verskillende stelselelemente.
Die resulterende oplossing se prestasie is gemeet deur vyf toetse wat op verskillende areas van die oplossing gemik was. Die algehele prestasie van die model blyk bevredigend, en dit voldoen aan die meerderheid van die aanvanklike vereistes en spesifikasies, en sodoende ook aan die probleemstelling wat relevant is vir hierdie navorsing.

Acknowledgements

I would like to give thanks to the following individuals and institutions for who they are, and for their support during the time that the research was conducted:

- I want to first and foremost thank Jesus for giving me the opportunities, talents, drive and passion to complete this project while loving every moment of it.

- I want to thank my supervisor Prof. Thinus Booysen for the opportunity to learn from him and conduct this research, while providing me with various opportunities for growth. Also, my co-supervisor, Dr. Willie Smit for his inputs and support throughout this project.

- MTN for their support and funding through the MTN Mobile Intelligence Lab, without which this research would not have been possible.

- The National Research Foundation for their financial support through their providing of a 'scarce skills research scholarship', which without this research would not have been possible.

Patents & Publications

Parts of the work in this paper has been published as follows:

- M.C. Swanepoel, M.J. Booysen, W.J. Smit, "*A Structural-Locking Bicycle Docking Mechanism to Enable Safe and Convenient Bicycle Usage in Urban Environments*", SACAM 2016: 1-6, Potchefstroom, South Africa.

The work in this paper has been submitted for a patent application as follows:

- M.C. Swanepoel, M.J. Booysen, W.J. Smit, "*Universal Bicycle Smart Dock*", Innovus – Stellenbosch University.

Contents

List of Figures

Page

List of Tables

Page

Nomenclature

Acronyms, Terms and Abbreviations

3D	Three dimensional
A/D	Analogue-to-digital
BBC	British Broadcasting Corporation
BOM	Bill of Materials
CAD	Computer aided design
CCTV	Closed-circuit television
CNC	Computer numerical control
GPS	Global Positioning System
HOQ	House of qualities
Hz	Hertz
ID	Identification
IoT	Internet of Things
IR	Infrared
MPa	Mega pascal
mV	Millivolts
MΩ	Mega Ohm
NCVS	National crime victimization survey
NMT	Non-motorised transport
PDS	Product design specifications
PIR	Passive infrared
PLA	Polylactic acid
PUB	Public use bicycle
PWM	Pulse width modulation
QFD	Quality Function Deployment
QR	(trademark for matrix-type barcode)
RFID	Radio frequency identification
SMS	Short Message Service
SPOC	Stellenbosch Parole Observation Centre
TPM	Technical Performance Measures
UK	United Kingdom
Urban	in, relating to, or characteristic of a town or city

List of Symbols Used

°	Degrees	-
Ø	Diameter	m
€	Euro (European currency)	-
”	Inch (distance)	-
ϵ	Stain experienced by a body or strain gauge	m/m
$F_{crow\ bar}$	Force generated by crowbar	N
G	Instrumentation amplifier gain	-
GF	Strain gauge, gauge factor	-
I_{shaft}	Steel hinge moment of inertia	$\mathrm{kg.m^2}$
L	Original body length – force transducer	m
ΔL	Change in body length – force transducer	m
L_{shaft}	Length of shaft	m
$M_{resulting}$	Resulting moment on shaft	N/m

R	Original strain gauge resistance	Ω
R_a	Strain gauge resistor a	Ω
R_b	Strain gauge resistor b	Ω
R_g	Instrumentation amplifier gain resistor	Ω
ΔR	Change in resistance of the strain gauge due to the strain experienced	Ω
SF_{yield}	Safety factor against yielding	-
σ_{max}	Maximum stress experienced due to applied moment	Pa
$V_{in-Wheatstone}$	Wheatstone Bridge input voltage	V
V_{out}	Wheatstone Bridge output voltage	V
V_s	Wheatstone Bridge applied source voltage	V

1 Introduction

Cycling holds various benefits for a wide variety of stakeholders when utilised as a form of transport in an urban environment. Improving the cycling modal share in an urban environment is accompanied as mentioned by extremely valuable benefits, but more importantly, highly sustainable advantages. The most significant benefits that accompany urban cycling are relevant to areas of social benefit, economic advantages, environmental impact, and health benefits. The rise in global urbanisation also leads to a growing need for improved urban mobility solutions, while cycling has proved that it is able to deliver very positive results in improving mobility within this context. More governments are shifting towards a focus on an integrated approach to urban planning and development, rather than adapting and improving for current motor vehicle growth [1] – amplifying the need for urban cycling to supplement urban transport systems. In South Africa, despite the strong presence of recreational cycling, the uptake on urban cycling is at a very low share. Current data indicates that approximately 1% of all trips in Cape Town are made by bicycle [2], while in the town of Stellenbosch, where 80% of all possible trips are deemed as ‘potentially cycle-able’, a mere 2% of trips are made by bicycle [1]. Recreational cycling, on the other hand, is one of the fastest growing sports in South Africa, with the country having the highest per-capita spend on bicycles and cycling equipment in the world [3].

Various barriers are identified that contribute to this low adoption rate of urban cycling despite the high and growing adoption of recreational cycling, with bicycle theft and inadequate bicycle storage facilities for on-street urban bicycle storage amongst these barriers. According to the British Transport Police, bicycle theft and damage rates have increased by 67% between 1999 and 2005 [4]. Bicycle theft in South Africa is following a similar trend, as the research presented in this paper found that 47% of active recreational cyclists have had at least one bicycle stolen in an urban environment, while 10% have had 2 bicycles stolen from them and 9% more than 2 bicycles. The current solutions aimed at on-street urban bicycle storage and protection are deemed to be inadequate and show clear room for improvement. This research paper develops a novel solution aimed at realising the potential improvement identified, by developing an on-street urban bicycle dock that establishes a synergy between mechanical and electronic solution elements.

The research presented in this paper commences by understanding the most important stakeholders relating to bicycle theft by investigating three primary stakeholders involved, in order to first develop a holistic view of the environment into which the solution developed should fit. It then concludes by producing and evaluating a prototype model that serves as the solution to the problem statement relevant to the paper.

1.1 Problem Statement

Urban commuting by bicycle holds various advantages for the user as well as other stakeholder in the urban environment, with numerous developed cities striving to increase the number of urban bicycle-commuters in the area. In theft-prone urban areas, urban cyclists are hampered by the prevalence of theft when bicycles are temporarily secured during urban commuting trips. This can negatively affect an individual’s attitude towards urban cycling, and increase the difficulty for regional authorities to draw from the advantages accompanying high urban-cycling prevalence. Although solutions aimed at protecting a bicycle in this context does exist, it is not effective enough to solve the existing problem.

A solution is required that provides urban commuters with on-street bicycle storage that is capable of adequately protecting their bicycle, and thereby aiding in the removal of the related barriers weighing against higher prevalence of urban cycling. The solution, in order to be sustainable in a holistic view, should also adhere to the requirements of the most important stakeholders involved in the implementation of the solution.

1.2 Motivation of Research Approach

The research approach followed in this paper can be divided into four broad and sequential areas. The areas include; understanding, conceptual development, prototype development, and prototype evaluation.

The first area consists of conducting a literature study to improve the general understanding of areas relating to the problem statement and potential solution elements involved in the prototype. Also included are the execution of three information capture activities that aim to improve the understanding of the holistic environment into which the solution to be developed should fit into. This understanding of the problem and environment is very important, as the overall success of the solution is dependent on both the environment and its relevant stakeholders, as well as the detailed solution.

The second area aims to generate a conceptual solution that is capable of addressing the problem statement while taking into account the holistic understanding developed in the first area. The third area develops a detailed design and model prototype based on the conceptual solution developed in the second area, in order to test the solution in a real-world environment. The motivation for the manner in which these two areas are executed is to integrate the holistic requirements for the solution with the detailed design of the solution's different elements.

The forth area evaluates the resulting prototype in a real world environment to obtain an understanding of the performance of the solution produced, in order to determine the degree to which the problem statement was addressed as well as to identify further areas of improvement.

1.3 Research Objectives

The problem statement presented above is addressed in this study through four separate, but complementary parts. These four parts are presented below as four research objectives which are sequentially addressed in this paper.

Objective 1: Define a set of requirements for a potential solution

Define requirements that a potential solution to be developed should adhere to, in order to satisfy all stakeholders involved in the research problem. This objective consists of three sub-objectives:

(a) Define the requirements of active recreational cyclists that can relate to the research problem
(b) Determine the detailed behaviour and motivation of bicycle thieves involved in urban bicycle theft
(c) Define the requirements of the parties involved in the implementation of the solution to be developed. These parties include the local municipality and local university.

Objective 2: Design a research model that addresses the requirements

Design a conceptual research model that is able to successfully address the problem statement, with the embodiment of the model being based on the set of requirements extracted in the previous objective.

Objective 3: Produce a prototype model of the conceptual design

Develop a prototype that represents the conceptual solution designed in the previous objective. The mechanical element of the solution should provide physical resistance against bicycle theft, and the electronic element of the solution should supplement the mechanical system by providing theft detection and user interaction capabilities.

Objective 4: Evaluate the performance of the developed model

The level of protection that is provided by the resulting model is measured and evaluated against the requirements, to determine the degree to which the problem statement and requirements are addressed.

1.4 Scope of Work

Scope restrictions within the following areas are applied to this research:

Information Capture Scope

The scope applied to the information capture activities limits the research to the Western Cape, South Africa. Information capture activities are only conducted in the specified region, and only investigates factors relating to this region.

Geographical Application

The geographic application of the solution is aimed at developing countries with similar or improved economic environments, technological infrastructure, and bicycle-theft prevalence as South Africa.

Model Refinement

The level of refinement for the model's developed is limited to a *proof-of-principle* standard. Limited "design for manufacturability" is included for any hardware elements developed. Measures to ensure adequate cyber security of the software systems developed, are not included. Cyber security is however deemed essential for the commercial application of the system, if continuation occurs.

Sensor Data Gathered

Bicycle-theft data gathered during the development of the sensor system is limited to simulated and recreated environments. Information capture activities will include actual thieves, although bicycle theft activities are recorded by means of recreated activities.

1.5 Contributions

The work presented here makes the following contributions:

- Presents an investigation of the three most relevant stakeholders involved in urban bicycle theft, i.e. cyclists, thieves, and the authorities involved in the solution implementation.
- Generates requirements and design specifications able to contribute towards a solution to increasing theft-protection of on-street bicycles in urban areas.
- Presents a conceptual model design that incorporates the above mentioned.
- Presents a sensor system that is able to detect attempts of theft executed on a bicycle, while adhering to the requirements and specifications identified in this research.
- Presents a locking mechanism that provides a bicycle-docking station with universal and key-less access, while adhering to the requirements and specifications identified in this research.
- Provide the performance evaluation of the above-mentioned systems as exposed to the root-causes of the research statement.

1.6 Paper Structure

The structure of this paper is divided into 6 sections, collectively consisting of 10 chapters. The paper structure is presented below in Figure 1, and explained further in this section.

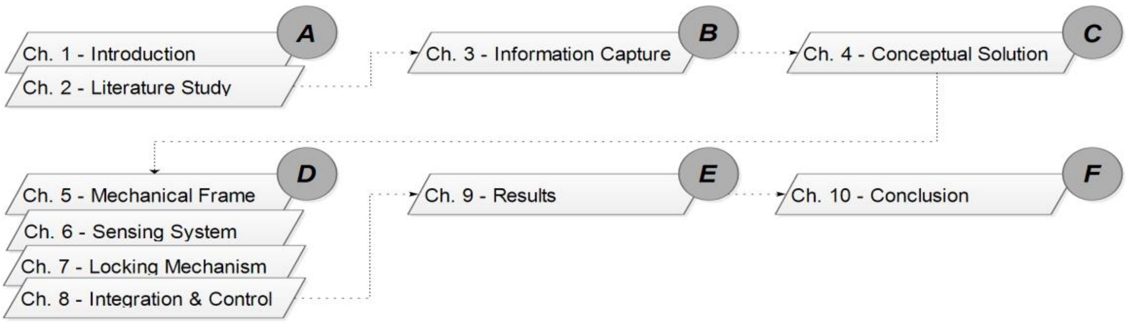


Figure 1: Research Paper Structure

Section A, *Problem & Background*, consist of chapters 1 and 2. These chapters provide the reader with a detailed introduction to the research problem addressed in the paper, an overview of the research methodology used, and gives a broad overview of the relevant background topics to provide context and support to the research conducted.

Section B, *Information Capture*, consist of chapter 3. This sections presents the approach, results and conclusions of the information gathering activities conducted during the research to gain a better understanding of the most important stakeholders related to the problem.

Section C. *Research Model*, consist of chapter 4. This section presents the paper's research model that aims to address the research question in focus, represented in this case by the conceptual solution developed. The research model is broken into four main solution parts.

Section D, *Development*, consist of chapters 5, 6, 7 and 8. This section presents the detailed development process that includes the design and development of the four main solution parts. The four solution parts are developed separately, but dependent on each other.

Section E, *Results*, consist of chapter 9. This section presents the performance of the resulting model relative to the requirements imposed by the research question. Various experiments are conducted to gather performance data for the model performance, after which the data is compared to determine the model's compliance to the original requirements.

Section F, *Conclusion*, consist of chapters 10. This section concludes the study by validating the research question presented in chapter 1 of the paper, based on the results obtained in chapter 9.

2 Literature Study

2.1 The Status Quo of Cycling

The use of a bicycle is divided into two primary categories, "recreational cycling" or "utility cycling". *Recreational cycling* refers to cycling as an activity executed with the primary purpose of enjoyment, including cycling as a sport. Leisure cycling that involves touring, exploration and sightseeing is also included in recreational cycling. *Utility Cycling* refers to cycling as a form of transport. During utility cycling a bicycle is used as a means to make moving an individual from a starting point to an intended destination, easier. This is also referred to as 'commuting' or 'urban cycling', and is encountered primarily in urban environments, and consists of shorter trips than those in recreational cycling.

2.1.1 Utility Cycling On the Global Front

Urban areas throughout the world have moved through a 40 year phase of mass motorisation, resulting in problems such as congestion, pollution, infrastructure wear and resource depletion. Each year more cities reach the point where road infrastructure improvements cannot keep up with the demand caused by motorisation, with more cities turning to methods of NMT (non-motorised transport) to help solve current and predicted mobility problems. One of the primary NMT solutions receiving focus for implementation and growth is urban utility cycling – yet the market-share of bicycles in urban transport remains small.

In a report by the *Institute for Transportation & Development Policy* and *the University of California* [5], it is calculated that globally, bicycles and e-bikes accounted for a mere 6 percent of urban trips in 2015 – a small but reasonable share. Growth of the market does seem positive, as a report published by *Lucintel* [6] states that the global bicycle market (for bicycle sales) is expected to grow at a compound annual growth rate of 2.7% between 2017 and 2022.

2.1.2 Cycling in South Africa

Recreational cycling is arguably one of the fastest growing sports in South Africa, with South Africa having the highest per-capita spend on bicycles and cycling equipment, in the world. Participation in competitive cycling in South Africa is steeply rising with approximately 300,000 cyclists annually competing in cycling events in South Africa, while over 750 mountain bike races takes place in South Africa each year – hence South Africa's reputation as a 'mountain biking mecca' of the world. The *Cape Argus Cycle Tour* that annually takes place in Cape Town is recognised as the world's largest individually timed cycle race, while the world's biggest annual mountain biking stage race, the *Nedbank Sani2c*, is also hosted in South Africa. [3]

Although the uptake on recreational cycling in South Africa is high and rapidly growing, the uptake of urban cycling is not showing any improvements and is currently at a very low share. According to The City of Cape Town's Transport and Urban Development Committee Member, Councillor Brett Herron [2], available data indicates that approximately 1% of all trips in Cape Town are made by bicycle. Despite the popularity of recreational cycling, the uptake of urban cycling remained stagnant over the past decade. The *Cycle Plan for the Town of Stellenbosch* report released by *Transport Futures* in 2015 [1] indicates a mere 2% cycling mode share for the City of Stellenbosch in 2009. As 80% of all possible trips in Stellenbosch are deemed ‘potentially cycle-able’, a strong case for potential improvement in urban cycling market share is clear.

Transport Futures [1] identified three key barriers for urban cycling in South Africa. These are: Inadequate cycling infrastructure due to “the continued focus of transport engineers on the motor vehicle as the main mode of transport without proper consideration of cyclists and pedestrians”, a culture of intolerance towards cyclists by motorised vehicle drivers which cause cyclists to feel unsafe, and the unaffordability of bicycles by a big portion of the population. Another barrier identified by Councillor Herron is safe bicycle storage facilities. According to Brett Herron, “if provided with the necessary facilities for safe storage, we are confident that commuters will use bicycles to ride to the closest public transport station from where they can complete the rest of their commute either by bus or train”.

2.2 The Motivation for a Focus on Cycling

Improving the cycling modal share in an urban environment holds various benefits for a wide variety of stakeholders. Although there are big challenges in different areas when attempting to do so, the potential rewards are extremely valuable, and more importantly, highly sustainable. With the rise in urbanisation and the growing need for improved mobility solutions, cycling has proved time and again that it is able to deliver very positive results in improving mobility in these circumstances. The majority of governments are also starting to realise that the solution to improving urban transport is not by adapting and improving for current motor vehicle growth [1], but rather to create a sustainable solution by developing an integrated approach to urban planning and development. Various research outputs show that investing in urban bicycle infrastructure, and thereby increasing cycling’s modal share, can be an intelligent and beneficial decision for municipalities. The most significant benefits are derived from the areas of social benefit, economic advantages, environmental impact, and health benefits. According to a report by *Lucintel* [6] on the growing market share of cycling, the major drivers of the growth comes from increasing fitness consciousness among people, increasing environmental concerns, increasing traffic congestion, and government programs that are promoting cycling amongst residents due to their realisation of its various benefits.

The biggest social and environmental benefits derived from urban cycling includes reduced congestions, improved user mobility, improve quality of life and less environmental strain. With Cape Town ranked in the top 50 most congested cities in the world, and Johannesburg in the top 70 [7], the reduction in congestion that a move from motorised transport towards cycling brings, can be very valuable and much needed. In congested areas, mobility is improved when using a bicycle for short-distance trips, and is more time-efficient than cars in highly congested areas. In the South African context where the quality of public transport in urban areas is substantially lower and costs much higher compared to international peers, cycling can improve a society’s mobility by increasing the availability and accessibility of a potential mobility solution. As cycling reduces the amount of motorised vehicles, a reduction in emissions, fuel usage and noise pollution is supplementary. This, in turn, removes strain from the global environment and improves the quality of life in the direct environment.

Cycling holds important economic benefits to various stakeholders when used as a form of urban transport. For the individual, choosing a bicycle over a motorised method of transport save on variable costs such as direct fuel and vehicle wear, or alternative public transport service costs. The fixed costs of maintaining a bicycle also result in a substantial saving relative to the use of a motorised vehicle. Other advantages that can be translated into economic value include transport time (in congested areas), personal health, safety, infrastructure cost and convenience. According to the *Copenhagenized Bicycle Friendly City Index* published by *Wired*, studies in Denmark revealed that for every kilometre cycled, society enjoys a net profit of 23 cents (Danish Krone), whereas for every kilometre driven by car, a net loss of 16 cents is suffered [8].

The *Office of Disease Prevention and Health Promotion* recommends that adults undertake "at least 150 minutes of moderate intensity physical activity or 75 minutes of vigorous physical activity a week" [9]. This form of activity can be achieved by means of cycling. Unlike many forms of exercise and leisure time physical activity, walking and cycling could be included in many people's daily routines as a means of travel from place to place. They might, therefore, be easier in principle to adopt and maintain than other forms of physical activity [10]. With today's busy lifestyles, many people have difficulty fitting exercise into their lives [11]. Increasing the use of cycling as method of transport thus creates an opportunistic physical activity that incorporates physical activity into people's normal, everyday lives to increase overall level of physical activity. Strong evidence exist, suggesting that physical inactivity increases an individual's risk of many adverse health conditions. With the majority of the world's population being inactive, this is a major consideration [12].

2.2.1 Cycling Incentives & Promotors

A study performed by Clearly et. al in 2010, identified key reasons that increased the urban bicycle commuting frequency amongst participants in the study. Two of these three reasons were identified as; (1) the provision of workplace bicycle storage facilities, and (2) increased awareness of the personal health benefits of cycling. The project report specifically suggests workplace bicycle storage facilities that are able to lock the bicycles safely, be weather protected, and have long-stay security measures (eg. CCTV) for the bicycles, will increase employees' commuting activity by bicycle. The facilities should also offer some degree of protection to the users, such as natural surveillance or lighting. [13]

2.3 The Status Quo of Urban Bicycle Theft

Bicycle theft is an ever increasing concern around the world, specifically in cities or areas with high population, as well as on college campuses. According to estimates from the NCVS (National Crime Victimization Survey), 1.3 million incidents of *theft-of* or *theft-from* bicycles occurred in the United States during 2006. This while the British Transport Police reported that bicycle theft and damage rates have increased by 67% between 1999 and 2005 [4]. These statistics are also commonly underrepresented, as the survey by the NCVS indicated that only 56% of bicycle thefts across 17 countries were reported to the police. Similarly in South Africa, most of the bicycles that are reported stolen are valued above R40 000 [14]. According to the *London Cycle Theft Survey* from 2016, 55% of the survey respondents stated them being 'very concerned' with the security of their bicycle in and around London, and 45% had at least one bicycle stolen. 91% of the bicycles stolen, had been stolen from a public space, with only 6% of the bicycles returned to the owner. [15]

Bicycle theft in South Africa is following a similar trend, with the Western Cape being the area with the most reported thefts. According to Matt Eager, Founder of *Bike Hub*, 60% of reported thefts across South Africa takes place in the Western Cape [14]. At the end of 2014, the South African cycling website *The Hub* launched an online "Stolen Bike Database" – a platform that allows cyclists to list the identification details of a bicycle after it has been stolen. By early 2017, the database already had 720 entries of stolen bicycles listed on it [16].

2.3.1 Types of Bicycle Thieves

The initiation of bicycle theft is categorised into two main groups, *opportunist thieves* and *professional thieves* [17]. A different type of thief will use different tools, will prefer different circumstances to commit their crime in, and have different criteria for the type of bicycle's they target. The *opportunistic thief* looks for any bicycle that is secured with conventional locking mechanisms such as cables, chains, U-locks and padlocks. Few bikes fall outside of their requirements for a target, with the circumstances usually playing the biggest role when choosing a target bicycle. The *professional* thief has a more direct and intentional approach in stealing a bicycle. They will have a much clearer specification of the type, cost and number of bicycles they are targeting, usually targeting higher priced bicycles and stealing larger quantities. They have stronger tools and better skills to breach locking mechanisms or sometimes facilities where a bicycle is stored. These thieves are difficult to stop with conventional locking mechanisms. Complete isolation in a private space usually is the best solution for protection. The most common tools that thieves use during urban bicycle theft are wire/cable cutters, a hacksaw, a hammer, a crowbar, a bolt cutter, a hydraulic jack or a portable angle grinders. [17]

2.4 Existing Solutions for Public Bicycle Protection

Various solutions exist to protect bicycles in a public urban environment. The main criteria by which a solution is measured is the level of security it provides to the bicycle, the portability of the solution, and the cost of acquiring or implementation. The most common solutions that are available include conventional bicycle locks, on-street or underground bicycle parking, bicycle lockers, and bicycle tracking devices.

2.4.1 Bicycle Locks

The most common solution used in bicycle protection is a conventional bicycle lock. The bicycle lock is used to deter a thief by fastening the bicycle to a fixed object such as a street pole or a bicycle rack, using the bicycle lock. Conventional bicycle locks include U-locks and D-locks, cable locks, chain locks, wheel locks and locking skewers. These bicycle locks vary in type, size, cost and security rating – with the most secure solutions usually being the heaviest and the least portable. Various test standards exist that rate the effective security of a bicycle lock, but the *Sold Secure* rating, produced in the United Kingdom, is found to be the most common – ranking a lock's effectiveness on a standard of *gold*, *silver* or *bronze*. As very few of the commercially available locks are truly unbreakable, a more universal ranking of a lock's level of security is measuring the duration taken by a thief to breach the lock.

Tests carried out by the *Cyclists Touring Club*, the largest charitable membership organisation that supports cyclists and promotes bicycle use in the UK, determined that the maximum time required to breach a variety of locks rated by *Sold Secure*, *ART* and *Thatchman* ratings, amounted to 43 seconds. Of all the locks used in the test, 62% was *gold rated* locks. The conclusion is that the most secure locks are U-locks and D-locks, since they are more resistant to cutting with hand tools such as bolt cutters and hacksaws. Cable locks are perceived as the weakest, as its individual strands can be cut using pliers. [18]

A major disadvantages of conventional bicycle locks is that for a lock to provide adequate to very good protection, it becomes bigger and less portable, and also more expensive due to the materials used. Conventional bicycle locks are seldom able to provide protection for more than the frame and one wheel at a time, leaving the rest of the bicycle's components vulnerable to easy theft.

2.4.2 Bicycle Parking

Bicycle Parking refers to designated bicycle storage space that is provided by a local municipality, and consists of the necessary infrastructure to allow individuals to park their bicycles for a certain amount of time. These facilities usually provide an adequate degree of security for the parked bicycles, and are conveniently located close to points of interest or public transport connections. Bicycle parking forms an important part of a municipality's transport infrastructure. When bicycle parking is scarce, any fixed objects nearby are used to secure the bicycles. The availability of adequate bicycle parking facilities is also a key factor that influences an individual's decision to cycle [19]. In Japan, automated bicycle parking systems exist that stores bicycles in an underground facility.

Bicycle parking facilities is an effective means of bicycle storage, since it makes efficient use of a relatively small amount of space in order to store a large amount of bicycles. It is achieved by providing a structured and condensed layout of bicycle storage racks. Security measures such as a fenced enclosure or manned security guards are provided to ensure the safety of the bicycles. Drawbacks of this implementation is the rising cost and decreased efficiency when it is implemented for smaller numbers of bicycles per parking facility. A large enough space within a city is also required to enable implementation of such a facility. Figure 2 shows an example of an enclosed and manned bicycle parking facility at the *Central Station* in Delft, Netherlands.

Figure 2: Bicycle Parking at Delft Central Station – Source: [20]

2.4.3 Bicycle Lockers

A bicycle locker is a box or enclosure in which a single bicycle is placed and then locked. A bicycle locker is considered the safest form of bicycle protection, since every part of the bicycle is protected from vandalism, theft and weather conditions. The actual lock used on the locker depends on whether the lockers are rented out on a long term basis (where internal locks with specific keys are used), or functions on a first-come first-serve basis (where users are required to bring their own lock). Bicycle lockers are considered optimal when bicycle safety is the main criteria. It also removes the burden of a big locking mechanisms having to be carried around by the cyclist in order to ensure good bicycle protection [21]. The lockers can be deployed on a smaller scale, making it a more implementable and versatile solution. The drawbacks of this solution is the high cost of manufacturing, and the ground space that is required per locker. Unit costs for these docks are usually high since the material used should provide an adequate level of protection, while a large amount of this material is required per dock - the costs for a municipality installing them on a large scale can thus prove much more costly than alternative solutions. The ground space required for a single dock is also much larger than conventional bicycle racks, making it less efficient in terms of implementation, than alternative solutions. An example of on-street bicycle lockers is provided in Figure 3.

Figure 3: Bicycle Lockers – Source: [22]

2.4.4 Bicycle Tracking Devices

Due to the rising cost of high-end bicycles, another increasing method used to protect bicycles is the installation of location tracking units onto bicycles. These units are small enough to be fitted to a bicycle being out of plain sight, and thereby allows a bicycle owner to retrieve the bicycle's position using the system's user interface once it was stolen. The majority of tracking units use a GPS (Global Positioning System) to identify and send its position. Although tracking devices do not serve any resistance in the initial theft of a bicycle, they do prove valuable in retrieving the bicycle after it was stolen, and therefore plays an important role in the general protection of a bicycle. A very valuable feature of tracking units is their ability to notify a bicycle owner as soon as the bicycle is on the move, enabling the owner to react the moment that the bicycle is stolen.

2.5 Methods of General Theft Prevention

A very common approach towards general theft prevention, is to raise awareness of an attempt of theft by detecting it while it is being executed, and then using a means of notification (such as an alarm system or specific notification channel) to raise awareness of the event. Common examples of this includes car alarms, retail store security systems (which sounds an alarm if unpaid goods is removed from the store), or an alarm systems in a building which triggers an audible alarm while also sending a notification to a response entity upon the detection of unauthorised entry. As seen in Chapter 2.4, bicycle theft is extremely difficult to prevent to the full. These techniques identified in this section therefore pose as valuable additions to the broader solution aimed at preventing bicycle theft.

This section looks at valuable methods of theft detection (*sensors*), and methods used to raise awareness of theft (*alerting devices*) once it has been detected, in order to gain insights from the positives and negatives of each method to potentially supplement the design of the system being developed.

2.5.1 Passive Infrared Sensor

A PIR sensor (Passive Infrared Sensor) is an electronic sensor used to detect the motion of an infrared- radiating object (such as a human, warm blooded animal, or certain objects) in a space. Any object or gas that has a temperature emits radiation (heat energy), which is invisible to the human eye but can be detected by electronic PIR sensors. The sensor creates a datum infrared image at sensor arm, and detects any changes from that image while it is active. The sensor output is binary, producing a 0 with no change in IR activity and a 1 when the pre-set threshold is detected.

PIR sensors is a popular element used for motion detection in residential or commercial burglar alarms. The sensors are very effective when used in a space that is enclosed and will only be triggered by a change in infrared emission, but due to its binary output it is more prone to false-positive outputs. The binary output and method of detection used makes the sensor "blind", as it cannot interpret the environment it is measuring. The "passive" component of the sensors refers to the sensor not emitting any form of radiation in order to detect objects, but only receiving – making it a very energy efficient solution for mobile systems. A valuable property of a PIR sensors is its ability to "map" its environment the moment that it is activated, and then keep that as a datum point. This enables the sensor to constantly measure the current input against the initial "mapping" that was created, and therefrom activates a trigger if the difference between the two is larger than a predefine threshold. [23] [24]

2.5.2 Vibration (Shaker) Sensors

A *vibration triggered sensor* detects vibration or movement on the structure which it is mounted on - such as a fence, door or gate. The sensor is intended to trigger when vibrations are caused by an attack on the structure itself. Both mechanical and electronic sensors exist. The mechanical sensor forms part of an electrical circuit, where "an unstable mechanical configuration" is tripped when a certain threshold of vibration is detected, leading to a break in the circuit and thereby activation of an alarm. The electronic sensors rely on piezo-electric sensors to convert vibrations into electrical signals that are given as output to be measured against a predefined threshold. Piezo-electric sensors can detect the amount of vibrations much more accurately, leading to more reliable sensors and less false alarms. An example of a mounted vibration sensor can be seen in Figure 4. [25]

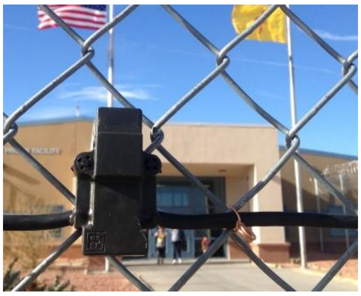


Figure 4: Fence-Mounted Mechanical Vibration Sensor – Source: [26]

Vibration sensors are known to have high reliability, affordability, and a low false alarm rate. A big benefit of vibration sensors is the ability to adjust the sensitivity threshold of the sensor in order to make it more effective in a specific environment. Alternatively a variety of sensors with different thresholds can be used to detect a wider range of possible attacks. The piezo-electric sensors increase the resolution of the sensors dramatically due to the sensitive nature of the sensors. This also provides the sensor with the ability to produce an analogue output rather than a binary – making it possible to interpret the environment measured and therefrom reducing the rate of false-positives created. The measuring-scope of a vibration sensor can be limited to the object it is fixed to, lowering the possibility of false-positives created by other elements in the environment that it is deployed in.

2.5.3 Alerting Devices & Notification Systems

Detecting an attempted theft does not hold value unless it is used to initiate the appropriate actions. This can be achieved by using a physical alerting system (an audible or visual alarm) or a party-specific notifications system (communication platform). Most of the current security systems make use of a combination of the two to ensure optimal protection. A common burglar alarm uses an audible siren to draw attention to the scene once it has detected an attempted theft, and also sends a notification to the party responsible for the protection of the area being monitored.

An audible alarm automatically draws the attention of any parties within range of the sound created, creating awareness of the activity taking place and thereby inducing others to act on it. This is valuable in environments where people will be in close proximity of the area and would be willing to act on the realisation of the alarm, but is less effective in this sense when implemented in less populated areas (such as neighbourhoods) where access to property is restricted and is further away from each other. An audible alarm is a very cost effective way to alert people of an activity, but can obtain a negative attitude towards it if triggered frequently and with high false-positive rates.

Notification systems are very useful when a specific party with required attributes should be made aware of an occurrence – as in the case of e.g. a bank robbery, fire, or potential disaster. A specified party is notified using a mobile communication channels such as SMS, cellular calls, system-integrated alerts or control-room contact points. This method holds value since the most relevant party can be informed, leading to the optimal reaction to the situation. The drawback is that parties that are notified via a notification system are not always in close enough proximity to arrive on the scene while the theft is still taking place. Another positive attribute of this method is that it allows the search party to start as soon as a theft is detected.

2.6 Analysis of Bicycle Sharing Systems

Bicycle-Sharing, also referred to as "*Public-Use Bicycles*" (PUBs), "*Smart bikes*" or "*Bikesharing*", is a short-term pay-per-use bicycle rental scheme that provides the public with bicycles in an urban environment, to help enable short distance trips. Bicycles are deployed throughout an urban environment by means of on-street bicycle docking stations which the bicycles are locked in, wherefrom users can obtain a bicycle on an as-needed basis, and then return it to any of the docking stations once they do not require use of the bicycle anymore. Users register to the service provider and provide payment details (such as credit card number), that is also used for a deposit. Bicycle-sharing was first introduced in Netherlands in 1965, and has developed drastically since then – passing through 4 generations of bicycle sharing systems [27]. Analyzing the development of bicycle-sharing, and investigating what it is and how it works today, provides valuable lessons relating to on-street bicycle docking as addressed in this research.

2.6.1 Bicycle Sharing Theft and Vandalism

One of the greatest challenges in public bicycle-sharing systems is theft and vandalism of the bicycles used in the program, this despite the use of custom components and user identification technologies incorporated by the third generation systems [28]. In a study of the *Vélib`* bicycle sharing system (Paris, France) in 2009, BBC News [29] states that since the *Vélib`* launch in 2007, 7,800 bicycles have disappeared and another 11,600 bicycles have been vandalised, this from a total of 20,600 bicycle deployed. Various methods exists to help decrease vandalism and theft. Methods such as GPS tracking, RFID, bicycle-part alterations and more secure docking stations help to decrease the vandalism and theft of bicycles, but they increase the implementation cost of the system as well. The Hangzhou system in China, one of the largest bicycle-share systems in the world, incorporates fixed gearing and inexpensive bicycles in an attempt to decrease bicycle theft. Both these methods proved successful in decreasing theft of the system's bicycles. According to Shaheen et. Al, the latest fourth generation bicycle-sharing systems should focus primarily on "using robust bicycles that can operate with less maintenance, and docking stations that increase the locking capability of the bicycles" [30].

2.6.2 Bicycle Sharing Docking Stations

The *Transport Canada Bike Sharing Document* [31] divides bicycle-sharing docking stations into three major categories; *fixed-permanent*, *fixed-portable*, or *flexible* systems. A *fixed-permanent system* is one where the bicycles are docked to permanently installed stations. These stations are physically secured to the street or pavement by using permanent joining methods. As the stations are permanently fixed and cannot be moved after installation, bicycle monitoring and redistribution is crucial in order to compensate for the varying flow of bicycles. Some systems compensate for this by installing a great deal more bicycle docks than the number of bicycles in the system, including the *Vélib`*system - which has 70% more docks than bicycles in the system. The installation costs for such a system accounts for a great deal of the project cost, and is also less forgiving for errors related to the layout planning of the stations. The vast majority of bicycle-sharing systems make use of the fixed-permanent system. A *fixed-portable* system is based on the principle of "portable modular stations". The service terminal, station control-hardware, power supply and station connectivity hardware are mounted onto a single unit, while the bicycle dock is designed to form a separate modular unit. Each station is then made up of a combination of at least one main control unit, and is joined with the required number of bicycle dock units. These systems are usually solar powered and uses a wireless communication network. The fixed-portable system BIXI, in Montreal, Canada, is one of the significant innovators in the field of fixed-portable systems. The BIXI system does not require any anchoring to the ground, allowing for stations to be installed and moved around in a resource-efficient way. This also allows the system's layout to be optimised after installation to match actual bicycle flow, and to accommodate for spikes/drops in demand due to events and changing weather cycles during the year. A *flexible* system is one where the bicycles are not locked to designated docks or stations, but where the bicycle is rather equipped with the necessary general purpose locking devices such as a chain or a cable, to be locked to any stationary device (eg. traffic sign, standard bicycle rack, etc.) when the bicycle is not in use.

Table 1 below presents the advantages and disadvantages of the fixed-portable system, which is the most attractive system that relates to this research.

Table 1: Fixed-Portable System Summary

Advantage/ Disadvantage	Description
A	Fast, labour efficient and inexpensive to deploy or re-deploy stations
A	Independent of the local power grid & communication network
A	Distribution of stations can be easily adapted to meet actual flow and demand
A	Distribution optimization can occur after installation, at little cost
A	Stations can be moved to meet demand for special occasions eg. festivals/concerts
A	Stations can be removed in periods of system inactivity (eg. winter in certain countries)
D	Not as aesthetically integrated with the streetscape as fixed-permanent systems are
D	Increased cost due to dependence of own power supply

3 Information Capture

Three research activities which incorporates the most important stakeholders relating to the research question, were executed with the primary objective of gaining a better holistic understanding of the research questions and the relevant requirements of the solution. These stakeholders were identified as: cyclists who directly experience the research problem addressed, the individuals responsible for initiating and executing the bicycle theft, and the authorities and institutions who are responsible for the eventual implementation of the solution being developed. The required learnings from these research activities were to understand the most important factors to take into account for each stakeholder when developing a solution, to derive possible system requirements for the solution, and to gain measurable metrics of success and performance for the model being developed. This section presents the results gathered from these various research activities performed. The research activities performed includes research questionnaires with the recreational cyclists, user interviews with the bicycle thieves, and user interviews with authorities and institutions responsible for the solution's implementation.

The information gathered in this section plays an important role in the development of requirements for the solution. The final requirements and design specifications derived from these research activities are presented in Section 4.1 on page 23. The documentation for ethical clearance relating to this section's research activities can be found in Appendix C on page 99.

3.1 Questionnaire for Active Cyclists

Questionnaires targeting active recreational and utility cyclists were used to learn more about their perceptions of urban cycling and bicycle theft. The objectives were to (1) better understand active cyclists' attitudes towards utility cycling, (2) identify reasons why they do not fully adopt utility cycling in urban areas, and (3) find possible requirements that they would want in the solution being developed. The motivation for performing the questionnaire was to obtain insight from cyclists in the South African context, as there exists very little literature on this specific group relating to the research question addressed.

3.1.1 Approach

The interviewees targeted are categorised as 'active cyclists', implying that they cycle at least 2 times per week. 'Active cyclists' were targeted due to their high level of exposure to the problem investigated, therefore implying that needs and insights amongst these users are amplified relative to other users experiencing the problem at lower frequencies. The "barriers towards cycling" identified amongst this specific group of active cyclists is also seen as extremely valuable since it identifies those factors that are preventing individuals who already agree with the intrinsic value of cycling, from using cycling in the form of urban utility cycling.

The research questionnaire was sent out using an electronic-form format, making use of *Google Sheets* to capture and process the feedback received. This approach was chosen since more users can be reached using an electronic format, while larger quantities of data can also be processed. An electronic form is generally also more flexible and convenient for interviewees than physical questionnaire forms. Various cycling clubs in the Western Cape assisted with spreading the questionnaires, sending it to club members categorised as 'active cyclists'. 90 cyclists in total contributed to the questionnaire's results.

The questionnaire consists of 20 questions divided into 5 main categories – each category addressing a different objective. The first category defines a user description by gathering information on the user's age and fitness, type of cyclist and cycling frequency. The next category investigates the interviewee's perception of urban cycling, and what benefit he/she sees in it. Category three investigates the interviewee's experience and perception of urban bicycle theft. Category four tests the interviewee's attitude towards proposed methods able to solve the problems experienced, while category five investigates the interviewee's direct requirements for a solution aiming at solving the current situation of urban bicycle theft.

The questionnaire that was used can be found in Appendix A on page 95.

3.1.2 Results

From the 90 respondents, 93% use their bicycle at least 2 times per week, while 72% use their bicycles 3 or more times per week. This verifies the requirement of the targeted group to be classified as 'active cyclists'. The majority of respondents are older, with 44% aged 44+, and 17% aged 19 – 25. The respondents rely on their cars for the majority of their urban commuting, with 62% of their urban commuting trips being done with their car, while cycling is their second most used form of commuting at 24% utilisation. When using their bicycles to commute in an urban environment, 45% of respondents cover distances of more than 8km per trip, while 26% cover distances of 3-8 km.

The cyclists' perceived individual and societal value of urban cycling correlates very well to the benefits identified throughout the literature. The cyclists realise the potential societal benefits of urban cycling, and are aware of the value that it holds if it is implemented. The most common perceived benefits are ones related to personal health, cost saving, reducing traffic and the improved environmental impact. Also, a very positive attitude and willingness towards urban cycling is recorded from the respondents, with 70% of the respondents willing to cycle more than 8 km when commuting in the ideal urban environment, and another 19% willing to cycle between 5 and 8 km.

The biggest barriers that keep them from more frequently using a bicycle in an urban environment were identified as road safety, violence and bicycle theft. When asked what the biggest barriers towards urban cycling is for the respondents, 44% mentioned bad cycling infrastructure and unsafe roads, 29% mentioned the risk of bicycle theft or a lack of safe bicycle storage facilities at their destinations, and 22% mentioned violence and attacks on cyclists as their biggest barrier. 47% of the respondents have had at least one bicycle stolen while it was locked in an urban environment, with 10% having 2 bicycles stolen from them and 9% of the respondents more than 2 bicycle. 13% have also had individual parts stolen from their bicycles (lights, saddle bags, lights), although users mentioned that they are very hesitant leaving easy-to-remove items on their bikes while it is docked, possibly explaining this low figure.

The respondents' attitudes towards bicycle-sharing and a proposed conceptual solution to keep their bicycles safe was positive, with 86% of the respondents stating that either one will, when implemented, lead to an increase in their frequency of using a bicycle for urban commuting. When asked what the most important requirements for such a system would be, respondents stated protecting the bicycle from theft (88%), quick bicycle lock-up (53%), ease-of-use (48%) and low user cost (46%) as their main requirements.

3.1.3 Conclusion

The research questionnaires clearly show that there is a willingness amongst active cyclists to increase the frequency of their urban cycling, but that there exists clear barriers that are preventing them in doing so. The majority of the respondents fell into the category of ‘active recreational cyclists’, thereby ensuring the relevance of the data gathered from them. This research activity highlights the importance of bicycle protection, showing that it is one of the current barriers preventing the adoption of urban utility cycling. Clear requirements are extracted from the research which will aid in the design process. These requirements are presented in Section 4 on page 23.

3.2 Interviews with Experts on Bicycle Theft

Interviews were held with bicycle thieves to help develop a better understanding of the dynamics of bicycle theft. The individuals interviewed are individuals who were previously involved in bicycle theft, and who have prior or current knowledge of ongoing bicycle theft activities in the Western Cape region. The motivation for this research activity was to better understand the methods and motives involved in bicycle theft in the Western Cape, to determine exactly how and why bicycles are stolen. The insights gained are used to aid in the development of the solution’s requirements, specifications and performance measure criteria.

3.2.1 Approach

The interviews were executed in collaboration with the Stellenbosch Parole Observation Centre (SPOC) in Reyneveld Street, Stellenbosch. The interviewees were individuals who were currently under parole supervision at the SPOC, who have previously been involved in bicycle theft and who also have exposure to current activities of bicycle theft due to networks they are involved in. The appropriate candidates were identified and approached to participate in the interviews by the SPOC, with all interviews set-up and facilitated by the SPOC. All interviews occurred at the SPOC facilities, with the names and personal details of the interviewees staying anonymous during the entire process.

The interviews were structured into three main sections, each with a different objective. The overall objectives for the respective sections were to (1) determine the motives for bicycle theft occurring in the Western Cape, (2) understand the methods used to identify and steal the bicycle(s), and (3) test different conceptual methods that can be used to protect bicycles against theft. The first section’s requirement is therefore to determine the question of why bicycles are being stolen, and therefrom providing insights into what bicycles will be stolen and to what extent thieves will go to steal the bicycles. The second section’s requirements is to help understand the methods used to steal the bicycles, and identify attractive situations in which a bicycle can be stolen. This includes the whole process from how a bicycle is identified, what time of the day is best preferred, what tools are used and what locking mechanisms is seen as the ‘easiest’ targets. Results from this section will provide insights into how a bicycle should be protected in order to accommodate for the methods used to steal the bicycles. The third section’s requirements were to test hypotheses derived from possible methods of bicycle protection, to see if it is validated by the experts on bicycle theft. These hypotheses were derived from known methods of protection, as well as some novel concepts. The ethical clearance for the interviews was approved under proposal number SU-HSD-002129.

3.2.2 Findings

Bicycles that are stolen in the Western Cape are mainly sold to syndicates that operate within the region, or occasionally to random individuals in the neighbourhood who then use the bicycle as a means of transport. Syndicates allocate people under his/her network, who are requested to go and steal bicycles that fit a certain broad specification, with the number of bicycles required also specified. After the bicycles are stolen, they are brought to the syndicate where they are exchanged for cash. The sales of the bicycles or its parts are onwards then managed by the syndicate. Bicycles are usually sold in another town or neighbourhood, but very seldom to areas close to where they were stolen from.

The main motivator for the theft of these bicycles is to sell it quickly and make money – primarily to fund 'drug habits'. Bicycles with a retail value of approximately R24 000+ will be sold to syndicates for R2 000 – R3 000, while cheaper bicycles will be sold to random individuals for anywhere between R150 – R250. The bicycle is mostly sold as a unit, but can sometimes be broken up into different parts and then sold per-part. The bicycle or its parts are only sold for cycling purposes, implying that no breakdown of the materials occur for e.g. selling to metal smelters.

The factors that determine the type of bicycle that is stolen include: (1) the specification requested by the syndicate (if present), (2) the method used to lock the bicycle and the environment it is locked in, (3) the bicycle's age and perceived value, and (4) the type of bicycle (road or mountain bike). The preferred bicycle is a "disc brake bicycle", which refers to a bicycle of higher value and usually implies a more recent model (by year). Mountain bicycles are more preferred than "thin wheeled bicycles" (road bicycles). The interviewees stated that road bicycle's and much older model bicycles will very seldom be stolen, except if the opportunity (bicycle's lock-up method, time of day, environment) is very favourable when such a bicycle is encountered. Very distinctive bicycle's such as the *Stellenbosch University Matie Bicycle's* or yellow *MTN Qhubeka Bicycles* will also be stolen despite their distinctiveness, since they can be resprayed or broken up into parts.

If a bicycle as a whole cannot be stolen, it is also favourable to steal valuable bicycle parts. The interviewees made it clear that "almost any [bicycle] part" will be stolen if the opportunity exists. The wheels and frame are certainly seen as the most attractive parts to steal, but items such as seats, gears, handlebars, brakes and saddlebags will all be stolen if the situation is attractive enough.

The execution of a bicycle theft is found to include careful planning and observation, combined with improvisation and risk taking. The initiating factor for stealing a bicycle is not spontaneous, as it is requested by a syndicate or client, so thieves go out with the intention of stealing a bicycle and prepare accordingly. Yet, due to the broad specification given for the bicycle to be stolen, the specific bicycle that is chosen comes down to an opportunistic situation that requires spontaneity and risk. Thieves go out with the intention to steal a bicycle and therefore prepare accordingly by having the right equipment and choosing an appropriate time of day. They plan and prepare thoroughly before attempting to steal a bicycle, carefully choosing bicycle locking mechanisms and environments that are the easiest and least risky, sometimes working in teams to monitor the environment or distract bystanders. The most attractive opportunity is looked for based on the direct environment the bicycle is in, the way the bicycle is secured, the threat of authorities, and the potential for attention to be drawn to them within the surroundings.

The ideal time for stealing a bicycle is between sunset and sunrise, although this does not limit the potential window in which a bicycle is stolen. Less populated areas with little traffic is the most favourable by area, but interviewees claim they will even steal a bicycle in a busy public space such as the exit of a mall. "We help each other to keep others busy, and the other one steals the bicycle", one interviewee explained. The ideal scenario for a thieve is to "identify a potential bicycle in a vacant area, remove a bolt cutter from your back pack as you approach the bicycle, cut the chain and drive away with the bicycle". The most common equipment used by thieves to break the locking mechanisms on a bicycle is a bolt cutter to cut cables or locks, a crowbar to break open locks or any steel frames the bicycle is locked to, a hacksaw to cut through pipes or smaller cables, and a hammer to break a lock with impact. These methods are very effective in breaching the majority of existing bicycle lock-up methods. Any chain or cable that can fit into a bolt cutter is the easiest to cut open, while locks are also removed easily with a crowbar or hammer. Thicker steel is difficult to breach, as a saw is required to cut through it.

Various hypotheses involved in protecting a bicycle was tested, and possible conceptual solutions proposed and tested with the interviewees. The method of bicycle protection that was the most affective according to the interviewees was a bicycle tracker – a unit that is placed inside the bicycle's frame and allows the bicycle's owner to determine the location of the bicycle after the bicycle has been stolen. The most effective methods to physically secure the bicycle came down to any material that is too big to fit into a bolt cutter, material that cannot be broken by utilising a crowbar's leverage, and materials which are difficult to cut through with a hacksaw.

The most effective theft deterring methods according to the interviewees are CCTV cameras in the vicinity, and an alarm system linked to the bicycle. According to the interviewees, "we will be very cautious to enter where there is cameras", but "if people can reach the camera they will cover it and steal the bicycle." An alarm system connected to the bicycle, or one that is triggered during the attempted theft of the bicycle, is also found to be a very effective method of deterring thieves. The reason for the effectiveness of the alarm comes down to the attention that is drawn as the alarm sounds. The bicycles are stolen in a manner that is as quick as possible and draws the least amount of attention, therefore the sounding of an alarm draws attention and notifies authorities, deterring the thief. One interviewee stated that "if an alarm sounds if I am stealing a bicycle, that bicycle will immediately be left alone and we will run". Even if the alarm is not connected to a response team, the attention that is drawn to the individual is enough to stop him from stealing the bicycle. If any form of sensors or possible alarm systems are noted, the interviewers were "very cautious" to go there. When the interviewees were asked what methods they would use to protect a bicycle as effectively as possible, proposals included a camera, an alarm system, or an electric shock on the locking mechanism when trying to breach it.

The full interview's question paper and summarised notes can be found in Appendix B on page 96.

3.2.3 Conclusion

This chapter provides valuable insights on the motives behind bicycle theft, the methods and tools used to steal the bicycles, as well as evaluations of concepts to potentially protect a bicycle. The insights gained from this research activity is extremely valuable, and will aid in the formulation of the requirements, product design specifications, and will also provide strong performance metrics that will be used to measure the results.

3.3 Interviews with Local Authorities and Institutions

The third group of stakeholders are the authorities and institutions that will play a big role in the eventual implementation of the solution. The most important authorities and institutions identified in this case includes the local municipality (the Municipality of Stellenbosch), the party responsible for developing the transportation plan for the region (Transport Futures) and the local university (University of Stellenbosch). These parties play a big role in shaping the future of a region's transport infrastructure, allocated resources, requirements and vision. It is therefore important to have a thorough understanding of their available resources, most important requirements and their existing vision, in order to develop a solution that meets the needs of these factors and thereby the needs of the stakeholders.

3.3.1 Findings

Interviews and discussions were held with individuals involved in the University of Stellenbosch's top management and transportation infrastructure management. The individuals involved were vice-rector Prof. Eugene Cloete, and the head of the university's Transport & Parking division Mr. Roelof Loubser. The findings from these interviews revealed a very positive attitude existing at the university's management regarding the improvement of the current transportation infrastructure in Stellenbosch, with a great deal of effort being allocated to using cycling as a means to it. Stellenbosch is the first South African university to incorporate a "bicycle-renting" service which provides students and staff with the opportunity to rent a bicycle from the university for a year, at an affordable price. This initiative started in 2012. The university also strongly supports incorporating a system such as bicycle sharing onto the campus that can provide even more student with the opportunity to use cycling as a means of transport. The University has recently been approached by international suppliers of bicycle-sharing systems, with offers of incorporating their bicycle-sharing systems onto Stellenbosch campus. Although the idea was supported by the University, the primary barrier for the University is of a financial nature – as importing these systems into South Africa requires a very big financial investment, one which does not make sense when looking at the financial return on investment of the implemented system. The university acknowledged the rising threat of bicycle theft and violence, and is acting strongly to help counter these forces. [32]

Valuable findings were also derived from an interview with Mr. Richard Gordge, an employee at *Transport Futures* in Stellenbosch, and one of the two individuals responsible for compiling the *Cycle Plan for Stellenbosch* in 2015. The goal of the cycle plan is to "guide and aid the development of cycling as a transport mode of choice in Stellenbosch" [1]. The plan was developed with the aim of supporting the *Sustainable Stellenbosch* objective which aims to improve the sustainability of various community aspects, as it focuses on cycling as a means of transport rather than recreational or sports cycling. The proposed cycle plan emphasise the need for bicycle parking and end-of-trip facilities in Stellenbosch. The importance of "parking facilities along the route network and at both trip starts and destinations" is stated, and proposals for on-street, off-street, long & short term, as well as commercial building parking is presented. The report states that a single on-street car parking bay can accommodate "around 20 bicycles", and proposes that Stellenbosch Municipality convert 20 on-street parking bays into bicycle parking, in order to accommodate 400 bicycles' parking needs. The relevant requirements stated for short term bicycle parking is that the parking should "be arranged so that parking manoeuvres will not damage adjacent bicycles", "be well lit by appropriate existing or new lighting", "be protected from the elements", and "be managed by a cycling version of the 'car guard'". The cycle plan's stated requirements for the long-term bicycle parking is that it should “be locked ‘cages’ or other compounds with communal offering secure and permission-based access”, or “be devices to which the bicycle frame and wheels can be locked, positioned close to and directly visible from inside the place of employment”. [1]

3.3.2 Conclusion

Valuable insights relating to implementation barriers, requirements, specifications and potential opportunities have been identified in the research activities conducted in this section. The most valuable insights gained from the interviews, as well as the corresponding design relevance, are presented below in Table 2. The various insights gained are used in the development of the solution requirements and design specifications, which are presented in Section 4.1 on page 23.

Table 2: Design Insights Gained from Local Authorities & Institutions

Insight	Specification	Design Relevance
Strong effort towards safer bicycle storage.	The university is spending resources on creating safer bicycle storage, and to improve the general safety of pedestrians and NMT commuters.	Emphasis on the solution’s level of protection provided.
Financial barrier towards implementation of infrastructure.	Although the university does support the implementation of a platform such as bicycle sharing or a platform to assist mobility using bicycles, the existing products are too expensive to incorporate.	Keep the total cost of the system as low as possible.
Expectation of bicycle parking density.	The report states that a single on-street car parking bay can accommodate “around 20 bicycles”.	Relevant to the embodiment design specifications.
Short-term bicycle storage requirements.	Arranged so that parking manoeuvres will not damage adjacent bicycles, be well lit by appropriate lighting, be protected from the elements, be managed by a cycling version of the ‘car guard’.	General design specifications.
Long-term bicycle storage requirements.	Locked ‘cages’ or other compounds with communal offering, providing secure and permission-based access; or be devices to which the bicycle frame and wheels can be locked, positioned close to and directly visible from inside the place of employment.	General design specifications.

4 Conceptual Solution

This section presents the conceptual solution, which serves as the research model proposed to address the research question. Relevant insights that are obtained from the literature study and information capture activities, are first converted into requirements and characteristics for the research model. These requirements and characteristics are then further transposed into the Product Design Specifications which serve as a quantitative template to guide the development of the conceptual solution into the research model. The conceptual solution is produced by breaking the required solution into its core functional areas, where after each area is developed as a separate conceptual solution. These individual conceptual solutions are then combined after development, into the resulting overall conceptual solution.

4.1 Design Specifications

The design specifications are developed by extracting and processing the various requirements and characteristics obtained from the various research activities, with the main objective of defining a detailed description of qualities required in the solution model. The resulting Product Design Specifications (PDS) are presented in Section 4.1.3. This section presents the formulation of these PDS.

4.1.1 Derived Requirement

The derived requirements capture all the qualities that are directly or indirectly needed and wanted. The requirements are primarily derived from the Literature Study activities presented in Chapter 2, together with the Information Capture activities in Chapter 3. The top priority requirements are summarised in Table 3 below, with the full list of derived requirements presented in Appendix D on page 100.

Table 3: High-Level Top Priority Derived Requirements

Requirements			
Requirement	**Rank (/ 5)**	**Requirement Source**	**Description**
Protect the bicycle from theft	5	Research Question	Provide adequate protection to a bicycle that is docked in the system
Detect Attempts of theft on the bicycle	5	Interviews – Ch. 3.2	Sensors that can detect attempts of theft on a docked bicycle
Prevent physical removal of certain bicycle parts	5	Bicycle Sharing – Ch. 2.6	Mechanical locking capabilities
Alert, notify and communicate remotely	5	Bicycle Sharing – Ch. 2.6	Remote communication capabilities
Improved performance compared to conventional locks	5	Bicycle Locks – Ch. 2.4	Greatly increase the level of protection provided to a bicycle (relative to the level provided by conventional U-locks & D-Locks)
Primary protection of critical components	5	Interviews – Ch. 3.2	The bicycle frame and wheels should be given higher priority in terms of

			protection, as these are defined as the "most wanted" parts by bicycle thieves

4.1.2 Engineering Characteristics

The engineering characteristics presents a transposition of the derived requirements into a set of technical specifications and qualities that are used to embody the model being developed. The engineering characteristics also serve as the foundation for the PDS (Product Design Specifications) that are defined in the next section. The engineering characteristics stream from the derived requirements defined in Section 4.1.1. In order to guide design emphasis and resource allocation during the development phase of the solution, the relative importance of all the engineering characteristics are calculated using the method of QFD (Quality Function Deployment). A HOQ (House of Qualities) is used to relate the derived requirements to the engineering characteristics. The HOQ analysis results in the ranked and importance-weighted engineering characteristics that is used in the proceeding development activities. Only rooms 1 to 5 of the conventional HOQ are considered in the QFD analysis conducted here.

The full HOQ analysis and the resulting list of ranked engineering characteristics are presented in Appendix E on page 102. The importance-ranked engineering characteristics that are derived serve as an important guideline during the project's remaining design and evaluation phases. It is also used to define the final PDS. A graphical representation of the resulting engineering characteristics is presented below in Figure 5.

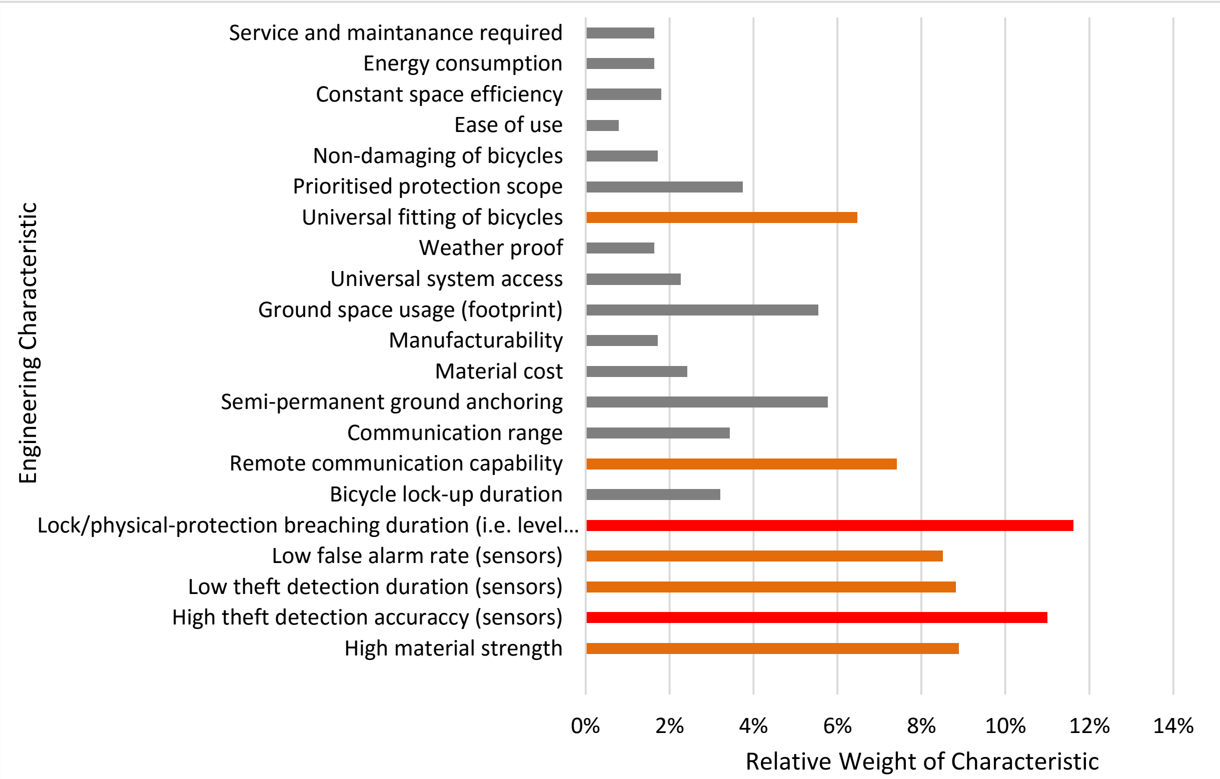


Figure 5: Relative Weighted Engineering Characteristics

4.1.3 Product Design Specifications

The PDS (Product Design Specifications) present low-level specifications and quantitative characteristics of the model that should be developed. The PDS guides the design and development phase by defining what the model should be capable of, what measure of performance it should have, and how strictly it should comply with the derived requirements. The PDS are also used as technical performance measures, to aid in the final results' performance achievements. The respective PDS relevant to each design section are presented at the beginning of each concept solutions' development section, i.e. Sections 5.1, 6.1, 7.1, and 8.1.

4.2 Functional Decomposition

The functional decomposition defines a series of original functions in such a manner that, when reconstructed, forms a general solution model required to address the problem statement. The functional decomposition simplifies the broader model that needs to be developed, and provides a platform for clearer low-level insights related to the identity of the required functional solutions. The interactions between the various functions are not always clearly observable but are very important as they interdependently contribute to the broader solution. After decomposition, each of these components' solutions is developed individually, where after they are combined at the end to form the overall solution. The constituent functions presented in the functional decomposition originate from the derived functional requirements which were identified in Section 4.1.1. The resulting functional decomposition is presented in Figure 6.

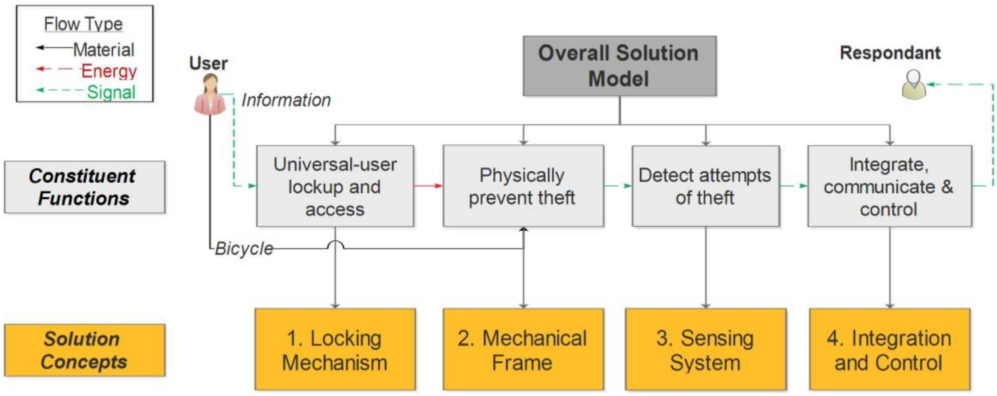


Figure 6: Functional Decomposition

The resulting decomposition consists of four primary constituent functions. The first function of the solution is to allow universal user access, through the locking mechanism providing access to the bicycle. The method of locking should therefore be performed in a way that is universally accessible, not limiting access to the system due to physical requirements (e.g. key or card). The second function is to provide the bicycle and its parts with the required amount of physical protection against theft, as the bicycle is locked up. The third function monitors the bicycle while it is locked, with the purpose of detecting attempts of theft on the bicycle and initiating the relevant alerts. The fourth function is responsible for the integration and control of the various system elements, and to provide communication capabilities for it to do so. The flow of *material*, *energy* and *signals* are presented in Figure 6, illustrating the interactions of the *user* and possible *respondents* together with the different functions. The *respondent* refers to parties identified as relevant in the communication and alerting process for specific activity detected by the system (e.g. Attempt of theft, or system errors).

The resulting s*olution concepts* are then derived from the respective constituent functions presented in the decomposition. These solution concepts serve as the foundations of the functional concept development that follows. The first solution concept defined is a "locking mechanism" able to engage or disengage the protection of the docked bicycle, in a universally accessible manner. The concept entails a solution that is able to serve as a locking mechanism that can provide access to any user without posing restrictions such as a physical access key. The second solution concept defined is a "mechanical frame" that physically protects the bicycle. This entails a solution that is able to provide the required degree of physical protection to the bicycle, by making use of a mechanical structure that secures or protects the bicycle. The third solution concept defined is a "sensing system" that can fulfil the role of detecting any attempts of theft on a bicycle that is secured by the system. The fourth solution concept, the "system integration and control", is responsible for integrating the various elements within the model, while enabling and controlling the interactions of the system. All solutions developed are strongly dependent on each other.

The four solution concepts defined in this section serves as the building blocks of the overall solution model to be developed. Each concept is developed individually by drawing their relevant requirements and specifications from the relevant research areas, while still taking dependencies and relationships with other concepts into account during their respective development. The overall solution model is created by the integration of the respective concepts.

4.3 Functional Concept Selection

The functional concept selection consists of the process by which a final concept is chosen, for each of the four solution concepts identified in Section 4.2. The various concepts that were considered for the respective solution concepts are presented, together with the criteria and reasoning by which the final concepts are chosen. The PDS document and the information capture literature served as the main basis used during the reasoning and selection criteria when choosing the final concepts. A broader system's approach was also incorporated into the reasoning during the selection process, taking into account the different concepts' relationships with one another, and how the sum of the parts can contribute to the overall solution. These relationships and interdependent contributions are illustrated when the final conceptual solution is presented in Section 4.4.

4.3.1 Mechanical Frame

The mechanical frame solution is responsible for the physical protection of the bicycle. This involves preventing physical removal of the bicycle's high-priority components. The high-priority components were identified from the research activities in Section 3.2, and consists of the bicycle frame, rear wheel and front wheel. The various concepts generated and the respective concept selection process, are presented in Table 4.

Table 4: Mechanical Frame Concept Evaluation

Mechanical Frame			
Function Involved	Physically prevent theft of the bicycle's high-priority components		
Description of Potential Concepts & Relevant Information			
Concept	**1**	**2**	**3 (DATUM)**
Method	Bicycle Locker	Structural Frame Protection	Bicycle Parking

Description	A structure that encloses the whole bicycle, restricting physical access to all parts of the bicycle.	A frame that is anchored to the ground, which provides protection to the bicycle by providing ways that the bicycle can be attached to the frame.	An enclosed area that restricts access to the bicycles by requiring user access upon entry to the area.
Illustration	 Source: [22]	 Source: www.linuxsky.net	 Source: [20]
	Concept Evaluation		
Material required	-1	+1	0
Production and implementation cost	-1	+1	0
Footprint size	-2	-1	0
Efficiency on small scale	+1	+1	0
Level of protection provided	+1	-1	0
Fraction of critical components protected	0	0	0
Fixed-portable potential	+1	+1	0
Cumulative Score	**-1**	**+2**	**0**

The conceptual solution for the mechanical frame will be fulfilled by Concept 2, a structural frame. The three main reasons that the decision is based on are the cost, physical implementation requirements and flexibility, and the alignment with the prioritisation of bicycle part protection. Concept 1 (bicycle locker) provides a high level of protection to the whole bicycle, making it the best possible concept by which a bicycle can be protected, although it is a much higher costing solution, requires a large implementation space, and is less flexible after installation. Concept 3 also provides a high level of bicycle protection, and is known to be extremely space and cost efficient when built at high volumes – but lacks this efficiency at lower volumes. There is also no flexibility after installation, and smaller implementations at higher frequencies in an urban area is also very ineffective. These two options therefore poses potential in certain aspects of the required characteristics, but does not show good performance in all characteristics.

Concept 2 is ranked the lowest in the area of bicycle protection, although this is reasoned to be due to the locks that are generally used in combination with this solution, and not the intrinsic qualities of the frame method itself. This concept is a highly attractive solution in the area of cost, space efficiency and portability after implementation. This concept therefore holds great potential if the method of locking the bicycle can be improved upon.

Two other factors that contributes to the attractiveness of this solution are the prioritisation of bicycle parts during protection, and the incorporation of other protective elements in the solution to contribute to the overall effectiveness of the solution. The prioritisation of bicycle parts during protection refers to the insight gained in Section 3.2 (Interviews with Experts on Bicycle Theft) that the wheels and bicycle frame are the top priority parts that requires a high level of protection, whereas the rest of the parts can be protected by a lower level of protection. The three top-priority parts can adequately be protected by this solution concept, while protection of the secondary parts will be covered by the supplementary sensing system solution to be developed. This strategic implementation therefore removes the 'protection of the secondary parts' from this concept requirements.

4.3.2 Sensing System

The sensing system solution is responsible for capturing environmental disturbances, and then translating them into insights that can determine whether an attempted theft is being executed on the bicycle. The potential concepts identified, and the respective concept selection process are presented below in Table 5. As concepts 1 and 2 are not generally applied in the context of theft detection, and since none of these concepts has been applied in this specific context, the different concepts were prototyped on a basic level to test the outcomes of the most important measurement criteria used in this specific application.

Table 5: Sensing System Concept Evaluation

Sensing System			
Function Involved	Detecting any attempts of theft on a bicycle secured by the system		
Description of Potential Concepts & Relevant Information			
Concept	**1**	**2**	**3 (DATUM)**
Method	Force Sensing Bed	Capacitive Sensing	P.I.R.
Description	Measuring any physical disturbances on the bicycle using force transducers.	Measuring the presence and certain characteristics of a physical object in a controlled area around the bicycle.	Measuring the activity of energy-releasing objects in a predefined window around the bicycle.
Illustration	 Source: forsentek.com	 Source: dir.indiamart.com	 Source:lightmotionsensor.com
Concept Evaluation			
Cost	0	0	0
Energy Efficiency	0	0	0
Scope of detection	+2	+1	0
Noise interference	+1	+1	0
Sensitivity adjustment	0	0	0
Insights from inputs	+2	+1	0
Detection duration	0	0	0
Cumulative Score	**+5**	**+3**	**0**

The concept choice for the sensing system is Concept 1, to implement a force sensing bed. The force sensing bed uses force transducers to translate any physical force or disturbance that is executed on the bicycle, into an electrical signal that can be processed to gain insights and therefrom detect possible attempts of theft. Any physical disturbance on the bicycle or force bed (bumping the bicycle, cutting the frame, removing a wheel) is translated into an electronic signal by the force transducers. This electric signal created is then processed by an algorithm to determine whether the disturbance measured is of a theft-related nature, or not. The main criteria leading to the choice of Concept 1 is (1) the potential to gain insights from the measured variables, (2) the ability to precisely define the physical scope of disturbance measurement, and (3) the ability to adapt and improve the sensors, and thereby efficiency, after implementation.

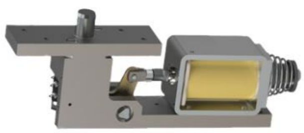
The most valuable aspect of Concept 1 is the ability to limit the physical scope of what is measured, and then the ability to gain insights from the disturbances measured. The measurement scope is restricted by placing the bicycle on a platform that rests on the force transducers - serving as the force bed. Since the theft of a bicycle relies on physical actions (cutting, breaking, and movement) performed on the bicycle and its dock, and since this concept only measures variables of that nature, it is able to ignore any other possible environmental factors that is not related to theft. As the chosen concept uses an algorithm to process the signals produced, it provides the possibility to adapt the detection and signal processing as changes occurs in the environment.

The cost, energy efficiency and detection duration are also important criteria used in the decision, but the differences between the concepts within these fields are all negligibly small.

4.3.3 Locking Mechanism

The locking mechanism is responsible for locking and unlocking (engaging or disengaging) the mechanical frame that physically protects the bicycle, in a way that is universally accessible to different users without them requiring a physical method of access (such as a key or access card). The solution is highly dependent on the physical frame design that is developed for the mechanical frame solution, also having similar requirements and PDS. The potential concepts identified, and the respective concept selection process, are presented below in Table 6.

Table 6: Locking Mechanism Concept Evaluation

Locking Mechanism			
Function Involved	Provide the capacity to lock or unlock the bicycle in a way that is universally accessible to different users		
Description of Potential Concepts & Relevant Information			
Concept	**1**	**2**	**3 (DATUM)**
Method	Magnetic Contact Lock	Electronic Latching Mechanism	Electronic Combination Lock
Description	Combination of an electromagnet and armature plate that joins two surfaces by means of electromagnetic force	A latching mechanism that is locked/unlocked using an electrically operated motor or solenoid	An electronic locking mechanism that is unlocked by entering a corresponding access code
Illustration	 Source: keyreels.com	 Source: magnetschultz.co.uk	 Source: www.brownsafe.com
Concept Evaluation			
Cost	+1	+2*can be self-manufactured	0
Level of protection	+1	0	0

Energy consumption	-1	0	0
Accessibility	+1	+1	0
Complexity in design	+2	+1	0
Manufacturability	-1	+1	0
Fail-Safe locking	-2	0	0
Operational requirements	+2	+1	0
Cumulative Score	**+3**	**+4**	**0**

The concept selected for the locking mechanism is Concept 2, an electronic latching mechanism. An electronic latching mechanism makes use of a low-power electronic motor or solenoid to engage and disengage a mechanical latch, which then prevents the disengagement of the mechanical parts related to the locking mechanism.

The main criteria used during the selection of Concept 2 were production cost, potential level of protection, manufacturability and operational requirements. The cost of the locking mechanisms chosen is a large fraction of the overall solution's cost, emphasising the requirement of a low cost solution. The manufacturability of this unit, as well as the cost of the parts required, are the biggest contributors to the total unit cost. The manufacturability of Concepts 1 and 2 are argued to be the easiest and therefore most attractive options in that category. The cost of manufacturing is therefore also likely to be lower for concepts 1 and 2. Since Concept 3 requires an access code, it adds a barrier to its level of 'easy universal access', making it a less attractive option. Concept 2 is subject to less demanding operational requirements as it only requires a low supply of power when the locking mechanism is engaged or disengaged. Concept 1 requires a constant supply of power to keep the locking mechanism engaged, and loses all protection once the supply of power is interrupted. Although Concept 1 provides the easiest and most effective method of protection, the operating requirements will pose additional requirements on the system as a whole.

Concept 2 is thus chosen based on the possibility of self-manufacturability, easily achievable operational requirements, low cost, and the potential for a high level of protection obtained from it.

4.3.4 System Integration and Control

The system integration and control concept is responsible for integrating the various elements within the model, managing the interactions amongst them, and enabling communication between the different system elements. The concept consists of three elements; (1) a *user interface*, (2) *system integration*, and (3) *system control*.

The user interface chosen is a smartphone application. The motivation for this choice is based primarily on the 'universal access' that a smartphone provides, as it consist of minimal barriers for user to enter into the system using this means. Smartphone applications also provide high levels of flexibility to create an interface that can easily integrate into the system. Smartphone penetration is also observed to be increasing in developing countries, decreasing the risk of potential users not able to use this means of access.

The control of the various elements within the system will be administered by a cloud-based platform, connecting to a hardware controller situated on the various docking units. The cloud based system will serve as middle-man for the user interface and hardware controller, and integrate the platform with elements such as a user database and payment processes. The hardware controller housed on the dock will administer the components on the dock such as the sensing system and the locking mechanism, and will pose as gateway between these elements and the cloud-based platform.

Communication and integration of the user-interface, cloud-platform and hardware controller will be wireless, and be realised by integrating all elements into the Internet of Things. Wireless communication is important in order to fulfil the requirement of fixed-portable frames. It also removes the costs associated with installation of communication infrastructure for the stations once installed. The integration of the elements present on the frame is hardwired, and converges at the hardware controller used for system control on the frame. Table 7 provides a summary of the conceptual solution of the system integration and control concept.

Table 7: System Integration and Control Concept Evaluation

System Integration and Control		
Level 1	**Level 2**	**Solution**
Integration and Control Concept	User Interface	*Smartphone application.*
	System Integration	*Wireless communication (IoT) for user-interface, cloud and hardware controller. Hardwired component on the frame.*
	System Control	*Cloud-based management platform. Hardware controller on frame.*

4.4 Final Conceptual Solution

The final conceptual solution is created by integrating the respective functional concepts selected throughout Chapter 4.3, into a single-system solution. This final conceptual solution serves as the conceptual research model that will be developed during the research. Figure 7 illustrates the integration of the different functional concepts into the final conceptual solution.

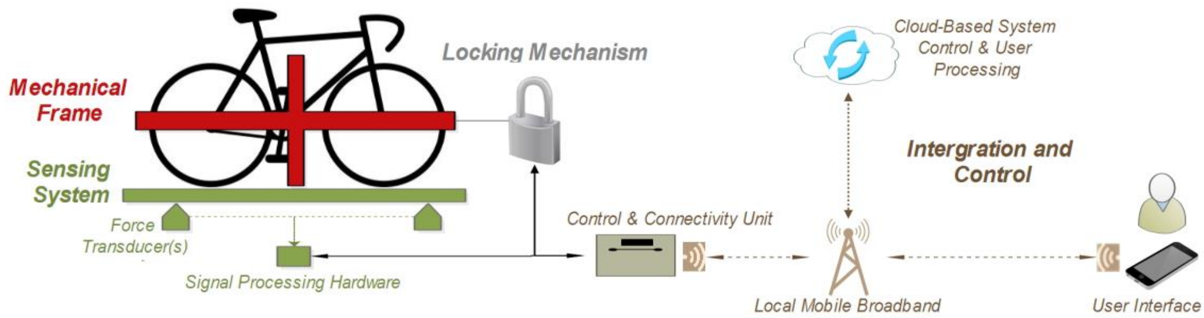


Figure 7: Conceptual Solution Illustration

The theft-protection of the bicycle is accounted for by the combination of solutions 1 & 2 - the mechanical frame and the sensing system. The mechanical frame provides physical resistance against any attempts of theft on the bicycle while it is locked. The bicycle parts accounted for by this system includes the bicycle's main frame, the front wheel and the rear wheel. These parts are physically secured. Physical theft-protection is only allocated to these three parts due to the high-protection priority of the parts, as learnt from the research activities. The sensing system serves as a supplementary theft-prevention system that covers the remainder of the bicycle's parts, as well as the mechanical frame. The sensing system force-bed consists of two force-transducers which converts any forces applied to the bicycle and force bed, into electric signals. The bicycle and the mechanical frame rests on the force bed, converting any disturbance on any of these two elements into electric signals that is monitored for potential theft. The electric signals generated are then processed by signal processing hardware which consists of hardware filters, amplifiers, analogue-to-digital converters and a processing unit – feeding the signal into the processing algorithm developed to detect attempts of theft.

The locking mechanism engages and disengages the physical theft-protection of the system once a bicycle is docked or undocked, securing the bicycle into the mechanical frame and enables system 1 and 2. The locking mechanism is controlled by the control and connectivity unit. The control and connectivity unit is responsible for receiving and administrating *lock & unlock* transactions from the cloud-platform, controlling the hardware involved in these transactions, and to also process any theft-detection notifications produced by the sensing system. Internet connectivity for communication to and from this unit is performed through a mobile broadband connection, enabled by the hardware included in the control and connectivity unit.

The system control, integration and user processing is performed by the system integration and control elements. User interaction is realised through the user interfacing platform that is executed on the user's mobile phone. Transaction information is sent to the system's cloud-based server, where the transaction is processed. The cloud-based server is responsible for processing the user transactions, handling the user registrations and payment, contains the user database, and corresponds communication from the different system elements. Once a user transaction has been approved, the corresponding command (the bicycle should be locked or unlocked) is directed to the appropriate docking station's control & connectivity unit, which administers the transaction accordingly.

5 Mechanical Frame

This section presents the development of the mechanical frame. The mechanical frame is responsible for physically securing the three top-priority bicycle components which includes the bicycle frame, front wheel and rear wheel. The development process followed in this chapter is guided by the general design specifications that is developed in Section 4.1.3, with the specifications derived for this solution presented here in Section 5.1. The concept on which the mechanical frame solution based is defined in the conceptual design in Section 5.2, while the embodiment of this solution is presented in the functional embodiment section. The resulting detailed design solution is presented in Section 5.3. Further improvement and validation activities were executed on the frame design during development, which are presented in Section 5.4.

5.1 Derived Product Design Specifications

The derived product design specifications provides the specific design criteria that the solution to be develop in this section, should adhere to. Table 8 presents these derived design specifications relevant to this solution, and also provides the design criteria that is implied by each requirement. The design specifications are derived and defined by drawing from the research activities conducted in Sections 2 and 3, as well as from the PDS defined in Section 4.1.3.

Table 8: Mechanical Frame Product Design Specifications

Product Design Specification	PDS #	Desired Outcome	Implied Design Criteria
Bicycle components to be physically secured	2.1	Secure the frame, rear wheel, and front wheel	*The frame's protection scope should include the listed components*
Prevent the utilisation of specific tools on the frame	2.2	Bolt cutter, hammer, and crowbar	*Increase the physical size of materials chosen to prevent bolt-cutter from fitting on to it, choose the materials' strength to withstand hammer blows, and prevent crowbar leverage. Do not use steel cables (easily cut)*
Provide physical resistance against a hacksaw	2.3	> 45 seconds	*Use materials with high cutting resistance*
Material cost	2.4	(minimum)	*Low-cost of materials used*
Dock footprint size	2.5	0.6 m^2	*Efficient space usage. Target relating to current on-street docking footprint sizes.*
Dock deployment	2.6	Ability to deploy solution as independent unit	*Units are designed individually, then joined together at installation*
Types of bicycles accommodated by frame	2.7	All frame types	*Relevant to solution fit*
Bicycle sizes to accommodate	2.8	24" – 29"	*Relevant to frame sizing and lock-up method. This includes the great majority of all urban commuting bicycles.*
Ground anchoring method	2.9	Fixed-permanent	*Use semi-permanent anchoring method to secure the dock to the ground*

Total bicycle lock-up duration	2.10	< 23 seconds	*Frame lock-up method. Related to time required to lock up a bicycle using a conventional cable lock.*

5.2 Conceptual Design

The conceptual design incorporates all aspect considered thus far, to provide a high-level design concept that meets the relevant design requirement. The design concept provided is then further developed into the detailed design by improving the operational principle of the locking mechanisms, choosing materials and defining the critical geometrical dimensions.

5.2.1 Functional Embodiment

The functional embodiment presents the frame's operational principle and geometry which the frame is based on. The proposed solution takes the form of a skeleton-like frame which uses two locking mechanism to secure the bicycle's critical components to the dock's frame. The functional principle by which the frame locks the bicycle's components, is derived from an insight that is drawn from a universal geometrical element present on all bicycle frames – the *rear triangle* of a bicycle. The rear triangle is created by the region bound in by the main frame's rear triangle and the rear wheel's rim. It is illustrated by the green area in Figure 8. The rear triangle should be present in a bicycle's frame to ensure the structural integrity of the frame. The majority of bicycle rely on a rear triangle, with only a few specialist-type bicycles using alternatives to the rear triangle in the frame's design. The presence of the rear tringle is a valuable insight used in this design, since it provides a feature that is universal, ensuring a design that will work for the majority of bicycles (PDS 2.7). A locking mechanism which utilises this feature is therefore chosen. The locking solution is thus a locking mechanism that swivel about a hinge, and locks the frame and rear wheel by inserting a pin through the rear triangle area. A pin placed through this area will lock the bicycle's frame and rear wheel – ensuring that 2 of the 3 required components are locked. A static locking mechanism based on the same pin-type principle is placed at the front wheel, to lock the front wheel to the frame and thereby ensuring all 3 components as secured (PDS 2.1). The operational principle is presented in Figure 8, illustrating the concept design and positioning of the locking mechanisms.

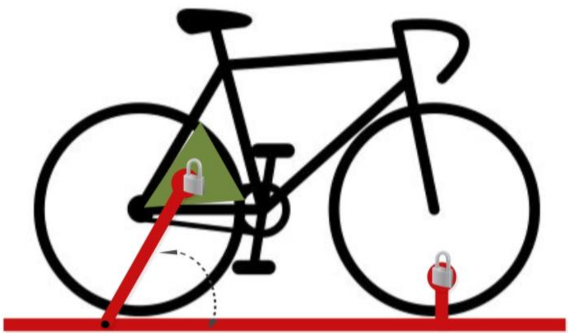


Figure 8: Frame Functional Embodiment

The materials used in the frame are chosen with PDS 2.2, 2.3 and 2.4 as priority. This implies using materials that are either too large to fit into a bolt cutter, are able to withstand hammer blows, can withstand the force executed by a crowbar, and which takes longer than 45 seconds to cut through with a hacksaw. Material cost should be low, parts easy to manufacture, and preferable sourced locally. The material used for the primary functionality and protection of the frame is therefore chosen as conventional square tubing that is too large to fit into a bolt-cutter (material's sectioned dimensions > 18x18mm), but with a minimum thickness of 3mm to improve its cutting resistance against a hacksaw. Also, the solid steel bars used for the locking mechanism are to be larger than diameter 14mm to increase the cutting resistance against a bolt cutter and hacksaw. The frame design should prevent the utilisation of a crowbar on any of its parts as far as possible. In the case that crowbar utilisation is possible on any part, the material chosen should be of adequate strength to prevent damaging the frame using a crowbar (PDS 2.2). Any additional materials (non-critical for protection) that contributes to frame functionality only needs to adhere to the remaining material cost requirement (PDS 2.4).

5.2.2 Dock Sizing

Bicycle geometry is complex, with various important variables such as frame angles, wheelbase, wheel trail, tube lengths and the frame type responsible for determining the precise geometry of a bicycle [33]. Determining dock dimensions that fits the required bicycle sizes and geometries (PDS 2.7 & 2.8) is a complex design step, yet it is of utmost importance in order to ensure that the dock will be able to fit all the required bicycles. Figure 9 illustrates the frame-skeleton various geometric variables that should be calculated in order to achieve this on the current concept. The purpose of the sizing calculations is to ensure that points L1 and L2 are positioned so that it always aligns with a bicycle's rear triangle and front wheel, respectively, in order to lock any bicycle when it is placed in the frame. The bicycle is inserted into the frame so that the front axis of the bicycle is positioned vertical with point L2. Dimension C1 can therefrom be determined as anything between 40mm (29" bicycle's maximum tyre & rim width) and 550mm (24" bicycle's maximum wheel height) to ensure the pin enters through the front wheel. Dimension C1 is chosen as 150mm.

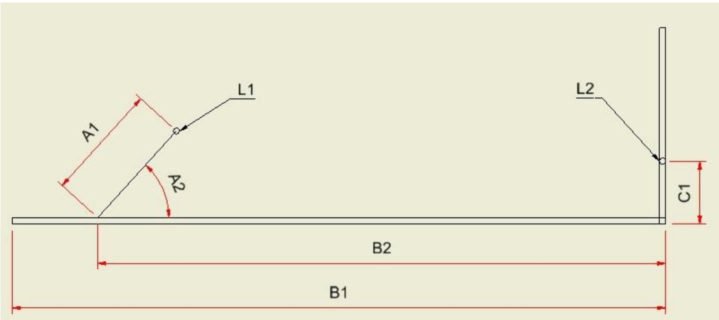


Figure 9: Frame Geometric Variables

5.2.2.1 Geometrical Variable Calculations

To calculate the remaining geometric variables, a diverse dataset of bicycles' geometric dimensions were used to solve the variables by means of iterative simulations. A broad range of bicycle types, sizes, frame designs and wheel sizes - including the upper and lower ends of each type – were included in the dataset. The bicycles used in the dataset are listed in Appendix F on page 104. The mechanical frame's unknown geometric variables are determined by finding a frame geometry that meets a potential rear-triangle lock placement requirement for every bicycle in the dataset.

The various potential rear-triangle lock placement positions for the bicycle frames included in the dataset, are calculated by using the respective frames' geometrical characteristics (frame size, frame type, wheel size, tyre size, frame angles, etc.). The results for these potential boundary condition lock-placement positions (x & y coordinates) are presented in Figure 10 below. The results are positioned on a coordinate system in mm.

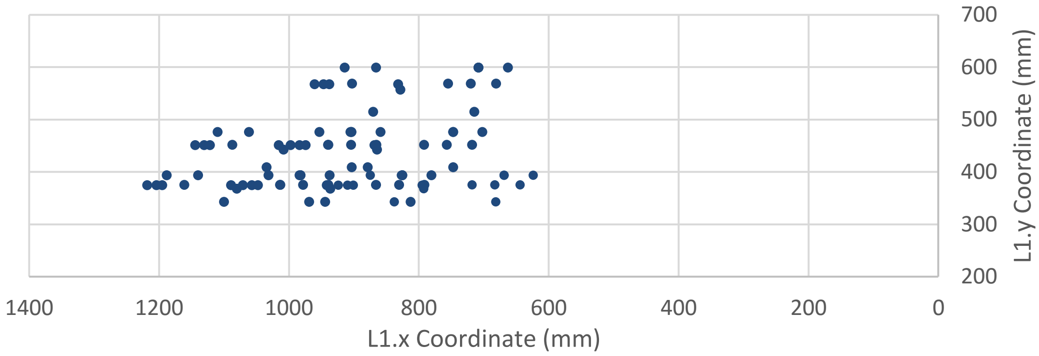


Figure 10: Rear Triangle Lock Placement Positions

To find a frame geometry that falls within the boundary conditions determined above, the conceptual frame-design is converted into a mathematical model that calculates the position of L1, as a function of the frame's various geometrical variables (B1, B2, A1, and A2). The mathematical model that represents the position of L1 ($L1_x$ & $L1_y$) is described by equations 5.1 and 5.2 below.

$$L1_x = B2 - \cos(A2) \times A1 \tag{5.1}$$

$$L1_y = sin(A2) \times A1 \tag{5.2}$$

The required geometric variables are then solved by finding a combination of values for B1, B2, A1, and A2 which produces the positioning of point $L1_{x(0-n),y(0-n)}$ able to meet at least one potential rear-triangle lock placements position for each bicycle frame in the dataset used. These values for the geometric variables are calculated by means of computed mathematical iterations. The resulting geometrical variables are presented in Table 9 below. The results obtained here are used in the detailed design.

Table 9: Resulting Geometric Variables

Geometrical Variables	Result
A.1	509 mm
A.2	0° - 90°
B.1	1250 mm
B.2	> 1320 mm

5.3 Detailed Design

The resulting detailed frame design for the mechanical frame is presented in Figure 11 below. On the left, the figure illustrates a vacant frame from the rear, as well as on the right, the resulting frame with a 26" bicycle docked in it. The materials used for the frame consists of: 50x50x3mm hardened steel square tubing for the three base bars of the frame, 38x38x2mm hardened steel square tubing for the two locking mechanisms' tubes, and Ø15mm medium-carbon steel rods that are places through the bicycle's frame and wheels (used in the locking mechanisms). The full list of material used in the dock is available in the BOM in Appendix P on page 126. The top-level detailed design drawings for the mechanical frame is presented in Appendix G on page 105.

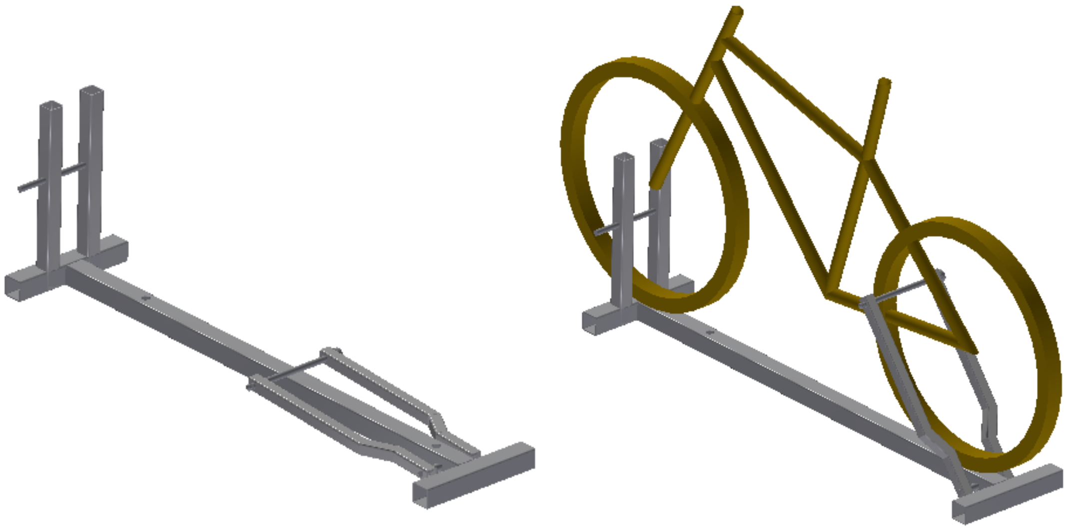


Figure 11: Detailed Frame Design

To insert the bicycle into the frame in order to lock it up, the locking mechanisms' rods are pulled out, and the bicycle pushed into the frame until the front wheel axis is above the front locking mechanism. The front rod is pushed through the front wheel into the opposite end of the frame, where after the rear locking mechanism is lifted up to a point where the lock-up rod aligns with the rear triangle, with the rod then pushed through the bicycle and wheel until it enters the opposite locking frame member. The actual locking of the rod within the frame member is addressed by the locking mechanism solution covered in Section 7. The frame's front and top views are illustrated in Figure 12 below. The embodiment dimensions of the frame is illustrated by these figures, with the length, width and height being 1395mm, 320mm and 450mm respectively.

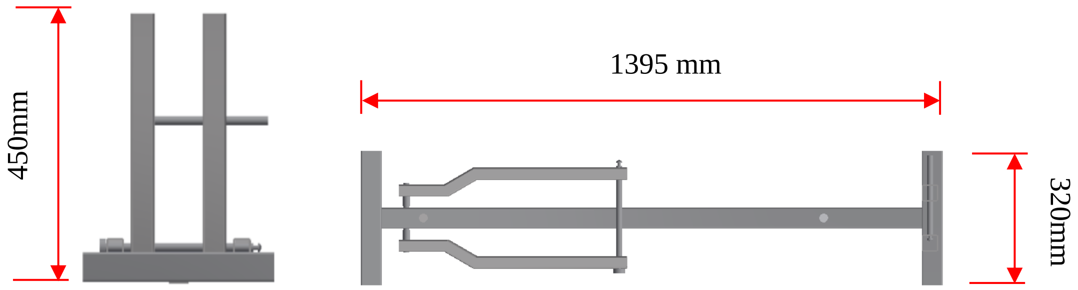


Figure 12: Boxed Dimensions

The front and rear locks in the *engaged*-state is illustrated in Figure 13.

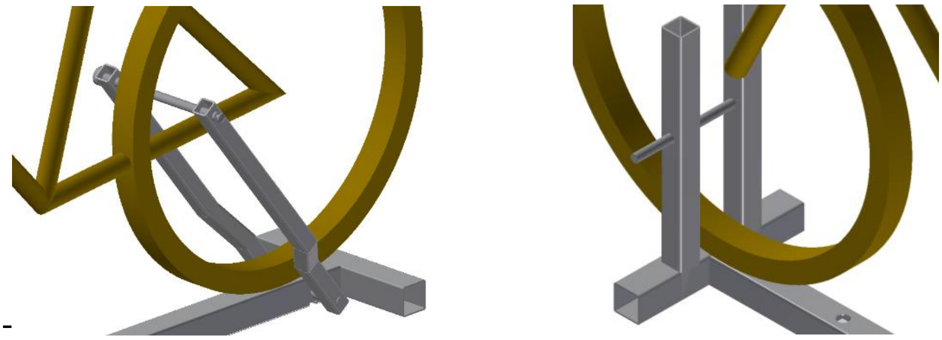


Figure 13: Engaged Front & Rear Locks

5.4 Frame Improvement

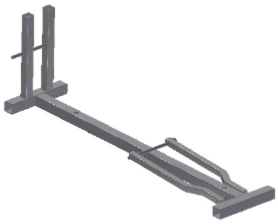
A series of activities were executed during the frame's development stage in order to improve and validate the final mechanical frame model. The procedures followed and results obtained during these activities are presented in this section.

5.4.1 Prototype Iterations

Throughout the frame design process, 10 different frame designs were developed and 5 physical prototypes created in order to test concepts and to get in-field feedback on design's development. Table 10 present some of the most significant frame designs and corresponding prototypes that was developed to improve the mechanical frame. The insights gained from the various frames which led to the design improvements, is also mentioned in the table below.

Table 10: Mechanical Frame Prototype Development

Design	Prototype	Insights & Improvements
		Basic proof-of-principle wooden prototype. **Insight(s)**: The frame's bicycle lock-up principle is validated.
		First steel structured proof-of-principle prototype. Rear wheel protected with locking mechanism arm. Front wheel protected by side plates restricting the removal of it. Saddle protection added. **Insight(s)**: Locking mechanism too difficult to operate. Too much material used in the production of the frame. The concept does show potential.

		Improvements in the form of a simplified base frame, and easier handling locking mechanism arm. **Insight(s)**: The wheel covers on the sides is removed, as it is found it does not prevent the wheels from being removed. The design is found to be very difficult to manufacture.
		Testing a different front wheel securing method. Frame design improved for easier manufacturability. **Insight(s)**: Front wheel locking mechanism not effective enough. The top seat protector is deemed ineffective, and not-required (by users).
		*Resulting design:* Front wheel secured with a locking mechanism. Seat protector removed. Simplified frame.

5.4.2 Usability Testing

To improve the usability of the solution, and to also validate the performance of the frame design as a multi-dock type implementation, a detailed design and prototype was developed to be used in a customer co-creation pilot test. The pilot test included four students from the University of Stellenbosch who actively make use of their bicycles for urban commuting, and normally lock their bicycles in conventional on-street bicycle lock-up frames. The users were enrolled in the pilot test, and used the prototype for a period of two weeks on a daily basis to lock up their bicycles – in order to compare the usability of the dock to their current methods of bicycle lock-up. The users were asked to comment on the general usability of the frame, as well as the perceived protection they have of the prototype. Due to the development of the locking mechanism still being in development at the time of the pilot, normal bicycle-lock heads were used as a replacement. Figure 14 presents the design of the multi-dock prototype that was developed for the pilot test.

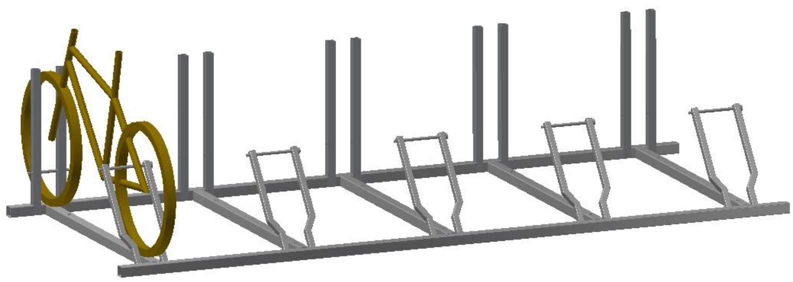


Figure 14: Multi-Frame Pilot Test Prototype CAD

The general feedback received from the pilot participants were very positive, with useful feedback and constructive criticism drawn from them. Users valued the fact that the solution provides much better protection for their bicycles (perceived protection), while simultaneously removing the burden of having to carry a large locking mechanism to acquire that level of protection. The usability feedback was also positive, with users easily able to understand the operational principle of the locking mechanisms used. An important problem that was identified is that the front locking rod posed a problem when docking the bicycle. A proposal is made that the rod should stay permanently in the open-position – implying that the user can insert their bicycle into the frame and therefrom lock the bicycle, rather than having to put their bicycle down and remove the rod first. The users also had a problem that the bicycles does not stay upright during docking. Additional rear-wheel support was thereafter added to support the bicycles in docking. The above mentioned issues contribute to the length of time required to dock a bicycle, which was also a strong point of critique by the users. The detailed user feedback that was received, is presented in Appendix H on page 108. Figure 15 below present the prototype that was used for the pilot test.

Figure 15: Multi-Frame Pilot Test

5.4.3 Force Validation Calculations

As stated in the functional embodiment of the frame design, the frame design should prevent the utilisation of a crowbar on any of its parts as far as possible, but in the case that crowbar utilisation is possible on any part, the material chosen should be of adequate strength to prevent damage using a crowbar. The frame design successfully prevents crowbar utilisation on the frame on all of the frame parts except at the rear locking mechanism's shaft. In order to ensure the shaft material chosen can adequately resist an attempted breach from a crowbar, force validation calculations are performed to determine the safety factor that the rear shaft provides against an applied crowbar force.

The steps to determine the safety factor for the rear shaft is as follows: (1) calculate the applied force and resulting moment on the shaft exerted by a crowbar, (2) determine the shaft's moment of inertia, (3) calculate the maximum resulting internal material stress, and (4) therefrom calculate the resulting safety factor. Figure 16 presents the diagram illustrating the various forces and distances relevant to the calculations. L_{shaft} represents the length of the shaft that sticks out of the mechanical frame body, and together with the force applied by the crowbar ($F_{crow\ bar}$), contributes to the internal moment ($M_{resulting}$) experienced by the shaft. Applying the crowbar force at the point illustrated in the diagram will maximise the distance of L_{shaft}, maximising the moment $M_{resulting}$, and thereby maximise the internal stress experienced by the shaft.

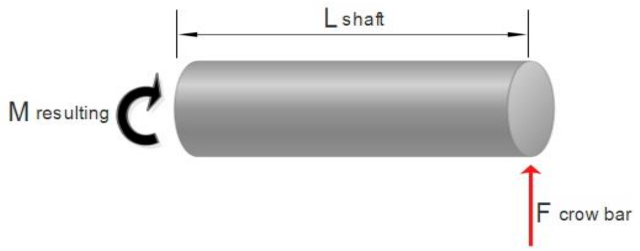


Figure 16: Shaft Stress Analysis Force Diagram

The force applied by the crowbar, $F_{crow\ bar}$, is based on the force producible using a 700mm crowbar with a hinge ratio of 7:1.5, and the maximum force application capacity of a human as 800N [34]. The length of the shaft exposed to the resulting moment is L_{shaft} = 50mm, with a shaft diameter of 30mm. This results in a crowbar force of $F_{crow\ bar}$ = 3,734 kN. The resulting moment experienced by the shaft is then calculated in equation 5.3 as,

$$M_{resulting} = L_{shaft} \times F_{crow\ bar} \quad (5.3.1)$$
$$M_{resulting} = 50mm \times 3\,743\ N \quad (5.3.2)$$
$$M_{resulting} = 187{,}15 \text{ N.m} \quad (5.3.3)$$

The shaft, being a filled circular area, has a moment of inertia as calculated by equation 5.4;

$$I_{shaft} = \frac{\pi}{4} \times r^4 \quad (5.4.1)$$
$$I_{shaft} = \frac{\pi}{4} \times 0{,}015^4 \quad (5.4.2)$$
$$I_{shaft} = 3{,}9761 \times 10^{-8} \quad (5.4.3)$$

The maximum resulting internal stress experienced by the shaft is calculated at the outer edges of the shaft, at distance Y = 0,015mm from the centre. The maximum stress experienced by the shaft is calculated according to equation 5.5;

$$\sigma_{max} = \frac{M_{resulting} \times Y}{I_{shaft}} \quad (5.5.1)$$
$$\sigma_{max} = \frac{187{,}15\ x\ 0{,}015}{3{,}9761 \times 10^{-8}} \quad (5.5.2)$$
$$\sigma_{max} = 70{,}6\ MPa \quad (5.5.3)$$

The yield stress σ_{yield} for the shaft (medium carbon steel) is found as 305 MPa [35]. The shaft's safety factor against yielding can thus be calculated by equation 5.6;

$$SF_{yield} = \frac{\sigma_{yield}}{\sigma_{max}} \quad (5.6.1)$$
$$SF_{yield} = \frac{305 \times 10^6}{70{,}6 \times 10^6} \quad (5.6.2)$$
$$SF_{yield} = 4{,}32 \cong 4 \quad (5.6.3)$$

From the above calculations, the shaft's safety factor against yielding caused by a crowbar is calculated as SF_{yield} = 4. This safety factor is high enough to verify the design as adequately protected against an attempted theft using a crowbar, and thereby successfully incorporating the corresponding part of PDS 2.4.

6 Sensing System

This section presents the development of the sensing system. The sensing system serves as a supplementary theft-prevention system that provides protection to the non-critical bicycle parts, as well as the mechanical frame, by detecting theft and therefrom initiating relevant alerts. The purpose of the system is to detect attempts of theft aimed at the bicycle or any of its parts, and therefrom initiate notification methods such as an audible alarm or mobile notifications that can assist in preventing or demotivating the detected theft.

The development process followed in this chapter is guided by the general design specifications that is developed in Section 4.1.3, with the design specifications derived for this specific solution presented here in Section 6.1. The detailed conceptual solution on which the solution is based, is presented in Section 6.2. The development of the hardware responsible for the signal capturing and processing is presented in Section 6.3, while development of the signal processing software is presented in Section 6.4. The implementation of the sensors as well as the verification of the resulting system's functionality is presented in Sections 6.5 and 6.6 respectively.

6.1 Derived Product Design Specifications

The derived product design specifications provides the design criteria to which the solution developed in this section, should adhere to. Table 11 presents the derived specifications relevant to this solution, and also provides the design criteria that is implied by each requirement. The design specifications are derived and defined by drawing from the research activities conducted in Sections 2 and 3, as well as from the PDS defined in Section 4.1.3.

Table 11: Sensing System Product Design Specifications

Product Design Specification	**PDS #**	**Desired Outcome**	**Implied Design Criteria**
Theft attempt types to detect	3.1	Sawing on locking mechanism, hacksaw on the frame, loosening of major bicycle components	*These are the types of methods used during an attempted theft which the sensor system should be able to detect.*
Disturbances to be ignored	3.2	Wind-induced movement, neighbouring bicycle docking events, accidental bumps to bicycle, general environmental noise	*These are the types of unintentional disturbances that can act on the bicycle, but which should be ignored by the sensors – and not cause a false-alarm to trigger*
Detection sensitivity adjustment	3.3	Be able to adjust the sensitivity of disturbance detection	*The system should be able to adjust its sensitivity in the case of environmental changes*
Limit measurement scope	3.4	Only measure actions & disturbances executed on the bicycle & mechanical frame	*Only actions applied to the bicycle and frame should be measured by the sensors*
System cost	3.5	(minimum)	*The total system cost*
False-negative rate	3.6	<15%	*The percentage of false-negatives produced by the system*
Detection duration	3.7	< 25 seconds	*The time required for the system to detect a true-positive*

False-positive rate	3.8	< 10%	*The percentage of false-positives produced by the system*

6.2 Conceptual Solution

The sensing systems' conceptual solution is based on both the product design specification defined in the previous section, as well as the overall system conceptual solution defined in Section 4.4.

The sensing solution acts as a supplementary means of protection for the mechanical frame presented in Section 5. The mechanical frame provides physical protection to the bicycle's critical components by physically securing the parts. In order for a thief to remove the bicycle or any part of the bicycle from the frame, physical interaction between the thief (or the tools used by the thief), and the bicycle, is required. The principle on which the sensing solution functions, is derived from Newton's 3rd Law of Motion, which states: "*For every action, there is an equal and opposite reaction"* [36]. The law implies that in any interaction between two bodies, there is a pair of equal (in magnitude) and opposite (in direction) forces acting on the two interacting objects. The conclusion drawn is therefore that in order to remove the bicycle or any part of it from the frame that protects it, a force will have to be applied to the bicycle or its frame, and therewith an opposite force will be applied by the bicycle on the object where the force originates from, as well as the frame that supports it. Figure 17 illustrates how the different elements involved in the solution utilises this insight to create the principle on which the concept is based.

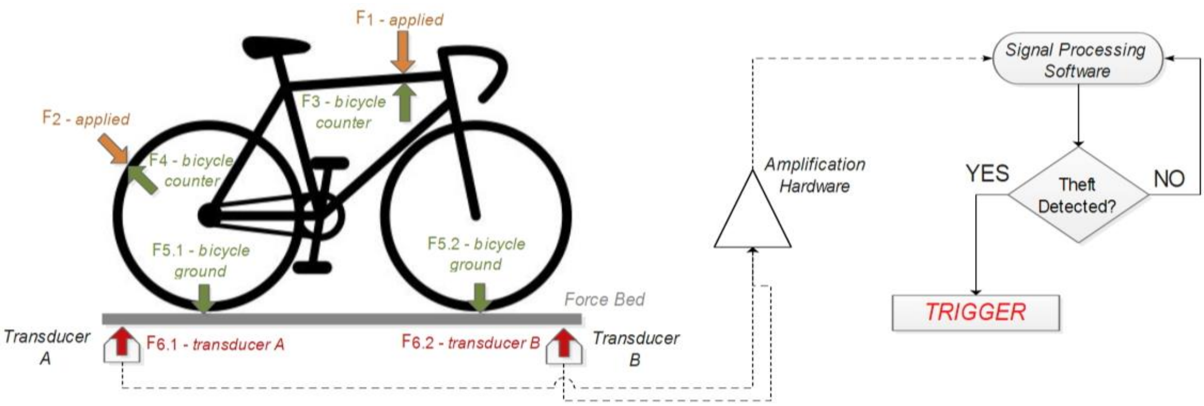


Figure 17: Sensing System Functional Concept

In Figure 17, forces F1 and F2 represents any force or combination of forces that are applied to the bicycle or components on the bicycle. These forces may be *intentional* (caused by an attempted theft) or *unintentional* (caused by a natural disturbance eg. wind or pedestrians bumping into the bicycle). According to Newton's 3rd law, these forces will be countered by the bicycle with equal and opposite forces – forces F3 and F4. Since the bicycle cannot accelerate in a vertical direction, the sum of the vertical components of forces F5.1 and F5.2 will be equal in magnitude to the sum of the vertical component of forces F3 and F4. Forces F5.1 and F5.2 acts on a force bed which the bicycle rests on, causing the two force-transducers that the force bed rests on to experience forces F6.1 and F6.2 – with the sum of forces F5.1 and F5.2 being equal in magnitude to the sum of forces F6.1 and F6.2 in a vertical direction. Forces F6.1 and F6.2 are therefore equal to the vertical components of any forces (F1 and F2 in this case) acting on the bicycle, and are converted to a corresponding electric signal that can be further processed. Since only the forces acting on the bicycle or frame are measured, the sensors' measurement scope is limited to the bicycle and frame – conforming to PDS 3.4.

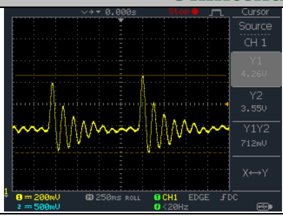
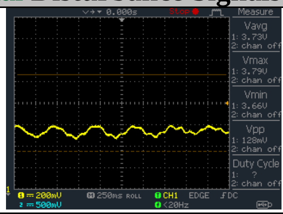
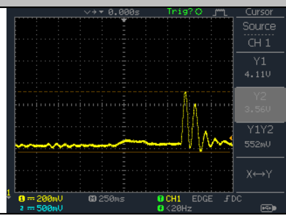
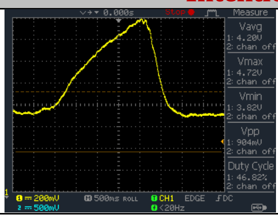
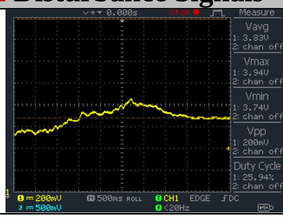
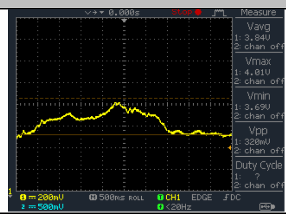
The electric signal produced by the transducers is amplified and converted to a time-discrete signal that can be interpreted by the software signal-processing part of the solution. The software processes the signal by applying the required filters and extracts certain characteristics from the signal. The signal characteristics are then analysed to determine whether the signal is deemed to be of an intentional or unintentional nature. A binary YES or NO is produced by the signal processing software if the signal is intentional or unintentional, respectively.

6.2.1 Technical Conceptual Validation

Due to the novelty of the proposed concept, a proof-of-principle experiment was required to first validate the critical assumptions of the concept's technical elements before the detailed design and development phases were engaged. The experiment also helped to gather data and therefrom gain insights into the design and development of the solution.

At the conceptual stage, the concept's success is dependent on two critical assumptions that are made; these are (1) that there is an adequate and capturable characteristics differences between intentional disturbances (steeling the bicycle) and unintentional disturbances (noise) executed on the bicycle, when the disturbances are converted into an electrical signal format, and (2) the converted signal that is received from the hardware is of high enough quality and resolution to allow for accurate identification and processing of the signal characteristics. An experimental bicycle docking setup was developed in an attempt to gather data. The experimental setup used stock load cells, a basic Wheatstone-Bridge, and an operational amplifier. The resulting signals were captured with an oscilloscope. Some of these unintentional and intentional signal traces, as well as certain extracted signal characteristics are presented below in Table 12.

Table 12: Oscilloscope-Captured Signal Traces

Unintentional Disturbance Signals			
Signal			
Signal Description	Disturbance: Impact to bicycle saddle from above (x2) Resolution: 712 mV Duration: 1 sec Frequency: 8.0 Hz	Disturbance: Wind causing bicycle oscillation Resolution: 145 mV Duration: n.a. Frequency: 2.0 Hz	Disturbance: Pedestrian walking into the bicycle's rear wheel Resolution: 552 mV Duration: 0.75 sec Frequency: 8.2 Hz
Intentional Disturbance Signals			
Signal			
Signal Description	Disturbance: Loosening a wheel nut	Disturbance: Loosening handle bars	Disturbance: Removing the saddle bolt

	Resolution: 900 mV Duration: 3.5 sec Frequency: none	Resolution: 380 mV Duration: 3.8 sec Frequency: none	Resolution: 280 mV Duration: 3.6 sec Frequency: none

The results obtained from the experiment validated the assumptions that there are clear and definable characteristics (amplitude, frequency, energy, duration, etc.) that can be used to distinguish the intentional and unintentional signals from one another. The signals are also of adequate amplitude to enable the signal processing process to accurately extract the characteristics from the signals produced. The insights gained from the experiment also show that the hardware used in the experiment is adequate, and can be incorporated into the detailed design of the solution. The resolution of the signal also provides as a guideline for the type of A/D converter and processing capacity that is required to extract the signal characteristics.

6.3 Hardware Design

The sensing system's hardware is responsible for transposing the forces experienced by the bicycle into a time-discrete signal that is processed by the signal-processing software. The hardware layout of the theft detection sensors is presented below in Figure 18.

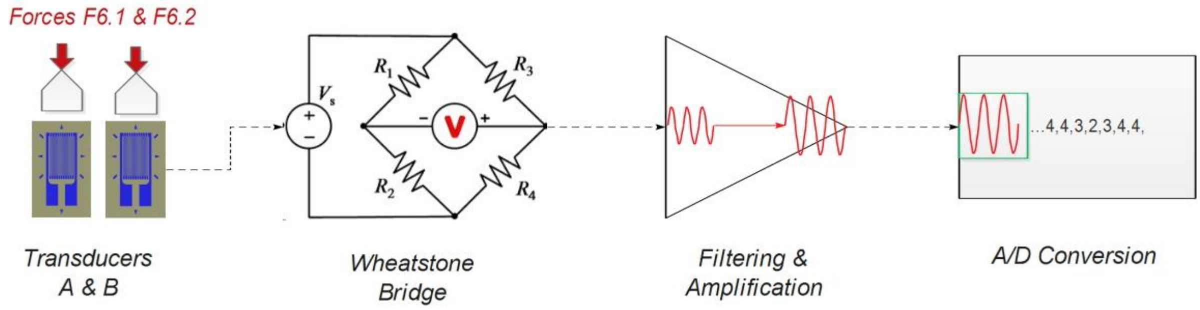


Figure 18: Layout of Sensing System Hardware

Figure 18 illustrates the four main phases that the hardware solution consists of. Starting from the left, the forces created by the force bed acts on the electro-mechanical force transducers that the bed rests on. The purpose of the force transducers are to serve as the first step in converting the mechanical force applied to it, into a corresponding electrical signal. It does so by first converting the applied force into mechanical deformation of a steel plate that the force is applied to. A strain gauge, which acts as a resistor, is attached to the metal plate and undergoes the same deformation as the plate. The change in resistance of the strain gauge as it deforms, is directly proportional to the force applied to the transducer. The Wheatstone bridge, which serves as the next phase, converts the change in resistance of the strain gauge to a change in electrical voltage. The strain gauges are placed in a balanced Wheatstone bridge, which receives an applied bridge voltage V_S, and produces an output voltage V that is proportional to the change in resistance of the strain gauges. The voltage V is very small, with a signal peak of approximately 60mV at the transducer's maximum applied-force capacity. The bridge output voltage is therefore filtered and amplified in the third phase, to a level of 0V (min) to 5V (maximum), in order to increase the signal resolution before the A/D conversion that follows. The final phase is the conversion of the resulting voltage signal into a digital format, using an analogue-to-digital convertor. The detailed design of the various hardware parts are further presented in this section.

6.3.1 Force Transducer Design

The purpose of the force transducer is to convert the mechanical forces originating from the force-bed, into a proportional change in resistance. In this transducer application, a bending-strain type strain gauge load cell is chosen. This allows for a robust and simple method of force conversion, with the bending-type load cell allowing higher resistor changes to be obtained by a smaller force, resulting in a higher measurement resolution at smaller applied forces. As a force is applied to the load cell, it bends the body and causes the body to elongate, resulting in a strain ϵ of

$$\epsilon = \frac{\Delta L}{L} \tag{6.1}$$

as presented in equation 6.1. L represents the original body length and ΔL the change in length. The magnitude of elongation experienced by the body is primarily dependent on the force applied to the body, and the body's material type. To accurately measure this strain, a strain gauge is fixed to the load cell's body, which experiences the same strain ϵ as that of the body at the point where the gauge is fixed. The relationship between a strain gauge's change in resistance and the strain experienced by the gauge, is illustrated by equation 6.2,

$$\epsilon = \frac{\Delta R/R}{GF} \tag{6.2}$$

with *GF* representing the 'gauge factor' of the specific strain gauge, *ΔR* representing the change in resistance of the gauge due to the strain experienced, and *R* representing the original resistor size. In this design scenario, the required design criteria for the transducer is to (1) maximise *ΔR* during strain measurement in order to reduce the required performance of the half-bridge and amplification circuit that follows, and (2) maximise the utilisation of the load cell's potential operational band (possible strain experienced).

From the above mentioned arguments and equation, it is derived that the main criteria that influences the magnitude of *ΔR* is the force that is applied, the load cell's body material type, the gauge factor (GF), and the strain gauge's static resistor magnitude. In order to ensure the load cell achieves design criteria no.1, a mild-carbon steel load cell body is chosen (which allows for easier elongation at lower applied forces), a strain gauge with a gauge factor of > 1.5, and a static gauge resistor size of >800Ω. To ensure that the load cell achieves criteria no.2, the load cell and strain gauge should be chosen such that all forces applied to the transducer should be measurable without reaching the transducer's rails. The force applied to the force bed is a component of the bicycle's weight, combined with any force applied to the bicycle during an attempted theft – with the maximum potential force experienced being the scenario where both these forces are at their potential maximum. For the bicycle, an assumed maximum bicycle weight of 187N (19kg) is used. For the maximum applied force during an attempted theft, the maximum biological force application capacity of a human, 800N [34], is used. These two components equate to a maximum applied force of

$$F_{applied,max} = 187\text{N} + 800\text{N} = 987\text{N} \cong (100\text{kg}) \tag{6.3}$$

The capacity required per transducer is therefore 50-60kg. For the resulting hardware design, a 1MΩ resistor, half-bridge strain gauge with a medium-carbon steel transducer body is chosen. This load cell that is used is presented below in Figure 19. The strain gauge consists of two 1MΩ resistors R_a and R_b, with R_a being active (reacting to strain and temperature change), and R_b being inactive (only reacting to temperature change). This allows the strain gauge to complete half of the bridge, while incorporating temperature compensation. The transducer has a 55kg rated force capacity, with a 150% overload capacity. The transducer body that the load cell is housed in is presented in Section 6.3.5.

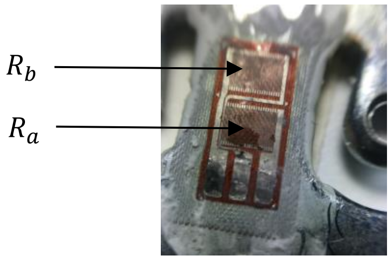


Figure 19: Half-Bridge Load Cell

6.3.2 Wheatstone Bridge Design

The Wheatstone bridge converts the change in resistance that is experienced by the strain gauges into a corresponding change in electric voltage. The change in resistance experienced by a strain gauge under maximum strain is normally in a region of <1% of the resting resistance value. The Wheatstone bridge allows for a very accurate measurement of the resistance change experienced, and translates it into a corresponding change in voltage that can be further processed. Figure 20 illustrates the conventional full-bridge Wheatstone bridge circuit, which is used in this design.

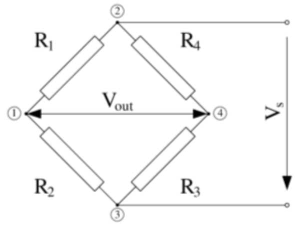


Figure 20: Full Bridge Configuration Schematic

The Wheatstone bridge consists of two series-parallel arrangements of resistance connected between a voltage supply V_s and ground, producing zero voltage difference between the parallel branches as long as the parallel branches are balanced (resistances stay equal in magnitude). If one resistor changes in magnitude, the bridge becomes unbalanced and a voltage difference V_{out} is created, that correlates to the change in resistance. The voltage difference V_{out}, produced in this specific full-bridge is expressed by equation 6.4:

$$V_{out} = \frac{1}{4}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right) \times V_s \tag{6.4}$$

The load cell's active strain gauge resistors (R_a) are placed in positions R_1 and R_3 of the Wheatstone bridge, while the inactive strain gauges (R_b) are placed in positions R_2 and R_4. This allows all applied strains to be measured by accumulating the outputs from the different transducers ("+" terms of ΔR_1 and ΔR_3), while any temperature effects that could lead to inaccurate measurements are cancelled out by the "-" term of the inactive gauges ($-\Delta R_2$ and $-\Delta R_4$). The final circuit design for the Wheatstone bridge as incorporated with the half-bridge strain gauges, is presented in Figure 21 below.

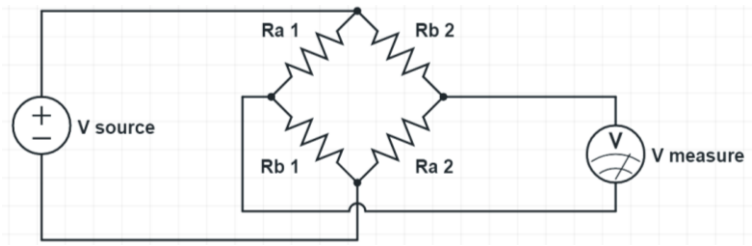


Figure 21: Wheatstone Bridge Circuit Design Schematic

6.3.3 Amplification Circuit Design

The voltage signal produced by the Wheatstone Bridge when maximum strain is applied, is of a magnitude ranging between 0 to 45 mV. In order for the A/D converter to have adequate resolution when measuring the signal, the output signal produced by the Wheatstone Bridge must be amplified to occupy a range of 0 to 5V. This is achieved by means of an operational amplifier circuit. The amplifier circuit requires a minimum gain of G = 120 to achieve this amplification. Since signal sampling occurs at high frequencies, the amplification circuit should have a response time allowing undisturbed signal amplification at up to 100Hz, while allowing unaffected gain at the same frequency.

The *INA125P Instrumentation Amplifier* is chosen as operational amplifier that meets the required design criteria. The circuit design for the operational amplifier as integrated with the Wheatstone bridge and A/D converter, is presented below in Figure 22.

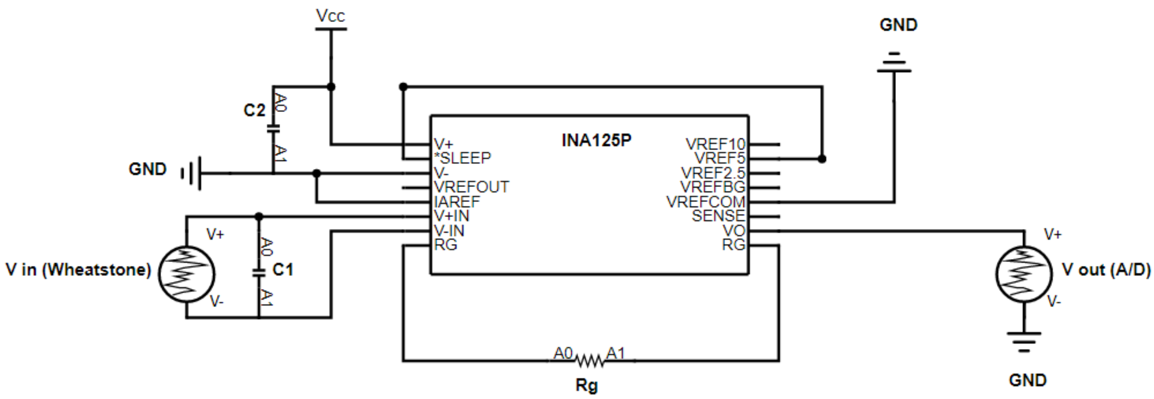


Figure 22: Amplifier Circuit Design Schematic

The gain resistor R_g is given a value of 470Ω, producing an amplifier gain of G = 131. The circuit receives as input the signal produced by the Wheatstone Bridge ($V_{in-Wheatstone}$), amplifies the signal, and produces an output ($V_{out-A/D}$) that is read by the A/D converter. Two capacitors, C1 (7μF) and C2 (1μF) are inserted to eliminate high-frequency noise prior to amplification.

6.3.4 A/D Conversion

The analogue to digital (A/D) conversion of the voltage signal produced by the amplifier circuit is performed by the A/D converter on the *Arduino Mega* – which is used for the system integration and control hardware (Section 8). The *Arduino Mega* contains a 10-bit A/D converter that maps input voltages between 0 and 5 volt, translating readings into integer values between 0 and 1023. This transposes the voltage signal into a time-discrete signal that can be read and processes by the signal-processing software that is housed on the *Arduino Mega*. The *Arduino Mega* in combination with the A/D converter allows for an adequate maximum sampling frequency of 10kHz.

6.3.5 Force-Bed Hardware

The force-bed hardware components are essential to enable the physical integration of the theft detection concept with the dock's mechanical frame. The functional concepts of the force bed consists of the force-bed base that the bicycle rests on, the load cell housing that captures force from the force-bed and directs it to the load cell, and frame fittings to fix the base and housings to the frame.

The final assembly of the force-bed as it is installed in the frame, is presented below in Figure 23. The aluminium base (grey) that is supported by two pins is seen as they rest on the two transducer housings (orange). Below the transducer housings are brackets that enables fixing the housings to the mechanical frame.

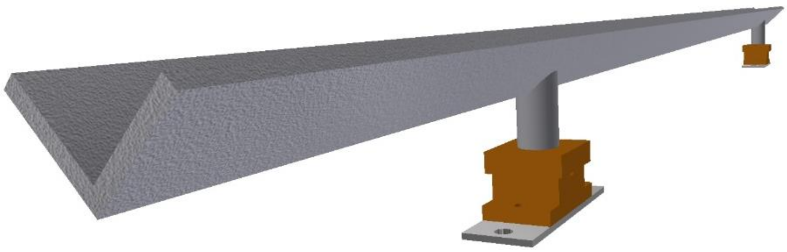


Figure 23: Force-Bed Assembly

The force-bed base consists of a 6mm thick aluminium *angle-iron* with a length of 1350mm, resting on two Ø18mm pins. The base is triangle shaped, with the lead angle pointing downwards to ensure that the bicycle wheels stay in the middle of the force-bed, in order to direct all force directly down into the pins and into the load cells. Aluminium is chosen to keep the platform as light as possible. The load cell housing channels all forces that are executed through the force-bed pins, into the load cell, and hereby into the strain gauge within the respective housing. Figure 24 presents a realistic (left) and clear (right) CAD model of the housing with the load cell inserted.

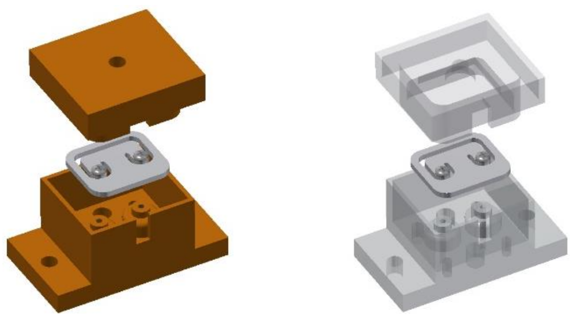


Figure 24: Transducer Housing Design

The housing consists of a base and a crown, with the load cell encapsulated in the middle. The load cell's inner body rests on the housing's base, with the base being fixed to the main mechanical frame. The force-bed's pins rests on the housing's crown, with the crown of the housing resting on the load cell's outer body – thereby directing all forces going through the pins into the load cell. The strain gauge is situated between the load cell's inner and outer body, which is where the bending occurs. The housing's parts are 3D printed. The final parts are presented in Figure 25 below.

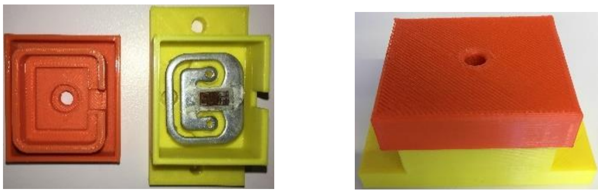


Figure 25: Transducer Housing Printed Parts

6.4 Signal Processing

In order to develop the software solution responsible for the signal processing, the signals relating to the various disturbances are first understood and analysed to gain insights into the performance and characteristics of the different signal cases.

6.4.1 Data Capturing

The objective of the data capture activities is to capture a range of data that is as-representative as possible of the infinitely possible cases of signals that can be created – and therefrom identify constant characteristics that can serve as the foundations of the signal processing solution, and would thereby provide a universal solution that can apply to any signal to be analysed during operation. Product Design Specifications 3.1 and 3.2, which specify the types of disturbances the system should be able to differentiate between, served as the primary guideline as to which data is captured. Additional data was also included in capture activities to allow for a more universal solution. Table 13 below presents the different signal types that was captured. The signals were captured in various environments, being as close to the natural environment as possible. Seven volunteers partook in generating the disturbances that involve human intervention.

Table 13: Breakdown of In-Field Signal Data Captured

Intentional Signals	Loosening and removal of the *front wheel*
	Loosening and removal of the *rear wheel*
	Loosening and removal of the *handlebars*
	Loosening and removal of the *saddle*
	Removal of the *saddle bag*
	Removal of the *bicycle pump*
	Loosening and removal of a *pedal*
	Loosening of the bicycle *brakes*
	Loosening and removal of the *water bottle holder*
	Hammer blows on the dock – with the intention of braking the locking mechanism
	Hacksaw on dock front frame intending to weaken the locking mechanism
	Hacksaw on dock base frame intending to weaken the locking mechanism
Unintentional Signals	60 min idle - capturing *environmental noise*
	Effects on dock created by *neighbouring bicycles* docking/undocking
	Pedestrians bumping into frame / bicycle
	Oscillations generated by *wind* (*physically simulated)
	Bicycle *shifting* in dock

The hardware developed in Section 6.3 is used in the experimental data-capture setup to generate and record the signals. An experimental setup is built that allows the signals to be captured by writing it to an SD card, with the setup relying on battery power. The signals are captured with the *Arduino MEGA* A/D converter, and is sampled at a rate of 42 Hz. The battery and SD card functionality allowed the setup to be implemented in different environments, being able to capture data for extended durations within a natural environment without human intervention. Figure 26 illustrates an example of an in-field unintentional (60min idle) signal capturing experiment.

Figure 26: Unintentional Data-Capture Setup

The signal data is recorded as a time discrete signal in text-format. The signals are then imported and processed in the *MATLAB Signal Processing Toolbox*.

6.4.2 Resulting Data

The resulting raw data that was captured, as well as the results of the data processing that is to follow in this chapter, can be found at the following online directory:
http://staff.ee.sun.ac.za/mjbooysen/BicycleDock/
Some of the signals that was captured and processed is illustrated in Appendix I on page 110.

6.4.3 Characteristics Utilised & Software Functions

Through processing, inspection and experimentation of the captured data, certain characteristics were identified which are utilised in functions that are present in the signal processing algorithm. These characteristics identified are ones that pose potential to provide valuable insights from any signal being analysed, such that the insights extracted from that characteristic are of valuable contribution towards the aim of classifying the signal as either *intentional* or *unintentional* of nature. The insights are either directly extracted from the signal characteristics measured, or extracted after the signal is processed in some manner. The different characteristics that are used to provide insights, and the utilisation of these insights are summarised in Table 14 below. These characteristics and their utilisations within the various algorithm functions are further discussed throughout this section.

Table 14: Signal Characteristics Utilised for Signal Processing

Characteristic / Process	Fundamental Insight	Utilisation
Signal Steady Check	The signal clearly deviates from states of *activity* and *rest* as disturbances are experienced and again dies out	Use the states of *active* and *rest* to execute different signal processing activities

Signal Noise Level	Certain types of intentional disturbances produce high-magnitude noise levels that are not found in any unintentional disturbances	Differentiate high-noise signals as intentional
Amplitude Integral	There exists an observable difference between the integral of the signal amplitude (i.e. energy) of intentional and unintentional signals	Measure the amplitude integral and use as basis for differentiation
Rolling-Average Filter	The *rolling average filter* creates a smoother signal that still follows the raw signal-profile closely	Process signals in this manner to extract certain signal characteristics
Median Filter	A median filter applied to the raw signal removes any impulsive noise and spikes, while preserving the signal edges and raw signal-profile	Use to extract raw signal profile, used for extracting certain signal characteristics
Signal Active Duration	There exists an observable difference between the duration of activity of intentional and unintentional signals	Use the duration that a signal is active as a factor of differentiation

6.4.3.1 Signal Steady Check

Signals vary between states of *rest* and *activity*, as brought forth by disturbances that come and go. With no disturbance acting on the bicycle or the dock, the signal is in a state of rest (i.e. the current signal value measured = rest datum value ± 2 *A/D units*). In the case of a disturbance starting to act on the measured environment, the signal changes from its state of *rest* into a state of *active* (signal value measured ≠ rest datum value ± 2). After the disturbances' acting out, the signal returns to a state of *rest* again. The signal *steadyCheck()* function constantly monitors the *rolling average signal* (Section 6.4.3.4) to determine whether the signal is in a state of *rest* or a state of *activity*. It does so by comparing the current signal value D_x to a historical signal value D_{x-2}, to determine if the current signal value has moved 2 or more units above or below a prior datum value.

This function makes a contribution to the signal processing in the following two ways; it (1) captures specific signal properties (*signal timestamp*, *signal amplitude value*) at the moment the signal transitions from *rest* to *active* and back, and (2) clears any cumulative measured variables while the signal is in a state of rest. By capturing the *signal timestamp* when the signal transitioned to *active*, the duration that the signal remains active can be measured – calculating an important characteristic to be discussed later in the section (6.4.3.6). By measuring the *signal amplitude value*, the signal amplitude can be measured at any future stage – again calculating an important characteristic to be discussed later in this section (6.4.3.3).

6.4.3.2 Signal High Frequency Content

Destructive intentional disturbance produced by a hammer and a hacksaw, have much higher levels of high frequency signal content, as compared to any unintentional signal. Therefore, an effective way of identifying these types of *destructive intentional disturbance* signals is to measure the high frequency content in any given signal. The *signalNoiseDetect()* function is developed to calculates the level of high frequency content in a signal, by measuring the difference between the raw signal and the median-filtered signals' (Section 6.4.3.5) values. A new signal is created as output that represents the absolute value of this difference calculated. Figure 27 illustrates the raw signal (top, blue) of a hacksaw on the dock frame, and the respective extracted noise signal (bottom, red). A window size of 50 values (100ms time frame @ 50Hz sampling) are then averaged with a rolling average filter, to produce a resulting high frequency measurement.

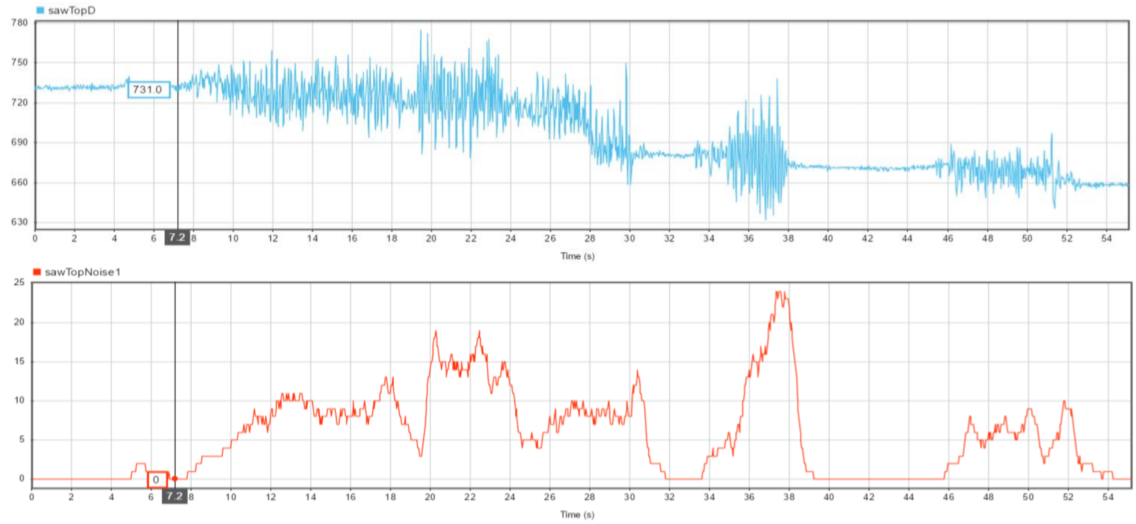


Figure 27: High Frequency Output of a Signal

When measuring the high frequency content of the captured data, signals of *destructive intentional disturbances* were observed to maintain a high frequency level of minimum 3 units, for a minimum of 0.3 second per event. Thus, the threshold to have a signal classified as intentional on the basis of high frequency content requires a 3 unit level to be measured for a duration of 0.25 seconds.

6.4.3.3 Amplitude Integral

A major difference identified between *intentional* and *unintentional* signals are the magnitude of the area below the graph (signal integral/energy) over a period of time larger than 300 milliseconds (the natural frequency of the system is experimentally determined to be between 6-8Hz, with the difference only significant after two periods completed). As *unintentional* signals are mainly a result of impulsive forces or forces that do not act on the measured environment for longer than 500 milliseconds, the forces are damped out by the natural damping present in the system, producing a fixed-frequency oscillating signal as a result. Since an oscillating signal's consecutive peaks and troughs cancel each other out when the integral is taken over a duration larger than the one period, *unintentional* signals have an integral value $\cong 0$ per period. *Intentional* signals result from forces that are applied for durations significantly large than the impulsive forces relating to *unintentional* forces, also with higher magnitude forces causing bigger amplitude values. These two factors result in the integral value of *intentional* signals accumulating to bigger values in a shorter period of time.

The implementation of this insight is by the function *signAmpCalc()*, combined with the accumulation of the calculated amplitude delivered by *signAmpCalc()*. The function *signAmpCalc()* takes as inputs the current median filtered amplitude value, and the signal's datum amplitude, in order to calculate the current signal amplitude as measured relative to the datum amplitude captured when the signal exited the state of *rest*. The median filtered signal is used to calculate the amplitude, with the aim of preventing noise and impulse forces from affecting the amplitude measurement which is aimed at the low frequency constant forces (captured by the signal profile). The absolute value of the calculated signal amplitude is repeatedly added to the accumulated value while the signal is in the *active* state. Figure 28 below illustrates the median filtered signal (blue) of an event where the handle bars are being removed from the bicycle (*intentional* signal), and the resulting accumulated amplitude value (orange). The datum amplitude, and calculated amplitude for the instance of 42 seconds is also illustrated.

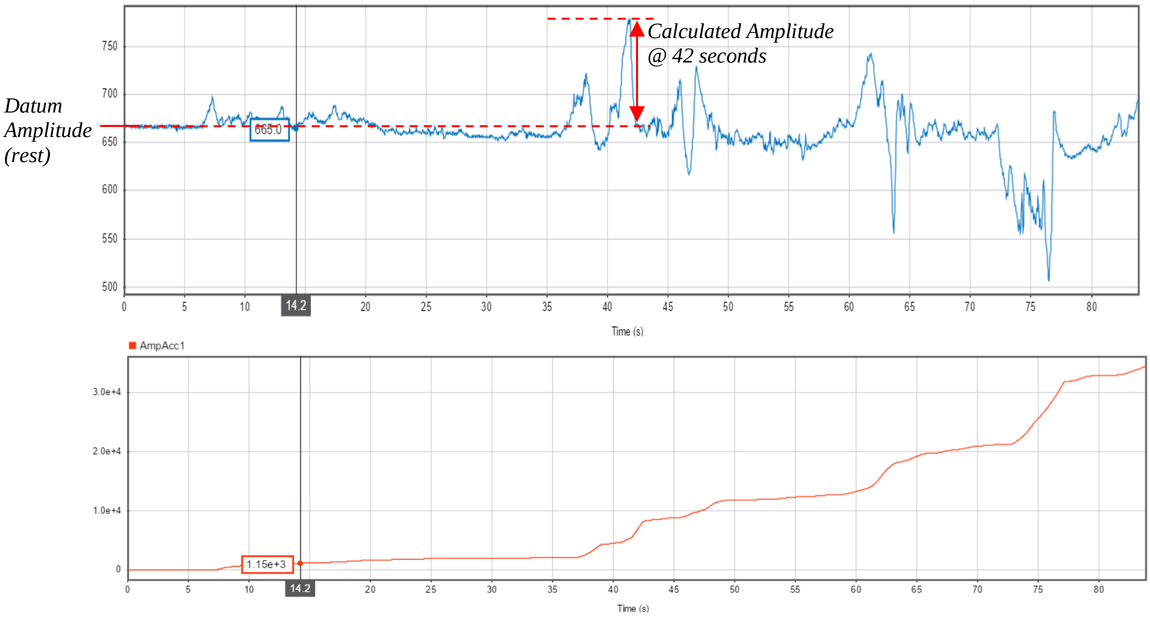


Figure 28: Signal Integral Accumulation

The amplitude that is calculated at every measurement cycle is added to the accumulated value which is again cleared when the signals transitions from *active* into *rest*. To classify the signal as intentional or unintentional by the processing software, the accumulated value is constantly compared to the threshold *signalAmplAccThreshold*. Once the accumulated value passes the threshold magnitude, the signal is classified as *intentional*. The threshold *signalAmplAccThreshold* is chosen by calculating the cumulative thresholds of all recorded data, and finding a threshold that is not reached by any unintentional signal, but reached within 10 seconds (PDS 3.7) by 75% of the intentional signals' thresholds. Table 15 shows an example of the accumulation values relating to a signal's active duration. By analysing all the available signal data and adhering to the above mentioned requirements, the value for *signalAmplAccThreshold* is calculated as 375.

Table 15: Amplitude Accumulation Table

Accumulated Value	Time Passed (seconds)
0	0
100	0.3
300	0.8
800	2.5
1200	7.7
1420	10
4000	31
6000	35.3

6.4.3.4 Rolling Average Filter

The *rollingAverageFilter()* removes low-intensity signal spikes and noise that is created by the A/D converter and amplification hardware, to create a smoother signal that still follows the raw signal-profile closely. The *rolling average filter* is used when monitoring the signal during periods of rest or low activity, which is a state when low-magnitude noise can have a big effect on signal analysis due to the low-magnitude signal activity.

A rolling average of the signal is created by applying a *rolling average software filter* to the raw signal. The rolling average filter uses $n = 4$ (filter constant n is determined experimentally) consecutive data points as input, and returns the average of all these data points as the new signal value at that timestamp. Equation 6.5 illustrates how the filter's sliding window constantly calculates the new signal value at the current data point D_n, by accumulating all data points in the current window and dividing it by a window size equal to n:

$$RollAvg_n = \frac{D_n + D_{n-1} + D_{n-2} + D_{n-3}}{n} \tag{6.5}$$

6.4.3.5 Median Filter

The *intentional* signals that are captured are a result of (1) the primary forces and disturbances that manifest in the recorded signal as the main signal profile, and (2) secondary forces and disturbances that result from the system's natural properties (damping, resonating frequency) and electronic hardware noise, with these manifesting in the recorded signal in the form of impulsive and smaller high-frequency noise elements added to the primary signal-profile. A median filter is applied to remove any secondary impulsive noise and spikes from the raw signal, while preserving the signal edges and raw signal-profile. The resulting *median-filtered signal* serves as a noise-free reference signal by which the raw signal is measured against when determining the raw signal's noise levels and impulse amplitude. The filter functions by using a sliding window size of n = 30 that takes into account the current data point, the previous 15 data points, and the next 14 data points - and returns as output the median value amongst all data points taken into account for the window. All data points taken into account are sorted from low to high, and the middle value (median) is returned as the filter output value. The median filter output (red) that is applied to the raw signal (blue) of a saddle bag being removed, is presented below in Figure 29.

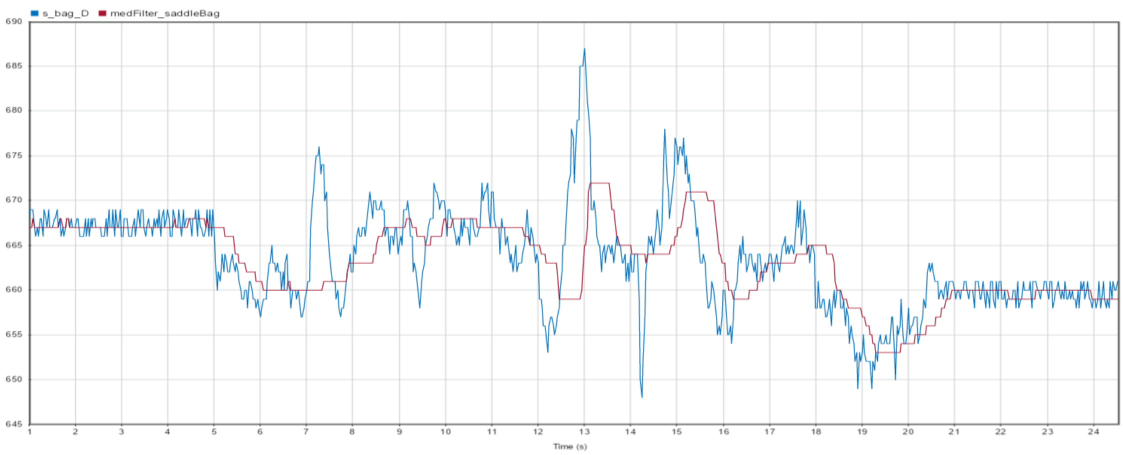


Figure 29: Application of the Median Filter

6.4.3.6 Signal Active Duration

The duration that an *intentional* signal is in the *active* state differs in the majority of cases from the duration that *unintentional* signals are in the *active* state – by a magnitude that is adequate to base signal differentiation on. For *unintentional* signals, the peak of the signal activity mostly falls in a duration of <0.6 second. For *intentional* signals, the majority of signal activity occupy a duration of >1 seconds – with the exception of hammer blows, which are short and impulsive disturbances. This characteristic identified is of a strong nature, and were true for the majority of the cases in the captured data - yet exceptions does exist, making this characteristic unreliable to fully differentiate all signals on.

The utilisation of this characteristic within the software implementation is therefore to combine this characteristic with the accumulation of a signal's amplitude. The implementation is thus that the calculated amplitude integral (Section 6.4.3.3) of a signal is only considered after 0.6 seconds (85% safety factor on the 1 second maximum of *unintentional* signal duration captured) of the signal being in the *active* state. The purpose of this implementation is to eliminate potential false-positives from impulsive *unintentional* disturbances by not taking them into account for signal processing, thereby adding to the overall accuracy of the system.

6.5 Signal Processing Implementation

The signal processing software program presented in this section is responsible for the integration of the signal processing activities. The program draws from the various characteristics and signal processing functions presented in Section 6.4.3 to analyse the signal that are produced by the amplification hardware (Section 6.3), in order to create a software solution that is capable of differentiating between intentional and unintentional signals. As output it produces a binary TRUE in the case that any *intentional* signal is detected.

6.5.1 Hardware

The signal processing software is executed on the Arduino MEGA 2560, in the form of C/C++ programing language. This same Arduino is also used for the signal A/D conversion and system management hardware (Section 8). The Arduino consists of an ATmega2560 microcontroller with a 16MHz clock, providing a potential sampling frequency much higher than the 200 Hz frequency that the experimental data was captured at, and signals are required to be processed at.

6.5.2 Software Program

The signal processing software program consists of three activity classes; *sampling*, *calculating* and *comparison*. The execution of these activities occurs repetitively and in a sequentially order, and the initiation of the first activity occurs at a constant frequency. Figure 30 illustrates the execution of the various activities involved.

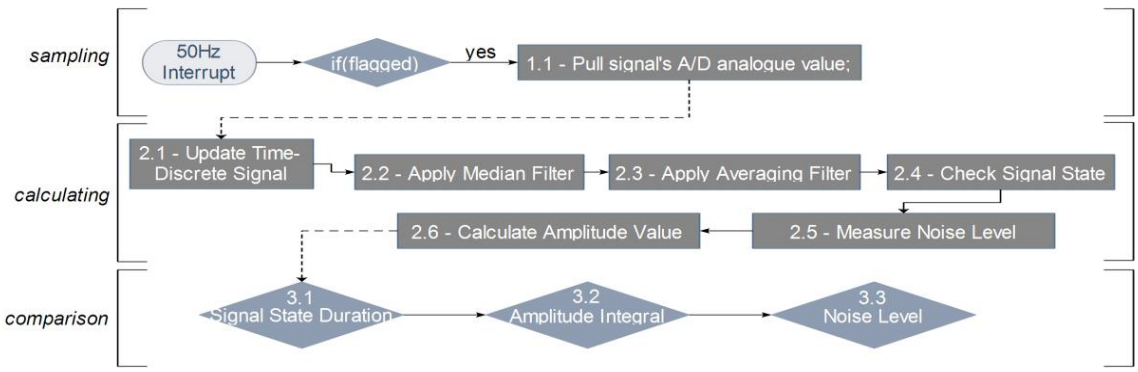


Figure 30: Signal Processing Program Flow

The first *sampling* activity is triggered by a set-frequency interrupt, and is aimed at obtaining the latest signal value (1.1). The newly read value is then used by the *calculating* activities to first update the time-discrete signal (2.1), and therefrom calculate the latest signal characteristics (2.2 – 2.6). During *comparison* that follows, the calculated characteristics are measured against the predefined thresholds (3.1 – 3.3) to determine whether the characteristics have developed to that of a potentially *intentional* signal. The three activity classes and functions related to them, are further discussed in this section. The source code relating to the various characteristic extraction functions mentioned in this section, can be found in Appendix J on page 112. The source code for the signal processing program can be found in Appendix K on page 114.

6.5.2.1 Sampling

The *sampling* activity entails obtaining the input signal's analogue value at a constant frequency, in order for it to be processed the remaining signal processing activities. Table 16 provides an overview of the function involved during the sampling activity.

Table 16: Sampling Function Overview

1. Sampling	
Function 1.1	**Pull Signal Value**
Function Prototype	`void pullSignal()`
Code Reference	Appendix K, page 114
Notable Variables	int signalValue – *global variable that stores the analogue value of the signal* int pullSignalFlag – *global flag variable, flagged after successful read*
Dependency	Initiated by *Timer1* @ 50 Hz

Function 1.1, `pullSignal()`, uses the `analogRead()` function to obtain the analogue value of the A/D pin which receives the transducer sensors' signal as input. The value is stored in the global variable *signalValue*. The *signalValue* variable is used by the *calculating* and *comparison* functions. The `pullSignal()` function is initiated by the interrupt timer *Timer1* with an interrupt period of 20 milliseconds, leading to a signal sampling frequency of 50 Hz.

The sampling frequency of 50 Hz is chosen as it allows adequate execution time for the *sampling*, *calculating* and *comparison* activities. The execution time of all activities are measured as ≅ 15 milliseconds (67 Hz). A sampling frequency of 50 Hz is still faster than the sampling frequency at which the experimental data was captured, thereby ensuring that the signal resolution is not lost due to the sampling frequency chosen.

6.5.2.2 Calculating

The *calculating* and *comparison* activities are both administered by the `analysisControl()` function, which is called when the `pullSignal` (1.1) function completes execution. The *calculating* activities starts by drawing the most recent value of *signalValue* and updates a buffer which stores the time-discrete values x_0 to x_{-15}. It then applies various processing and manipulation activities to the signal in order to extract the characteristics required for the *comparison* activities. Table 17 provides an overview of the functions involved during the *calculating* activity.

Table 17: Calculating Functions Overview

2. Calculating	
Function 2.1	**Sort Time-Discrete Buffer**
Function Prototype	No prototype, executed within `analysisControl()`
Code Reference	Appendix K - page 114
Notable Variables	sensValIn – *Most recent time discrete value, as received by the function* sNValx - *Stores previous signal analogue values* ST_FIilt_min0 – *Stores previous rolling averaging filter values* MED_Filt_min0 - *Stores previous median filter values*
Description	Updates the time-discrete signal variables, stores the 15 most recent values, stores certain calculated characteristics' values.
Function 2.2	**Median Filter**
Function Prototype	`int insertionSort(int sigValIn)`
Code Reference	Section 6.4.3.5 & Appendix I - page 110
Notable Variables	sigValIn – *The most recent signal analogue value sent to the function*
Description	The filter applies an averaging filter to the raw time-discrete signal. The operating principle is explained in Section 6.4.3.5.
Function 2.3	**Rolling Average Filter**
Function Prototype	`long ST_Signal_Filter(long SigVal)`
Code Reference	Section 6.4.3.4 & Appendix I - page 110
Notable Variables	SigVal - *The signal's analogue value sent to the function. Note, signal value* x_{-12} *is used in order to accommodate for the median function's lag*
Description	Removes low-intensity signal spikes and noise, creating a smoother signal that still follows the raw signal-profile closely. The operating principle is explained in Section 6.4.3.4.
Function 2.4	**Signal Steady Check**
Function Prototype	`int steadyCheck(int ST_Filt_In_min1, int ST_Filt_In_min0)`
Code Reference	Section 6.4.3.1 & Appendix I - page 110
Notable Variables	ST_Filt_In_min1 & ST_Filt_In_min0 – *Two consecutive values of the averaging filter is used by the function*
Description	Constantly monitors the *rolling average signal* to determine whether the signal is in a state of *rest* or of *activity*. It is achieved by comparing the relative-magnitude difference between two consecutive signal values. The operating principle is explained in Section 6.4.3.1.
Function 2.5	**Signal Noise Level**
Function Prototype	`int signNoiseDet(int sensVal, int medFiltVal)`
Code Reference	Section 6.4.3.2 & Appendix I - page 110
Notable Variables	sensVal – *Sensor value* x_{-14} *is used to accommodate for the median filter lag* medFiltVal – *Most recent median filtered value output*
Description	Calculates the level of noise in a signal by measuring the difference between the raw signal and the median-filtered signals' values. The operating principle is explained in Section 6.4.3.2.
Function 2.6	**Calculate Amplitude Value**
Function Prototype	`int signAmpCalc(int sensVal, int medFiltVal)`
Code Reference	Section 6.4.3.3 & Appendix I - page 110
Notable Variables	sensVal – *The signal's datum amplitude value, the instance it transitions from rest to active* medFiltVal - *Most recent median filtered value output*
Description	Takes as inputs the current median filtered amplitude value, and the signal's datum amplitude, in order to calculate the current signal amplitude as

	measured relative to the datum amplitude captured when the signal exited the state of *rest*.

6.5.2.3 Comparison

The *comparison* activities draw from the signal characteristics obtained during the *calculating* activities, and then compares these characteristics against the experimentally-calculated variables to determine whether the characteristics has an *intentional* or *unintentional* signal origin.

The first comparison function performed is the Signal State Duration (3.1) check. The function performs certain calculations based on the signal state that is checked. The function flow is illustrated below in Figure 31. If the signal is determined to be in the *active* state, two actions are executed; (1) the counter *steadyRolCount* is incremented by the magnitude of *steadyRolCountInc*. Since the function is executed at a constant 50Hz frequency, the duration of the signal within the active state is calculated as $Duration = 20ms \times steadyRolCountInc$. Also, (2) the counter that accumulates the amplitude of the signal is updated, adding the current calculated amplitude value to the value accumulated so far. If the signal is determined to be in the state of *rest*, the *steadyRolCount* value is decremented by the value of *steadyRolCountDec*, again relating to a timed duration due to the constant execution frequency. While the signal is in rest, the signal's current magnitude value (drawing from the median filter) is captured in the *signalDatum* variable. This allows the signal datum value to be used once the signal moves out of the *rest* state.

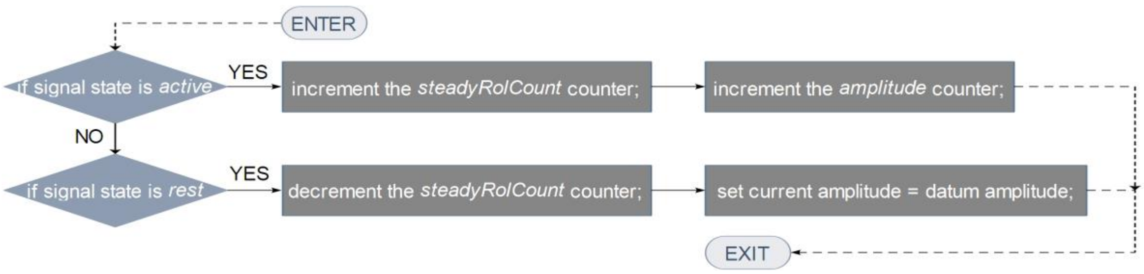


Figure 31: State Duration Check Activity Flow

The second comparison function performed is the Amplitude Integral check (3.2). The function tests whether the signal has been in the active state long enough to justify the next action, which is testing whether the *amplitude integral* has passed the *intentional* signal threshold. The function flow is illustrated below in Figure 32. The first comparison performed by the function is to determine whether the signal has been in the active state for a minimum duration of 840 milliseconds (Section 6.4.3.6). It is done by comparing the variable *steadyRolCount* to the calculated threshold variable *rolCountThresh* (both converted to variables relating to the 50Hz execution frequency). If the case is true, the *steadyRolCount* variable is first prevented from incrementing further towards infinity, after which the amplitude integral check is performed. The value of the accumulating amplitude integral is compared to the calculated threshold (Section 6.4.3.3), and in the case of a *true*, the alarm flag is flagged, indicated that the current signal being processed is identified to be of an *intentional* nature. In the other case that the signal's duration in the active state is equal to 0, the *steadyRolCount* variable is prevented from going negative (since it is continuously decremented while the signal is in the *rest* state), and the amplitude integral value is reset to a value of 0.

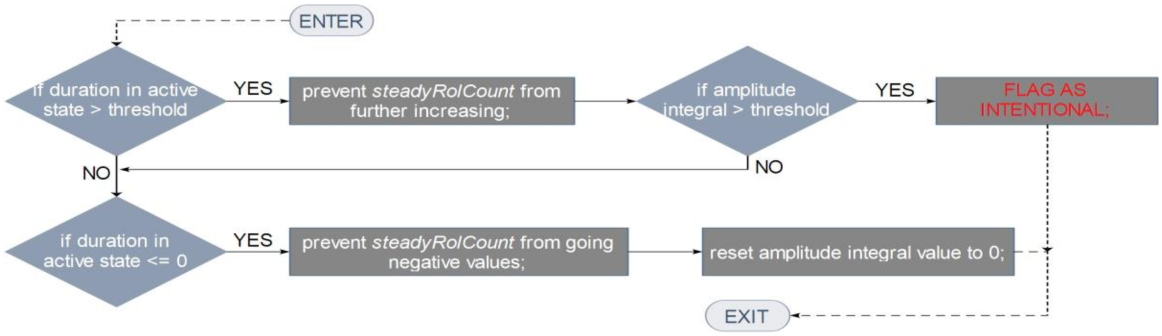


Figure 32: Amplitude Integral Check Flow

The third comparison function performed is the signal Noise Level check (3.3). The function calculates the duration that the signal stays above a certain threshold of noise, and differentiates the signal by comparing the results to the predetermined thresholds. The function flow is illustrated below in Figure 33. The function starts to check if the current signal noise level is above the predetermined noise threshold for intentional signals (Section 6.4.3.2), and while the case is true, a counter is incremented which keeps track of the total duration that the signal's noise level is above the threshold. After incrementing the counter, the function check if the duration counter is bigger than the duration threshold identified for this context, if the case is *true*, the alarm flag is flagged, indicating that the current signal being processed is identified to be of an *intentional* nature. Else, the function is ended. If the signal noise is below the threshold and thus the first case is false, the function only resets the duration counter to 0, and exits the function.

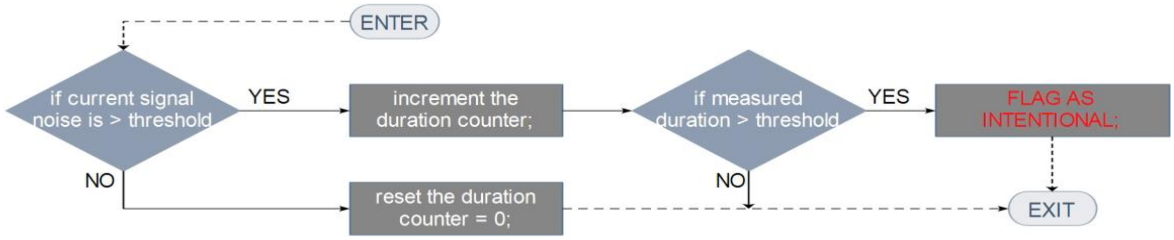


Figure 33: Noise Level Check Flow

6.6 Signal Processing Simulations

To enable experimental testing and improvement of the signal processing software during the development stage, the disturbances that was recorded at the beginning of the sensing system's design phase were used as basis in the execution of signal processing simulations. The objective of the simulations were to determine the performance of the signal processing software at any given stage during the development, in order to validate core functionality and identify areas of improvement. The simulation performance at different development stages were used to gather feedback on the system's performance in different processing aspects, and thereby provide insights aimed at further improving the solution.

The simulations were performed by integrating the signal processing algorithm as developed at any stage, with an executable program that draws from the earlier recorded sensor data. The program thus runs a real-world simulation of the current processing algorithm with any pre-recorded data set.

6.6.1 Simulation Improvement Approach

The approach followed with the simulations were that of an iterative and insight driven development approach. Prior to a simulation, specific thresholds used within the signal processing algorithm, or specific functional principles in the algorithm are changed based on assumptions for a required improvement. The simulation outcome would thereby provide feedback and insights as to how the changes affected the signal processing capabilities of the specific data scenario, and therefrom allowing improving the signal-differentiating accuracy of the system by accepting or rejecting the changes made to the thresholds and algorithm.

Figure 34 illustrates an example of an optimisation iteration performed on the *steadyCheck* function. The top image shows the raw signal being processed – representing three consecutive impacts on the bicycle's saddle. The images below shows the progress made in the outcome of the *steadyCheck* function improvement, with the goal of only having the function result in a 1 during the time of the recorded signal spikes. In this instance, the short term filter constant and steady check window size was adapted to improve the function's performance.

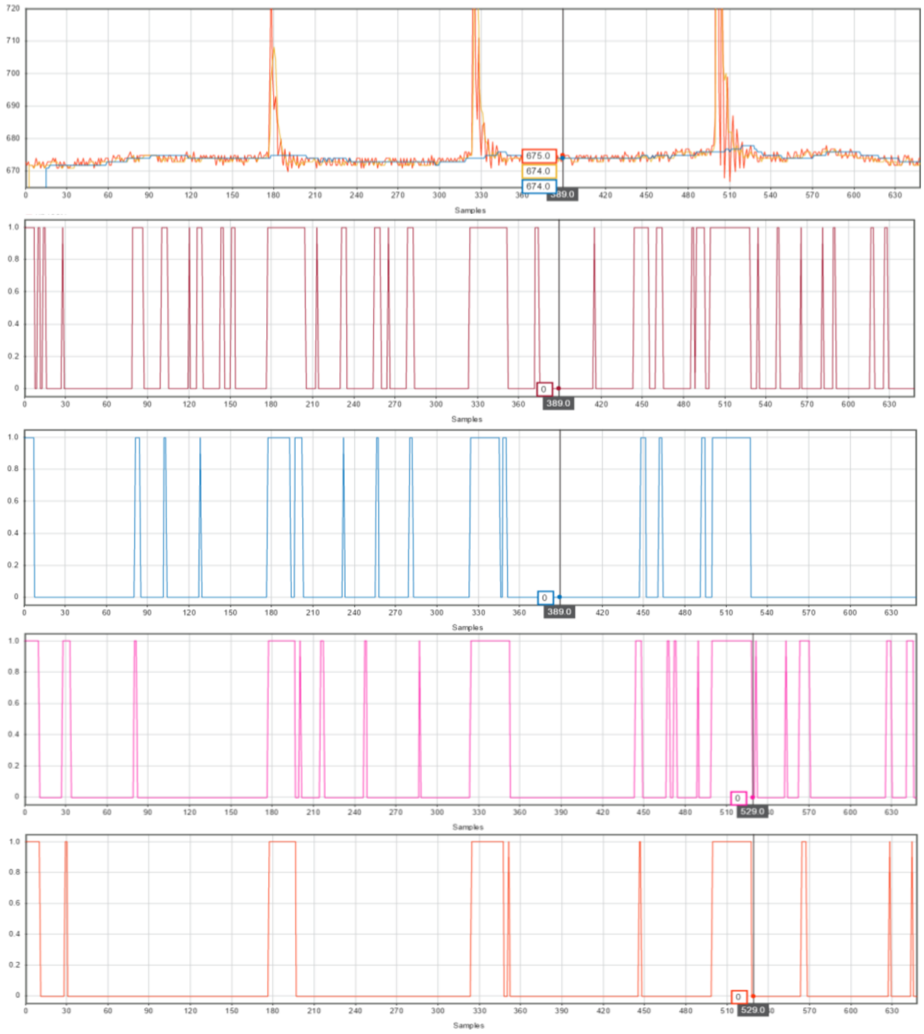


Figure 34: Iterative Signal Improvement Example

6.6.2 Sensing System Simulation Results

The performance of the resulting signal processing algorithm was preliminarily investigated by performing simulations on a variety of the pre-recorded data sets. This was done to determine the development progress of the sensing system, and to find a stage of adequate development of the solution. Not all the recorded data were legible for simulation, since some of the original recorded sensor data sets deferred in the sampling frequency compared to that of the signal processing software, while other data sets were deemed illegible due to unwanted signal characteristics caused by the signal capturing hardware used at the time of recording. A set of clean and legible data sets were chosen for the simulations, aiming to be as representative as possible of the required processing scope of the solution. The results provided here only served as guidelines during development. The sensing system's final performance results, consisting of in-field performance experiments conducted, can be found in Section 9.

Table 18 presents a summary of the simulation results obtained. It presents the data set used for the specific simulation, the resulting processing performance, as well as the insights drawn from the specific simulation. The performance results obtained from the simulation were majority positive, with incorrect signal differentiation occurring only once with simulated disturbances executed on the bicycle.

Table 18: Simulation Results of the Signal Processing Algorithm

Signal Type	Data Set	Performance Result
Intentional Signal	Hacksaw on front frame	Theft detected successfully
	Remove front wheel	Theft detected successfully
	Handle bars removal	Theft detected successfully
	Remove saddle bag	Theft detected successfully
Unintentional Signal	7 minutes environmental noise exposure	No false-thefts detected
	Effects on dock created by *neighbouring bicycles* docking/undocking	No false-thefts detected
	Simulated environmental disturbances on the dock	False thefts detected
	Bicycle hit from the side	No false-thefts detected

7 Locking Mechanism

This section presents the development of the locking mechanism. The locking mechanism is responsible for locking and unlocking the mechanical frame, in a way that is universally accessible to different users without them requiring a physical method of access.

The development process followed in this chapter is guided by the general design specifications that is developed in Section 4.1.3, with the design specifications derived for this specific solution presented here in Section 7.1. The chapter starts by defining the relevant PDS in Section 7.1, followed by the conceptual design of the solution presented in Section 7.2. The development of the detailed design of the solution as well as its various parts are presented in Section 7.3, with the resulting prototype model presented in Section 7.4.

7.1 Derived Product Design Specifications

The derived product design specifications provides the design criteria to which the solution developed in this section, should adhere to. Table 19 presents the derived specifications relevant to this solution, and also provides the design criteria that is implied by each requirement. The design specifications are derived and defined by drawing from the research activities conducted in Sections 2 and 3, as well as from the PDS defined in Section 4.1.3.

Table 19: Locking Mechanism Product Design Specifications

Product Design Specification	PDS #	Desired Outcome	Implied Design Criteria
User accessibility	4.1	Universal user access	*The mechanism should be fully universal in who it can provide access to. Implying no physical restrictions as to who can obtain access to the lock (e.g. a physical key)*
Source of control	4.2	Microcontroller I/O port	*The source used to control the lock/unlock of the mechanism*
Mechanism status feedback	4.3	Lock/unlock status feedback	*Give a TRUE of FALSE return of the lock's status after lock/unlock command is requested*
Locking duration	4.4	<2 seconds	*Time required for a lock/unlock operation to complete*
Fail-safe locking	4.5	OBTAIN	*Keep the bicycle locked in the event of a system-type failure (power supply, controlling logic, management system)*
Provide resistance against the following techniques of theft	4.6	Bolt cutter, hammer, crowbar, hand	*Since the frame provides the physical protection, the requirement is aimed at the pull-out force applied to the rod that the mechanism should be able to handle*
Supply voltage requirement	4.7	Max 9V	*Maximum voltage supply required*
Electric current draw	4.8	Max 700mA	*Maximum current requirement during operation*
Electric current draw, at idle	4.9	15mA	*Current requirements at lock idle (any time outside of locking or unlocking)*
Material & parts cost	4.10	(minimum)	*Cost of all materials & parts used*
Production cost	4.11	(minimum)	*Manufacturing costs involved*

Lock/Unlock Reliability	4.12	98%	*Fraction of lock & unlock actions that should be successful during operation*

7.2 Conceptual Design

The conceptual design presents the functional principle that the solution is based on, and is influenced by three primary areas; (1) the derived Product Design Specifications, (2) the constraints imposed by the frame design, and (3) insights obtained from an existing locking solution. The relevant constraints and insights are presented below, followed by the resulting conceptual design.

7.2.1 Imposed Constraints

The frame design developed in Section 5 imposes two main constraints onto the locking mechanism: The first is a physical sizing constraint created by the frame's inner dimensions where the locks are housed, and the second is the use of the Ø15mm steel rod used to secure the bicycle's frame and wheels.

To ensure that the locking mechanism is protected from the means identified by which a bicycle is stolen, the locking mechanism is to be housed within the frame in order to utilize the frame as protection for the lock. The locking mechanism's maximum outer-dimensions are therefore limited by the minimum inner-dimensions of the frame at the location where the lock is housed – these dimensions are 34x34mm.

The second constraint is the frame design's use of Ø15mm rods to secure the bicycle's frame and wheels. The rod is placed through the bicycle, and into the frame where the locking mechanism is housed. The locking mechanism, therefore, should be able to lock-up the Ø15mm steel rod by using the servo mechanism identified in the Concept Selection. The locking mechanism to be developed is therefore designed with these two constraints in mind.

7.2.2 Insights for the Functional Principle

The functional principle on which the locking mechanism is based streams from the principle on which a conventional cylindrical lock is used to lock a door. A cylindrical lock utilises a rotational force to displace a hardened steel "plunger", which then creates a wedge that counters any force applied in the direction that is required to open or remove the object being secured. Figure 35 presents an example of the cam-type mechanism within the lock that is responsible for displacing the plunger.

Figure 35: Conventional Cylindrical Locking Mechanism – Source: multipointlocks.co.uk

A rotational force, such as turning a key, is used to rotate the cam-type mechanism which drives a linear-moving plunger. The end of the plunger is then pushed from the locking mechanism, into the object used to secure the locking mechanism (e.g. door lock into door frame). The plunger thus creates a linkage between the locking mechanism and the object used to secure the lock, providing resistance against forces that are applied to the object in which the locking mechanism is housed. The same cam-to-plunger principle is used as insight in the locking mechanisms conceptual design.

7.2.3 Resulting Conceptual Design

The functional principle for the conceptual design is based on that of the conventional cylindrical lock. In this case, a servo is used to provide the rotational force, removing the need for keys or any physical interaction and thereby adhering to PDS 4.1 and 4.2. The servo acts as a cam mechanism, driving a linear plunger that follows the cam profile by using a spring to ensure constant contact between the plunger and the cam. The top of the plunger houses a key that is pushed into corresponding key slots on the steel locking rod. The plunger-key, fitting precisely into the steel rod, serves as a semi-permanent physical extension to the steel rod after it is inserted.

The steel rod is inserted into the locking mechanism's housing through an Ø15.40mm hole. The size of the steel rod is therefore effectively increased when the lock (and plunger-key) is engaged, thereby preventing the rod to exit through the same Ø15.40mm hole. This functional principle achieves the same successful outcome as the conventional cylindrical lock – since it utilises a simple mechanism that requires very little input, to provide a substantial level of resistance to forces applied to remove the secured object. The level of protection provided by the lock is dependent on the size and material of the plunger-key, the rod, and the housing in which the lock is housed.

Since no ongoing inputs are required to maintain the level of resistance provided by the locking mechanism after it is locked, this functional principle is deemed fail-safe in the context that it will stay locked in the case of a loss of power or system failure – thereby meeting PDS 4.5.

7.3 Detailed Design

The detailed design section presents all relevant design choices and prototype development procedures that was followed to reach the final design. The servo and material selection presented in this section, is combined with the conceptual design and constraints discussed in the previous section, in order to develop the resulting solution presented in the form of computer aided designs. The relevant feedback and software control design is presented at the end of the section. Top-level detailed design drawings for the locking mechanism is presented in Appendix L on page 116. The relevant hardware pin assignments can be found in Appendix N on page 121.

7.3.1 Servo Selection

The servo used to drive the locking mechanism is a critical component contributing to the mechanism's performance. Careful consideration was taken during the servo selection process, with a wide variety of components investigated and tested. The main considerations taken into account, were the servo's size restriction to ensure it can fit into the frame, the cost per unit (PDS 4.10), the required servo control hardware (PDS 4.2), and the electric voltage and current limitations (PDS 4.7 – 4.9). The most attractive servo choice based on these requirements is the Tower Pro *SG90 Micro Servo*. The servo is presented below in Figure 36.

Figure 36: SG90 Micro Servo - *source: communica.co.za*

The *SG90 Micro Servo* requires an operating voltage of 3,5V – 6V. At 5V supply voltage, the servo delivers a stall torque of 1.6 kg.cm, draws a stall current of 650±80 mA, and draws an idle current of 6±10 mA. The retail price for the servo is between R50 and R85, although costs can be reduced by up to 48% if large quantities are directly imported from *TowerPro.com*. The servo is controlled using a 50Hz PWM signal, which can be provided by the microcontroller chosen in Section 8. The above mentioned characteristics all meet the specifications presented in Section 7.1.

7.3.2 Material Selection

Two primary considerations are taken into account when selecting the components' materials; (1) financial costs and (2) the level of protection provided by the lock.

The only critical parts within the locking mechanism of which the material can influence the level of protection provided by the lock, and which has not yet received a material allocation, is the plunger-key. The plunger key will be subject to high forces during an attempted lock-breach, and should therefore be able to withstand great tensile forces. It should also not be difficult to manufacture, as the keys within the plunger-key requires processing or machining. The material and corresponding manufacturing method for the plunger-key is therefore selected as aluminium, which will be machined using CNC machining. Although this a high cost material and manufacturing method, it is justified by the importance of this component, as well as the small physical portion that this component contributes to the whole mechanism.

The primary factor considered in the remainder of the locking-mechanism's parts is cost. All other parts merely needs to be functional, and will not be subject to additional forces besides their operation loads. As the material and manufacturing costs will be the main contributor to overall costs, the parts will be 3D printed using PLA plastic. In the case of mass production, the parts will be converted to a plastic mould and moulded. Using plastic will lower the material costs involved, and also reduce the manufacturing time and costs involved.

7.3.3 Computer Aided Design

Figure 37 presents the final locking mechanism design in CAD format, illustrating the full locking mechanism on the left, the locking mechanism with the upper-body removed in the middle, and an exploded view of the locking mechanism on the right. The orange outer shells make up the "body" – consisting of an "upper body" and "lower body". The inner parts of the locking mechanism consists of the servo (blue), servo cam (white), plunger (black), plunger spring and plunger-key (silver).

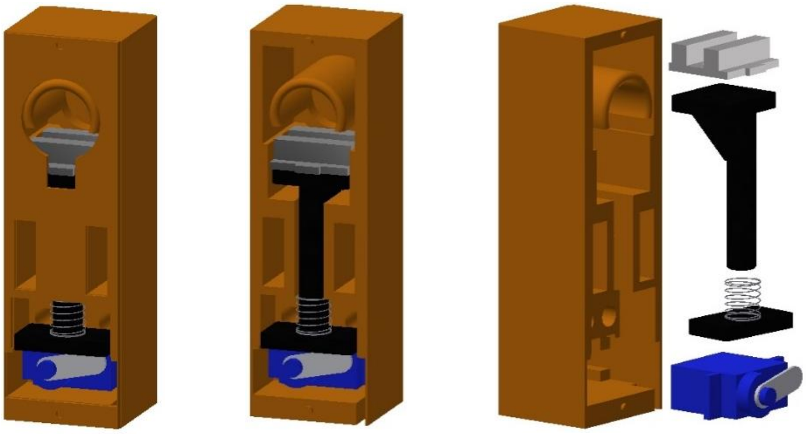


Figure 37: CAD of an Assembled Universal Locking Mechanism

The body serves as the structural housing that keeps all the inner parts aligned, and ensures that the locking mechanism fits tightly into the mechanical frame. The body guides the steel rod into position as it enters the lock, and guides the plunger-key into the rod when the servo is activated. The body is 3D printed using PLA plastic, requires 40g of plastic to be printed, and has a printing duration of 3.2 hours. The inner fill of the body consists of a honey-comb structure (30% infill) that helps to reduce material usage, and increase the structural integrity of the parts. Figure 38 presents an exploded view of the body on the left, a wireframe sketch of the lower-body in the middle, and a wireframe sketch of the upper-body on the right. The two parts are aligned by two pin-and-holes at the top and bottom of each part.

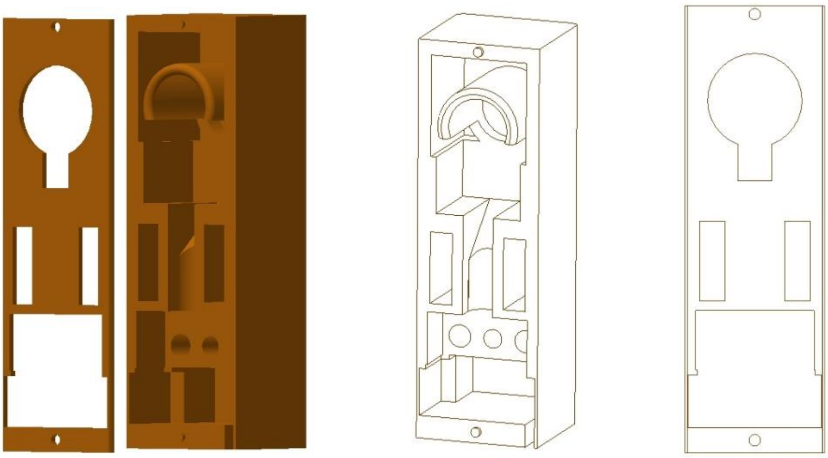


Figure 38: Locking Mechanism's Upper and Lower CAD

The servo (Section 7.3.1), plunger, spring and plunger-key are responsible for the internal mechanics of the locking mechanism. Figure 39 presents these components in an extracted assembled view on the left, and an exploded view on the right. The plunger consists of two separate parts (as seen in the exploded view) which are 3D printed using PLA plastic. The parts are joined after printing using a PLA-compatible epoxy. The spring is self-manufactured using piano string, and fitted to the plunger after it is joined.

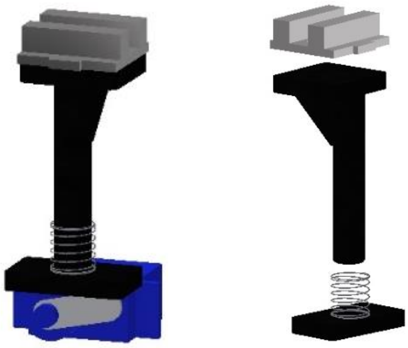


Figure 39: Locking Mechanism Internal Mechanics

The placement of the locking mechanisms after installation is seen below in Figure 40, as a clear-material view of the parts housing the two locking mechanisms are shown.

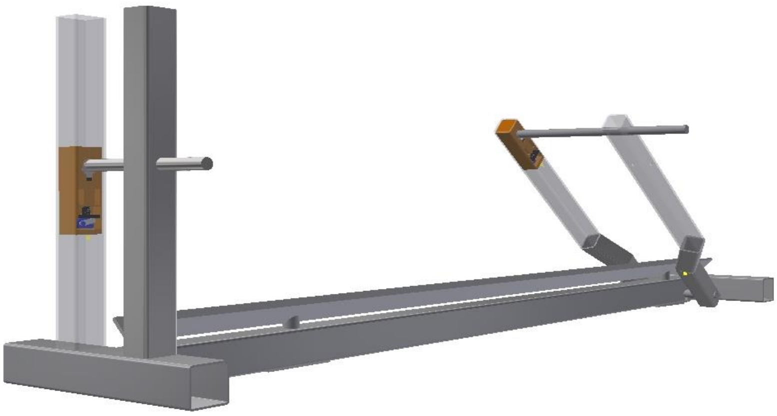


Figure 40: Locking Mechanism Placement

The process through which the locking mechanism is engaged and thereby the steel rod secured, is illustrated below in Figure 41.

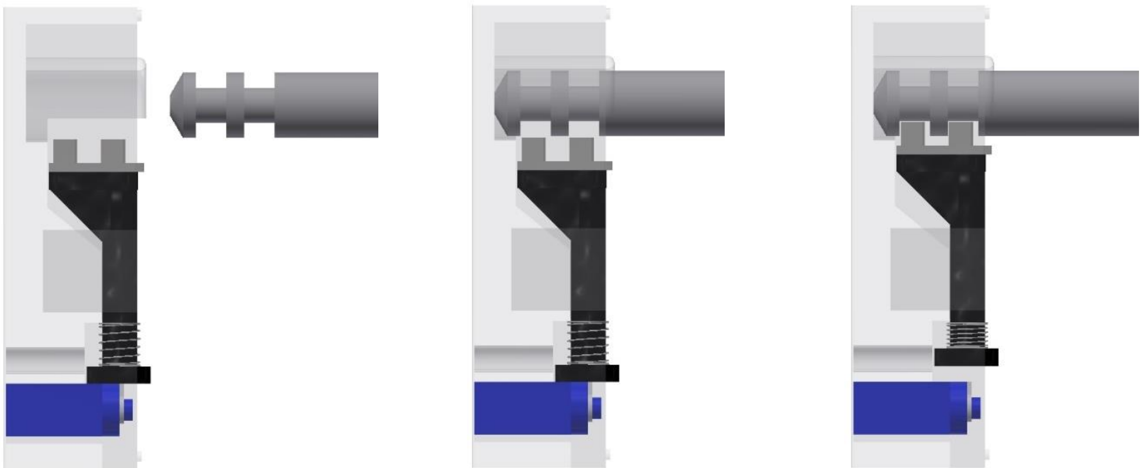


Figure 41: Locking Mechanism Engagement Process

The steel rod is inserted into the locking mechanism, with the rod's leading end pushed against the body's inner wall. This aligns the steel rod's grooves with the keys of the plunger-key. This part is illustrated by the left and middle images in Figure 41. The servo is then activated to rotate in an anti-clockwise direction, turning the cam which is attached to its shaft, resulting in the plunger-assembly being pushed upwards towards the steel rod. The plunger-key is thereby slotted into the grooves of the steel rod, as seen in the right-side image in Figure 41. If a force is applied to the rod that attempts to remove it from the locking mechanism, the rod's grooves engage with the plunger-key, which in turn provides resistance by pushing against the locking mechanism's body. Since the body is housed within the mechanical frame, the force is distributed through the locking mechanisms body into the frame, which has the capacity to withstand the resulting pressure.

7.3.4 Locking Status Feedback

In the case that the plunger-key and steel rod's grooves do not properly align (Figure 41), or that a physical obstruction is present within the rod's keys, the plunger-key will not fully slot into the grooves to successfully engage the lock. PDS 4.3 states that the lock should be able to give a binary output of the locking mechanism's status after a lock/unlock command was executed. This therefore entails incorporating a means to determine whether the servo and plunger has reached the intend position after a lock/unlock command was executed. By doing so, the possibility of the system generating a false-positive regarding the lock-up of a bicycle is removed. It also prevents the danger of servo burn-out due to a continuously active servo that is unable to reach its defined position.

The locking mechanisms feedback is provided as follows. The idle current for the servo is a mere 1% of the stall current, making it possible to use the servo's current measurement as a useful indicator of the servo's activity status. In order to determine whether an attempted lock/unlock was successful, the servo current is checked to determine whether the servo was able to reach its intended position, by determining the current flow in the servo after the lock/unlock activity was initiated. The solution consist of a hardware and software component. The hardware component is presented in Figure 42.

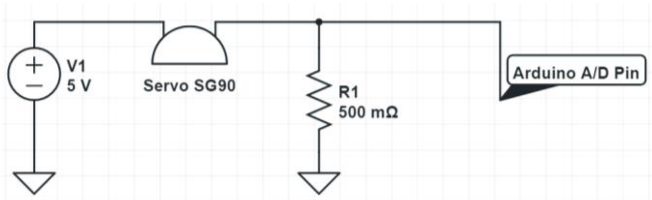


Figure 42: Current Measuring Circuit Schematic

The hardware component consists of a 0,5 Ω resistor (R1) that is placed in series with the servo motor within the power circuit. The voltage over R1 is measured using the Arduino's A/D converter. During servo idle, the maximum current drawn is 16mA, resulting in a voltage measurement calculated in equation 7.1 as

$$0{,}016A \times 0{,}5\Omega = 0{,}008V \cong 0{,}01\,V \tag{7.1}$$

over R1. The analog measurement for maximum idle current, converted by the Arduino's 10-bit A/D converter, results in a analog reading calculated in equation 7.2 as

$$\frac{0{,}01}{5} \times 1024 = 2{,}048 \cong 2 \text{ units.} \tag{7.2}$$

Following similar calculations in equations 7.3 and 7.4; at the servo motor's stall current (730mA), a voltage difference of

$$0{,}73A \times 0{,}5\Omega = 0{,}365V \tag{7.3}$$

is created over R1, resulting in an analogue reading of

$$\frac{0{,}365}{5} \times 1024 = 74{,}75 \cong 74 \text{ units.} \tag{7.4}$$

The difference between the analogue reading obtained at stall and at idle, provides an adequate resolution to detect whether the servo is still active, or if it has reached it's intended position. A 7,3% supply voltage reduction to the servo motor is caused by the 0,365V used at R1. This will not have an substantial affect on the servo's performance and is therefore acceptable.

The software component enabling the feedback, functions by measuring the servo current and determining whether it is above the maximum idle threshold current. In the case that it is, a counter is incremented. If the counter reaches a predefined threshold, the locking transaction is demed unsuccessful. The flow diagram for the software component is illustarted by Figure 43 below. The function returns a *successfull* or *unsuccessfull*, which is used by the locking mechanism's overall control function presented in Section 7.3.5.

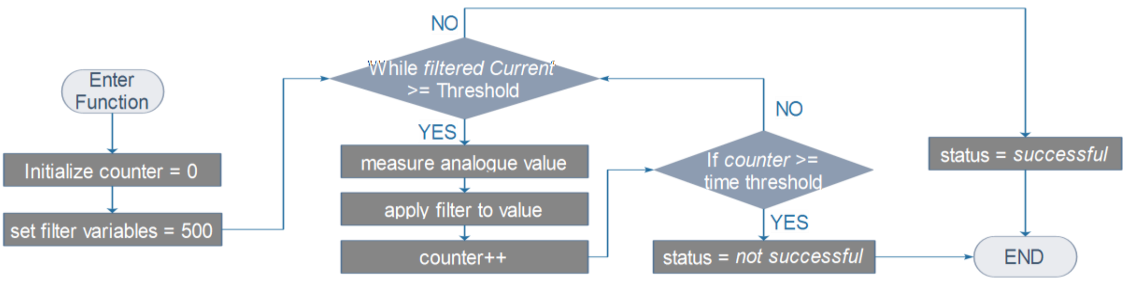


Figure 43: Locking Status Function Flow Diagram

The function starts by reseting all relevant variable used by the function. It then measures the servo current and determines whether it is above or below the maximum idle current threshold. If the current is below the threshold, it is assumed that the servo has reached the intentded position and the opperation is deemed as *successfull*. If the current measured is above the maximum idle threshold, a counter is incremented and the servo current measurement filtered. If the current stays above the threshold, resulting in the counter being incremented above the *time threshold* value, the opperation is deemed as *unsuccessfull*. The servo current is measured as an analogue reading, and is obtained from the hardware discussed earlier in this section. The avaraging fiter applied uses five consequative readings, and returns the avarage of all values that serves as the new value that is used by the function. The filter is applied to remove any high-frequency noise present on the A/D input signal. The source code for the function can be found in Appendix M on page 119.

7.3.5 Locking Mechanism Control Function

The locking and unlocking of the locking mechanism is realised by altering the position of the servo axis, which rotates the cam attached to the servo and thereby engages the plunger-key into the steel rod's keys. Any servo axis position required is obtained by sending a PWM signal to the control line of the servo - with the width of the pulse that is sent, determining the position of the servo's axis. The required servo axis positions for the "locked" and "unlocked" state of the locking mechanism was determined experimentally, and is illustrated in Figure 44.

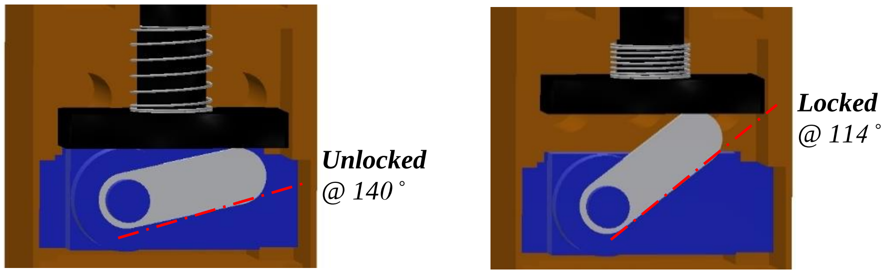


Figure 44: Servo Axis Control Positions

In this system, the servo control is executed by the Arduino microcontroller responsible for the system management (Section 8). The Arduino library consists of a *Servo* function which takes the required servo position (in degrees) as input, and adjusts the attached PWM output pin accordingly, in order to obtain the required servo position. The servo positions determined in Figure 44 are defined in the control function's declarations, and are used as inputs to the servo function when a "lock" or "unlock" command is initiated. The *Servo* function is combined with the *status feedback* function (Section 7.3.4) to administer the servo control and thereby the locking mechanism control. The flow diagram for the locking mechanism control function is presented in Figure 45.

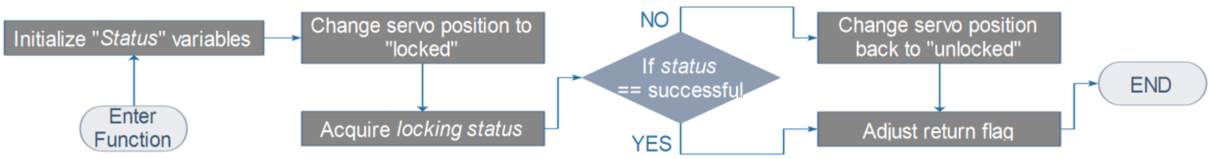


Figure 45: Servo Control Function Flow Diagram

Two functions are responsible for the locking mecanism's control– they are the *lockPin_Lock()* and *lockPin_UnLock()* functions. Both functions are based on the same opperational principle, but use different servo positioning variables. Figure 45 illustrates the *lockPin_Lock()* function. The function starts by initialising the function's *status* variables. Next, it uses the *Servo* function to change the servo axis position to the "locked" position, by transfering the servo's locked position variable to the Arduino *servo* function. The *locking status* is then obtained by drawing from the function presented in Section 7.3.4 above. If the *locking status* is returned as succesful, the return flag is set equal to 1, and the function ended. If the *locking status* is returned as unsuccesful, the servo is returned to the initial position (unlocked in this case), to prevent servo burn-out. The return flag is set equal to 0 and the function ended. The complete source code for this function can be found in Appendix M on page 119.

7.4 Resulting Prototype Model

The resulting prototype for the locking mechanism is presented below in Figure 46. The parts in the middle and left make up the body, while the full plunger assembly is found in the top-right. In the bottom-right corner, the *SG90 Micro Servo* is seen.

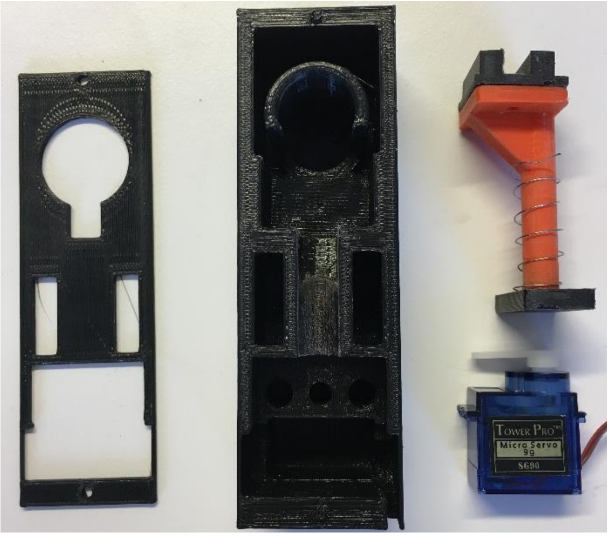


Figure 46: Disassembled Locking Mechanism Prototype

Figure 47 presents the locking mechanism after assembly and prior to installation, with the upper-body removed. The image on the left shows the lock in the *unlocked* state – where the pin can be inserted or removed from the lock. The right side image shows the lock in a *locked* state – after the servo has been activated, and the plunger-key engaged.

Figure 47: Assembled Locking Mechanism Prototype

8 System Integration and Control

This section presents the development and implementation of the system's integration and control elements. The system integration and control is responsible for administering and actualising the synergy of the various model elements, to provide functionality to the system as a whole by providing the integration framework and system control process. It consists of four primary elements; (1) the user interface that is the first point of contact for a user, (2) a cloud-based platform to administer general system management, (3) communication hardware and software to enable connectivity of the various elements, and (4) hardware controllers to administer the control of the hardware components.

The development process followed in this chapter is guided by the general design specifications that is developed in Section 4.1.3, with the design specifications derived for this specific solution presented here in Section 8.1.

The chapter starts by defining the relevant PDS in Section 8.1, followed by an elucidation of the system integration approach presented in Section 8.2. The development of the four primary elements are discussed in Sections 8.3 – 8.6, with the system state machine presented in Section 8.7.

8.1 Derived Product Design Specifications

The derived product design specifications provides the design criteria to which the solution developed in this section, should adhere to. Table 20 presents the derived specifications relevant to this solution, and also provides the design criteria that is implied by each requirement. The design specifications are derived and defined by drawing from the research activities conducted in Sections 2 and 3, as well as from the PDS defined in Section 4.1.3.

Table 20: Integration and Control Product Design Specifications

Product Design Specification	PDS #	Desired Outcome	Implied Design Criteria
User accessibility	5.1	Universal user access	*The method used to access the system should be as universal as possible*
User communication	5.2	Enable user alerts & notifications	*Notify users and relevant parties of the status of the dock*
Communication type	5.3	Wireless	*Communication capabilities should be wireless to enable fixed-portable docking*
Communication coverage	5.4	Urban areas	*The area type that the communication should be able to function in*
Low cost	5.5	(minimum)	*Total cost related to the solution*
Total lock-up procedure duration	5.6	< 5 seconds	*The time that it takes to complete the locking of the bicycle, after it has been docked*
Controlled accessibility	5.7	Permission based access	*Consist of a method of user verification to approve or decline access to the system*

Physical access constraints	5.8	"Key-less" access	*Remove the dependency on a physical key-type method of access*

8.2 Elucidation of System Integration

The system integration with respect to overall system management is illustrated below in Figure 48. The figure presents the various elements involved in the general operation of the system, and how these various elements are integrated and managed during operation.

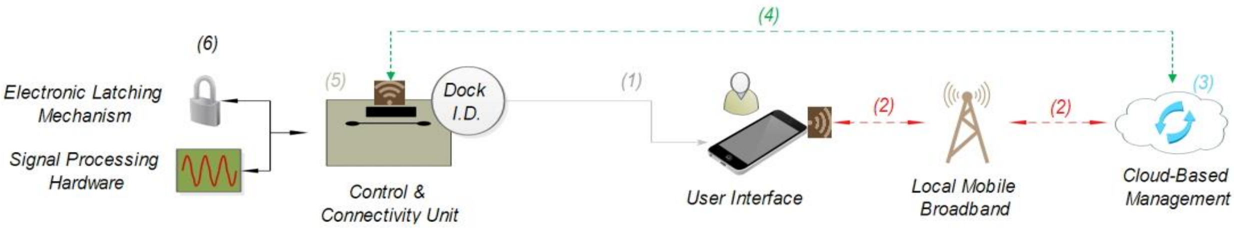


Figure 48: System Integration & Management Concept

The first step (1) in the system operation requires the dock ID to be input to the User Application, which is hosted on the user's mobile smart-phone (Section 8.3). The User Application then sends the dock ID obtained, as well as the user's ID, to the Cloud Based Management platform through the available local mobile broadband infrastructure (2). The protocol and transaction relevant here are discussed in Section 8.5. The Cloud Based Management platform receives this information and processes the transaction accordingly (3). This is explained in Section 8.6. In the case of a successful transaction, the appropriate command ("lock or unlock the dock") is directed to the relevant docking station (4), again using the available local mobile broadband infrastructure and the communication protocol described in Section 8.5. Each docking station houses a Control & Connectivity unit (5). The unit receives the command and processes it according to the docking station's state machine that is discussed in Section 8.7. The Control & Connectivity unit consists of two hardware components; one that is responsible for providing the communication capabilities to the Cloud Based platform, and another on which the state machine is executed and with which the dock sensors and lock interact. The various hardware elements are discussed in Section 8.3.

8.3 User Application

User interaction with the system is enabled through a mobile smart-phone application. The application is housed on the user's mobile smart-phone, and serves as an interface to obtain the relevant information from the user in order to complete the lock and unlock transactions. The application communicates with the cloud based platform, which stores and processes the information as sent from the smart-phone application. Communication between the smart-phone application and cloud based platform is realised through the local mobile broadband infrastructure, and uses the protocol described in Section 8.5 to send transactions.

The application is used to register the user with a unique user profile containing the information required for user authentication and billing, with the user databased stored and managed in the cloud database. To initiate a transaction, the dock ID is obtained from the dock by scanning a unique QR code that is placed on each dock. The QR-ID is extracted by the application, and sent with the user ID to the cloud platform. In the case of unsuccessful lock/unlock transactions, or if an attempted theft is detected by the dock, the relevant notifications are sent to the user's smart-phone application.

The motivation for this user interaction method is primarily based on the observed growing availability and use of smartphones which leads to a more universal solution (PDS 5.1), the improvements in usability that relates to using a smart-phone compared to another form of physical authentication such as a physical key or card access (PDS 5.8), and to enable effective user notifications (PDS 5.2). Although the concept and design of the user interface is presented, the physical development of the user interface is not included in the scope of this research.

8.4 Control & Connectivity Unit Hardware

The *control & connectivity unit's* hardware is subject to two main requirements; (1) to provide wireless communication capabilities (PDS 5.3) from the dock to the cloud based platform, and (2) to provide a platform to execute the dock's state machine and therefrom control the locking mechanism and signal processing sensors. The proposed solution consists of two separate hardware elements: a *Particle Photon* Wi-Fi module, and an *Arduino Mega ADK 2560*.

The *Particle Photon* is a Wi-Fi connected development board consisting of an *STM32 ARM Cortex* microcontroller and a *Cypress* Wi-Fi chip – providing the board with computing capabilities and a connection to the IoT using any available Wi-Fi gateway. The *Particle* platform also provides a cloud platform that can be used for development with the *Photon*. The *Arduino MEGA* is a microcontroller board based on the ATmega2560 microprocessor. It provides the solution with the processing capacity to implement the dock state machine and control, and to allow control and interfacing with the locking mechanisms and sensing system sensors.

The *Particle Photon* is the first receiver of data from the cloud based platform, and acts as a data gateway between the *Arduino* and the cloud based platform. The data received by the *Particle* is sent directly to the *Arduino MEGA* through a Serial TX-RX interface existing between the two hardware components, and vice versa when data is sent from the *Arduino*. Figure 49 presents the resulting hardware solution developed. The full pin assignment of the various components, as well as the serial-gateway source code can be found in Appendix N on page 121.

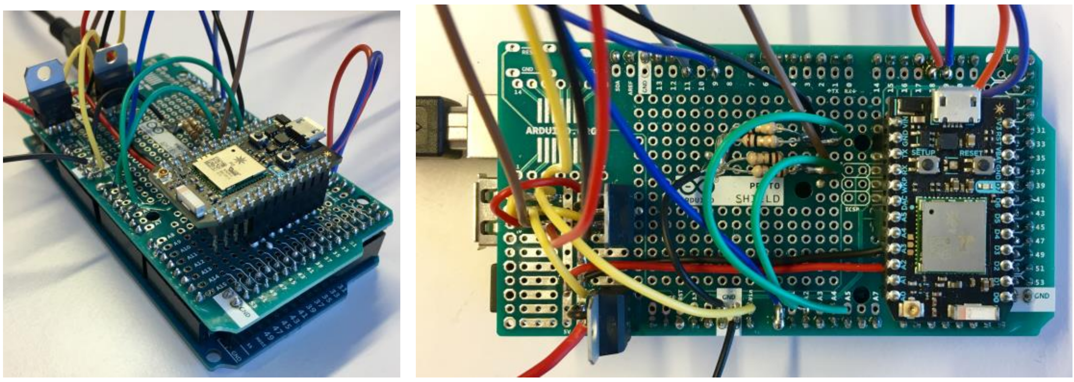


Figure 49: Control and Connectivity Hardware Produced

For further optimisation of the model developed, it is proposed that a *Particle Electron 3G* be used to replace the hardware solution presented in this section. The *Particle Electron* consists of a cellular-sim modem which removes the dependency of a Wi-Fi gateway for connecting to the IoT, and also has adequate processing capacity to execute the processing operations currently performed by the *Arduino MEGA* – leading to a simpler, more versatile, and cheaper solution.

8.5 Data Transmission Protocol

Data transfers occur through two interfaces; between the smart-phone application and the cloud platform (interface 1), and between the cloud platform and the dock state machine (interface 2). A data transmission protocol is developed for both interfaces to ensure consistent and structured data transfer. The relevant information is sent between the elements involved in the interface in the form of character strings.

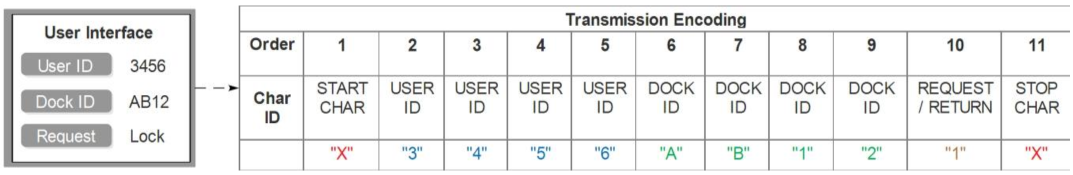


Figure 50: Interface 1 Transmission Protocol

Interface 1 exists between the user interface and the cloud based platform, with bi-directional data transfer using the same protocol, occurring. The data transferred within this interface includes the ID of the user initiating the transaction, the ID of the dock that is interacted with, and the action requested from the user (lock/unlock). Figure 50 above provides an example of a user requesting the lockup of a dock. A "X" character is placed at the beginning and end of each transmission to allow a check for complete transmission. The user ID as obtained from the user profile is sent to the cloud in positions 2 – 5. The dock ID as obtained from the dock QR-code, and is sent in positions 6 – 9. For user-to-cloud transmission, position 10 is set to "1" for a lock request, to "2" for an unlock request, and to "3" to request a lock-status check. For cloud-to-user transmission, position 10 is set to "9" to confirm a successful transaction, "8" to report an unsuccessful transaction due to a locking mechanism error, or set to "7" to report an unsuccessful transaction due to a sensor calibration error.

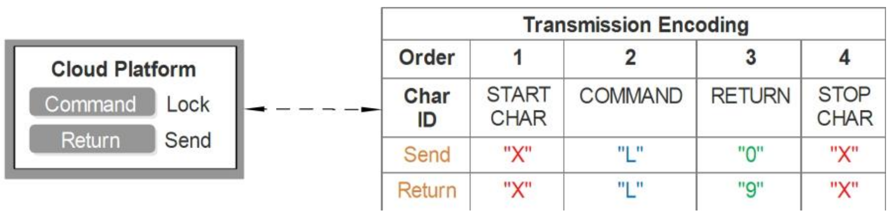


Figure 51: Interface 2 Transmission Protocol

Interface 2 exists between the cloud based platform and the dock state machine, with bi-directional data transfer using the same protocol occurring. The data transferred within this interface consists of the command requested from the dock, and a "return" variable that describes the state of the command requested. Figure 51 above provides an example of a lock command being sent and returned in the interface. A "X" character is placed at the beginning and end of each transmission to allow a check for complete transmission. Position 2 contains the command being sent to the dock, with "L" implying locking the bicycle and activating the sensors, "U" implying unlock and deactivate the system, and "S" implying to check the current status of the system (locked/unlocked). In the case of the command being sent to the dock, the RETURN variable in position 3 is not utilised and set to "0". After the command is executed by the dock, the same string is returned to the cloud, with position 3 set to "9" if the command was successfully executed, to "8" if the command was unsuccessfully executed due to a locking mechanism error, or set to "7" if the command was unsuccessfully executed due to a sensor calibration error.

8.6 Cloud Functionality

The cloud platform serves as the central processing platform that integrates and administers the various elements and their interactions within the system. The high-level functionality on which the platform is based is presented in Figure 52.

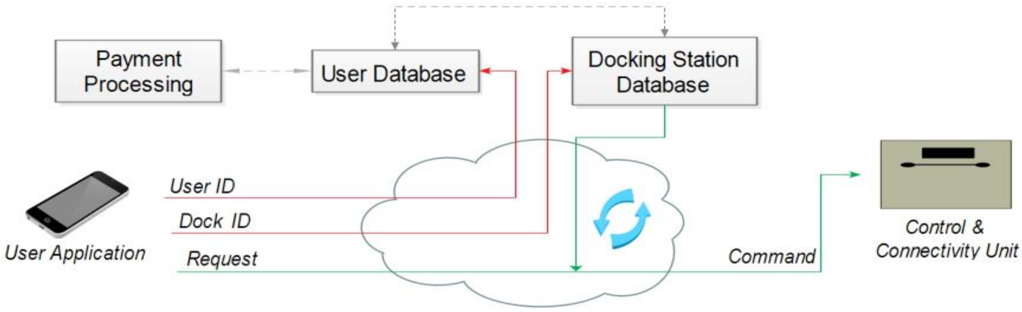


Figure 52: Cloud Platform Functionality Diagram

The user ID, dock ID and request is received. The user ID is used to extract the respective user profile from the User Database, which contains the relevant information of all users as collected from a registration process upon entry to the system. The dock ID is used as pointer to the respective docking station's profile, which provides the dock's current status and communication specifications to enable communication with the dock's connectivity unit. The user and dock is validated to ensure both are available for a transaction, and if successful, the related command is sent to the dock. The dock processes the command, and returns the processing status. If the status is "successful", the user and dock is engaged in a transaction and the relevant payment processes executed. If the status is "unsuccessful", the user and dock is disengaged and the necessary error message returned to the user interface.

A basic functional representation of the concept described above is developed for this model, although the database and payment functionality is not included in the scope.

8.7 System State Machine

The docking station management is administered through the implementation of a state machine. Four system states exist, each relating to specific state-entry paths and actions. The states are: *standby*, *locked*, *unlocked* and *alarm*. The *command handler* function presented in Section 8.7.1 administers the commands initiated by the user and the system, and integrates the command with the *change state* function. The *change state* function presented in Section 8.7.2 administers the state navigation and implementation.

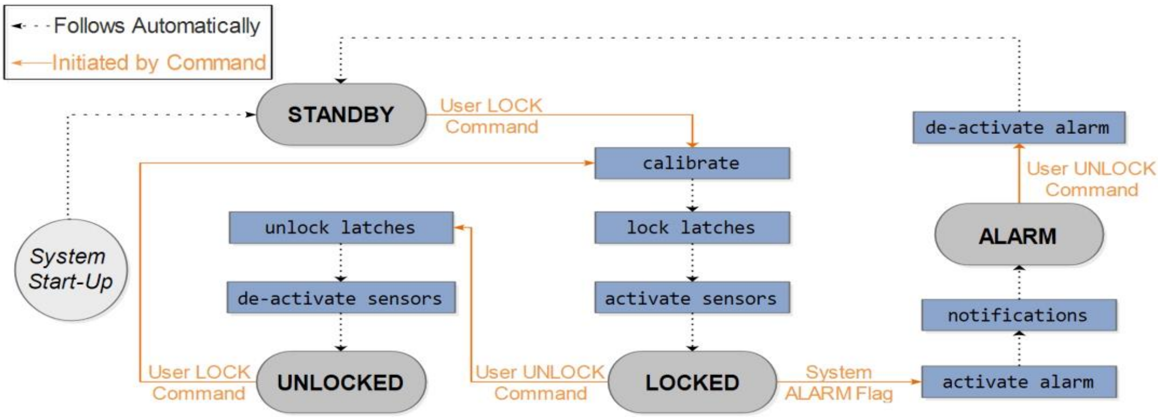


Figure 53: System State Machine Flow Diagram

Figure 53 above illustrates the state machine flow, as well as the main actions performed upon state entry and exit. Upon system start-up, the *standby* state is entered. All locking mechanisms remain unlocked and the sensors inactive. Upon receiving the *lock* command, the system enters into the *locked* state. Upon entry of the *lock* state, three actions are performed; the theft detection sensors are calibrated and tested, the latching mechanisms are engaged, and the theft detection system is activated. Sensor calibration prevents the system from locking and activating without a bicycle being present, or with the sensors being in an unstable state. Only if all actions are performed successfully does the system enter the *locked* state. While the system is in the *locked* state, the latches remain engaged and the theft detection system remain active to detect any attempts of theft. Upon receiving the *unlock* command, the system initiates entry into the *unlocked* state. Entry into the *locked* state includes disengaging the latching mechanisms, and deactivating the theft detection system. In the case that the system is in the *locked* state, and the alarm flag is triggered by the theft detection system, the system moves into the *alarm* state. Upon entry of the alarm state, an audible alarm is activated, while relevant parties are notified of an identified attempt of theft. The system is then in the alarm *state*. To exit the *alarm* state, an *unlock* command from the user is required. Exiting the *alarm* state disengages the audible alarm, and places the system in the *standby* state – with the latching mechanism still engaged and the signal processing software still active. To exit the *alarm* state, the *unlock* command is required from the user.

8.7.1 Command Handler Function

The *command handler* function administers the reception of commands from the user though the serial-communication gateway, and integrates the command with the *change state* function. The *command handler* function is situated in the main program loop, and responds to any data that is available on the *Serial1* channel which interfaces with the *Photon Particle* IoT gateway.

In the case of the function responding to data available on the *Serial1* interface, the relevant command is extracted from the data according to the protocol discussed in Section 8.5. The command is then translated to the corresponding format, and forwarded to the *change state* function – which then interprets the state change and administers the functions related to the command's corresponding state change request.

In the case of the theft detection sensor systems detecting an attempted theft, the alarm flag is raised. This results in an "alarm" command being created by the theft detection system, which is then processed by the *command handler* function to administer the actions relating to the *alarm* state change. The functions' relevant source code is found in Appendix O on page 123.

8.7.2 Change State Function

The *change state* function is situated outside the main program loop, and is executed upon call-up from the *command handler* function. The function manages the state navigation as illustrated in Figure 53 on page 78, and administers the actions and functions to be executed that relates to a specific state change. Figure 54 presents the function flow diagram of the *change state* function.

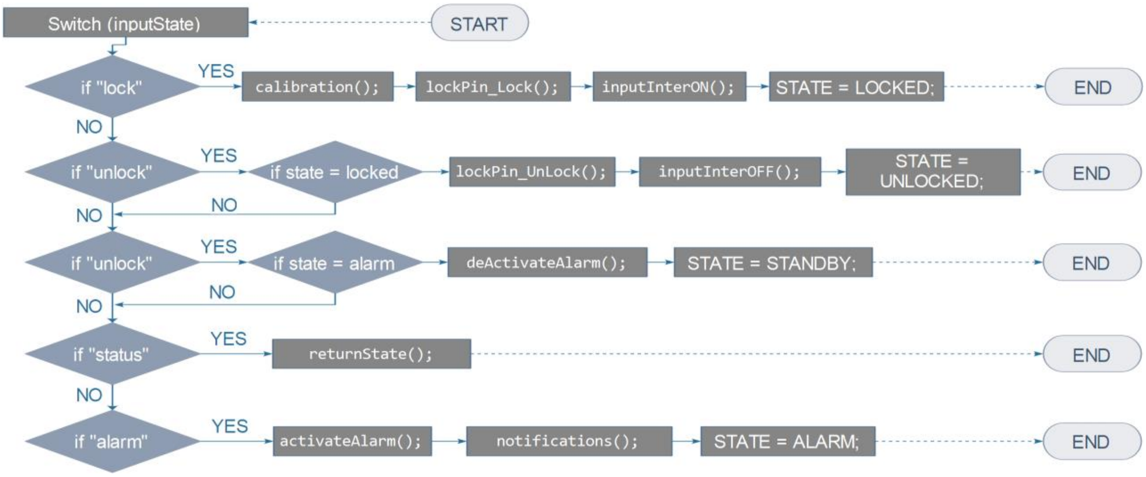


Figure 54: State Change Function Flow Diagram

The function structure is a switch-case implementation that receives the desired state as input and switches accordingly. State navigation is performed by the switch implementation, which channels the execution into relevant *lock*, *unlock*, *status* or *alarm* streams.

If the *lock* state is requested, the *calibration*(), *lockPin_Lock()* and *inputInterON()* functions are called. These functions checks weather the sensors are stable, locks the latching mechanism and activates the sensors. If all three functions are executed successfully, the current state is changed to *locked* and the function ended. If the *unlock* state is requested, the function checks to see what the current state is in order to determine the required actions based on the state exiting from. If the *locked* state is the current state, the *lockPin_Lock()* and *inputInterON()* functions are called. This disengages the latches and deactivates the sensors. The bicycle can now be removed from the dock. If the *unlock* state is requested, and the current state is the *alarm* state, the audible alarm is deactivated with *deActivateAlarm()*, and the *standby* state is entered. If the alarm state is requested, the *activateAlarm() and notifications()* functions are executed. These trigger the audible alarm and executes the relevant parties' notifications. In the case that the *status* state is requested, the *returnState()* function is executed which send the current state to the *Serial1* gateway, with no permanent state changes that are made. All these functions' relevant source code is found in Appendix O on page 123.

9 Results

This chapter presents the performance results of the resulting research model developed. The chapter consists of three parts. The first part presents the final research model that was obtained, and consequently used to perform the tests and experiments contributing to the performance results of this chapter. This model is presented in Section 9.1. The second part presents five test setups that was used to determine the performance of different performance areas relating to the resulting model. The test setups, procedures performed, and results for the respective tests, are presented in Section 9.2. The last part uses the results obtained from the performance tests, and interprets them to determine the model's compliance to the requirements defined at the beginning of the research – in order to determine the overall performance of the developed solution. This compliance to requirements of the solution is presented in Section 9.3.

9.1 Resulting Model

The resulting model is presented below in Figure 55 and Figure 56. All elements developed above is integrated into the resulting model. The performance tests presented in this section are all executed using this resulting model, with the performance results therefore streaming from the model resented below.

Figure 55: Resulting Model -Vacant

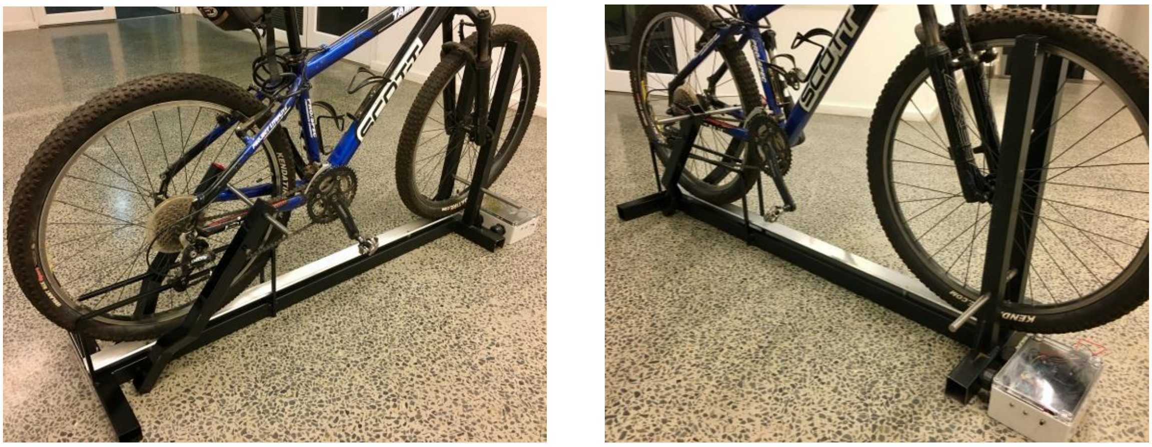


Figure 56: Resulting Model - Occupied

9.2 Tests Setup & Results

Five tests were executed to collect data in key performance areas of the resulting model. Tests relating to the mechanical frame's protection, the sensing system's performance, and the locking mechanism's performance were performed, with these producing quantitative performance data. Tests relating to the mechanical frame's sizing, and the solution's financial results were performed, producing more qualitative performance results.

9.2.1 Mechanical Frame

To determine the level of protection provided by the mechanical frame, destructive tests were performed to measure the duration required to remove the bicycle's critical components from the frame. As required by PDS 2.2 (*prevent the utilisation of specific tools on the* frame) and 2.3 (*provide physical resistance against a hacksaw*), the tools that were used during the experiment included a hacksaw, hammer, crowbar and 24" bolt-cutter. Two mechanical frames were produced, with the locking mechanisms on the frame replaced with steel locking mechanisms to prevent failure due to the locking mechanism developed in this model underperforming.

For the experiment, two candidates from the *University of Stellenbosch's Mechanical & Mechatronic* workshop, who has experience in using the toolset described, attempted to remove the bicycle from the mechanical frame using the mentioned tools. Table 21 presents the resulting mechanical frame performance for the most successful attempts (rom the *thieves'* perspective) using each tool. The tool used (attempt), the part of the frame that was targeted (targeted area), the duration required to physically breach the targeted part (breach duration), and the total duration required to remove the parts and thereby complete the whole theft (total duration) are presented in Table 21.

Table 21: Destructive Tests Results

Attempt	Targeted Area	Breach Duration	Total Duration
Hacksaw (a)	Rear Ø15mm steel rods	58 seconds	87 seconds
Hacksaw (b)	Rear locking mechanism arm	18 (*32) seconds	61 seconds
Crowbar	Rear locking mechanism hinge	Unsuccessful breach	
Bolt Cutter (a)	Rear locking mechanism arm	Unsuccessful breach	
Bolt cutter (b)	Ø15mm steel rods	Unsuccessful breach	
Hammer	Welds on the frame	Unsuccessful breach	
* refers to breach duration that includes time required to break the component using force additional to the tool used			

The most successful breach attempts were recorded using the hacksaw. The first hacksaw attempt (a) was aimed at cutting the Ø15mm steel rod that is placed through the rear wheel, thereby freeing the rear wheel and frame. The bicycle's front wheel is thus loosened from the bicycle and remains locked in the frame, and only the rear wheel and bicycle frame is stolen. Using a hacksaw with a new blade, the Ø15mm steel rod required 58 seconds to cut through the rod. The total duration of the theft required 87 seconds. The execution and result of attempt (a) is illustrated in Figure 57 below. The front steel rod could not be cut by the hacksaw as the wheel restricted access of the blade to engage with the rod.

Figure 57: Hacksaw Attempt (a)

The second hacksaw attempt (b) attempted to cut the locking mechanism arm just below the steel rod, and thereafter bending the remaining locking arm to remove the rod from the rear wheel. Using the hacksaw, the locking mechanism arm was cut through in 18 seconds, and the remaining arm bent open within a total of 32 seconds. The total duration of the theft was 61 seconds. The factors responsible for the weak performance in this case are the locking mechanism's arm material (too soft & thin), and the weak welds on the locking mechanism arm that allowed the arm to break, and thereby freeing the rear wheel and bicycle frame. The execution and result of attempt (b) is illustrated below in Figure 58.

Figure 58: Hacksaw Attempt (b)

The crowbar, bolt cutter and hammer were all unsuccessful. The hammer was unable to inflict any major damage, accept for material deformations – but not leading to weakening of the structure or components. The bolt cutter is only able to fit onto the Ø15mm steel rods, but no damage could be inflicted on the rods since the rods are too hard and thick for the bolt cutter's cutting capacity. All other frame parts were verified as inaccessible for the bolt cutter.

The crowbar was utilised at the rear locking mechanism's hinge. Although serious damage was inflicted on the frame, the frame could not be manipulated enough to allow any part of the bicycle to be released. Although the attempt was unsuccessful, the degree of damage inflicted on the frame implies that further improvements should be done in this area with continuation of the work. The execution and result of the crowbar attempt is illustrated below in Figure 59.

Figure 59: Crowbar Attempt

9.2.2 Sensing System

The sensing system's performance is determined by the accuracy through which it can identify and differentiate the disturbances affecting a bicycle that is docked in the frame. The ideal performance of the system is to identify and classify all actual attempts of theft on the bicycle as *intentional* actions, and to identify and classify all environmental disturbances or noise affecting the bicycle as *unintentional* actions. In the case that a signal which originates from an intentional source is classified as "unintentional" by the system, the error is termed as a *false-negative*. In the case that a signal which originates from an unintentional source is classified as "intentional" by the system, the error is termed as a *false-positive*.

Optimal system performance is thus where false-positives and false-negatives are at a minimum, and the detection duration of true-positives as low as possible. The system performance is thus determined by measuring the results of the system processing intentional signals (measuring false-negatives ad detection time), and of the system processing unintentional signals (measuring false-positives).

9.2.2.1 Intentional Signal Test

The system's performance when measuring intentional signals is derived from the fraction of false-negatives recorded, and the duration required for the system to detect true-positives. A false-negative occurs when the signal processing incorrectly indicates that a signal is identified as unintentional or idle, when in fact it is of an intentional source.

The experimental setup used to measure the sensing system's performance during intentional signal processing consisted of six candidates performing seven different intentional actions on the bicycle. The types of actions executed on the system during the experiment is determined by PDS 3.1 (*theft types to detect*). The results obtained from the experiments are presented below in Table 22.

Table 22: Results for Intentional Signal Processing

Candidate #	Action Executed and Relating Detection Duration						
	Remove Front Wheel	**Remove Handlebars**	**Remove Pedal**	**Remove Brakes**	**Remove Saddle Bag**	**Hacksaw on Rear Locking Arm**	**Hacksaw on Front Frame**
1	8.4 sec	4.9 sec	5.6 sec	9.2 sec	False-neg.	2.3 sec	22.1 sec
2	3.2 sec	22 sec	11 sec	1.2 sec	False-neg.	2.5 sec	False-neg.
3	3.1 sec	4.9 sec	9.6 sec	5.2 sec	False-neg.	3.4 sec	8.1 sec
4	2.1 sec	4.2 sec	4.1 sec	5.3 sec	9.2 sec	3.5 sec	9.2 sec
5	3.4 sec	11.5 sec	15.1 sec	25.3 sec	21.7 sec	5.1 sec	False-neg.
6	5.8 sec	5.4 sec	3.1 sec	7.1 sec	False-neg.	2.4 sec	7.4 sec
Detection Accuracy	**100 %**	**100 %**	**100 %**	**100 %**	**33 %**	**100 %**	**67 %**
Average Duration	**4.3 sec**	**8.8 sec**	**8.1 sec**	**8.8 sec**	**15.4 sec**	**3.2 sec**	**11.7 sec**

The results obtained from the experiments shows a general positive system performance. The detection duration and accuracy on the first four activities are very positive, with no false-negatives detected. An average detection duration of 8.6 seconds is obtained for all events detected. The detection of a hacksaw on the rear locking mechanism is also very positive with no false-negatives detected and an average detection duration of 3.2 seconds for all relating events. This specific area's results are very positive as it supplements the underperformance of the mechanical tests on the same component.

The detection of the *saddle bag removal* (saddle bag situated below the bicycle's seat) resulted in 33% detection accuracy, producing 4 false-negatives from 6 events. This results can be explained as resulting from the little effort and force required to loosen the saddle bag, making it a very difficult event to detect. The results obtained from this event is not deemed highly problematic, since the research activities showed that very few urban commuters leave accessories that can be easily removed on a docked bicycle. The *hacksaw on the front frame* produced 2 false-negatives from 6 events. Although the performance in this area is not acceptable, it is justified by the high performance of this specific scenario (hacksaw on front frame) in the mechanical frame test.

9.2.2.2 Unintentional Signal Test

The system's performance when measuring unintentional signals is derived from the fraction of false-positives recorded during constant signal processing. A false-positive occurs when the signal processing incorectly indicates that a signal is identified as intentional, when in fact it is of an unintentional origin.

The procedure used to measure the sensing system's performance during unintentional signal processing consisted of exposing the system to various direct unintentional disturbances, as well as to circumstances where unintentional environmental noise is effectuated on the system. The system is exposed to six types of disturbances during the experiment, with the types of disturbances motivated by the requirements defined in PDS 3.2 (*disturbances to ignore*). Table 23 presents the disturbance type, a description of the execution of the disturbance, the duration of the disturbance or the number of events relating to the disturbance, and the resulting false-positives detected during the execution of the disturbances.

Table 23: Results for Unintentional Signal Processing

Disturbance	Description	Duration / Events	False-Positives Detected
Environmental Exposure (a)	The system is placed in an on-street urban bicycle docking area, where environmental noise is captured. No direct or indirect contact with the system and other humans are made.	40 minute duration	none
Environmental Exposure (b)		40 minute duration	none
Neighbouring Dock/Undock Events	The system is fixed to a ground-anchored bicycle docking frame, thus causing the system to experience any noise resulting from neighbouring bicycles' docking and undocking events	8x neighbouring docking/undocking events	0 / 8
Simulated Wind	The docked bicycle is swayed side-to-side in a similar manner that wind is observed to affect a docked bicycle	30x induced oscillations	4 / 30 *(13.3 %)*
Impact on the Rear Wheel	Impulse forces applied to the rear wheel (as potentially experienced in a natural environment due to e.g. pedestrians)	5x from the back 5x from the top 5x from the side	0 / 5 0 / 5 1 / 5 *(6.67 %)*
Impact on the Front Wheel	Impulse forces applied to the front wheel (as potentially experienced in a natural environment due to e.g. pedestrians)	5x from the front 10x from the side	0 / 5 2 / 10 *(13.3 %)*
Impact on the Handlebars	Impulse forces applied to the handle bars (as potentially experienced in a natural environment)	10x from the side 5x from the top	2 / 10 1 / 5 *(20 %)*

The overall performance of the system during unintentional signal processing is highly satisfactory. During environmental exposure and neighbouring docking events, no false-positives were created by the system, generating major confidence for the system during idle and low-magnitude disturbances. The simulated wind disturbances generated 13.3% false-positives. Although this result is worrying, this disturbance type generated is representative of strong wind conditions, which is a circumstance that will be present at very low frequencies in the majority of urban implementations and therefore reduces the risk it presents. The disturbances on the front wheel generated 13.3% false-positives, and disturbances on the rear-wheel generated 6.67% disturbances. The performance in this area is still very positive since the impacts executed on the wheel was of a high magnitude, not to be experienced commonly on a docked bicycle. The impulse forces applied to the handlebars resulted in 20% false-positives. The reason provided is due to the oscillation generated when a force is applied to the handlebars, resulting in the noise-detection alarm producing the false-positive. This can be improved by further stabilising the bicycle in the frame to prevent oscillations after impact is experienced by the bicycle.

9.2.3 Locking Mechanism

The locking mechanism performance is dependent on three factors. The first is the reliability of the locking mechanism in successfully engaging and disengaging during locking and unlocking actions (PDS 3.12 - *Lock/Unlock Reliability*). The second is the degree of physical resistance provided by the locking mechanism against attempts to remove the locking pin (PDS 4.6). And the third is the locking mechanism's lock/unlock duration (PDS 4.4 - *locking duration*).

The reliability of the locking mechanism is tested by performing repetitive locking and unlocking cycles on the locks. A sample size of 20 lock-and-unlock cycles per lock (front and rear) was obtained. The results of the experiment is presented below in Table 24.

Table 24: Results for Locking Mechanism Reliability

Action	Front Lock			Rear Lock		
	Success	Fail	Success Rate	Success	Fail	Success Rate
Lock	19	1	95 %	20	0	100 %
Unlock	20	0	100 %	18	2	90 %

The lock reliability results are highly satisfactory. The worst reliability of a lock is found on the rear lock during unlocking events, with a success rate of 90%. The failed disengagements occurred due to internal friction on the locking mechanism's plunger and the frame's steel rod – resulting in a holding force on the plunger that is larger than the force applied by the mechanism's release spring. This error is overcome by slightly forcing the rod back into the lock to release the internal friction, resulting in the mechanism unlocking. The second worst reliability measured is the front lock during locking, at 95% reliability. The failed engagements occurred due to a misalignment between the keyways in the rod and the locking mechanism's plunger. The misalignment results from the rod not being pushed far enough into the locking mechanism. These error can be permanently prevented by increasing the force of the plunger's release spring, in order to prevent the steel rod from stopping the plunger from disengaging. Additionally, decreasing the steel rod's diameter by approximately 1mm to ensure that the rod is easily pushed into the locking mechanism.

The lock and unlock durations of the locking mechanisms were measured by hand, with 10 lock/unlock cycle's measured. The locking duration is observably higher, and therefore only the locking transaction is timed to determine the resulting system performance. The locking duration is measured as the time elapsed between the instances where the lock command is initiated, and where the system returns a successfully locked response. The resulting lockup duration is measured as an average of 1.38 seconds, which is a successful result. The results for the physical resistance provided by the lock is not tested, since the material used for manufacturing this model is not representative of the intended material to be used, and will therefore not provide meaningful performance results.

9.2.4 Financial Analysis

The financial expenses relating to the solution developed is calculated to determine the solution's cost performance relative to similar solutions. Table 25 provides the resulting costs associated with the solution. The *Model Costs* presents the actual development costs associated with the prototype model developed during the research, while the *Production Version Estimate* provides the estimated costs of a production version of the solution after the proposed recommendations have been incorporated. The *Production Version Estimate* integrates the sensing system, locking mechanism and control system hardware into one hardware component (as mentioned in the recommendations), thereby further reducing hardware expenses. The material costs are reduced by buying in larger quantities, and labour hours are reduced through decreased assembly and manufacturing requirements (experience curve). The labour costs are also decreased since less-skilled (lower-cost) labour can be used.

Table 25: Resulting Solution's Costs Analysis

Cost Element	Model Costs	*Production Version Estimate*
Material – Mechanical Frame	R 1 000	*R 600*
Labour – Mechanical Frame	R 1 280 (16h@ R80/hour)	*R 450 (9h@ R50/hour)*
Hardware – Sensing System	R 1 400	*R 550*
Hardware – Locking Mechanism	R 300	*R 120*
Hardware – Control & Integration	R 650	*R 50*
Labour – Final Assembly	R 640 (8h@ R80/hour)	*R 150 (3h@ R50/hour)*
TOTAL	**R 5 270**	***R 1920***

An indication of the system's cost performance determined by comparing it to the cost of implementing existing bicycle sharing systems, as well as alternative bicycle protection solutions. In 2016 the cost to implement a bicycle sharing system in South Africa that is produced by *Smoove* (a bicycle sharing platform manufacturer with systems implemented in Finland, Canada, France, USA and Russia), amounted to € 1,400 per bicycle (± R 21,000) – with cost including development, production, import and system implementation. The information was obtained in a meeting with Mr. G Le Berre, a project manager from *Smoove*. Additional competing solutions include existing bicycle locks, a bicycle tracker, and bicycle parking facilities provided by service providers or bicycle shops within the city. A comparison of the solution's cost performance relative to potential alternatives, is presented below in Table 26.

Table 26: Cost vs Protection Performance Comparison

Solution	Description	Cost	Relative Cost	Relative Protection
Smart Dock (production estimated)	Solution developed	R 1 920 / unit	(datum)	(datum)
***Smoove* System**	Bicycle sharing docking platform	≅ R 20 000 / unit	↓↓↓	0
Bicycle Parking	Enclosed, indoor bicycle storage provided by *Masons Bicycle Shop* in Stellenbosch	R 2 420 / year (R 10 / day @ 242 work days per year)	↓	↑↑
D-Lock	Steel u-type bicycle lock	R 300 / unit	↑↑	↓
Cable Lock	Combination-type cable lock	R 290 / unit	↑↑	↓↓
Bicycle Tracker	*Spybike* bicycle tracking unit	R1 100 / unit	↑	↓↓

Since various estimates are involved in these calculations, and also due to additional development costs required on the solution before it can be commercially implemented, the results obtained in Table 26 only provides a qualitative case that a production version of the solution is able to compete on a financial basis with other competing solutions. Although the D-lock, cable lock and bicycle tracker does perform better on a financial basis, the protection provided by any of these single units are much less than the protection provided by the docking solution developed in this research.

9.2.5 Frame Sizing

The PDS 2.8 (b*icycle sizes to accommodate*) and 2.7 (*types of bicycles accommodated by frame*) requires the solution to accommodate bicycles of all type, within the range of wheel sizes 24” to 29”. To validate the system achieving this requirement, bicycle fitting tests were executed with a broad range of bicycles within the specified frame and size range. *BMT Cycle Shop* and *Mason's Bike Inn*, two of the biggest bicycle suppliers in Stellenbosch (South Africa), participated in the validation tests. A mechanical frame prototype was taken to these two bicycle shops, with access provided to their whole range of bicycles within the stores. The widest possible range of bicycles in the specified wheel-size range was tested to see if they can be locked up by the frame. Three potentially-odd bicycles outside of the bicycle shops’ ranges were also tested. These include the *MTN Qhubeka Buffalo Bicycle*, the *Stellenbosch University Matie Bicycle’s (model 2016),* and the *210 OV Fiets (Matie Bicycle 2012 model)*.

All the bicycles fitted during the experiment was successfully locked up by the frame, with the “*Fat Tire Bicycle*” type being the only bicycle that was not compatible with the mechanical frame. This is due to the abnormally wide tires on the bicycle which prevents it from fitting into the frame. Since *Fat Tire Bicycle* are not commonly used for urban commuting but rather for rough-terrain cycling, it does not bear significant weight in the results of this experiment. The results for this experiment is therefore very positive, concluding the successful achievement of the universal sizing requirement of the solution. Figure 60 presents an example of a *Fat Tire Bicycle* that was not compatible with the frame.

Figure 60: Fat Tire Bicycle - *source: bicycling.com*

9.3 Compliance to Requirements

This section compares the results of the solution obtained in Section 9.2, to the various performance specifications and requirements derived at the initial stages as well as throughout the paper’s various development stages. The performance specifications used in the comparison specifically consists of the product design specifications (PDS) and technical performance measures (TPMs) developed throughout the research. The systems compliance to the TPM is presented in Section 9.3.1, followed by the systems compliance to the PDS presented in Section 9.3.2.

9.3.1 TPM Performance

The quantitatively measurable PDS are translated into the TPMs of the system. The performance of the various TPMs are presented below in Table 27. The table provides the TPM that is measured, the quantitative performance requirement that is associated with the TPM, the outcome achieved by the solution developed, and therefrom the solution’s compliance relative to the required TPM performance. The compliance to each TPM is finally expressed as a percentage value, which provides a standardised performance value that is achieved relative to the initial TPM target value.

Table 27: TPM Compliance Results

Source	TPM	Performance Requirement	Performance Achieved	% Achieved
Mechanical Frame	Resistance provided against a hacksaw	> 45 seconds	32 seconds	71 %
	Footprint size	0.6 m^2	0.526 m^2	100 %
	Bicycle docking & lock-up duration	< 23 seconds	29 seconds	80 %
Sensing System	False-negative rate	< 15%	≅ 8%	100 %
	False-positive rate	< 10%	≅ 15%	85 %
	Detection duration	< 25 seconds	8.6 seconds	100%
Locking Mechanism	Locking duration	< 2 seconds	1.38 seconds	100 %
	Lock reliability	> 95 %	96 %	100 %

All but three of the TPMs were achieved by the system. The first one that was not achieved, *resistance provided against a hacksaw*, is due to the material choice made for the locking mechanisms arm. This result can be improved by using a harder and thicker material type, or changing the design to make use of a solid, instead of hollow, arm. The second TPM, *bicycle docking & lock-up duration*, is only achieved by 80%. The performance of this TPM cannot be improved, since it is a result of the functional principle of the solution. The performance of this TPM, although not achieved, will not alter the performance of the overall solution significantly, and can therefore still allow a satisfactory solution performance. The third TPM, *false-positive rate*, relates to the system producing false alarms due to environmental noise that is mistakenly interpreted as attempted thefts. The underperforming of this TPM will require improvement as it significantly contributes to the system's general performance, and should be addressed in continuation of this research by improving the signal processing algorithm.

9.3.2 PDS Performance

The system's compliance to the binary and qualitative PDS are presented in this section. The PDS by nature capture the most important design requirements and specifications defined, and their performance therefore represents a valuable measurement of the solution's success. Table 28 presents the compliance results of the system relating to the various remaining PDS.

Table 28: PDS Compliance Results

Source	Product Design Specification	PDS #	Compliance
Mechanical Frame	Deploy solution as independent unit	2.6	ACHIEVED
	Types of bicycles accommodated by frame	2.7	ACHIEVED
	Ground anchoring method	2.9	n.a.
Sensing System	Sensitivity adjustment	3.3	*NOT ACHIEVED*
	Limit measurement scope	3.4	ACHIEVED
Locking Mechanism	Universal user access	4.1	ACHIEVED
	Source of control	4.2	ACHIEVED
	Lock/unlock status feedback	4.3	ACHIEVED
	Fail-safe locking	4.5	ACHIEVED
System Integration & Control	Universal user access	5.1	ACHIEVED
	User alerts and notifications	5.2	*ACHIEVABLE*
	Communication type	5.3	ACHIEVED
	Permission based access	5.7	*ACHIEVABLE*
	"Key-less" access	5.8	*ACHIEVABLE*

All PDS relating to the mechanical frame were achieved, accept for PDS 2.9, which is excluded from the direct scope of the project although it can still be achieved with further development of this solution. PDS 2.1 (*Bicycle components to be physically secured*) and 2.2 (*Prevent the utilisation of specific tools on the frame*) are not mentioned above, since these are successfully addressed by incorporating them into the data collection activities and performance tests conducted earlier in this section.

PDS 3.3, referring to the sensitivity adjustment of the sensing system, was not addressed in the solution provided. The principle on which the sensing system is developed, which uses threshold variables to classify the signals as intentional or unintentional, still allows room for incorporating the adjustment of the system's sensitivity with further development of the system. Although PDS 3.1 (t*heft attempts to detect*) and 3.2 (*disturbances to be ignored*) are not mentioned above, they are successfully addressed by being incorporated into the data collection activities and performance tests conducted earlier in this section.

All the above mentioned PDS relating to the locking mechanism were achieved. PDS 4.6 to 4.11 are also achieved yet not measured, since they were all successfully incorporated into the design process of the locking mechanism. The system integration and control solution successfully complies with PDS 5.1 and 5.3. PDS 5.2, 5.7 and 5.8 are not explicitly complied with in the resulting solution, but has been successfully incorporated into the design, and is therefore achievable with further development of the solution provided.

9.4 Summary

This chapter successfully presents the performance results of the resulting research model developed. The resulting solution's performance was successfully measured by executing five tests on various performance areas relating to the solution. The overall performance of the model is satisfactory, with the majority of the areas of performance complying with the requirements and specifications developed throughout the research. The mechanical frame showed satisfactory results on most of the methods required for protection, with only *resistance provided against a hacksaw* not meeting requirements. The sensing system's false-negative and detection duration performance are determined as complying to requirements, with the false-positive rate underperforming against its requirement by 15%. The locking mechanism's performance is measured as compliant to the requirements set, while the financial analysis also showed satisfactory improvements and potential benefits of the solution developed as measured against existing solutions. The frame sizing experiment revealed a very good performance, with all bicycle types except one, fitting into the frame. The system's compliance to its requirements are deemed predominantly positive. Certain areas are found as not complying with its requirements, but all of these show potential for compliance with continuation of the research.

10 Conclusion

Improving the cycling modal share in an urban environment is accompanied by extremely valuable and highly sustainable advantages for a wide range of stakeholders. Despite the strong presence and growth of recreational cycling in South Africa, the uptake of urban cycling is at a very low share. Bicycle theft and inadequate bicycle storage facilities for on-street urban bicycle storage were identified as contributing barriers towards this low adoption rate of urban cycling despite the high and growing adoption rate of recreational cycling.

A bicycle docking solution that is capable of providing urban commuters with on-street bicycle protection, by storing their bicycle during urban commuting stopovers, was developed during this research to address the identified barriers. The conceptual solution developed in this research incorporates the requirements and behaviour of three important stakeholders namely active cyclists, bicycle thieves, and a local municipal and academic institution, in order to ensure success and sustainable implementation of the solution from a holistic perspective.

The solution model presents a mechanical frame design that physically secures the three primary components of the bicycle, successfully improving on the degree of protection provided relative to existing locking solutions. The mechanical frame is locked up by a universal locking mechanism that is developed to allow electronic control of the locks, and thereby providing the possibility of universal and permission-based access to the system through a means such as a smartphone application. A theft sensing system was developed, with the sensors situated below the docked bicycle and able to capture and process any force that is applied to the bicycle or its components, in order to detect attempts of theft and therefrom enable relevant alerts or notifications. The dock also consists of machine-to-machine communication capabilities, allowing the dock to connect to the *internet of things* and enabling remote user access and cloud based database operations.

The resulting prototype model was evaluated by conducting five performance tests. The mechanical frame and sensing system showed a satisfactory performance, and thereby increased bicycle protection relative to existing solutions. The locking mechanism performance showed the required reliability and locking duration. A financial analysis was performed that indicates a favourable position of the resulting model, compared to existing solutions on the basis of financial costs in combination with the level of protection provided. The solution's performance is also measured against the various PDS and TPMs defined during the design stages, in order to determine the compliance of the solution towards the TPMs and PDS. The majority of TPMs and PDS were complied with, while the areas that were found as not complying with requirements all showing clear potential for compliance with the continuation of this research.

10.1 Evaluation of Objectives

The problem statement was systematically addressed by breaking it down into four main objectives. The outcome of these objectives are discussed throughout this section.

Objective 1: Define a set of requirements for a potential solution

The research activities conducted in Chapters 2 and 3 produced valuable insights around stakeholders, the current problem statement's status quo, and environment into which the solution should be implemented into. These served as a foundation for a representative set of requirements that was successfully defined in Chapter 4. Further derived requirements were also defined in Chapters 5 – 8, providing lower-level guidance for the solution to be developed.

Objective 2: Design a research model that addresses the requirements

The research model presented successfully incorporates the requirements defined in the first objective, while providing a concept that is capable of addressing the problem statement relevant to this paper. The model was developed in Chapter 4 by breaking up the general concept into four constituent functions, which are the mechanical frame, the sensing system, the locking mechanism, and the system integration and control. These functions were developed separately but interdependently throughout Chapters 5 to 8. The constituent functions were then integrated to create the resulting research model.

Objective 3: Produce a prototype model of the conceptual design

A functional prototype that represents the research model (developed in the second objective) was successfully produced, as is presented in Chapter 9. The prototype incorporates the majority but not all of the required functionality. The mechanical frame, sensing system and locking mechanism obtained very good functionality in the resulting prototype, while the system integration and control's functionality was not developed to the same extent as it is defined in the conceptual research model. The system integration and control hardware lacks the development of a full user database and cloud management platform. The user interface (smartphone application) was also not addressed. Although these aspects were not included in the physical prototype model, it does not hinder the measurement of the solution's performance relating to the problem statement addressed in this paper.

Objective 4: Evaluate the performance of the developed model

The level of protection that the solution provides, as well as the degree to which the solution adheres to the requirements and PDS defined, was successfully measured in Chapter 9. This provides the performance of the solution relating to the problem statement addressed.

The overall performance of the model is deemed satisfactory, with it meeting the majority of the requirements and specifications and successfully addressing the problem statement. The mechanical frame's results showed only one of the areas tested being unable to meet the required specification. The sensing system achieved full functionality and very good performance, with the false-positive rate not fully complying with its required specification. The locking mechanism produced good reliability and performance results, with the design and performance meeting the desired outcomes.

All PDS were achieved except for five. These include (1) the dock's required ground anchoring method, (2) the system's ability to adjust the sensing system's sensitivity, (3) user notifications and alerts, (4) permission based access and (5) key-less access.

10.2 Deductions

From the work completed it is deduced that an improvement in on-street urban bicycle protection can have an impact on the increase of urban cycling's modal share, and that this improvement can therefore be achieved by the solution presented in this paper. The holistic and requirement-drive approach followed in the development of this solution served valuable in developing the solution, while also providing further insights around the research problem addressed. It is seen that the mechanical locking frame that is developed throughout this research is able improve the physical protection of on-street bicycles while serving as a competitive financial alternative. The combined use of force transducers and signal processing is also found to be a possible solution in detecting attempts of theft on a bicycle. Furthermore, it is learnt that although the solution presented in this paper does hold potential in addressing the relevant problem statement, further improvements will be required to enable the solution to serve as a real-world implementation.

10.3 Future Work

Taking into account the above mentioned conclusions as well as the initial problem statement, the following recommendations for future work is made in order to improve the system performance and research contribution:

Sensing system optimisation:

Further optimisation of the sensing system to improve (decrease) the false-negative and false-positive occurrence rates. Improving the detection algorithm is recommended by using a larger and more in-field based set of data, to ensure more reliable and representative results. Also to improve the sensing system's hardware in order to reduce the noise present in the amplified sensor signal.

Mechanical frame material optimisation:

Optimise the materials used in the mechanical frame design. Investigate the potential of a reaction-injection moulded frame, in order to improve material strengths, decrease production costs at high quantities and to improve manufacturability.

Communication capabilities:

Improve the current communication hardware used, in order to enable the docks to communicate independently of an available Wi-Fi network (as currently required).

Locking mechanism improvement:

The locking mechanism was not exposed to destructive tests within this research scope. It is recommended that the locking mechanism be produced in the form of a proof-of-principle prototype consisting of the as-designed materials, and then be exposed to destructive tests to determine the mechanisms degree of protection. Also, investigate the internal mechanics of the locking mechanism to increase reliability and durability against vandalism.

System database & user application:

The system database responsible for user management, dock allocation and user payments should still be designed and developed if the implementation of the system is to be realised. Also, the user interface (proposed as a smartphone application) should be developed to provide a system-user interface for the solution.

Appendices

Appendix A Research Interviews

Age
<18 | 19-25 | 26-34 | 34-42 | 42+

Gender
Male | Female

How often do you use your bicycle? (on average)
3 + times / week | 2 times / week | Once (1) / week | Once (1) / 2 weeks | Once / month

What type of cyclist are you?
Recreational | Urban Commuter | Both

What form of transport do you use the most in your urban environment? *
Cycling | Car | Walking | Bus/Taxi | Other

What is your average URBAN commuting distance when using a bicycle?
-1km | between 1-3km | between 3-5km | between 6-8km | 8km+

What proportion of your urban commuting is done by bicycle? *
0% | 0-25% | 25-50% | 50-75% | 75-100%

Why do you think urban cycling can be valuable to an individual who cycles? *

Why would you NOT choose a bicycle as form of commuting in an urban environment? (barriers towards urban cycling) *

Why do you think large-scale urban cycling can be valuable to a city and to society? *

How many bicycles have been stolen from you in an urban environment?
0 | 1 | 2 | 2+

Have any bicycle parts been stolen from your bicycle in an urban environment? Which parts. *

How far are you willing to cycle during urban commuting?
<1km | Between 1-3km | Between 3-5km | Between 5-8km | 8km +

If a platform exists in your urban environment that enables you to SAFELY LOCK your bicycle close to your destination(s), removing the possibility of bicycle THEFT. What percentage of your urban commuting trips (motorised trips) will be replaced by cycling?
0% | 0-10% | 10-30% | 30-50% | 50-75% | 75-100%

If a platform exists in your urban environment that makes it MORE CONVENIENT to quickly and easily LOCK-UP your bicycle, and also SUPPLY you with the necessary locks. What percentage of your urban commuting trips will be replaced by cycling? *
0% | 0-10% | 10-30% | 30-50% | 50-75% | 75-100%

What are the 3 most important characteristics that you would like such a platform to have? *
Protect bicycle from theft | Quick bicycle lock-up time | Easy to use | Low user cost | environmentally friendly | aesthetically pleasing

What other characteristics would you like such a platform to have?

If a bicycle-sharing system existed in Stellenbosch, what percentage of your urban commuting trips will be replaced by cycling? (bicycle-sharing enables you to obtain a shared bicycle at various locations throughout a city and then return the bicycle to any of the other stations when you're done using it) *
0% | 0-10% | 10-30% | 30-50% | 50-75% | 75-100%

How much will you be willing to pay to lock your bicycle in one of the platform's docks (as described in the questionnaire), in order to keep your bicycle safe from theft.
R0 | R0 - R3 / hour | R3 - R6 / hour | R6 - R9 / hour | R9 - R14 / hour | +R15 / hour

In the case of the ideal urban cycling environment (no theft, easy cycling), would you prefer to use your personal bicycle or a bicycle-share system's bicycles for commuting? *
Personal bicycle | Bicycle-share system's bicycles

Appendix B Interviews with Individuals Involved in Bicycle Theft

What are the motives behind bicycle theft? Why do people steal bicycles?
Sell the bicycles to fund drug habits.
What are the bicycles used for after they are stolen?
They break up the bicycle into various parts, or sells the bicycle as a whole. The bicycle parts are then bought and added onto their existing bicycles. An "expensive" bicycle (in the region of R24 000) that is stolen will be sold for about R2 000 – R3 000, and the cheaper bicycles will be sold for R150 – R200.
What other uses do you have for bicycles or bicycle parts besides uses for cycling?
Nothing. They don't sell it for eg. metal smelting, only for actual cycling use.
What are the types of bicycles that are stolen the most and why?
They go for the "disc brake" bikes, because they are good bicycles. (*the assumption is made that the "disc brake bicycles" refer to better and more valuable bicycles, as this is a newer technology.)
Bicycles closer to a mountain bicycle, and not the "thin wheeled" (road) bicycles.
Why will a bicycle not be stolen?
If it is very old and not worth much it is not a big priority to steal, but it does not mean it will not be stolen. If it is a "thin wheeled" (road) bicycle.
The bicycles with back-pedal brakes will also be stolen, it does not matter. They still brake it up into parts and sell those parts. Even unique bicycles such as the Maties Bicycle will be stole as they frame can be resprayed and the parts once again broken up.
Would you steal bicycle part if you are not able to steal the bicycle as a whole?
Yes. Most certainly! Any bicycle part will be stolen.
What are the bicycle parts that gets stolen if the bicycle as a whole can't get stolen?
Anything! The wheels and the frame are the ideal, BUT the seat, gears, handlebars etc. will all be stolen if that is what they can reach. Even the brakes are not much effort to steal. If you want to protect the bicycle you must protect the whole bicycle!

<u>Methods</u>
And are they order by other individuals to specifications?
There is a main syndicate(s) who has people working for him. He will then request people to go and steal the bicycles, which they will then bring to him. He will then pay them for the bicycles, and he then manages the sales of the bicycles and the parts from there. Usually to close by neighbourhoods, or sometimes to nearby cities.
Is the stealing of bicycles a spontaneous event, is it planned and then executed.
The people therefore go with the intention to steal a bicycle, and it's not opportunistic or spontaneous.
What are the factors that require great consideration when steeling a bicycle? What do you look out for?
The person also gives details of the bicycles when he requests bicycles to be stolen. The type of bicycle is therefore determined to a large extent by the person requesting the bicycle theft.
How is a bicycle deemed steal-able, in terms of the environment, time, and locking methods? What do seek out when stealing a bicycle?
Night time is ideal, but does not limit the times to stealing a bicycle.
Even outside the mall will be a place where you steal bicycles. We help each other to keep others busy, and the other one steals the bicycle.
Explain the procedures involved when stealing a bicycle?
Look for a vacant are, have the bolt cutter in your back pack. Remove the bolt cutter, cut the chain and drive away with the bicycle.

Explain the methods & tricks used when stealing a bicycle?
Round bar leverage, hammer, bolt cutter, crowbar, hacksaw, steel saw.
What will deter someone from stealing a bicycle?
Cameras, people are afraid to steal where there is cameras. But if people can reach the camera they will cover it and steal the bicycle.
Also, where people and movements is, it's not ideal.
Sensors & alarms play a big role to deter thieves from stealing a bicycle. If you can see alarms and sensors on a bicycle it will deter a thief.
As soon there is attention drawn towards an individual, it will keep him from stealing the bicycle.
What locks/ways of securing a bicycle makes it really easy for you to steal a bicycle?
Any chain or cable that can fit into a bolt cutter is easy to cut open. The thieves walk with a bolt cutter in their back pack, and then simply cut the chain or cable. Locks are also not difficult to remove. If thicker steel/cable is used, a saw will be used to cut through it, which will make it more difficult.
What are the most effective ways that people protect bicycles?
A bicycle tracker is the best way. The tracker sits in the frame and we don't look fr that. It's also a quick for the police to find the bicycle.
No lock or chain or cable really help. It's really not that difficult to seal a bicycle.
Is the time spent to remove a bicycle a big consideration? Will you go for they bicycle that can be stolen the quickest?
Not really, we will put in the time to steal the bicycle that we want to.
What effect does people have on location of stealing a bicycle? And also to have attention drawn to you by other people? DO you care if someone except the police notice?
Not really. If the police doesn't see you it's not that big deal. The thief knows the short cuts and knows how to get out of that area. He therefore knows that he can run if someone responds, and will then still try to steal the bicycle.

Concept Evaluation

If an individual does not know what is in eg. a box, will that have an effect on whether he/she will go through the trouble to steal it?
We will do effort or make a plan to see what is in the box. But it will make it less attractive if we cannot see what is in the box.
Will cameras have an effect on the decision of stealing a bicycle?
Yes. We will be very cautious to enter where there is cameras.
Will an alarm have an effect when stealing a bicycle?
Yes if an alarm sounds during a bicycle theft, that bicycle will immediately be left alone and we will run. (put an alarm on the bicycle so that it sounds when it leaves. Or put a way of marking the bicycle when it was stolen)
Will motion detection lights have an effect on stealing a bicycle at night? And what is the effect of lights in general?
Not really. The lights will not make a big difference at night.
What will the effect of theft detection sensors & equipment be?
Yes if we know there is sensors & security on a bicycle we will not get there!
Ask opinions on materials: Chains (sizes), cable(sizes), cloth, steel pipes, square tubing, flat bar, plastic, rope.
All materials are the same if it can fit into a bolt cutter. If it is bigger and has to be cut through, it makes a difference
Is it a good idea to make it as clear as possible the sensors and equipment on the bicycle? Thus is it a good idea to make it clear that a bicycle is not easy to steal?
Yes for sure, make it clear that there is protection on a bicyce!!

What will be your suggestions for keeping a bicycle safe from theft?
Use electric shock on the locking mechanism to protect the bicycle.
Use cameras also, put them where we cannot reach them.
Even if there is only an alarm and it is not necessarily connected to a response team, it will also deter the thief.
Design Concept Evaluation: Discussed concept principle 4, and the response was positive and the interviewees agreed that it is a good method for protecting the bicycle.

Appendix C Ethical Clearance Reference Document

Approval Notice
New Application

29-Mar-2016
Swanepoel, Mardu MC

Proposal #: SU-HSD-002129
Title: Development Of An Urban Cycling Platform

Dear Mr Mardu Swanepoel,

Your **New Application** received on **03-Mar-2016**, was reviewed
Please note the following information about your approved research proposal:
Proposal Approval Period: **17-Mar-2016 -16-Mar-2017**

Please take note of the general Investigator Responsibilities attached to this letter. You may commence with your research after complying fully with
these guidelines.

Please remember to use your **proposal number** (**SU-HSD-002129**) on any documents or correspondence with the REC concerning your research
proposal.

Please note that the REC has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor
the conduct of your research and the consent process.
Also note that a progress report should be submitted to the Committee before the approval period has expired if a continuation is required. The

Committee will then consider the continuation of the project for a further year (if necessary).
This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki and the Guidelines for Ethical

Research: Principles Structures and Processes 2004 (Department of Health). Annually a number of projects may be selected randomly for an external
audit.

National Health Research Ethics Committee (NHREC) registration number REC-050411-032.
We wish you the best as you conduct your research.
If you have any questions or need further help, please contact the REC office at 218089183.

Included Documents:
DESC Report
REC: Humanities New Application

Sincerely,

Clarissa Graham
REC Coordinator
Research Ethics Committee: Human Research (Humanities)

Appendix D Derived Requirements

Table 29: Derived Product and User Requirements

Requirements				
#	**Requirement**	**Rank (/ 5)**	**Requirement Source**	**Implication**
1.1	Protect the docked bicycle from theft	5	Research Question	Provide the required level of protection to any bicycle that is docked in the system
1.2	Detect attempts of theft on the bicycle	5	Interviews – Ch. 3.2	Incorporate a sensing method that can detect attempts of theft on a docked bicycle
1.3	Prevent physical removal of certain bicycle parts	5	Bicycle Sharing – Ch. 2.6	Provide required mechanical locking capabilities
1.4	Alert, notify and communicate remotely	5	Bicycle Sharing – Ch. 2.6	Provide remote communication capabilities
1.5	Improved protection performance compared to conventional locks	5	Bicycle Locks – Ch. 2.4	Greatly increase the level of protection provided to a bicycle (relative to the level provided by conventional U-locks & D-Locks)
1.6	Primary protection of critical components	5	Interviews – Ch. 3.2	The bicycle frame and wheels should be given higher priority in terms of protection, as these are defined as the "most wanted" parts by bicycle thieves
2.1	Fixed-portable design	4	Bicycle Sharing – Ch. 2.6	The dock should have the characteristics of a portable-modular unit (as used in the fixed-portable bicycle sharing systems)
2.2	Low false alarm rate	4	Bicycle Locks – Ch. 2.4	A low false-alarm rate is required, through accurate differentiation between theft and noise
2.3	Low end-product cost	4	Authorities – Ch. 3.3	The final product should be low-cost, reducing the financial burden on authorities involved in implementation
3.1	Low theft detection duration	3	Interviews – Ch. 3.2	Detect attempts of theft as quickly as possible
3.2	Urban Implementation	3	Bicycle Sharing - Ch. 2.6	Focus on urban implementation of the system, specifically in public spaces
3.3	Remove dependency on user-provided lock	3	Bicycle Locks – Ch. 2.4 & Interviews – Ch. 3.1	Remove the user's burden of providing and carrying a locking mechanism
3.4	Handle outdoor conditions	3	General	Be able to handle conditions associated with outdoor implementation
3.5	Accommodate all common urban-commuting bicycle types	3	Users – Ch. 3.2	Should accommodate the most common types of bicycle that are likely to commute in an urban environment.

3.6	Protect all bicycle parts	3	Users – Ch. 3.3	A certain element of protection should be provided for all bicycle parts as thieves "will steal anything they can get"
3.7	Small ground space usage	3	Authorities – Ch. 3.3	Take up as little ground space as possible when installed
3.8	Universal user access	3	Bicycle Locks – Ch. 2.4	The locking capabilities should be universal i.e. it can be used without requiring physical possession of an access key
3.9	Quick lock-up procedure	3	Users – Ch. 3.2	Require very little time to engage a dock, insert your bicycle and lock it up
3.10	Permission based access	3	Bicycle Sharing – Ch. 2.6	Manage who are able to dock and undock bicycles in the system
4.1	Protection Scope: Opportunistic thieves	2	Bicycle Locks – Ch. 2.4 & Interviews – Ch. 3.1	Accommodate for protection against opportunistic thieves (scope: tools, area, circumstances) only. Professional thieves are very difficult to stop, and occurrence by professional thieves are much lower.
4.2	Keep theft detection method a secret	2	Interviews – Ch. 3.2	If thieves know how a system detects theft, they can more easily bypass it. Therefore prevent thieves from knowing the method used to detect theft
4.3	Non-damaging design	2	Users – Ch. 3.1	Should not damage a bicycles that interacts with the dock
4.4	Easy to use	2	Users – Ch. 3.2	Be more user friendly than existing methods of bicycle protection. Referring to portability, locking method and usage
4.5	Constant space efficiency at any dock size	2	Authorities – Ch. 3.3	Space efficiency should stay constant regardless of the number of docks installed
4.6	Potential to be conveniently located/installed (city centres)	2	Authorities – Ch. 3.3	The areas where cycling is the most effective are in busy areas. The dock's implementation requirements and characteristics should fit accordingly

Appendix E Engineering Characteristics

Table 30: House of Qualities Analysis

House Of Qualities

Num	Requirement	Importance		High material strength	High theft detection accuracy (sensors)	Low theft detection duration (sensors)	Low false alarm rate (sensors)	Lock/physical-protection breaching durati	Bicycle lock-up duration	Remote communication capability	Communication range	Semi-permanent ground anchoring	Material cost	Manufacturability	Ground space usage (footprint)	Universal system access	Weather proof	Universal fitting of bicycles	Prioritised protection scope	Non-damaging of bicycles	Ease of use	Constant space efficiency	Energy consumption	Service and maintanance required
	Direction of improvement			↑	↑	↓	↓	↑	↓	↑	↑	↑	↓	↑	↓	↑	↑	↑	↑	↓	↑	↑	↓	↓
	Unit			n.a.	%	sec	%	sec	sec	n.a.	km	n.a.	R	n.a.	m2	n.a.	n.a.	%	n.a.	n.a.	n.a.	n.a.	Wh	n.a.
1.1	Protect bicycle from theft	5		5	5	5	5	5	1									5	1					
1.2	Detect Attempts of theft on the bicycle	5			5	3	3																	
1.3	Lock the bicycle to prevent unauthorised acces	5		5				5								1		1						
1.4	Be able to allert, notify and communicate remot	5			5	3	3	1		5	3													
1.5	Performance compared to conventional locks	5		5	3	3	3	5	3	1			1		1			1						
1.6	Primary protection of critical components	5		3	1	1	1	5											5					
2.1	Fixed-portable design	4								5	5	5			5							1	3	
2.2	Low false alarm rate	4			5	3	5																	
2.3	Low end-product cost	4										5	5	5										3
3.1	Low theft detection duration	3			1	5	1																	
3.2	Urban Implementation	3						1		1	3	5			5	1						3	1	
3.3	Remove dependancy on user-provided lock	3		1				3		3								3	1					
3.4	Handle outdoor conditions	3															5							3
3.5	Accommodate all urban-commuting bicycles	3														1		5						
3.6	Protect all bicycle parts	3		5	5	3	3	5										3	5	1				
3.7	Small ground space usage	3										3			5									
3.8	Universal user access	3							3	5						5		5						
3.9	Quick lock-up procedure	3						1		3										1				
3.10	Permision based access	3								3						1								
4.1	Protection Scope: Opportunistic thieves	2		3	3	1	1	5																
4.2	Keep detection method a secret	2			1																			
4.3	Non-damaging design	2						1	1											5				
4.4	Easy to use	2						1	5											3	5			
4.5	Constant space efficiency at any dock size	2													5							5		
4.6	Potential to be conveniently located/installed	2										5	3	1	3		3						3	
	Raw score:	**1282**		114	141	113	109	149	41	95	44	74	31	22	71	29	21	83	48	22	10	23	21	21
	Relative weight	**%**		8,9	11	8,8	8,5	12	3,2	7,4	3,4	6	2,4	1,7	6	2,3	1,6	6,5	3,7	1,7	0,8	1,8	1,6	1,6
	Rank order			**3**	**2**	**4**	**5**	**1**	**12**	**6**	**11**	**8**	**13**	**16**	**9**	**14**	**18**	**7**	**10**	**16**	**21**	**15**	**18**	**18**

Table 31: Ranked Engineering Characteristics

Engineering Characteristics			
Num. #	**Characteristic (Description)**	**Rank**	**Relative Weight**
5	Lock/physical protection breaching duration (i.e. level of safety)	1	11,60%
2	High theft detection accuracy (sensors)	2	10,90%
1	High material strength/protection	3	8,90%
3	Low theft detection duration (sensors)	4	8,80%
4	False alarm rate (sensors)	5	8,50%
7	Remote communication capability	6	7,40%
15	Universal fitting of bicycles	7	6,40%
9	Semi-permanent ground anchoring	8	5,70%
12	Efficient ground-space usage (footprint)	9	5,50%
16	Prioritised protection scope	10	3,70%
8	Communication range	11	3,40%
6	Bicycle lock-up duration	12	3,10%
10	Material cost	13	2,40%
13	Universal system access	14	2,20%
19	Constant space efficiency	15	1,80%
11	Manufacturability	16	1,70%
17	Non-damaging when docking	16	1,70%
14	Weather proof	18	1,60%
20	Energy consumption	18	1,60%
21	Service and maintenance required	18	1,60%
18	Ease of use	21	0,70%

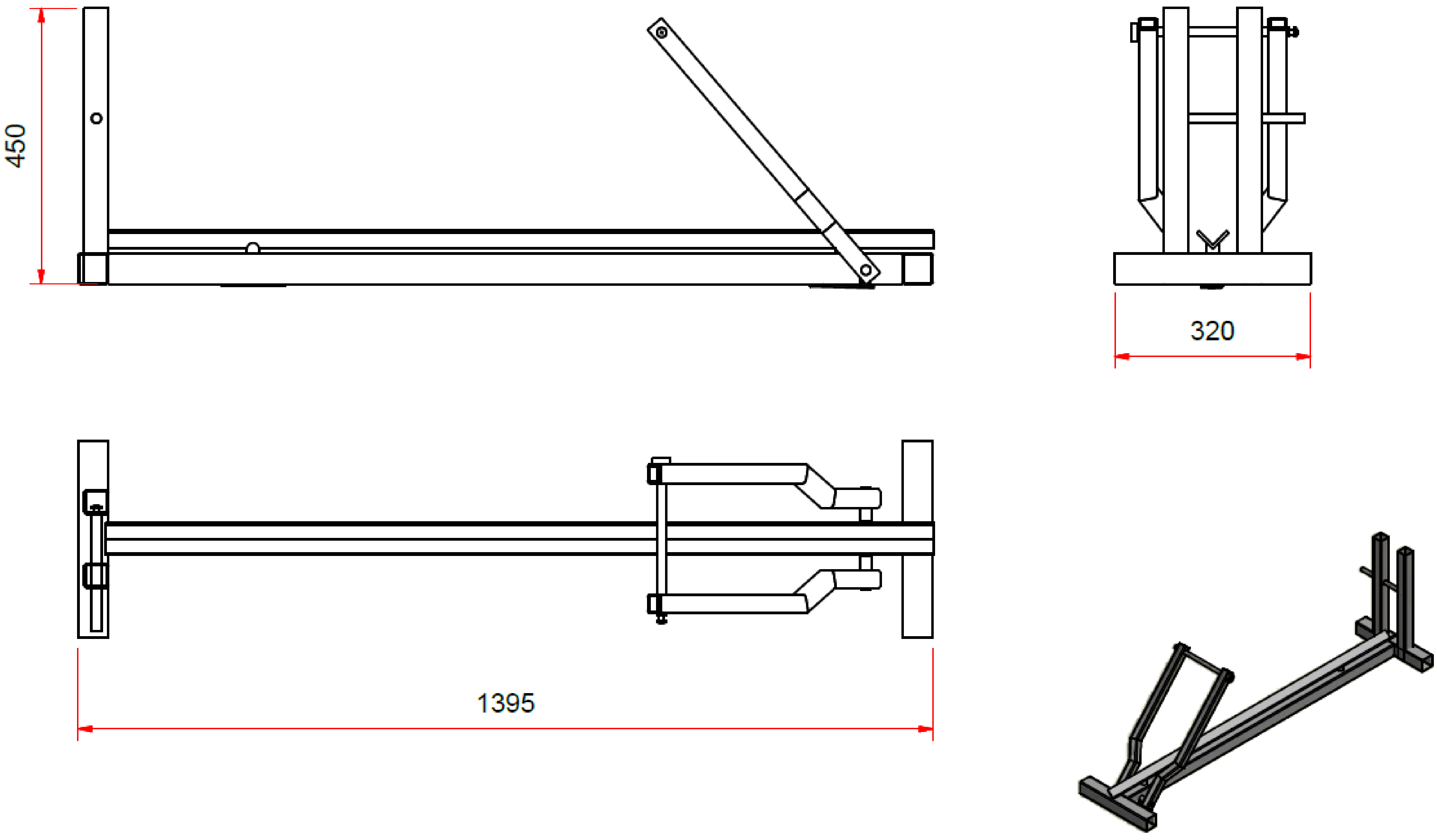
Appendix F Bicycle Dataset

Table 32: Bicycle Dataset Used in Dock Sizing

Manufacturer	Model	Bicycle Type	Wheel Base (mm)	Wheel Size (mm)
Buffalo		Cross Country	*1130*	*635*
Matie Bicycle		Urban Cruiser	*1110*	*685,8*
Scott	spark 910	Mountain Bike	*1170*	*736,6*
	genious lt 720	Mountain Bike	*1218*	*736,6*
	voltage 730	Mountain Bike	*1225*	*698,5*
	foil 20	Road Bicycle	*1012*	*736,6*
	solace	Road Bicycle	*1012*	*736,6*
	contessa	Road Bicycle	*967*	*736,6*
	Sub Sport	Urban Cruiser	*1119*	*698,5*
Trek	1 series	Road Bicycle	*1008*	*700*
	Crocet 9	Cross Country	*1043*	*700*
	Top feul 9	Mountain Bike	*1234*	*698,5*
Merida	1-20-7000	Mountain Bike	*1191*	*700*
	Reacto	Road Bicycle	*974*	*635*
Specialized	demo 8 carbon	Mountain Bike	*1248*	*698,5*
	Venge pro vias	Road Bicycle	*969*	*700*

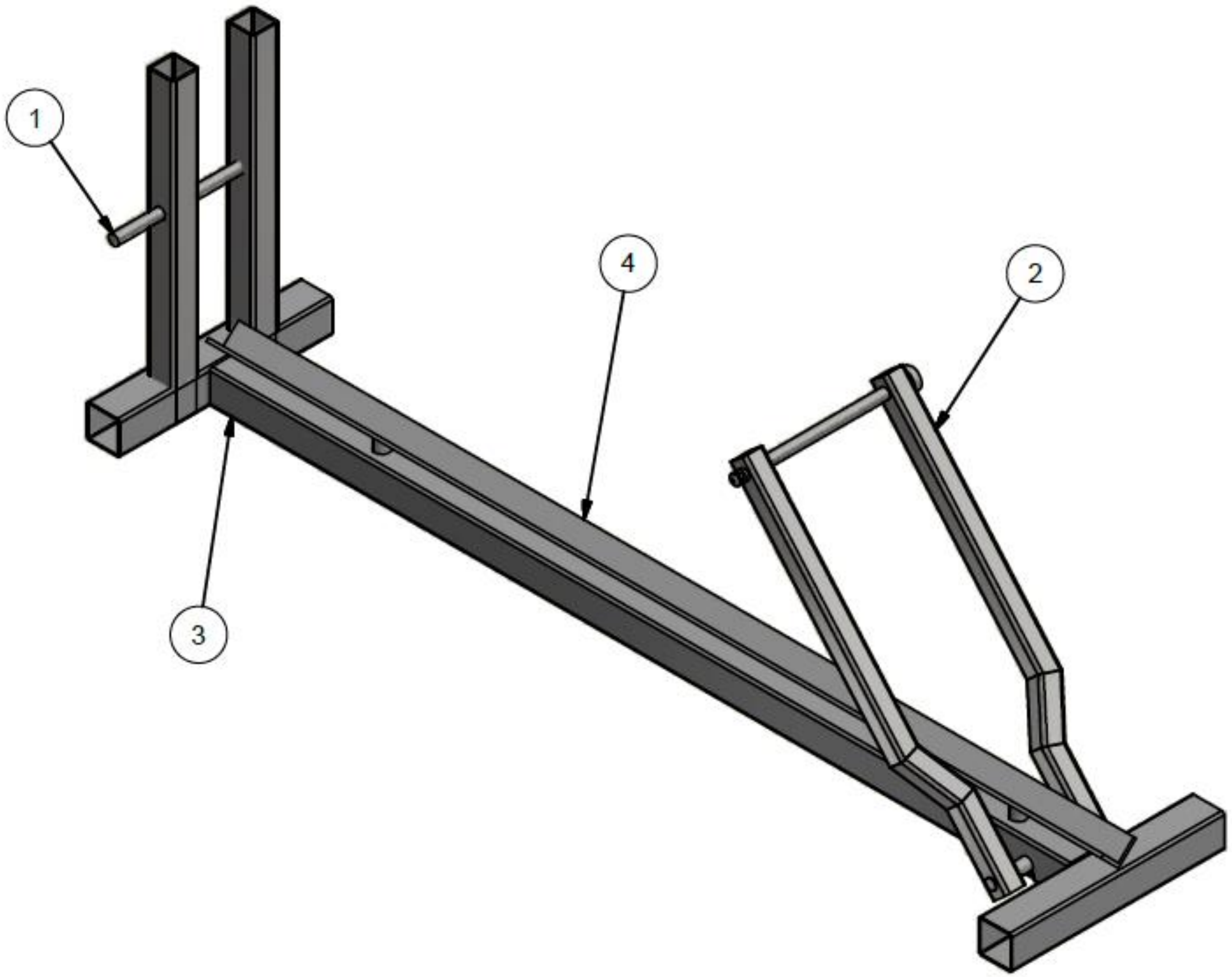
**The data used for the bicycles were all sourced from the respective bicycle manufacturer websites.*

Appendix G Mechanical Frame: Detailed Design Drawings



ITEM	BESKRYWING	AANTAL	MATERIAAL / SPESIFIKASIES

UNIVERSITEIT VAN STELLENBOSCH	SKAAL OP A 1 : 9 MATE IN mm	TITEL: MECHANICAL FRAME DESIGN	
STUDENTE No. 16951581	TEKENAAR M Swanepoel	NAGESIEN	
DATUM 08.2017	VEL No.	VAN VELLE	No.



4	Force Bed	1	Ref. - Drawing Pack
3	Base Frame	1	Ref. - Drawing Pack
2	Rear Lockng Unit	1	Ref. - Drawing Pack
1	Front Locking Unit	1	Ref. - Drawing Pack
ITEM	BESKRYWING	AANTAL	MATERIAAL / SPESIFIKASIES

UNIVERSITEIT VAN STELLENBOSCH		SKAAL OP A 1 : 8 MATE IN mm	TITEL: MECHANICAL FRAME ASSEMBLY
STUDENTE No. 16951581	TEKENAAR M Swanepoel	NAGESIEN	DATUM 08.2017	VEL No. VAN VELLE No.

Appendix H Pilot Test User Feedback

Table 33 contains the feedback received from the docking station's pilot project participants. The feedback was received via email after completion of the pilot test.

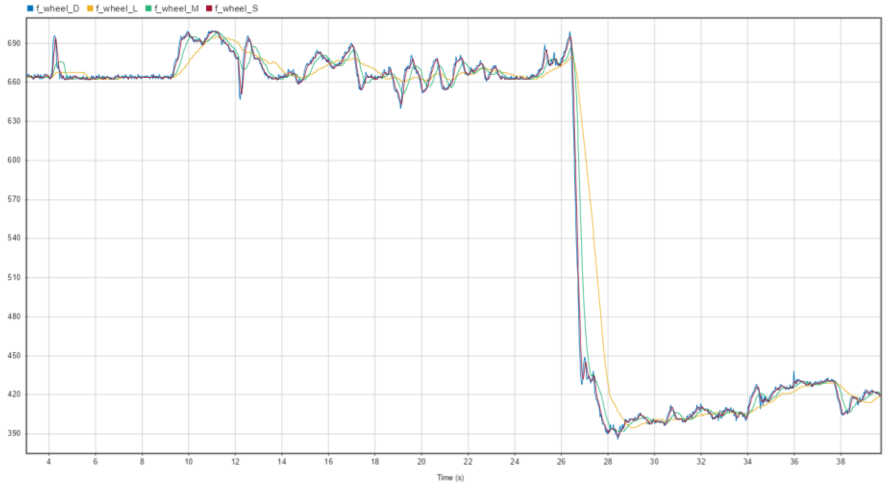
Table 33: Pilot Participant Feedback

Question	User 1	User 2	User 3	User 4
What is your general impression of the method used to lock the bicycle? Please explain your opinion.	General impression is good. The dock is stable and sturdy and gives the impression that the bike will be safe.	I liked the idea that I only needed to carry a key with me and that a lock wasn't necessary whilst using the dock. I also liked knowing that the tires is locked safe and that it can't be stolen while my bike is stored in the dock. However, trying to balance the bike while lifting the arm and putting the steel rod through the front wheel was a bit tedious.	With regards to safety I think the bike dock would be difficult to break open to get to the bike. I do however think that the hollow steel bars might not be as dettering as the tempered steel shafts going through the bike spokes. The method to lock the bike is also not easy to do with one hand (as your bike is held with your other hand). Once the bike is on the stand, the locks are easily inserted.	Very interesting and novel way of locking the bicycle, does seem like a safe way. The method uses little material to lock the important parts of your bicycle, which is great.
What way of locking your bicycle would you prefer between the Smart Dock, your conventional method of docking, and any other method you know of?	I would still prefer locking my bike the conventional way I am using at the moment on the grounds of the time I spend locking my bike. The conventional method is quicker. On grounds of safety and carrying a lock, I prefer the dock.	It depends, because the Smart dock assures that my bike's wheels are locked safe as well, in an area where a lot of bikes / wheels are stolen I would prefer the smart dock. But because it can take a bit longer to lock the bike in a smart dock, time wise, i would rather prefer the conventional way of docking.	I do prefer my own method as I can park my bike in visible areas with more pedestrian traffic. I am not always comfortable with my bike being in a far away corner. Also I would like to park my bike as close as possible to where I am so that I don't need to walk very far to reach my bike.	At the moment my own, as it is easier and much quicker than the smart dock. But if the smart dock could be improved to lock up quicker and easier I would certainly prefer that as it is much safer.
What did you like about the dock? Why did you like those specific factors?	I liked the opportunity to lock both the front and rear wheel. I appreciate the dimensions of the front wheel arches, it accommodates different wheel sizes and thus not damaging the rims.	I liked the fact that i didn't need to be concerned about whether there would be a space for me near the faculty to lock my bike, because only i had a key to that specific dock. As mentioned earlier it is much more convenient to only carry a key with you and not a lock as well, and that my bike is	I liked that it felt that the bike was safe.	That it provides much better protection than a conventional lock that one caries around with you. Also, that you do not have to carry the lock with you, but simply the key.

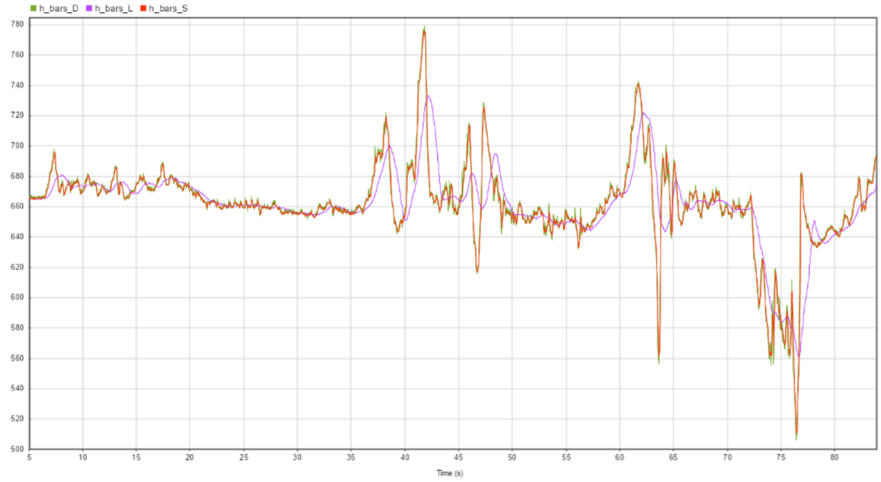
		safe, even the tires can't be easily stolen by using a ball cutter to cut a conventional chain lock.		
What did you not like about the dock? Why not?	I did not like the "trouble" needed to go through to lock the bike; reason being time it takes compared to my conventional way. I also did not like the bike being able to lean sideways (not being upright); reason being ease of locking bike.	Trying to balance the bike while lifting the arm and putting the steel rod through the front wheel was a bit difficult/tedious.	It was a little big (I think more bikes could be parked using less space), it was sometimes hard to get the bike on the stand and locked, there were sharp manufacturing edges and i once got my finger caught between two steel pieces.	It is difficult to insert and remove the bicycle from the dock. Also, the bicycle does not stay upright when placed in the dock.
Are there ANY improvements that you can suggest for the dock?	I would suggest extending the front wheel arches in the longitudinal (bike length) direction to allow the bike to stay upright. This may also help with the ease of locking the bike, allowing the dock to support the bike while opening the locks.	The arm that needs to be lifted the whole time can maybe be kept in a more upright position the whole time. The rods that is needed to push though the wheels can be held in place the whole time by some sort of groove so that it wouldn't fall on the ground.	I think the front lock could be smaller and lock the bike at a different spot, the back lock would work great if triggered by a spring mechanism that goes up when your bike is put on it.	Having the locking pins release with a spring when unlocked. And providing support for the bicycle to stand upright during docking.
Any other comments or remarks?	I think the dock is good and think a more revised version and working towards making it electronic will be great. My biggest critique is the ease of locking and the time it takes locking the bike.	The saddle is still not locked and can also be stolen. Other than that I think it is a very good concept and definitely hope to see being used in the future more often.	Good idea! needs some work/iterations.	Great idea, much needed solution. Can do with some more refinement.

Appendix I Signal Processing Data Capture

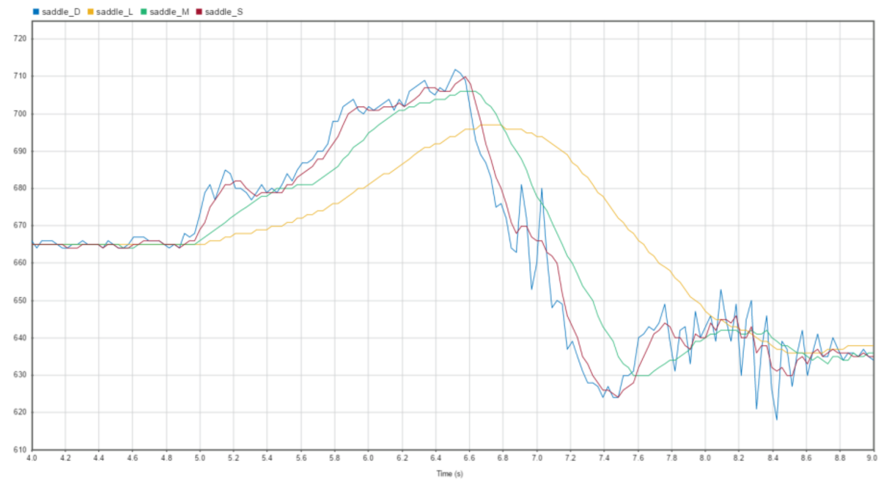
<u>Intentional signal origin</u>: Front wheel being removed.
<u>Signals shown</u>: raw, averaging filter (low, medium, high)



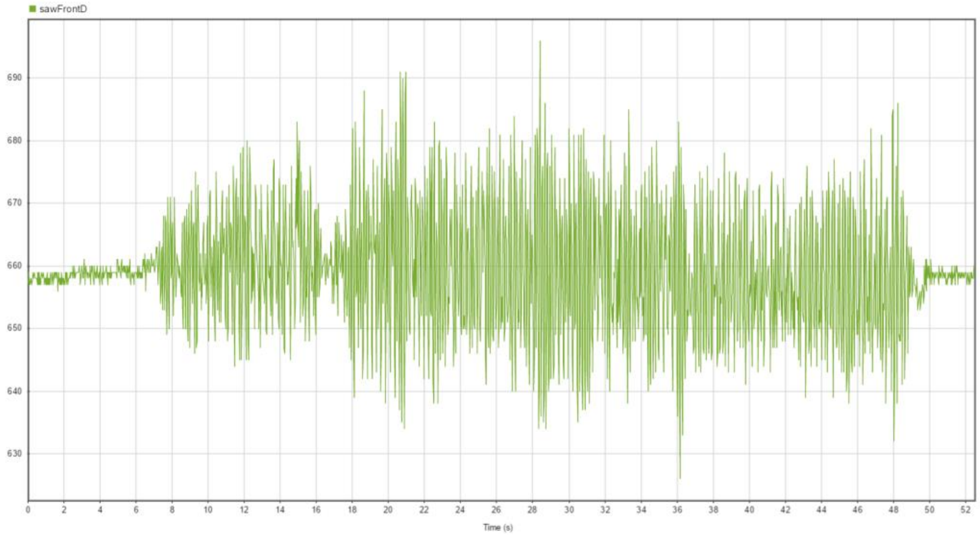
<u>Intentional signal origin</u>: Handlebars being removed.
<u>Signals shown</u>: raw, averaging filter (low, medium, high)



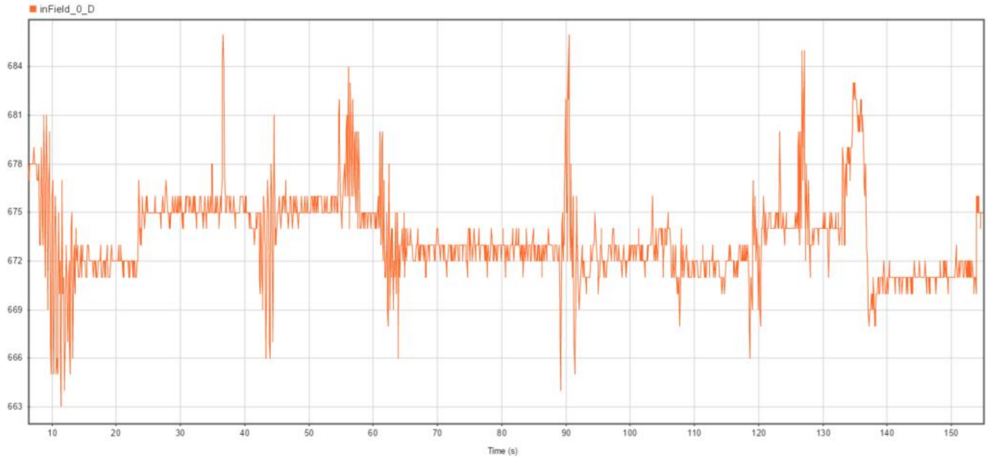
<u>Intentional signal origin</u>: Saddle being removed.
<u>Signals shown</u>: raw, averaging filter (low, medium, high)



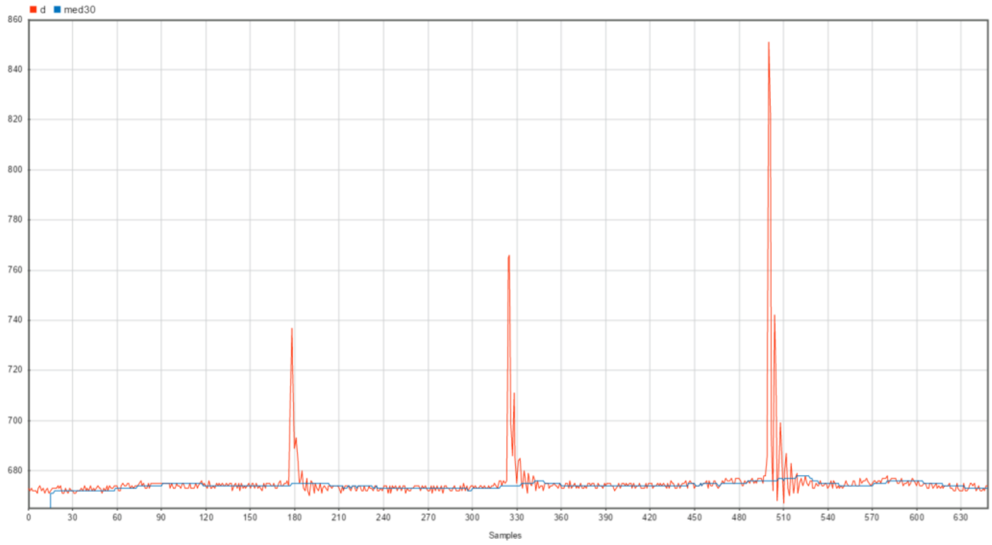
Intentional signal origin: Hacksaw on mechanical frame
Signals shown: raw



Unintentional signal origin: Neighbouring bicycle undocking
Signals shown: raw



Unintentional signal origin: Bicycle bumped on seat x3
Signals shown: raw



Appendix J Source Code - Signal Characteristics

Rolling Average Filter Source Code:

```
long ST_Signal_Filter(long SigVal) {
	ST_Sum = ST_Sum - ST_Filter_Values[ST_Value_Index]; // remove last used entry
	ST_Filter_Values[ST_Value_Index] = SigVal; // add new entry
	ST_Sum = ST_Sum + ST_Filter_Values[ST_Value_Index]; // update the sum
	ST_Value_Index = ST_Value_Index + 1; // prep (move on) the indexer
	if (ST_Value_Index >= ST_filter_Const) { // if the indexer is moved past
		ST_Value_Index = 0; // returns the array indexer to the start
	}
	signalST_Filter_Out = ST_Sum / ST_filter_Const; // return filtered value
	return signalST_Filter_Out;

}
```

Median Filter Source Code:

```
int insertionSort(int sigValIn)
{
	medianWindow[medianWindowIndex] = sigValIn;
	medianWindowIndex++;
	if (medianWindowIndex >= windowSize) {
		medianWindowIndex = 0;
	}
	int tempWindow[30];
	for (int z = 0; z < 30; z++) {
		tempWindow[z] = medianWindow[z];
	}

	int tm, i, j;
	for (i = 0; i < 30; i++) {
		tm = tempWindow[i];
		for (j = i - 1; j >= 0 && tm < tempWindow[j]; j--) {
			tempWindow[j + 1] = tempWindow[j];
		}
		tempWindow[j + 1] = tm;
	}
	return tempWindow[14]; //!!! always half - 1, due to [] starting at 0

}
```

Steady Check Source Code:

```
steadyCheckFlag = steadyCheck(ST_FIilt_min3, ST_FIilt_min0);

int steadyCheck(int ST_Filt_In_min1, int ST_Filt_In_min0) { // code sC
	int dx = 0; // difference between consecutive points
	int steadyFlag = 0; // flag: 0 = steady, 1 = disturbace detected
	dx = ST_Filt_In_min0 - ST_Filt_In_min1;
	if (dx < 0) { // id dx is negative, make positive
		dx = ST_Filt_In_min1 - ST_Filt_In_min0;
	}
	//used dx in moving average filter
	sC_Sum = sC_Sum - sC_Filter_Values[sC_Value_Index]; // remove last used entry
	sC_Filter_Values[sC_Value_Index] = dx; // add new entry
	sC_Sum = sC_Sum + sC_Filter_Values[sC_Value_Index]; //sum of the averag filter
	sC_Value_Index = sC_Value_Index + 1;//prep (move on) the indexer for next entry
	if (sC_Value_Index >= sC_filter_Const) { //if indexer moved past total constant
		sC_Value_Index = 0;//returns the array indexer to the start (@ entry 0)
```

```
	}
	//signalsC_Filter_Out = sC_Sum / sC_filter_Const; // return filtered value
	steadyLagCount;
	steadyLagCount_Threshold;
	if (sC_Sum >= 7) {
		steadyLagCount = steadyLagCount_Threshold;
	}
	else if (sC_Sum < 7) {
		steadyLagCount = steadyLagCount - 1;
	}
	if (steadyLagCount >= 1) {
		steadyFlag = 1;
	}
	else if (steadyLagCount < 1) {
		steadyFlag = 0;
	}
	return steadyFlag;
	//return steadyFlag;

}
```

Noise Level Calculate Source Code:

```
noiseReturn = signNoiseDet(sNVal14, MED_Filt_min0);
int signNoiseDet(int sensVal, int medFiltVal) {//--in Function declerations
	int diff1 = 0; // x - (x-1) --the difference due to noise in consecutive points
	int noiseLevelOut = 0; // moving avarage result of noise on the signal received
	 //int datumSign = 0; // median Filter applied on input signal
	//calculate dx1 = x - (x-1)
	diff1 = medFiltVal - sensVal;
	if (diff1 < 0) { // id dx is negative, make positive
		diff1 = sensVal - medFiltVal;
	}
	//noiseLevelOut = diff1;
	//used d in moving avarage filter
	sN_Sum = sN_Sum - sN_Filter_Values[sN_Value_Index]; // remove last used entry
	sN_Filter_Values[sN_Value_Index] = diff1; // add new entry
	sN_Sum = sN_Sum + sN_Filter_Values[sN_Value_Index]; // update the sum af the
averaging filter
	sN_Value_Index = sN_Value_Index + 1; // prep (move on) the indexer for the next
entry to be used
	if (sN_Value_Index >= sN_filter_Const) { // if the indexer moved past constant
		sN_Value_Index = 0; //returns the array indexer to the start (@ entry 0)
	}
	noiseLevelOut = sN_Sum / sN_filter_Const; // return filtered value
	//noiseLevelOut = sN_Sum; // return filtered valu
	return noiseLevelOut;//return moving avarage outcome

}
```

Noise Level Calculate Source Code:

```
signalAmplitude = signAmpCalc(MED_Filt_min0, signalDatum);
int signAmpCalc(int sensVal, int medFiltVal) {
	int ampl = 0; // x - (x-1) -- the difference due to noise in consecutive points
				//calculate dx1 = x - (x-1)
	ampl = medFiltVal - sensVal;
	if (ampl < 0) { // id dx is negative, make positive
		ampl = sensVal - medFiltVal;
	}
	return ampl;

}
```

Appendix K Source Code - Signal Processing Program

Sampling:

```
void InputInterON() {
	Timer1.attachInterrupt(pullSignal);  // attaches callback() as a timer overflow
interrupt
	//Serial.println("Inerupt attached");
}

void pullSignal() { // the function called by the interupt, used to fetch the Analog
reading at that instance
	signalValue = analogRead(signalPinIn);
	pullSignalFlag = 1;
	//return 0;
}
```

Calculating:

```
int steadyCheckFlag = 0;
int noiseReturn = 0;
int signalAmplitude = 0;
int AmpAlarmFlag = 0;
int NoisAlarmFlag = 0;

//--update time-discrete buffer
sNVal13 = sNVal12;
sNVal12 = sNVal11;
sNVal11 = sNVal10;
sNVal10 = sNVal9;
sNVal9 = sNVal8;
sNVal8 = sNVal7;
sNVal7 = sNVal6;
sNVal6 = sNVal5;
sNVal5 = sNVal4;
sNVal4 = sNVal3;
sNVal3 = sNVal2;
sNVal2 = sNVal1;
sNVal1 = sNVal0;
sNVal0 = sensValIn;
ST_FIilt_min3 = ST_FIilt_min2;
ST_FIilt_min2 = ST_FIilt_min1;
ST_FIilt_min1 = ST_FIilt_min0;

//--innitiate signal manipulation & characteristic extraction
ST_FIilt_min0 = ST_Signal_Filter(sNVal12);
MED_Filt_min0 = insertionSort(sensValIn); // input 0, output 14
steadyCheckFlag = steadyCheck(ST_FIilt_min3, ST_FIilt_min0);
noiseReturn = signNoiseDet(sNVal14, MED_Filt_min0);
signalAmplitude = signAmpCalc(MED_Filt_min0, signalDatum);
```

Comparison:

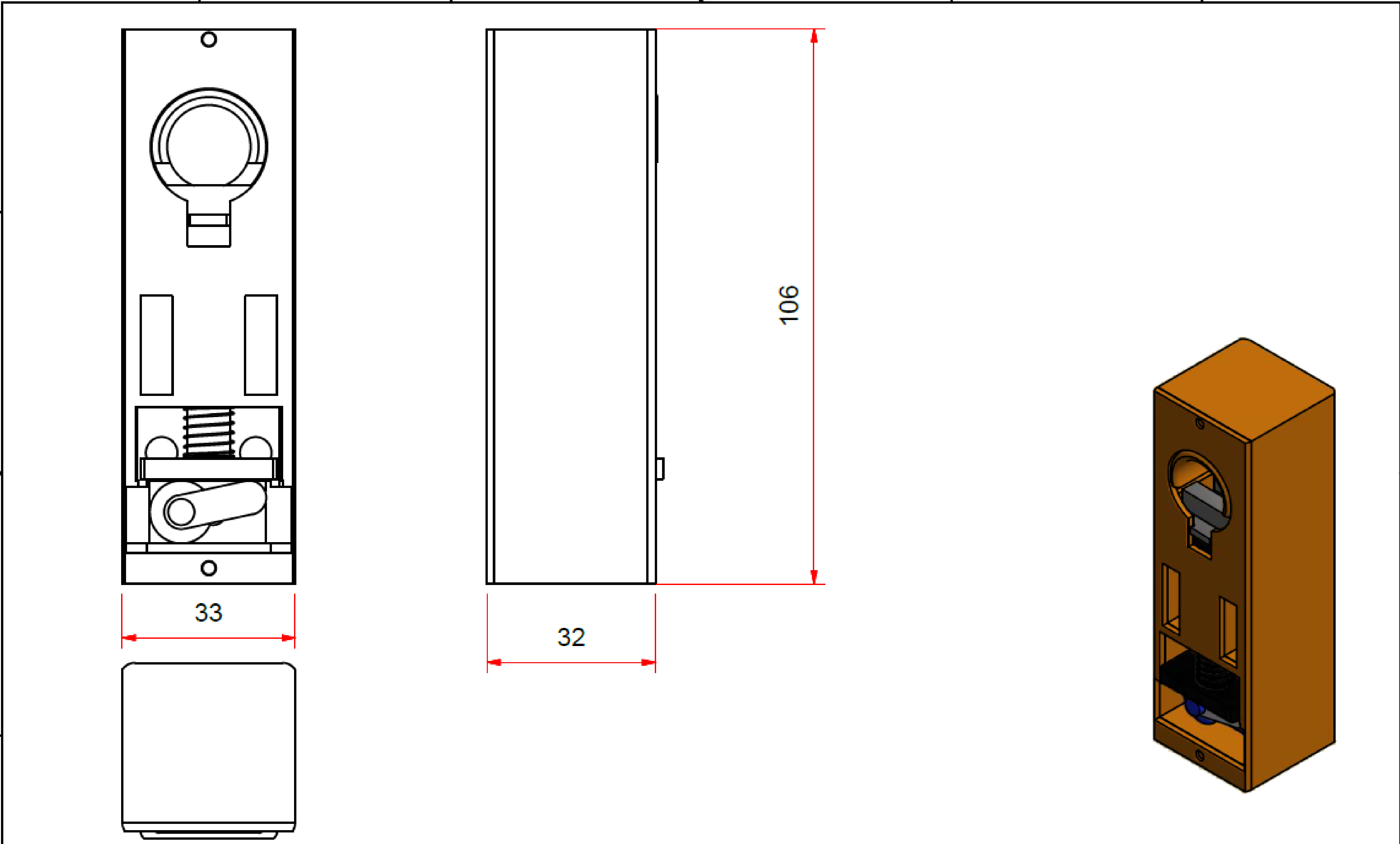
```
//-------BEGIN CHECKS----------
//---signal state check: steady /busy
if (steadyCheckFlag == 1) { // if activity on signal IS detected!!
```

```
            steadyRolCount = steadyRolCount + steadyRolCountInc; // increment the
steady rol count. To determine the time of signal ACTIVE STATE
        signalAmplitAccumulation = signalAmplitAccumulation + signalAmplitude; //
update/add the signal amplitude accumulator
        }
        else { // if activity on signal is NOT detected!!
            steadyRolCount = steadyRolCount - steadyRolCountDec; // decrement the
steady rol count
            signalDatum = MED_Filt_min0; // NB use the median filter output for that
instance
        }

        //--check the staedyRolCount
        if (steadyRolCount >= rolCountThreshH) { // if the rol counter is above it's
count threshold
            steadyRolCount = rolCountThreshH; // ensure rolcount does not go
infinitaly high, and that it can go back to below in X amount of time again.
            if (signalAmplitAccumulation > signalAmplAccTHreshold) { // if the
accumulated amplitude count is higher than the defined threshold, while the
staedyCheck is active -- ALARM!
                AmpAlarmFlag = 1;
            }

        }
        else if (steadyRolCount <= 0) { // if rolcounter is going bellow 0
            signalAmplitAccumulation = 0; // reset signalAmplitAccumulation to 0
            steadyRolCount = 0; // reset steadyRolCount to prevent it from going
below 0
        }
        //--if the amplitude accumulation goes&stays above the define threshold for a
certain time -- ALARM
        if (noiseReturn >= signNoiseThreshold) {
            noiseRolCount++; // while above threshold, increment counter
            if (noiseRolCount >= noiseRolCOuntThreshold) { // ALARM
                NoisAlarmFlag = 1;
            }
        }
        else { // if not above threshold, reset counter
            noiseRolCount = 0;
        }
```

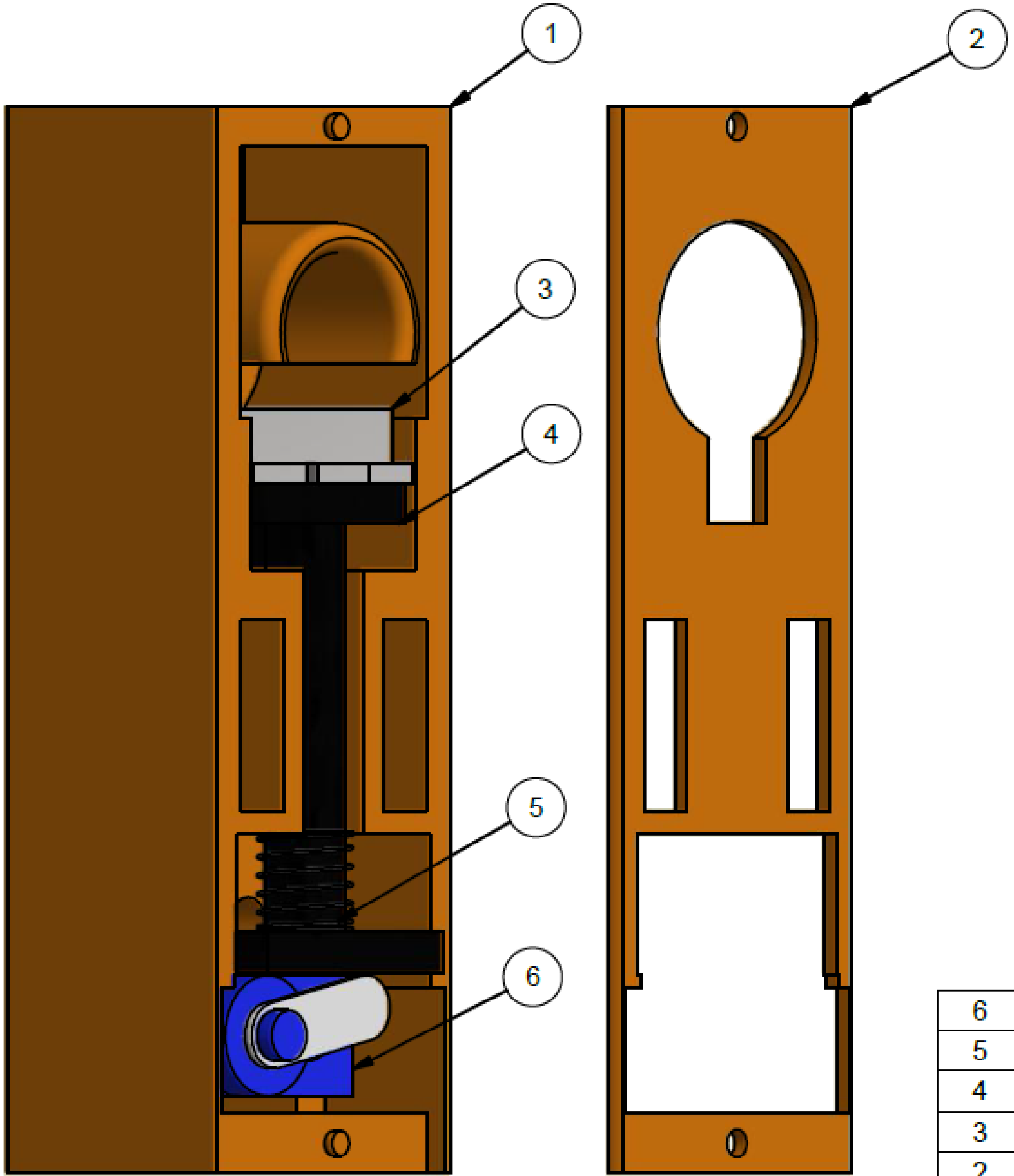
Appendix L Locking Mechanism Detailed Designs



ITEM	BESKRYWING	AANTAL	MATERIAAL / SPESIFIKASIES

UNIVERSITEIT VAN STELLENBOSCH

SKAAL OP A 1 : 1		TITEL: LOCKING MECHANISM: DESIGN	
MATE IN mm			
STUDENTE No. 16951581	TEKENAAR M Swanepoel	NAGESIEN	DATUM 08.2017
VEL No.	VAN	VELLE	No.



6	Servo & Cam	1	Ref. - Drawing Pack
5	Spring	1	Ref. - Drawing Pack
4	Plunger	1	Ref. - Drawing Pack
3	Plunger Key	1	Ref. - Drawing Pack
2	Lower Body	2	Ref. - Drawing Pack
1	Upper Body	2	Ref. - Drawing Pack
ITEM	BESKRYWING	AANTAL	MATERIAAL / SPESIFIKASIES

UNIVERSITEIT VAN STELLENBOSCH

SKAAL OP A 1 : 1
MATE IN mm
TITEL: LOCKING MECHANISM: ASSEMBLY

STUDENTE No. 16951581 | TEKENAAR M Swanepoel | NAGESIEN | DATUM 08.2017 | VEL No. VAN VELLE | No.

Appendix M Source Code - Locking Mechanism

Code for Declerations

```
//----------Locking Mechanism Declerations----------
#include <Servo.h>
Servo myservoFront;  // create servo object to control a servo
Servo myservoBack;  // create servo object to control a servo
int lockPosition = 114; // servo position when locked
int unlockPosition = 140; // servo position when unlocked
int successLockFlag = 0;
int servoPinFr = 9; // pin to which the servo attaches
int servoPinBa = 11;
int LockCurrentReadingF = 500; // analog reading to measure current through locking
servo, initiate high
int LockCurrentReadingR = 500; // analog reading to measure current through locking
servo, initiate high
int LockCurrentThreshold = 4; // maximum analog reading (current) to allow for
sucesfull locking
```

Code for *Void Setup { };*

```
//---Servo Setup-------------------------------------
myservoFront.attach(servoPinFr);  // attaches the servo on pin 9 to the servo object
myservoBack.attach(servoPinBa);  // attaches the servo on pin 9 to the servo object
myservoFront.write(unlockPosition); // initializes unlock position for servo
myservoBack.write(unlockPosition); // initializes unlock position for servo
```

Code for *Void Loop { };*

```
int lockPin_Lock() {
	successLockFlag = 0; // flag to indicate successfull locking/unlocking set to 0
	int FlockCurrentCounter = 0; // initialize locking counter to measure a certain
	amount of times only
	int LCR1 = 500; // most recent reading, prime readings
	int LCR2 = 500;
	int LCR3 = 500;
	int LCR4 = 500;
	int LCR5 = 500; // last reading
	LockCurrentReadingF = 500; // initiate high
	int RlockCurrentCounter = 0; // initialize locking counter to measure a certain
	amount of times only
	int RLCR1 = 500; // most recent reading, prime readings
	int RLCR2 = 500;
	int RLCR3 = 500;
	int RLCR4 = 500;
	int RLCR5 = 500; // last reading
	LockCurrentReadingR = 500; // initiate high

//Lock Check @ front lock
	myservoFront.write(lockPosition); // send servo to locking position
	delay(150); // allow servo to reach intended position
	while (LockCurrentReadingF > LockCurrentThreshold) { //while current is to high
		FlockCurrentCounter++; // inc. counter
		if (FlockCurrentCounter >= 80) { // if max time as eapsed
			myservoFront.write(unlockPosition); // return servo
			successLockFlag = 0;
			return successLockFlag;
		}
		delay(12);
		LCR5 = LCR4;
		LCR4 = LCR3;
		LCR3 = LCR2;
```

```
            LCR2 = LCR1;
            LCR1 = analogRead(A4);
            LockCurrentReadingF = (LCR5 + LCR4 + LCR3 + LCR2 + LCR1) / 5;
            Serial.println(LockCurrentReadingF);
      }


//Lock Check @ rear lock
      myservoBack.write(lockPosition); // send servo to locking position
      delay(150); // allow servo to reach intended position
while (LockCurrentReadingR > LockCurrentThreshold) { // while current is to high
            FlockCurrentCounter++; // inc. counter
            if (FlockCurrentCounter >= 80) { // if max measurements has been done
                  myservoBack.write(unlockPosition); // return servo position
                  successLockFlag = 3;
                  return successLockFlag;
            }
            delay(12);
            RLCR5 = RLCR4;
            RLCR4 = RLCR3;
            RLCR3 = RLCR2;
            RLCR2 = RLCR1;
            RLCR1 = analogRead(A2);
            LockCurrentReadingR = (RLCR5 + RLCR4 + RLCR3 + RLCR2 + RLCR1) / 5;
            Serial.println(LockCurrentReadingR);

      }
      successLockFlag = 1;
      Serial.println("Sucesfully Locked in lockPin_Lock()");
      //return criteria sucess=1, front.fail=2, rear.fail=3
      return successLockFlag;

}
```

Appendix N Hardware and Interfacing

Arduino MEGA and Particle Photon Hardware Pin Assignment

Table 34: Arduino MEGA Pin Assignment

Interface	Pin Name	Arduino Port	Connected To	Interfacing Purpose
1	*VCC*	Input Voltage	12V Voltage Regulator	Supply Arduino with power
	GND	Ground	Common round	Supply ground reference voltage
2	*A0*	Analog I/O	Sensing System Output Signal	Measure sensing system output signal's value
3	*D9*	Digital I/O	Servo 1 control line	Control servo 1 position
	A2	Analog I/O	Servo 1 status feedback resistor	Measure servo 1 current
4	*D11*	Digital I/O	Servo 2 control line	Control servo 2 position
	A4	Analog I/O	Servo 2 status feedback resistor	Measure servo 2 current
5	*D18*	Serial 1 - TX	Photon Serial RX	Arduino-Photon communication
	D19	Serial 1 – RX	Photon Serial TX	
6	*D29*	Digital I/O	Status LED	Provide visual feedback
	D51	Digital I/O	Status LED	

Table 35: Particle Photon Pin Assignment

Interface	Pin Name	Photon Port	Connected To	Interfacing Purpose
1	*Vin*	Input Voltage	5V Voltage Regulator	Supply Photon with power
2	*GND*	Ground	Common round	Supply ground reference voltage
3	*TX*	Serial 1 - TX	Arduino Serial RX	Arduino-Photon communication
	RX	Serial 1 – RX	Arduino Serial TX	

Photon Serial Gateway Source Code

```
nt lockingStatus = 0; // 1 = locked, 0 = unlocked
int CurrentUserID = 0;
//int DockHandler(String userIDin); // function that handles the lock/unlock of the dock
int comandSend(String toSend);
int lockTest = 0x4C;
int unlockTest = 0x55;
int status = 0x53;
int test = 0x54;

void setup() {
Serial1.begin(4800);
Particle.variable("LockStatus", lockingStatus);
Particle.variable("CurUserID", CurrentUserID);
Particle.function("testtodock", comandSend);
}
void loop() {
}

int comandSend(String toSend){
```

```
    int serReceive = 0;
    int count = 0;
    if(toSend == "L"){
        Serial1.write(lockTest);

    } else if (toSend == "U"){
        Serial1.write(unlockTest);

    }else if (toSend == "S"){
        Serial1.write(status);
        delay(800);
      // delay(800);
      while (Serial1.available() == 0) { // receive all serial data, 9600 baud = 0,9375 ms/byte
                    count++;
                    delay(15);
                    if(count >= 500){
                        return 2;
                    }
      }
      serReceive = Serial1.read();
    }else if (toSend == "T"){
        Serial1.write(test);

    }

    return serReceive;
}
```

Appendix O Source Code - State Machine

Command Handler Function

```
//----Program Input Command Handler----
int serialCount = 0; // keeps count of the serial data received
int serReceive; // stores serial data received
char serialDataReceived[] = { 0 }; //adds data received to the data receive buff
int commandIn = 0; // command received

	//-----------Command Handler on Serial1-------------
	if (Serial1.available() > 0) { // receive all serial data, 9600 baud = 0,9375
ms/byte
		serReceive = Serial1.read();

		if (serReceive > 1) { // eventual concept is to use comands above the
ASCII character values to enable characters to be sent to the string, and commands to
be sent with the values below ASCII
			commandIn = serReceive;
			Serial.println(commandIn);
		}
		else {
			serialDataReceived[serialCount] = serReceive;
			serialCount++;
		}
	}
	if (pullSignalFlag == 1) {
		analysisControl(signalValue);
		pullSignalFlag = 0;

	}
	//-------start command switch-------
	switch (commandIn) {

		/*COMMAND LIST
		* L -> switch to LOCKED
		* U -> switch to UNLOCKED
		* A -> switch to ALARM
		* S -> retrun STATUS
		* T -> switch to TEST
		*/
	case 0x4C: // "L", switch to state LOCKED
		Serial.println("enter state -> LOCKED");
		changeState(LOCKED);
		commandIn = 0;
		break;
	case 0x55: // "U", switch to state UNLOCKED
		Serial.println("enter state -> UNLOCKED");
		changeState(UNLOCKED);
		commandIn = 0;
		break;
	case 0x41: // "A", switch to state ALARM
		Serial.println("enter state -> ALARM");
		changeState(ALARM);
		commandIn = 0;
		break;
	case 0x53: // "S", return status
		Serial.println("return status..");
		Serial.println(CURENT_MAIN_STATE);
		commandIn = 0;
		break;
	case 0x54: // "T", switch to state TEST
```

```
        Serial.println("enter state -> TEST");
        changeState(TEST);
        commandIn = 0;
        break;
    }

    //-----------end command switch--------
```

State Machine Implementation Function

```
//----MAIN state machine
enum MAIN_STATE_TYPE {STANDBY, UNLOCKED, LOCKED, ALARM, TEST}; // declares types of
main system states
MAIN_STATE_TYPE CURENT_MAIN_STATE;
MAIN_STATE_TYPE PREVIOUS_MAIN_STATE;
void changeState(MAIN_STATE_TYPE CHANGE_STATE); // declare function


    //--------Implement State Machine Loop------------
    switch (CURENT_MAIN_STATE) {

    case STANDBY:
        break;

    case UNLOCKED:
        break;
    case LOCKED:
        break;

    case ALARM:
        //Serial.println(alarmRol);
        if (alarmRol == 20) {
            digitalWrite(rightLED, LOW);
        }
        else if (alarmRol == 40) {
            digitalWrite(rightLED, HIGH);
            alarmRol = 0;
        }
        break;
    case TEST:
        Serial.println(signalValue);
        //Serial.println("  ");
        //Serial.print(steadyRolCount);
        //Serial.println("  ");
        //Serial.print(signalAmplitAccumulation);
        //Serial.println("  ");
        //Serial.print(noiseRolCount);
        break;
    }


 //-----FUNCTIONS START-----
void changeState(MAIN_STATE_TYPE CHANGE_STATE) {

    switch (CHANGE_STATE) {

    case STANDBY:
        digitalWrite(leftLED, LOW);
        digitalWrite(rightLED, LOW);
        Serial.println("STANDBY state entered sucsessfully");
        CURENT_MAIN_STATE = STANDBY;
        break;
    case LOCKED: // loading a bicycle
```

```
}

        //calibrate
        if (CURENT_MAIN_STATE == STANDBY || CURENT_MAIN_STATE == UNLOCKED) {
        lockPin_Lock();
        delay(500);
        digitalWrite(leftLED, HIGH);
        digitalWrite(rightLED, LOW);
        CURENT_MAIN_STATE = LOCKED;
        Serial1.write(0x09);
        delay(850);
        InputInterON();
        delay(850);
        }
        break;
    case UNLOCKED:
        if (CURENT_MAIN_STATE == LOCKED) {
            InputInterOFF();
            lockPin_UnLock();
            digitalWrite(leftLED, LOW);
            digitalWrite(rightLED, LOW);
            CURENT_MAIN_STATE = UNLOCKED;
            Serial1.write(0x09);
        }else if (CURENT_MAIN_STATE == ALARM) {
            alarmOff();
            digitalWrite(leftLED, LOW);
            digitalWrite(rightLED, LOW);
            CURENT_MAIN_STATE = STANDBY;
            Serial1.write(0x09);
        }
        else if (CURENT_MAIN_STATE == STANDBY) {
            InputInterOFF();
            lockPin_UnLock();
            digitalWrite(leftLED, LOW);
            digitalWrite(rightLED, LOW);
            CURENT_MAIN_STATE = UNLOCKED;
            Serial1.write(0x09);
        }
        break;
    case ALARM: //
        //InputInterOFF();
        //alarmNum++;
        //Serial.println(alarmNum);
        alarmOn();
        //notifications();
        digitalWrite(leftLED, HIGH);
        digitalWrite(rightLED, HIGH);
        CURENT_MAIN_STATE = ALARM;
        Serial1.write(0x09);
        break;
    case TEST: // testing the signal received from the AMP
        InputInterON();
        delay(500);
        //Serial.println("test_signalIn state entered sucsessfully");
        CURENT_MAIN_STATE = TEST;
        Serial1.write(0x09);
        break;
    }
    return;
}
```

Appendix P Mechanical Frame Bill of Materials

Table 36: Mechanical Frame - Bill of Materials

Sub-assembly(s)	Part/material	Source	Qty.
Main Frame	Main Spine Bar – 50x50x3mm square tubing	E&E workshop	1
	Side Spine Bar – 50x50x3mm square tubing	E&E workshop	2
	Front Bars – 38x38x3mm square tubing	E&E workshop	2
	Wheel Supports – 8x8mm solid square bar, bent	E&E workshop	2
Force Bed	Triangle Bar, aluminium – 28x6mm	E&E workshop	1
	Round pins, aluminium – Ø20x30mm	E&E workshop	2
	Transducer housing	3D printed, MIL	2
	Transducer-body brackets – 2mm steel plate	E&E workshop	2
	Amplification hardware	Self-manufactured	1
Front Locking Unit	Ø15x310mm steel rod	E&E workshop	1
	Locking Mechanism Body	Self-manufactured	1
Rear Locking Unit	Hinge Shaft, Ø30mm steel rod		1
	Rear arm body – 38x38x2mm square tubing		1
	Locking Mechanism Body	Self-manufactured	1
	Ø15x330mm steel rod	E&E workshop	1

List of References

[1] Transport Futures, “Cycle Plan for the Town of Stellenbosch,” Stellenbosch, South Africa, 2015.

[2] City of Cape Town's Transport Authority, “Public Urged to Comment on City's Draft Cycling Strategy,” 7 January 2017. [Online]. Available: http://www.tct.gov.za/en/news/general/public-urged-to-comment-on-citys-draft-cycling-strategy/page-1/.

[3] H. Barry, “Cycling is the New Golf,” Money Web, 17 January 2014. [Online]. Available: https://www.moneyweb.co.za/archive/cycling-is-the-new-golf/.

[4] S. Johnson, A. Sidebottom and A. Thorpe, “Bicycle Theft,” in *Problem-Oriented Guides for Police - Problem-Specific Guides Series,* U.S. Department of Justice, Office of Community Oriented Policing Services, 2008.

[5] J. Mason, L. Fulton and Z. McDonald, “A Global High Shift Cycling Scenarion: The Potential for Dramatically Increasing Bicycle and E-bike Use in Cities Around the World, with Estimated Energy, CO2, and Cost Impacts,” Institute for Transportation & Development Policy and the University of California, 2015.

[6] Lucintel, “Opportunities for the Global Bicycle Market to Reach $34.9 Billion by 2022,” 21 March 2017. [Online]. Available: http://www.lucintel.com/press/global_bicycle_market.aspx.

[7] TomTom International BV, “TomTom Traffic Index,” 2016. [Online]. Available: http://www.tomtom.com/en_gb/trafficindex/. [Accessed 12 02 2017].

[8] M. Colville-Andersen, “The 20 Most Bike-Friendly Cities on the Planet,” 8 01 2017. [Online]. Available: https://www.wired.com/2015/06/copenhagenize-worlds-most-bike-friendly-cities/.

[9] ODPHP, “Physical Activity Guidelines for Americans 2008,” 2008. [Online]. Available: http://health.gov/paguidelines/pdf/paguide.pdf. [Accessed 28 January 2016].

[10] L. Yang, S. Sahlqvist, A. McMinn, S. Griffin and D. Ogilvie, “Interventions to promote cycling: systematic review,” *British Medical Journal,* vol. 341, no. 5293, 2010.

[11] S. Consolvo, K. Everitt, I. Smith and J. Landay, “Design requirements for technologies that encourage physical activity,” New York, NY, USA, 2006.

[12] I. Lee, E. Shiroma, F. Lobelo, P. Puska, S. Blair and P. Katzmarzyk, “Effect of physical inactivity on major non-communicable diseases worldwide: an analysis of burden of disease and life expectancy,” *The Lancet,* vol. 380, no. 9838, pp. 219-229, 2012.

[13] J. Cleary and H. Mcclintock, “The Nottingham Cycle-friendly Employers Project: Lessons for encouraging cycle commuting,” *Local Environment,* vol. 5, no. 2, pp. 217-222, 2010.

[14] L. Ramphele, “Bicycle theft on the rise in Cape Town,” Cape Talk, 23 September 2015. [Online]. Available: http://www.capetalk.co.za/articles/5380/bicycle-theft-on-the-rise-in-cape-tgown. [Accessed 03 01 2017].

[15] Stolen Ride London, “The London Cycle Theft Survey 2016,” Stolen Ride Ltd, 2016. [Online]. Available: http://www.stolenride.co.uk/2016-survey-cycle-theft/. [Accessed 20 01 2017].

[16] Bike Hub, “Stolen Bikes Database,” Hub Online Media, 20 05 2017. [Online]. Available: https://www.bikehub.co.za/forum/index.php?app=hubregistry&st=680. [Accessed 20 05 2017].

[17] The Best Bike Lock, “Who’s trying to steal your bike (and what tools are they using)?,” thebestbikelock.com, 20 05 2017. [Online]. Available: http://thebestbikelock.com/best-bike-lock/who-is-trying-to-steal-your-bike/. [Accessed 20 05 2017].

[18] C. Reid, “Gone in 42 seconds!,” in *Cycle,* Cyclists' Touring Club, 2008, pp. 43-46.

[19] Federal Highway Administration University - U.S. Department of Transport, “Federal Highway Administration University Course on Bicycle and Pedestrian Transportation,” July 2006.

[Online]. Available: https://www.fhwa.dot.gov/publications/research/safety/pedbike/05085/. [Accessed 01 05 2017].

[20] NL Cycling, “Bicycle Dutch,” [Online]. Available: https://bicycledutch.wordpress.com/. [Accessed 05 March 2017].

[21] Bay Area Rapid Transit, “BART to install electronic bike lockers,” San Francisco Bay Area Rapid Transit District, 01 January 2008. [Online]. Available: http://www.bart.gov/news/articles/2008/news20080125a. [Accessed 21 05 2017].

[22] Cycle Safe, Inc., “Cycle Safe - Secure Bicycle Parking,” Cycle Safe, Inc., [Online]. Available: https://cyclesafe.com/. [Accessed 05 March 2017].

[23] Glolab Corporation, “How Infrared motion detector components work,” Glolab Corporation, 2015. [Online]. Available: http://www.glolab.com/pirparts/infrared.html. [Accessed 14 February 2017].

[24] Sirius ET, “Sirius ET,” Ecoamica Tech , 2013. [Online]. Available: http://www.ecosirius.com/technology.html. [Accessed 03 February 2017].

[25] Kerberos Security, “Intrusion alarm,” Kerberos Co. Ltd., 2013. [Online]. Available: http://kerberossecurity.com/?page_id=422. [Accessed 10 May 2017].

[26] RBtec, “RB tec Perimeter Security Systems,” RB tec, [Online]. Available: http://www.rbtec.com/. [Accessed 08 March 2017].

[27] J. Bachand-Marleau, B. Lee and A. El-Geneidy, “Better Understanding of Factors Influencing Likelihood of Using Shared Bicycle Systems and Frequency of Use,” *Journal of the Transportation Research Board,* pp. 66-71, 2012.

[28] P. Midgley, “Bicycle-Sharing Schemes: Enhancing Sustainable Mobility in Urban Areas,” New York, 2011.

[29] BBC News, “Thefts puncture Paris bike scheme,” 10 February 2009. [Online]. Available: http://news.bbc.co.uk/2/hi/europe/7881079.stm. [Accessed 25 January 2016].

[30] S. A. Shaheen, S. Guzman and H. Zhang, “Bikesharing in Europe, the Americas, and Asia,” *Transportation Research Record: Journal of the Transportation Research Board,* no. 2143, pp. 159-167, 2010.

[31] Gris Orange Consultant, Bike Sharing Guide, Ottawa: Public Works and Government Services Canada, 2009.

[32] E. Cloete and R. Loubser, Interviewees, *Cycling Infrastructure in Stellenbosch.* [Interview]. 02 10 2015.

[33] A. Denham, “Understanding Bicycle Frame Geometry,” 4 October 2013. [Online]. Available: http://www.cyclingabout.com/understanding-bicycle-frame-geometry/. [Accessed 12 05 2016].

[34] University of Nottingham, “Strength Report,” DTI Publications, London, 2000.

[35] Cambridge University Engineering Department, “CMI Multidisciplinary Design Project,” 2003. [Online]. Available: http://www-mdp.eng.cam.ac.uk/web/library/enginfo/cueddatabooks/materials.pdf. [Accessed 5 June 2016].

[36] The Physics Classroom, “Newton's Third Law,” The Physics Classroom, 01 January 2016. [Online]. Available: http://www.physicsclassroom.com/class/newtlaws/Lesson-4/Newton-s-Third-Law. [Accessed 10 June 2017].