Industrial Electrical Engineering and Automation

Design of a Pole Climbing Unit

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Preface

This report is the conclusion of a master's thesis in Mechanical Engineering with Mechatronics and Industrial Design. The thesis was done in collaboration with a company in Lund, Division of Product Development and Division of Industrial Electrical Engineering at Lund's University. The master thesis will be available in two publications by these divisions.

The main aim of the thesis is to research the possibilities of designing a pole climbing unit and to make a prototype as a proof of concept.

To start we would like to thank our company mentors Thomas Ekdahl and Niclas Lewin for giving us the opportunity to make this thesis and for their guidance and support during the whole project.

Furthermore we would like to thank our mentors at the university, Karl-Axel Andersson and Gunnar Lindstedt for their thoughts and inputs during the project.

A special mention goes to the department of research and development in the company for their help and input.

Thereafter we would like to acknowledge all personnel at the company for their warm and open attitude. It has been a fantastic experience to always get a warm and helping attitude when you ask for help or thoughts on a problem.

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Abstract

Temporary surveillance with an easily deployable surveillance unit can give a tactical advantage for police in situations when big crowds suddenly gather. It can also be used by fire department during fires or in the private security sector on construction sites and other such temporary areas requiring surveillance. This report describes the process of developing the climbing system for such a surveillance unit. Firstly a pre-study is made to determine what is required of the climbing system. Poles are studied online and by walking around in different cities. Also researched in the pre-study is possible competition. Following the pre-study is research on possible customer needs. Concept generation follows where concepts compete against each other in concept screening and concept scoring based on the initial research. The final winner is developed to a working prototype. The prototype uses belts to tighten itself to a pole in two different places. By holding the pole with one belt the other belt can be lifted which allows the robot to climb. The final prototype works but needs improvements before it is market ready.

Keywords:

Climbing, Prototype, Pole, Robot, Development

Sammanfattning

Detta projekt är ett examensarbete på Lunds Tekniska Högskola med huvudsyftet att ta fram en stolpklättrande kamera. Denna ska i tidspressade situationer snabbt kunna installeras på en stolpe följt av att den själv klättrar upp i stolpen.

Projektet har börjat med en förstudie med huvudsyfte att ta reda på vilka krav som kan ställas på en stolpklättrande kamera. Förstudien har delats upp i en stolpstudie och en konkurrensstudie.

Stolpstudien visade att majoriteten av stolpar ej har hinder som skyltar men att det finns stadsdelar och städer som är mindre lämpliga för ett klättersystem endast implementerat mot stolpar utan skyltar. Därför ska klättraren klara vanliga hinderfria stolpar, men helst även hinder såsom skyltar och diameterskillnader. Bonus är även om den kan klättra på annat än lyktstolpar likt fasader eller stuprör.

I konkurrensstudien hittades en direkt konkurrent, Sherpa, vars produkt klarar av stolpar med en diameter mellan 75-150 mm. Detta blev ett minimumkrav för prototypen. Prototypen ska även klara av diameterskillnader på stolpen. Inga begränsningar sattes under konceptgenereringen men på grund av tidsbrist implementerades aldrig ett klättersystem som klarade av stolpar med skyltar.

Metodik som användes för produktutveckling kommer från boken "Product Design and Development" av Ulrich & Eppinger [1]. Först görs en "mission statement" där bland annat kundgrupp bestäms och därefter utrönas kundbehov för tänkt produkt. Kundbehov kom från intervjuer med kameraförsäljare inom övervakningsindustrin som har en god inblick i både kundbehov och potentiella problem gällande kamerainstallation. Primär marknad är polis och brandkår som kan ha behov av snabb installation för temporär övervakning.

Med en bättre inblick i behoven för en klättrande kamera började en mer fokuserad produktutveckling. Genom hela förstudien genererades koncept, men nu utfördes även en gemensam brainstorming med en grupp vana produktutvecklare. Koncepten delades in i grupper och en första grov sortering gjordes där orimliga koncept togs bort. En strukturerad sortering utfördes sedan enligt Ulrich & Eppingers process för produktutveckling. Detta började med att 20 koncept tävlade mot varandra i en "concept screening" där utvalda kundbehov användes för att jämföra koncepten mot ett referenskoncept. De koncept som gick vidare delades in i tre huvudgrupper: hävstångsklättrare, hjulklättrare och gripklättrare. Beräkningar utfördes och simpla modeller tillverkades både i trä och med CAD-modeller. Slutligen valdes ett koncept genom "concept scoring". Här tävlar koncepten mot varandra likt "concept screening" fast avgörande är de primära kriterierna för slutprodukten. Dessa får dessutom en viktning som bestämmer vad som är viktigast och mindre viktigt.

Vinnande koncept, som är en av gripklättrarna, använder kuggremmar för att gripa om stolpen på olika höjd. En klättercykel börjar med att båda remmar greppar om stolpen. Den övre remmen släpper stolpen och kan höjas medan den undre remmen

håller fast. Översta remmen kan greppa på en högre höjd och den undre remmen kan släppa stolpen för att höjas till en position strax under den övre remmen. Här kan den greppa och klättercykeln börjar på nytt.

Kuggremmar används för att dessa lätt dras in med kuggremshjul. Kuggremshjulen roteras med snäckväxlade motorer som stannar i den position de stängs av i. Detta betyder att när väl remmarna är spända krävs ingen extra energi för stanna på stolpen.

För att lösa problemet med diameterskillnad på stolpar används förhållandet mellan omkrets och diameter för en cirkel. Genom att en mothållsarm fälls ut långsammare än remmen dras in kan roboten alltid spännas parallellt med stolpen även om remmarna spänns på två olika stolpdiametrar samtidigt. Utväxlingen fås genom att kuggar kopplas till en motoraxel, kuggremshjul för remindragning, och en kuggstång för mothållsarmen.

Den vertikala rörelsen som fäller upp och ner kuggremmarna sköts av en planetväxlad motor kopplad med kuggremshjul till en skruv. En mutter på skruven hålls stilla genom att kopplas till en vagn i ett linjärspår som följer muttern. Då skruven roteras medan muttern är stilla tvingas muttern höjas eller sänkas på skruven. Till muttern kopplas den övre kuggremmen.

Samtliga motorer är DC-motorer och har rotationssensorer som skickar signaler till en mikroprocessor. Mikroprocessorn sitter på ett Arduino-kort som i sin tur är kopplat till ett specialtillverkat kretskort. Till detta kretskort kopplas samtliga sensorer, ström- och spänningsmätning, samt två H-bryggor för motorstyrning. En H-brygga styr de två snäckväxlade motorerna och en styr den planetväxlade motorn. Skulle mätningar för rotationssensorn i den planetväxlade motorn bli fel sitter det mikrobrytare i ändarna av skruven. Om muttern kommer i kontakt med en av dessas stoppas motorns rotation direkt så muttern inte kommer till slutet av skruven och slår i en fästpunkt.

För att inte spänna fast remmen precis på en diameterändring sitter en ultraljudsdistanssensor och mäter avståndet till stolpen. Ändras avståndet har en diameterändring skett och roboten ska inte spänna remmen här utan backas tillbaka.

Styrning av roboten sker med en IR-sensor som fångar upp signaler från en IR-kontroll. Användaren kan bestämma ifall roboten ska installeras, upp, ner, stanna eller avinstalleras. Vid installation ska två mikrobrytare tryckas in som säkerhetsåtgärd så användaren inte klämmer fingrarna i remmarna eller kuggarna.

Samtliga komponenter styrs, via det specialtillverkade kretskortet, av en Arduino. Programmering gjordes i den blandning av C och C++ som Arduino tillhandahåller. Programmet är en form av tillståndsmaskin för att bestämma vilken typ av operation som kan utföras av användaren via IR-sensorn. Vid klättring upp eller ner finns ytterligare två tillståndsmaskiner för att bestämma läge i klättercykeln.

För att tillverka denna robot gjordes en CAD-modell av alla delar tillsammans. Samtidigt utfördes beräkningar för dimensionering av komponenter som motorer, kugghjul och batterier. Processen blev således något iterativ då CAD-modellen fick anpassas efterhand som komponentberäkningar utförts. CAD-modellen fick även anpassas efter komponenter som hittades till rimligt pris, vikt och tillverkningstid.

Slutlig prototyp blev en blandning av egentillverkade och specialbeställda komponenter, blandat med industritillverkade delar. Så mycket som möjligt av egentillverkade och specialbeställda komponenter valdes att 3D-printas i plast då detta medger enklare tillverkning och väger mindre än delar i metall.

Slutlig produkt klättrar hjälpligt upp och ner för stolpar där största problemet är en lutning på grund av dåliga toleranser i mekaniken. Detta korrigeras med hjälp av stöttande mothållsarmar. Ett annat problem har varit mycket störningar i elektroniken när motorerna börjar använda mer energi. Detta har avhjälpts med mjukvarufilter.

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Terminology

List of acronyms and technical terms used in the master thesis report.

DC	Direct Current
IR	Infrared
LiPo	Lithium Polymer (Battery)
PCB	Printed Circuit Board
LDO	Low-Dropout (Linear Voltage Regulator)
H-bridge	Transistors in an H shape that enables DC motor control
MOSFET	Common type of transistor
PWM	Pulse-Width Modulation
LED	Light-Emitting Diode
Bootstrap Capacitor	Capacitor to charge high side MOSFETs in an H-bridge
TTL	Transistor-Transistor Logic (Level). Voltage level switching between on or off / 1 or 0
ABS	Acrylonitrile Butadiene Styrene (Plastic)
PLA	Polyactic Acid (Plastic)

1 Introduction

This chapter introduces background for the project.

1.1 Background

The usual solution to camera surveillance is preinstalled cameras. Certain situations like sporting events, parades, festivals, riots and other gatherings of people require surveillance, but the preinstalled cameras are immobile.

The solution to this problem is to make a unit that climbs a structure, like a lighting pole, and gets a high vantage point with a good overview of the crowd. To this unit a camera or other equipment can be installed. This project will research poles and other climbing options and with this research develop a pole climbing unit.

2 Aims

The project aims.

2.1 Aims

The final aim of the project is to manufacture a pole climbing unit that is easy to install and use. For a successful project, research has to be made on challenges for such a product. Therefore a number of aims for the project include:

- Investigate functions needed.
- Investigate different types of poles to solve the problem for.
- Investigate possible solutions for a pole climbing unit.
- Describe a few concepts to solve the problem.
- Investigate installation time and ease of installation.
- Evaluate the best concept.
- Manufacture a prototype and test the performance.

3 Method

An overview of method used in the project.

3.1 Project Plan

To be able to finish the project in a reasonable time and not get stuck too long on certain details a project plan was made and followed. This project plan can be found in Appendix A. The distribution of the work done by the two authors is found in the same appendix.

3.2 Pre-study

A pre-study will be done to understand the market and challenges for the product. The pre-study will be divided into three sections. Firstly an environmental study will be made that will look at different types of poles and structures for climbing. Following is a look at possible competition on the market. Finally some reflections from the study are presented.

3.3 Concept Development

The concept development theory comes from Product Design and Development by Karl T. Ulrich and Steven D. Eppinger [1].

3.3.1 Identify Customer Needs

The needs of the customers will be identified by interviews on an experienced surveillance company. Since the potential customers have not seen this type of product before, the interviews will serve as a help for understanding the customers' needs. The end result of this project, which is a prototype, can be used to give a better understanding for customer needs in a final market ready product.

3.3.2 Product Requirements

From the customer needs the product requirements will be generated. This will help in the upcoming phases of development.

3.3.3 Concept Generation

During the initial phases of the project a number of concepts and designs will be generated through workshops, brainstorming, personal ideas and discussions.

3.3.4 Concept Selection

With concept screening some concepts will be selected for further refinement. These refined concepts will compete against each other in a concept scoring round where a final concept will be selected for the prototype.

3.3.5 Prototype

The final prototype will be built and tested on real poles. A computer model will be used to fit the pieces together and to manufacture many of the parts needed. Manufacturing is both ordered and done by the authors. Electrical components are connected to a printed circuit board which is connected to an Arduino that controls the prototype.

4 Pre-study

To get to grips with some of the product requirements an environmental study is needed. The environmental study is divided into two different categories, what can be seen on pictures online and what can actually be seen on the streets in cities. For further understanding of the market possible competition is also studied.

4.1 Environmental Study

For the environmental study the online research enables a broader and faster perspective than traveling to cities and walking around. USA is a large market and therefore some large cities are researched with Google Street View [2]. Another large market is Europe and therefore Rome is researched along with Copenhagen and the cities Lund and Malmö in Sweden. Copenhagen, Lund and Malmö are researched by walking around the streets in person which gives another perspective than watching pictures online. Pole diameters are measured and pictures taken. A study of how many poles have obstructing signs are also made in these cities.

4.1.1 Real Life Studies

4.1.1.1 Lund

The poles mainly studied were street lamps and flag poles. Some consideration was also taken to gutters, trees and other structures, like the one on the right in figure 4-1. If later concepts can handle these it is seen as a bonus.

Figure 4-1 Different challenges for a pole climber

In Lund diameters of street lamps and flag poles varied between 60 mm and 215 mm. Some street lamps have signs on them and changing pole diameter. Flag poles might have an extra box on the side to accommodate wire that holds the flag. Both these types of challenges can be seen in figure 4-1.

When focusing on street lamps a study in Lund from Getingevägen into Bredgatan followed by Kyrkogatan was made. Street lamps with and without signs were counted and 69 % had no signs compared to 31 % that had signs. It was also noted that intersections had more signs than normal roads. The study leaves room for error and with more time more roads would have been studied.

Magnetism works on all the street lamps. This means there is a possibility for the concept to stick to the pole with magnetism.

When it comes to open areas as parks and market squares often the best alternative in Lund is a flag pole. Flag poles are commonly made of glass fiber which means magnets will not work.

4.1.1.2 Malmö

Going down some roads in Malmö, like Östra Förstadsgatan, it becomes apparent that a lot of lighting is hung on wires between buildings instead of on lampposts. In these situations mounting places for the product includes houses, trees and the wires between houses. These wires are hard to reach without extra climbing equipment.

Lampposts do still exist on many roads and a study counting street lamps with and without signs was made along Föreningsgatan into Östra Rönneholmsvägen followed by Pildammsvägen and Carl Gustafs Väg. 56 % of the lamp poles had no signs compared to 44 % that had signs. Diameter of poles varied between 60 mm and 250 mm in Malmö.

4.1.1.3 Copenhagen

In central Copenhagen even more lighting than Malmö was hung in wires between buildings. As a result poles were harder to find and many of the ones that could be found where of a framed structure, see figure 4-2. A product that can be mounted anywhere in central Copenhagen will have to be very flexible.

Figure 4-2 Framed structure found on many poles in Copenhagen

Outside of central Copenhagen lamps in wires are also found, but more poles are used for streetlamps than in the central parts. Poles are of different shape and varies from framed structure, like figure 4-2, to angular and round poles.

A study on a road with lampposts was made counting how many signs were put on poles. Outside of central Copenhagen on Panumsvej it was found that 12.5 % had signs while 87.5 % had no signs. In Copenhagen pole diameters varied between 60 mm and 220 mm.

4.1.2 Online studies

4.1.2.1 New York

After using Google Street View [2] in Manhattan, Brooklyn and some other suburbs around New York it is possible to say that nearly all lampposts have some kind of road sign attached to it. Therefore if the product is to be used in this area it is important that it can negotiate these obstacles to be an effective product. A more suitable product for this area may be if the product attaches to buildings and fire ladders. In the suburbs there is a possibility to use telephone posts to mount the camera.

4.1.2.2 Los Angeles

In Los Angeles there are many lampposts and the majority of them are without any road signs. The suburbs of Los Angeles are divided so that some streets have no poles at all and some have just telephone posts. Main areas such as shopping malls, parking

lots and other big public areas have lampposts. In general Los Angeles provides a good environment to use a climbing unit.

4.1.2.3 Houston

Houston has a good amount of lampposts that do not have any obstacles on them in the form of road signs or any other types of obstructions. In many of the stoplight intersections there are already fixed installations of surveillance cameras. The suburbs have telephone posts and lampposts.

4.1.2.4 Rome

In the bigger streets there are lampposts that are possible mounting points for a climbing unit. In the city center and its small streets there are lamps hanging in wires. Therefore in these environments a house mounted unit is preferable.

In the open areas such as squares and bigger streets fixed mounted cameras are often present. Streets have their cameras mounted at stoplight intersections. In these open public spaces the climbing unit can be a good compliment to the already existing surveillance system. It will be easily accessible and grant extra surveillance during big crowds.

4.2 Competition

Online research was made looking for other pole climbing units (especially with cameras). One product came very close, Sherpa's rapidly deployable CCTV. Sherpa claims on their homepage that it is the world's first and only climbing communications solution [3]. The product is a lift that climbs conical, hexagonal or tapered octagonal pole profiles and can handle poles between 75-150 mm [4]. The lift is mounted on a pole without any obstacles. On top of the lift different functions can be inserted into a housing that holds camera, Wi-Fi access point or 3G router. The lift takes this housing up the pole where an arm from the housing is extended to hold it in place. The lift then comes down again so it can be used for installation of other equipment if needed. The whole process takes about five minutes [3].

Functionality of the product seems excellent for when it gets up the pole. It also seems very robust. The biggest drawbacks are that it is big, heavy and can only handle unobstructed poles.

4.3 Reflections

In the pole study done in real life more than 50 % of the poles have no obstructing signs. A bigger problem in central parts of Malmö and Copenhagen is rather that there are no poles at all since lighting is hung in wires between houses. In these situations a climber that can negotiate drainage pipes or climb houses in some way would be better. The project aims towards a pole climber, so to climb poles will be the main target of the project. If the climber can negotiate other obstacles it will be seen as a bonus.

From the international online study it can be said that some cities, like New York, will be demanding for a pole climber since obstructions exists on most poles. Other cities,

like Houston, have many unobstructed poles which means a simpler climbing system can be used. In these cities a pole climber that can climb past a sign would be beneficial but in many cases a pole without a sign can be found in the vicinity.

Some poles have a high voltage power line and this may cause disturbances to the electronics in the pole climber. Warnings should be made to the operator to avoid these kind of situations and install the pole climber at a safe distance from the power lines.

Sherpa which will be the main competition for a pole climbing surveillance unit has chosen to build a climber that only negotiates ordinary poles without signs. It can handle pole diameters between 75-150 mm. The Sherpa also feels very heavy and clumsy. The project prototype will aim towards a less cumbersome product. Since the pole study showed that most poles have diameters between 60-180 mm this will be the minimum requirements for the climbing unit.

5 Development Kick-off

This chapter is the start of the product development described in Ulrich & Eppinger's Product Design and Development [1]. *The first step after planning is making a mission statement.*

5.1 Possible Markets, Scenarios and Other Assumptions

The primary market for a fast deployable climbing unit will be police and fire department. It will then be used during riots, fires and other time pressed situations. This means that it has to be very fast and easy to install. It also means that the product cannot be big and heavy.

Riots typically happen in cities and from the pre-study it became clear that in big parts of many cities streetlights hang in wires between buildings. This means the product can benefit from being flexible so it can climb house corners and drainage pipes. A drawback with such flexibility is that it might be hard to create a product that works without failure in all these situations. A product specifically designed for climbing a pole will probably handle a pole better than a product that can both climb a house and a pole.

Further exploration on the area from a police perspective the product can be used in hostage situations. In these situations the battery life might be crucial.

Other markets that might be explored are construction, festivals and the private security sector. In these situations the product should just work and battery should not be a constant issue.

5.2 Different Sensors

The product will in most situations have a camera. Other sensors that can be added are smoke detector, IR-camera, thermostat and sensors for wind speed and direction. A solar panel might also be added to charge the batteries. Different sensors for detecting objects and distances like ultrasound and rotary encoders might also be used. These will be added and implemented at a later stage if time permits and if they are deemed necessary.

5.3 Constraints

Early in the development process almost no constraints are put on the product. A discussion was held if it should only cope with ordinary poles, but this early in the development stage no such constraints should be put on the product. This is to enable a high level of creativity during concept generation further on.

5.4 Mission Statement

Early in the product development a mission statement should be made according to Ulrich and Eppinger [1]. Table 5-1 shows the mission statement for the pole climbing unit.

Table 5-1 Mission statement for the pole climbing unit

Product Description	• Pole climbing camera for poles of various thickness
Benefit Proposition	• Increase safety/security • Enable for easy temporary surveillance • Easy installation • Easy to handle
Key Business Goals	• Increase company's product range • Break in to an untapped market • Increase revenue
Primary markets	• Police • Fire Department
Secondary markets	• Construction sites • Festivals • Private security sector
Assumptions and Constraints	• Battery powered
Stakeholders	• Purchaser and User (Police, Fire Department) • Other end users • Sales department • Manufacturing operations

6 Identification of Customer Needs

Identifying customer needs for a product in a new market can be tricky since the end user has not seen the product before. A structured process might still help in development of a product and this chapter goes through steps for identification of customer's needs according to Ulrich & Eppinger [1].

6.1 The process

The goal of this project is to make a prototype for a climbing unit. Some focus is also towards a future goal in the development process which is to make a camera and climber in one complete system. Therefore the most similar product is the English based Sherpa [3], which is fairly unique.

Ulrich & Eppinger writes: "Developing an entirely new category of product is a risky undertaking, and to some extent the only real indication of whether customer needs have been identified correctly is whether customers like the team's first prototypes. Nevertheless, in our opinion, a structured method for gathering data from customers remains useful and can lower the inherent risk in developing a radically new product." [1, pp. 75-76].

Finding customers with experience of Sherpa is hard, especially in Sweden. The final climbing unit will be different from Sherpa because it is a climber and camera in one unit where the Sherpa climbing unit leaves the camera on its own on the pole. Therefore product development can be seen as development of a new category of product. Later identification of customer needs can be based on the prototype developed in this project.

Since a structured method will help, the process described by Ulrich & Eppinger [1] can be followed for the development of customer needs for the prototype. The steps are:

1. Gather Raw Data from Customers
2. Interpret Raw Data in Terms of Customer Needs
3. Organize the Needs into a Hierarchy
4. Establish the Relative Importance of the Needs
5. Reflect on the Results and the Process

6.2 Gather Raw Data from Customers

Gathering raw data from customers can be done with interviews, focus groups or observing the product in use [1]. Since the product can be seen as a new category of product the best way, and maybe even only way, is with interviews. These are

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conducted with experienced employees at a surveillance company that has a feel for market needs in terms of cameras.

Work for the project was mostly conducted in this surveillance company. The company culture is to always help a colleague that asks. This meant that data and ideas were also continuously gathered from experienced concept developing personnel at the company's department for research and development.

6.3 Interpret Raw Data in Terms of Customer Needs

Because customer needs can be interpreted differently customer statements can lead to different needs. Therefore a table of customer statements is set up. This table can be found in appendix F. Next to customer statements is how the project authors have interpreted the needs. These needs may not be technically feasible at a later development stage but should still be included in this step.

Many customer statements came from interviews on the surveillance company. The first interview was conducted with a more security oriented sales representative that previously has worked as a security consult for 2Secure in collaboration with police [5], [6]. Some of the work was crowd control. The second interview was with a more technical oriented sales representative which gave more insight into technical challenges [7].

Except for interviews some ideas that could be used as customer statements came from office discussions and meetings with project mentors [8].

Customer statements from environmental studies are the project authors own observations during the pre-study. These will lead to more interpreted needs for what the product needs to handle.

The project aims also translate into interpreted needs and are included in customer statements.

Finally comparing with the closest competition Sherpa gave ideas for product needs.

6.4 Organize the Needs into a Hierarchy and Establish Relative Importance of the Needs

Step three and four in section 6.1 is combined into one chapter. The interpreted needs are combined when possible and the relative importance is set. Since project aims are towards the climbing unit the camera capabilities are skipped in this stage. These aspects will be more crucial in a later design stage.

The result is inserted into a Concept Screening Matrix [1], see appendix C for the matrix. The result from this matrix will be used as a starting point for determining some main concepts to work with. These will then be tested by calculations, discussions, rudimental prototyping in wood and simple 3D models will be built in PTC Creo [9]. Finally a concept scoring matrix will decide the winner.

6.5 Reflect on the Results and the Process

The customer needs were tricky to present because customers do not know the needs before the product has been tested. Therefore realistic assessments were made for a prototype. This can be displayed to customers and at this later development stage more accurate customer needs can be made for the future product.

The next development step for the prototype would ideally be to set product specifications according to Ulrich & Eppinger [1]. This step was skipped since it is a prototype. A finished product has much more strict guidelines for technical requirements than a first prototype. For the prototype as much functionality as is possible within time constraints will be developed.

7 Concept Generation and Selection

Concepts were generated by brainstorming and gathering the whole team in the surveillance company's department for research and development. Concept screening lessened the candidates and the final process for concept selection is a combination of discussions, calculations and simple modelling where a final concept scoring round will be used to determine the winning concept.

7.1 Concept Generation

Through the whole process, including pre-study and customer needs, concepts were generated. The internet was browsed for similar products and other climbing robots and inspiration for some concepts even came from animals.

A workshop was held where the whole team in the surveillance company's department for research and development could attend and add their ideas during a brainstorming session. The group was presented with different scenarios and was given a time to make inventions that could solve these scenarios. The ideas were mixed with previous ideas and finally a big pile of concepts was sorted through and put into categories according to climbing style. Some concept drawings can be seen in figure 7-1. Some concepts were similar and grouped together and some concepts were deemed too unfeasible. Included in the concept screening matrix were 20 concepts. The matrix can be seen in appendix C.

Figure 7-1 Concepts drawings.

7.3 Concept Screening

Using some select interpreted needs from the customer statements in appendix E a basic scoring system for the concept screening matrix was made. The scoring with the concept numbers can be seen in the matrix in appendix C. The concepts were given three different scores (+1, 0, -1). The score given depended on if the task was performed better (+1), the same (0) or worse (-1) than the benchmark concept. Discussions between the authors were held for each scoring point and the 20 sorted concepts were gone through for each point. The process can be seen in figure 7-2.

In the end the concepts with positive scorers moved on for further investigation. The winners were presented to the project mentors where they were sorted into three groups, wheel based climbers, gripping climbers and leverage type climbers. These ideas will be reworked and solution feasibility will be done according to calculations and simulations on more advanced concept drawings. A concept scoring matrix will also be done for comparison between final concepts.

Figure 7-2 Concept screening process.

7.4 Concept Selection

The main ideas were grouped into three groups, wheel type, gripping type and leverage type climbing. During the process of making more detailed concepts and calculating feasibility, more concepts of these three types were made.

7.4.1 Leverage Type Climbing

The leverage type concept is good because it is easy to just hang the structure on the pole and if the wheels are locked it will stay there because of the leverage from the camera and battery weight. The principle can be seen in figure 7-3 which displays a rudimental model for the leverage type climbing.

Figure 7-3 Rudimental prototype for a leverage type climber.

Calculations were also done to show that this type of climber worked. These calculations are presented in appendix G.

The conclusion from calculations is that in normal conditions the leverage type climber can work but in icy conditions it will be an unpractical solution. The leverage arm, holding a hanging weight in figure 7-3, has to be made about 5.5 times larger than the arm connecting the wheels closest to the pole. This is not a feasible solution because the leverage arm then becomes over 2 m long. This kind of structure is both ugly and will be cumbersome to carry around. Because it is so big it will also be more eye catching and might get vandalized more. To keep the size down and cope with bad weather a new type of leverage climber is therefore designed that uses three wheels. The three wheeled type instead uses springs as leverage. These are connected between two wheels on one side of the pole. As the spring pushes the wheels away from each other the third wheel connected to the other wheels gets squeezed against the pole. This will also pull the other two wheels against the pole. The concept can be seen in figure 7-4.

The two wheeled solution is deemed feasible in most conditions and therefore both the two wheeled and three wheeled leverage type climber will continue to concept scoring. The three wheeled leverage climber becomes reference concept in the concept scoring and the two wheeled solution is called concept H.
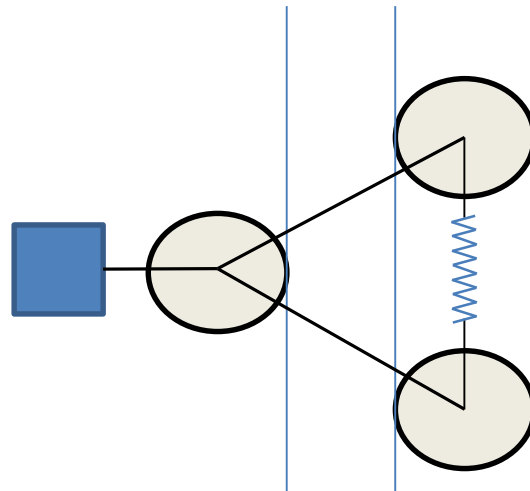
Figure 7-4 Three wheeled leverage type climber.

7.4.2 Wheel Type Climbing

For wheel type climbing three different concepts were evaluated. All the wheel type concepts are compact builds where one concept has two wheels and two of the concepts have three wheels. The three wheeled concepts differs in that one has its wheels installed straight, for a straight vertical pole ascent, while the other has slightly turned wheels, for an ascent where it spins around the pole. The spinning means that it can be turned to see in different angles by driving the robot up and down the pole. The principle for spinning up the pole and the wheel type concepts can be seen in figure 7-5. In concept scoring the three wheelers are called concept E and F where E has straight wheels. The two wheeler is called concept G.
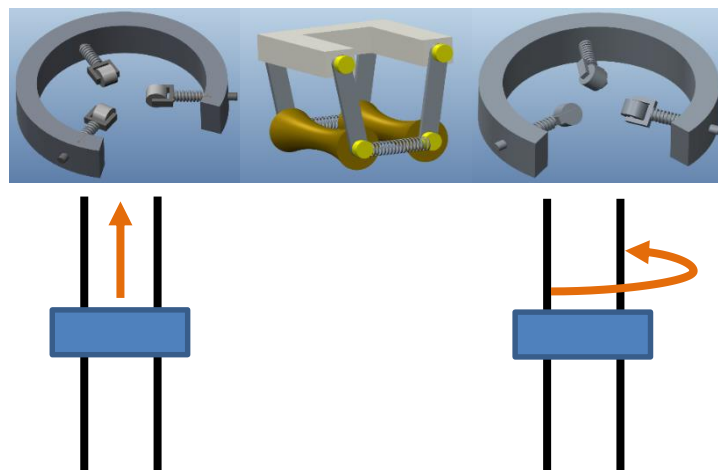
Figure 7-5 Wheel type concept.

7.4.4 Gripping Type Climbing

The grippers climb similar to how a human would climb up a pole. Two grippers will be connected with a linear unit. As the lower gripper holds the robot in place against the pole the linear unit connected to a motor will lift the upper gripper. When in top position of the linear unit the upper gripper grips the pole. Now the lower gripper lets go of the pole and as the linear unit moves down the lower gripper moves up. The lower gripper grips the pole when the linear unit has reached its bottom position. The top gripper can now let go and keep moving up again etc.

In the early concept stage many gripping concepts just pictured a robot gripping a pole with no more detail. In this stage the different ways of gripping had to be addressed in more detail. What is needed is that the gripper holds on to the pole without continuously adding electric force. The first thought was that springs needed to be used, but looking at linear electrical actuators a lot of them have self-hold, meaning they stay in their position when the electricity is turned off. This type of self-hold can also be gained with worm gear motors that stay in the same position when turned off. Five different concepts for grippers are evaluated.

Gripper A uses straps for holding on to the pole. These straps are tightened using worm geared motors. This solution will hold very steady to the pole but cannot handle signs or drainage pipes.

Gripper B, seen in figure 7-6, uses two u-shaped rods that are spun in different directions to grip the pole. If the design of the u-shape is made correctly it can center itself to the pole while not gripping around the pole. This means it can grip behind signs or grip drainage pipes without hitting the wall behind.
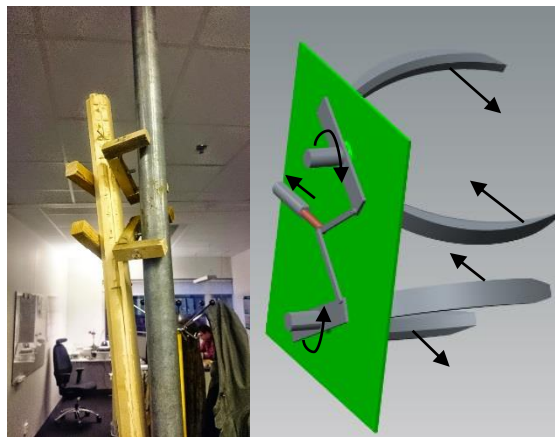
Figure 7-6 Gripper B.

Gripper C, seen in figure 7-7, is a bit more complex and uses wires and springs to grip centered despite different diameters of the pole. A motor is used to spin a cog connected to a toothed rack which in turn moves a larger arm inwards towards the pole. As the larger arm moves wires on pulleys moves with it. These are connected to the two smaller arms which will be pulled in against the pole with the larger arm. When the motor moves the larger gripper from the pole, the smaller grippers will be pushed out

with springs. This means that with one motor the gripping will be centered allowing the gripper to grip just past the center of the pole. This concept can grip behind a sign or grip a drainage pipe without hitting the wall behind it.
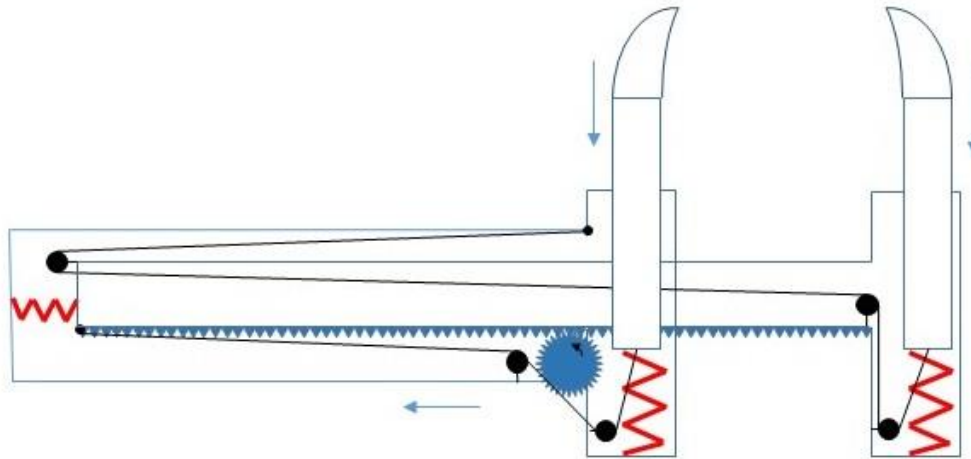
Figure 7-7 Gripper C.

Gripper D grips by simply pushing two plates towards each other against the pole. The plates will be shaped to maximize contact area with the pole. Figure 7-8 shows different ways of implementing such a gripper. Possibly this gripper can climb poles with signs and drainage pipes.

In the concept scoring the grippers will have the same names as above.
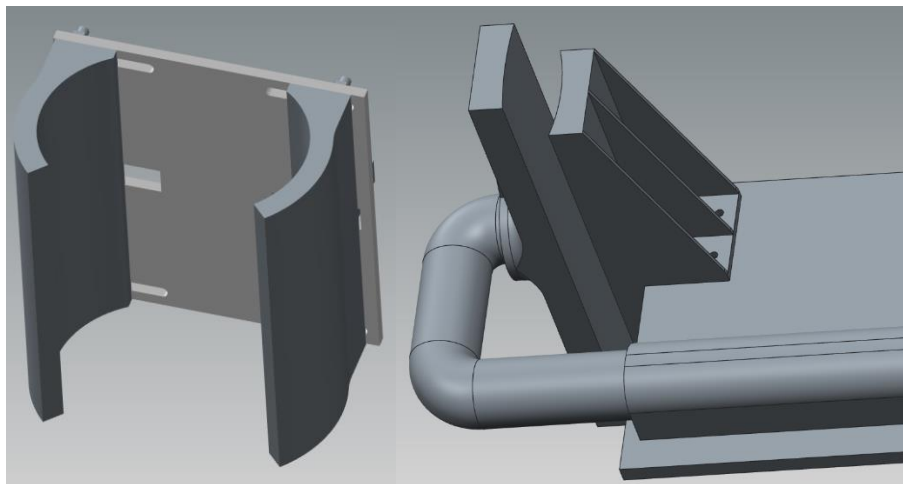
Figure 7-8 Different implementations of gripper D.

7.5 Concept Scoring

To choose between the different concepts a concept scoring was done [1]. Different important criteria were set up with independent weighting to determine importance.

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The reference (the three wheeled leverage type climber) got 3 points in all the important criteria and the other concepts scored from 1 to 5 compared to the reference where higher is better. The score was multiplied with the weighting and added up to a final score for each concept. The highest score wins and will be developed.

The process of finding correct weighting and which important criteria to use can be tricky. The authors came up with some important criteria and weighting for these. This was then discussed with the project supervisors [8]. The discussions led to changes that led to new discussions and so on. The final important criteria used are light weight, simple installation for one person, fast climber, simple solution and robust top hold. The concepts with names can be seen together in figure 7-9.
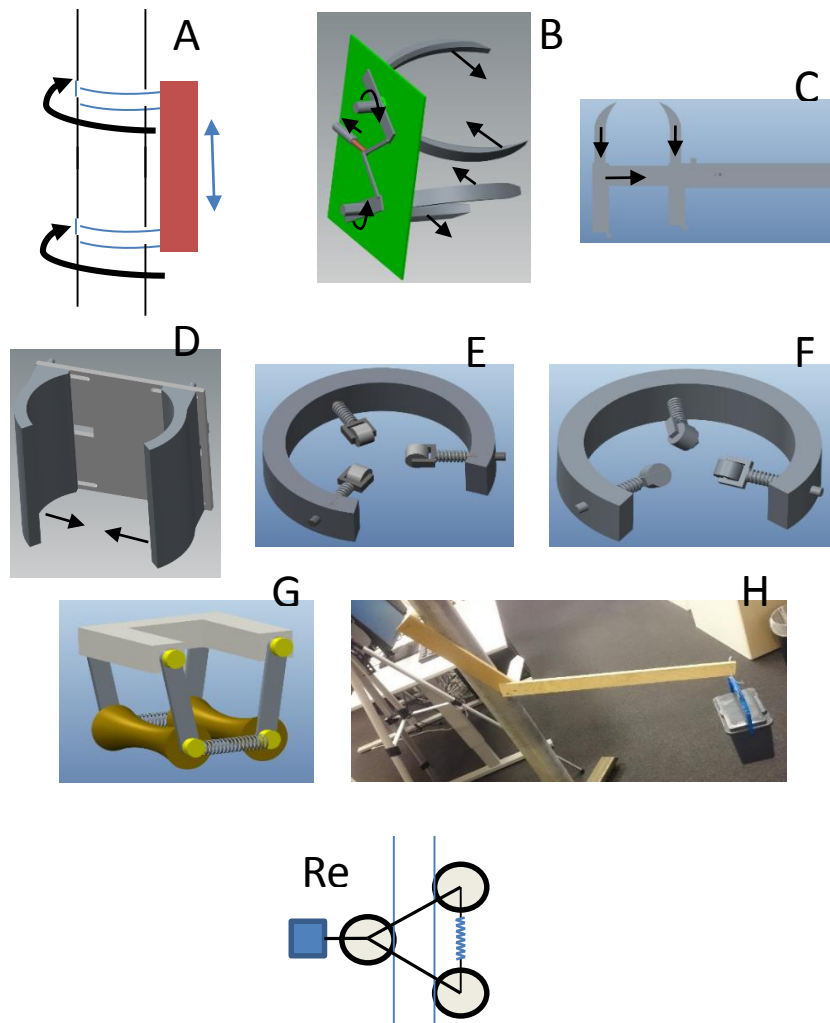
Figure 7-9 Concepts competing in Concept Scoring

Robust top hold became the most important criteria with the motivation that the operator have to trust the product when its left unsupervised. If the operator does not trust the product it will not be used and therefore not sold. Therefore robust top hold had a weighting of 0.3. A concept that feels more robust than the reference will score higher, which all the grippers and three wheeled concepts did. To differentiate between them all got four except for the straps that will have best grip with the pole at the top position and therefore scored five. The two wheeler scored the same as the reference while the leverage type two wheeler got two points because it will have a less robust top hold.

Simple installation for one person got a high weighting of 0.25. If the climber is hard to use for the operator the operator might not use it and consequently it will not be sold in the long run. Installation for the reference required the user to both squeeze together springs when installing on the pole and to fasten a metallic wire around the pole that is necessary for a robust top hold. Concepts B, C, D and H only required the user to make one thing before the robot is ready to move and therefore got four points. Concept A and G got two points because they required the user to do three things before robot is installed and concept E and F got the same score as the reference.

Fast climbing became prioritized as third most important because in a time pressed situation, like a riot, the camera can be used more quickly without supervision. Climbing also attracts attention which means a fast climber draws less attention and is less likely to get vandalized. All the grippers scored little points in this category while the wheel type climbers scored the same as the reference, except for G. Concept G has turned wheels and therefore will take a longer route which requires more time.

Light weight was the fourth most important criteria. It would have been more important in the weighting if not for the fact that the authors and project supervisors agreed that all concepts had to weigh less than 12 kg. A lighter robot is beneficial but if the robot weighs 9 kg or 11 kg might not be as important as some of the other criteria. To get some kind of idea of the weights the main parts in the structures were counted. Typical weights for these parts were then multiplied with number of parts in the concept and a total weight for the concept was added together. The weight chart can be seen in appendix D.

The last important criteria, with smallest weighting, was that the product should be a simple solution. Not only will this help with finishing the project on time but a simple solution can often be a better more cost effective solution during production. A cost effective product can be sold cheaper meaning more customers. It is hard beforehand to say exactly which product will be more or less complex. Mainly the authors looked at the mechanical complexity of the different concepts compared to the reference. Concept C that used springs and wires on pulleys in small spaces seemed to be the most complex product and therefore got one point. The rest of the grippers, except for A, seemed similarly complex as the wheel type concepts. As the reference automatically adjusts to different diameters it is a little less complex than these are, which gave them two points. Concept A that uses straps will have a mechanically simpler solution then the rest of the grippers and got three points. Simplest solution is the two wheeled leverage concept and this scored the highest with a four.

The final scores for the concept scoring was added together and the final chart can be seen in appendix E. Winner of concept scoring was concept A, which is the gripper that uses straps. Mainly it won due to its light weight and robust top hold. Its biggest drawbacks is the slow climbing speed and that it can be hard for one person to install it to a pole. With fast motors the climbing speed can still be acceptable and a smart solution during installation can still make it manageable for one person during installation to a pole.

7.6 Reflections

Seen in the concept scoring, in appendix E, is that concept A won with only a small margin. Before this final concept scoring round some more concept scoring rounds were tried with different weighting and with some different criteria. Concept A won most of the trial rounds too. Therefore concept A won even if the win was marginal in the final concept scoring round.

Another reflection to be made is that a decision was made to give a robust climbing system for ordinary poles an advantage in the concept scoring and not bother with a climbing system that can handle signs and drainage pipes. This decision took many discussions and weeks of trying to find the perfect concept that could handle everything. The biggest problem was that often a climber that could climb over many different obstacles did not feel very robust and reliable. The time plan did not allow for any more time being spent developing concepts and since the pole study showed that there are many poles out there that have no signs it felt reasonable that the user can find such a pole nearby. With the use of a ladder a light pole climber can even be installed fairly easily above a sign.

Necessary for the pole climber is that it can handle diameter changes on a pole. This is therefore a requirement for the prototype. To stay on track with the time plan it was also decided that mainly focus will be towards the climbing unit. This means no exact design features for fitting a camera will be made. Fitting a camera can be done in a temporary way for the prototype and later products can just add some extra design features for this purpose.

8 Conceptual Design

Described in this chapter is the final conceptual design for the pole climber.

8.1 Climbing

The mechanical design of the climber consists of two main functions. The first function is vertical climbing which is a linear movement that works along the pole's axial direction. The second function is a cog belt tightening mechanism used to fasten the robot on to the pole. By having two cog belts one belt can hold the robot while the other moves upwards along the pole. At a certain height the moving belt will be tightened and hold the climber so the other belt can move upwards. Both functions uses DC motors of 12 V, one motor per belt and one for the linear movement along the pole.

8.2 Vertical Movement

Conversion of the motors circular motion to a vertical climb is done with a trapezoidal threaded screw. The screw is connected to the DC motor by timing belt pulleys and a cog belt. To get the DC motor to spin at required speed and torque the motor will have a built in gearbox. The conversion from the motor spinning to the linear movement on the screw can also be considered a type of transmission. To enable the trapezoidal threaded screw to move straight a linear track with a cart will be used. This linear track will guide the static trapezoidal threaded bushing that is mounted to the screw. As the screw rotates the bushing is forced to move up or down on the screw since it is fastened to the cart on the linear track. The bushing will stay stationary when the motor is turned off since it is a trapezoidal threaded screw with a small pitch compared to the diameter.
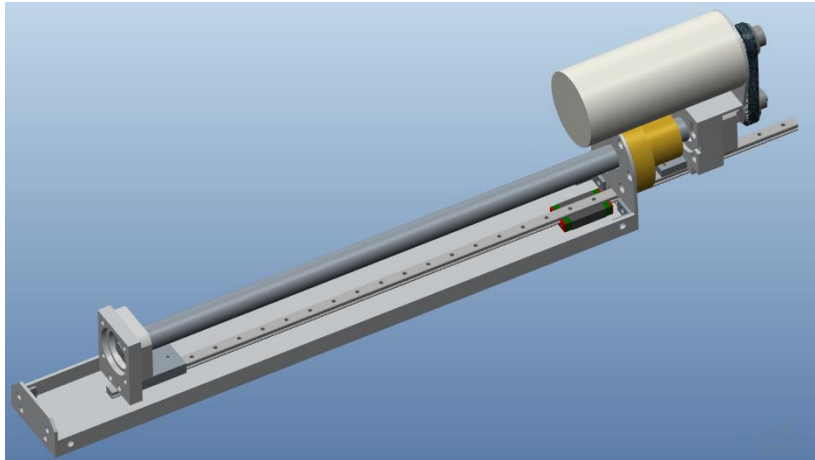
Figure 8-1 The unit for vertical motion.

8.3 Tightening

The second function that tightens the belt to the pole consists of a DC motor that has a worm gear. This enables self-holding of the belt while the motor is off and without using a brake. To enable the robot to always be parallel with the pole an arm has been constructed, see figure 8-3, to counter the force from the belt. This arm moves out slower than the belt is reeled in. This is because the belt has to take a longer way around the pole while the arm goes straight towards the pole. The reason to implement this kind of arm instead of tightening the climber with just the belts is to ensure that the robot always fastens with a constant distance to the pole center despite different pole diameters. This means the robot will always stay parallel to the pole. Except for the benefit of installing the camera straight this helps keep the belts straight without tangling during tightening. Tightening the belts straight also means less chance that the robot slips. Finally a parallel movement along the pole is also beneficial because as a plate with belts moves upwards it cannot hit the pole. If a slant towards the pole would exist the climber might collide with its top into the pole, see figure 8-2.
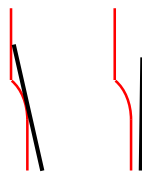
Figure 8-2 Safer climbing while parallel with pole

To keep the tightening system simple and weight efficient the DC motor that drives the belt also drives the arm. For this to work a spur gear and timing belt pulley system is implemented to get the right ratio between the belt and arm movement. Seen in figure 8-3 are the cogs that connect motor shaft, A, with the pushing arm, C, and the shaft connected to timing belt pulley, B. Above these cogs is where the cog belt runs and its path can be seen in figure 8-4. By having a larger diameter for the timing belt pulley that pulls in the belt, compared to the cog beneath, the belt moves faster than the

pushing arm. The cog belt is pushed against the timing belt pulley with a roll that has low friction. This roll is seen next to B in figure 8-4.

To collect the excess belt that is reeled in a spring mechanism with a timing belt pulley is used that rolls up the belt, D in figure 8-4. The reason for collecting the belt on a separate timing belt pulley instead of just rolling it up directly is that as the radius increases on the collected role more torque is needed from the motor due to the larger radius. The worst case for tightening is on small pole diameters and this is also the case when most belt will be collected. Therefore a system with separate belt retraction is beneficial.
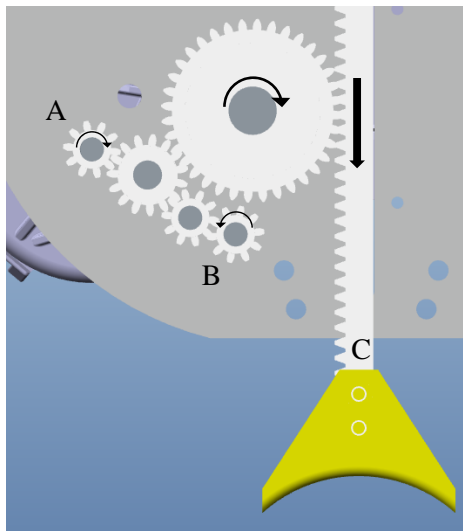
Figure 8-3 Gears used to enable the self-centering. In point A the motor drives the gears and point B is the shaft that drives the cog belt. Counter arm C is also seen.
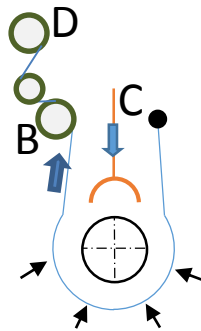
Figure 8-4 The path for the cog belt above the cogs seen in figure 8-3. Timing belt pulley for pulling in the belt, B, is installed on the same shaft as cog B seen in figure 8-3. The excess cog belt is gathered at the timing belt pulley D.

8.5 Installation

On the side of the belt not being fed into the timing belt pulley is a hook. This hook is fastened to a rod on the other side of the arm and cogs, seen in figure 8-3. The hook fastened to the rod can be seen in figure 8-5. By using a hook the belt can easily be attached and detached from the pole by a user when the belts are loose. To enable safe operation during installation to the pole the belts can only be pulled in as long as the operator pushes down two buttons at the same time. By placing these buttons so that the operator has to use one hand per button, the risk of getting stuck inside of belts or cogs is reduced.

Not implemented in this prototype are handles and a harness for lifting. With handles the buttons for installation can be placed conveniently where the thumbs rest and the harness enables lifting with the whole body instead of just the arms.
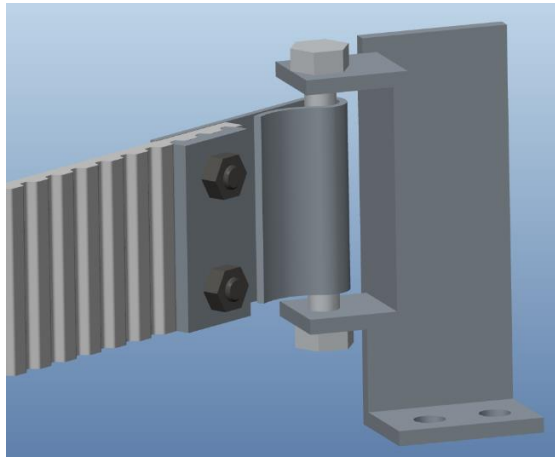
Figure 8-5 Fastener for the cog belt that enables a quick attachment.

8.6 General Structure

Holding together the whole system is the linear track with the cart. The lower part of this track is not used for the cart but for fastening the lower tightening system and the motor that drives the trapezoidal threaded screw. Fastened to the cart is a plate that holds the top tightening system. This plate is manufactured so that it stays just above the top of the trapezoidal screw when the cart is at its lowest position. As the cart moves up, the plate moves with it.
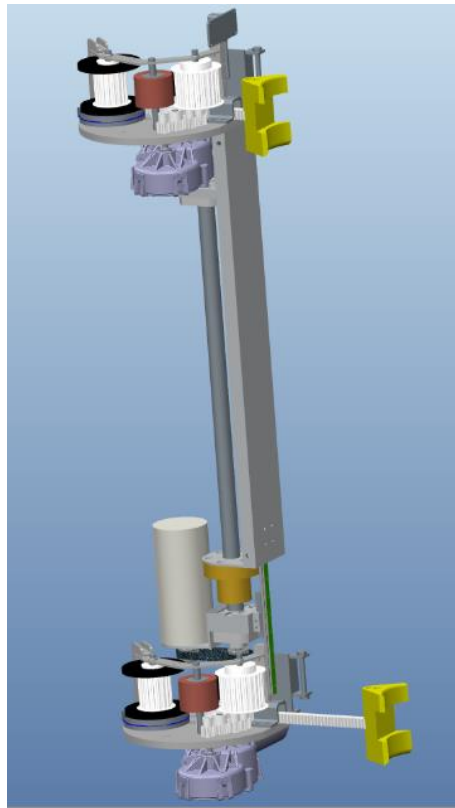
Figure 8-6 The climbing unit without belts.

At the ends of the trapezoidal threaded screw switches are fastened. For ordinary operation the motor will stop the trapezoidal threaded bushing in time from sensor readings. The switches are used as an extra safety measurement and if one of these switches are triggered the motor driving the screw will stop immediately. To control these switches and motors a micro controller is used. This will be installed on the lower plate. A battery is installed on the upper plate for better weight distribution. It will power the motors and the micro controller. The complete model for the system, without belts, can be seen in figure 8-6.

During climbing a distance sensor will monitor the distance to the pole. If the distance increases a diameter change has occurred on the pole. The robot will then stop, back up and tighten just under the diameter change. The next climbing cycle it will step over the diameter change with both belts.

During down climbing no distance measurement is done. Down climbing is instead done in exactly the same path as climbing up. By saving the screw motor's sensor values during ascent, this information can be used to backtrack down the pole again.

To control when the robot should stop, climb or climb down, an IR controller is used. The IR receiver will be mounted at the bottom of the climber for better connection to the IR transmitter. Also mounted at the bottom of the climber is the camera.

8.7 Mechanical Development

The whole system is first designed and built in PTC Creo 2.0 [9]. The CAD library for all the cogs, timing belt pulleys, worm geared motors, toothed racks, linear motion guide, trapezoidal threaded bushing and the bearing supports have been collected from the suppliers' homepages. The rest of the parts have been constructed by the authors with some help from the project mentors. All the parts are finally assembled in Creo to make sure that everything fits together and can be assembled without any parts interfering with each other.

9 Technical Review: Calculations and Component Selection

This chapter will describe the process of component selection for some key components like motors and battery.

9.1 Calculations of Belt Forces and Selection of Worm Geared Motor

During climbing it is required of the robot that it can hold its own weight statically in place with one cog belt while the other belt moves upwards. The worm geared motor will pull the belt until it has reached a certain torque and can then stop. To calculate required torque, the belt forces needs to be found. Per Lidström [10] from division of mechanics on LTH helped with these calculations.
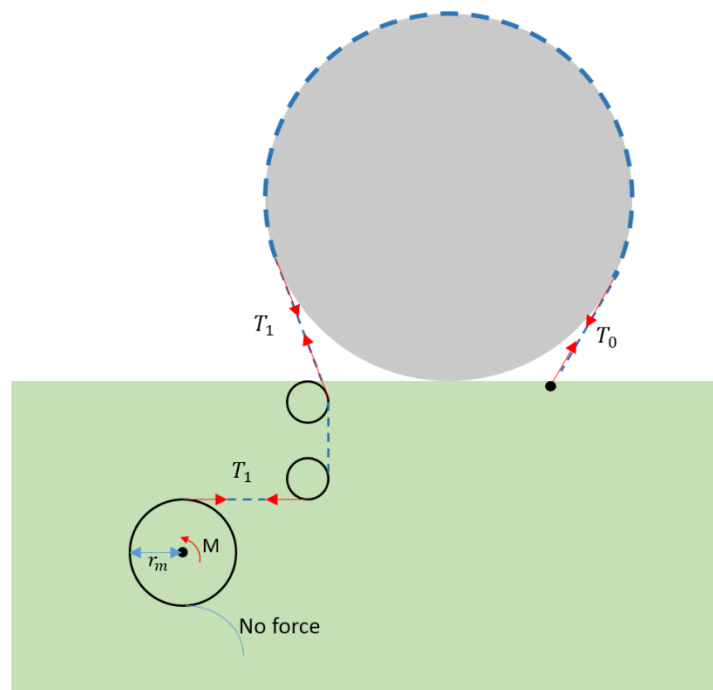
Figure 9-1 Pole and motor torque.

A simplified sketch of the system, without the extending arm, can be seen in figure 9-1. Also missing in figure 9-1 is the roll that pushes the cog belt against the cogs. For simplification such details have been removed and an assumption for the system is that

these extra forces are negligible and all the bearings are frictionless. Equation 9.1 calculates motor torque needed to keep the system statically at rest with one belt.

$$Equation\ 9.1: M = T_1 r_m$$

The radii, r_m, will be constant depending on which cog is chosen. The belt forces T_1 and T_0 are unknown. Christer Nyberg [11, p. 120] derives how to find the belt forces in two dimensions but this system also has a third dimension. Therefore the calculations have to be modified.

Figure 9-2 shows the pole and how the belt encloses it β degrees. Seen on the right is a very small part of the belt at the arbitrary angle θ. The ends of the belt at this small part can be found at θ and $\theta + \Delta\theta$. Also seen are normal force, ΔN, horizontal belt force, T, vertical belt force, K, horizontal friction force, f, vertical friction force, $f_\odot$ and angles, $\Delta\varphi$, where $2\Delta\varphi=\Delta\theta$.
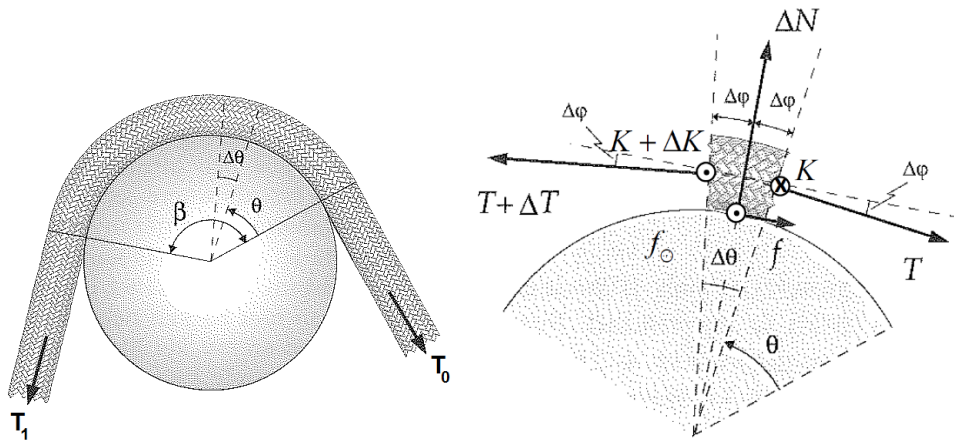
Figure 9-2 Forces acting on the belt (modified figure from [11, p. 120]).

The small part in figure 9-2 is affected by contact pressure between the pole and belt, $p=p(\theta)$, and the horizontal belt force, $T=T(\theta)$. The pressure generates the radial force (normal force) seen in equation 9.2.

$$Equation\ 9.2: \Delta N = p(\theta)R(\theta)\Delta\theta$$

$R=R(\theta)$ is the curvature radius for the pole and with a cylindrical pole this is constant, R, and does not depend on θ. Equilibrium equations become:

$$Equation\ 9.3$$
$$(\rightarrow): T cos(\Delta\varphi) - (T + \Delta T) \cos(\Delta\varphi) + f = 0$$
$$(\uparrow): \Delta N - T sin(\Delta\varphi) - (T + \Delta T) \sin(\Delta\varphi) = 0$$
$$(\odot)\ K + \Delta K - K + f_\odot - \rho R \Delta\theta g = 0$$

Here ρ symbolizes the mass of the belt per unit length and g is the gravitational acceleration. For a statically stable system with friction coefficient smaller or equal to the static limitations of friction, $\mu \leq \mu_s$ condition 9.1 can be used. μ represents friction between pole and belt.

$$Condition\ 9.1: f = \mu\Delta N, f_\odot = \mu\Delta N$$

Condition 9.1 and equation 9.2 are inserted into equation 9.3 to make equation 9.4.

Equation 9.4:
$(\rightarrow): -\Delta T\cos(\Delta\varphi) + \mu\Delta N = 0 \Longrightarrow -\Delta T cos(\Delta\varphi) + \mu p R\Delta\theta = 0$
$(\uparrow): \Delta N - 2T\sin(\Delta\varphi) - \Delta T\sin(\Delta\varphi) = 0 \Longrightarrow pR\Delta\theta - 2T sin(\Delta\varphi) - \Delta T sin(\Delta\varphi) = 0$
$(\odot)\ \Delta K + f_\odot - \rho R\Delta\theta g = 0 \Longrightarrow \Delta K + \mu\Delta N - \rho R\Delta\theta g = \Delta K + \mu p R\Delta\theta - \rho R\Delta\theta g$
$\qquad = 0$

$\Delta\theta = 2\Delta\varphi$ can now be used to rewrite equation 9.4.

$$-\frac{\Delta T}{\Delta\theta}\cos\left(\frac{\Delta\theta}{2}\right) + \mu pR = 0 \rightarrow -\frac{dT}{d\theta} + \mu pR = 0\ , when\ \Delta\theta \rightarrow 0\ (Eq.\ 9.5)$$

$$pR - T\frac{\sin\left(\frac{\Delta\theta}{2}\right)}{\frac{\Delta\theta}{2}} - \frac{\Delta T}{\Delta\theta}\sin\left(\frac{\Delta\theta}{2}\right) = 0 \rightarrow pR - T = 0\ , when\ \Delta\theta \rightarrow 0\ (Eq.\ 9.6)$$

$$\frac{\Delta K}{\Delta\theta} + \mu pR - \rho Rg = 0 \rightarrow \frac{dK}{d\theta} + \mu pR - \rho Rg = 0\ , when\ \Delta\theta \rightarrow 0\ (Eq.\ 9.7)$$

Equation 9.5 and 9.6 can be combined into a differential equation.

$$\frac{dT}{d\theta} - \mu T = 0 \Leftrightarrow \int\frac{1}{T}dT = \int\mu d\theta \Leftrightarrow \ln(T) = \mu\theta + C_1\ (Eq.\ 9.8)$$

Inserting the boundary condition $T(0)=T_0$ gives the constant $C_1=ln(T_0)$. Therefore equation 9.8 can be rewritten to equation 9.9 which is the belt friction equation [11, p. 120].

$$T(\theta) = T_0 e^{\mu\theta}\ (Eq.\ 9.9)$$

Equation 9.7 is rewritten with equations 9.6 and 9.9.

$$\frac{dK}{d\theta} = -\mu T + \rho Rg = -\mu T_0 e^{\mu\theta} + \rho Rg \Leftrightarrow K(\theta) = -T_0 e^{\mu\theta} + \rho Rg\theta + C_2\ (Eq.\ 9.10)$$

Boundary condition $K(0)=K_0$ gives the constant $C_2=K_0+T_0$. This is inserted into equation 9.10 to make equation 9.11 for vertical forces on the belt.

$$K(\theta) = T_0\left(1 - e^{\mu\theta}\right) + \rho Rg\theta + K_0\ (Eq.\ 9.11)$$

Figure 9-3 shows the forces acting on the pole climber. The belt has contact with the pole from angles 0 to θ_1. The belt will affect the robot with horizontal forces T_0, T_1 and vertical forces K_0, K_1. The pole will affect the robot with horizontal forces N_A, f_B and vertical force f_A. Finally the gravitation will affect the pole climber vertically with mg.

Inserting the angle θ_1 into equation 9.11 gives equation 9.12.

$$K(\theta_1) = K_1 = T_0\left(1 - e^{\mu\theta_1}\right) + \rho Rg\theta_1 + K_0\ (Eq.\ 9.12)$$
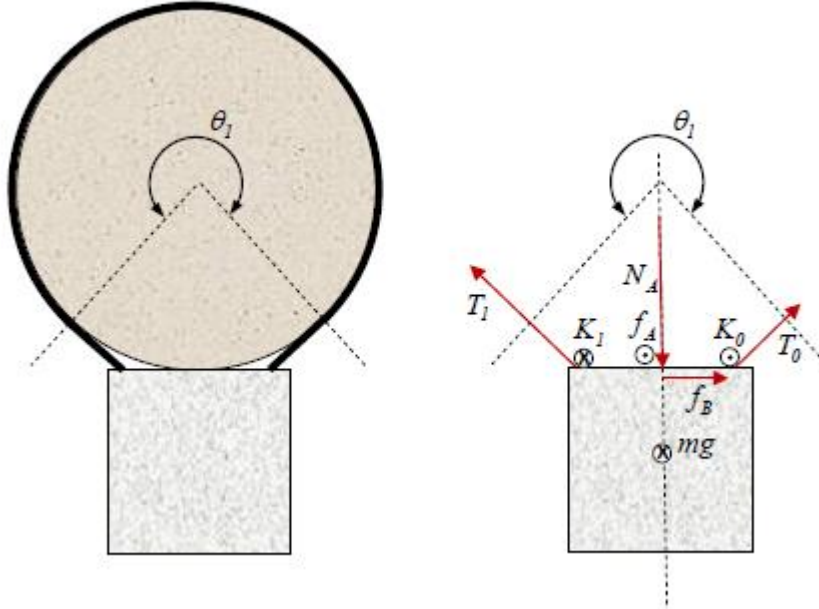
Figure 9-3 Forces acting on the pole climber.

Equilibrium equations for figure 9-3 gives equations 9.13-9.15.

$$(\rightarrow) - T_1 \cos\left(\pi - \frac{\theta_1}{2}\right) + f_B + T_0 \cos\left(\pi - \frac{\theta_1}{2}\right) = 0 \ (Eq. 9.13)$$

$$(\uparrow)\ T_1 \sin\left(\pi - \frac{\theta_1}{2}\right) - N_A + T_0 \sin\left(\pi - \frac{\theta_1}{2}\right) = 0 \ (Eq. 9.14)$$

$$(\odot)\ -K_1 + K_0 + f_A - mg = 0 \ (Eq. 9.15)$$

With the same argument as for condition 9.1 condition 9.2 can be made.

$Condition\ 9.2: f_A = \mu_A N_A,$ where μ_A is friction between pole and robot

Equation 9.12 and condition 9.2 are used in equation 9.15 to make equation 9.16.

$$(\odot) - K_1 + K_0 + \mu_A N_A - mg = -T_0\left(1 - e^{\mu\theta_1}\right) - \rho Rg\theta_1 - K_0 + K_0 + \mu N_A - mg$$
$$= -T_0\left(1 - e^{\mu\theta_1}\right) - \rho Rg\theta_1 + \mu N_A - mg = 0 \ (Eq. 9.16)$$

Equation 9.14 can be rewritten by inserting θ_1 into equation 9.9 to get equation 9.17.

$$N_A = (T_1 + T_0)\sin\left(\pi - \frac{\theta_1}{2}\right) = T_0(e^{\mu\theta_1} + 1)\sin(\frac{\theta_1}{2}) \ (Eq. 9.17)$$

This can be inserted into equation 9.16.

$$T_0\left(e^{\mu\theta_1} - 1\right) - \rho Rg\theta_1 + \mu_A T_0\left(e^{\mu\theta_1} + 1\right)\sin\left(\frac{\theta_1}{2}\right) - mg = 0 \ (Eq. 9.18)$$

Rewriting equation 9.18 the belt force T_0 can be found for a statically stable system.

$$T_0 = \frac{mg + \rho Rg\theta_1}{e^{\mu\theta_1} - 1 + \mu_A(e^{\mu\theta_1} + 1)\sin(\frac{\theta_1}{2})} \quad (Eq.\,9.19)$$

With the use of equation 9.9 and 9.19 the belt force T_1 can be found.

$$T_1 = \frac{mg + \rho Rg\theta_1}{e^{\mu\theta_1} - 1 + \mu_A(e^{\mu\theta_1} + 1)\sin(\frac{\theta_1}{2})}\, e^{\mu\theta_1} (Eq.\,9.20)$$

This force can finally be inserted into equation 9.1 to get the motor torque required to hold the robot statically at rest with one belt.

$$M = T_1 r_m = \frac{mg + \rho Rg\theta_1}{e^{\mu\theta_1} - 1 + \mu_A(e^{\mu\theta_1} + 1)\sin(\frac{\theta_1}{2})}\, e^{\mu\theta_1} r_m \quad (Eq.\,9.21)$$

To know exact values for the robot before it is built can be hard, therefore some reasonable values are used. Assuming that rubber will be used both for cog belt and the part of the robot in contact with the pole frictional coefficient of $\mu = \mu_A = 0.3$ can be used [11, p. 109] . A sample for a cog belt was used to measure the mass/meter for the cog belt. This gave the value $\rho = 0.035$ kg/m. Since the robot cannot be too heavy the robot mass is approximated to be below 10 kg and therefore $m = 10$ kg is used. To get the angle θ_1 a simplification is made that the robot is symmetrical and the belt will be reeled in and is anchored three centimeters from the center point for the robot. The worst case scenario where least belt will have contact with the pole is for the smallest diameter of the poles. For these cases the pole radii is three centimeters, $R = 0.03$ m, and θ_1 will be π. Finally the value for cog radius can from the design of the robot be between 10 and 20 mm. Worst case will be 20 mm and therefore is used in calculations as $r_m = 0.02$ m. Inserting these values into equation 9.21 gives required torque of $M = 1.86$ Nm. A worm geared motor that satisfies this condition is found at OEM motor [12]. Since an important aspect of the design is to keep the robot light a motor that can operate at 12 V is preferable to a motor that requires higher voltage. This means the battery can be smaller and therefore lighter. The motor has a nominal torque of 3 Nm and can work well above this torque if it needs to so there is still overhead room for extreme conditions with icy poles that require more torque to hold the robot in place.

9.2 Transmission for Extending Arm and Belt

By extending an arm at the same time as the belt is tightened the robot can stay vertical against a center point in the pole even if it has tightened the belts at different pole diameters. This is done by having a transmission for how fast the arm moves compared to how fast the belt moves. Figure 8-3 shows a picture of how cogs connected to the motor axle can make an arm move against the pole at the same time as the belt is pulled in. By using the relationship between pole diameter and pole circumference the transmission between belt and pushing arm can be found. This relationship would be linear if the belt exactly matched the circumference of the pole when tightened, but this is not the case. In the calculations the pole radius is compared to the belt length used to tighten the robot to the pole. How far out the arm moves directly matches the pole radius while the belt length differs in a nonlinear way for different radiuses.
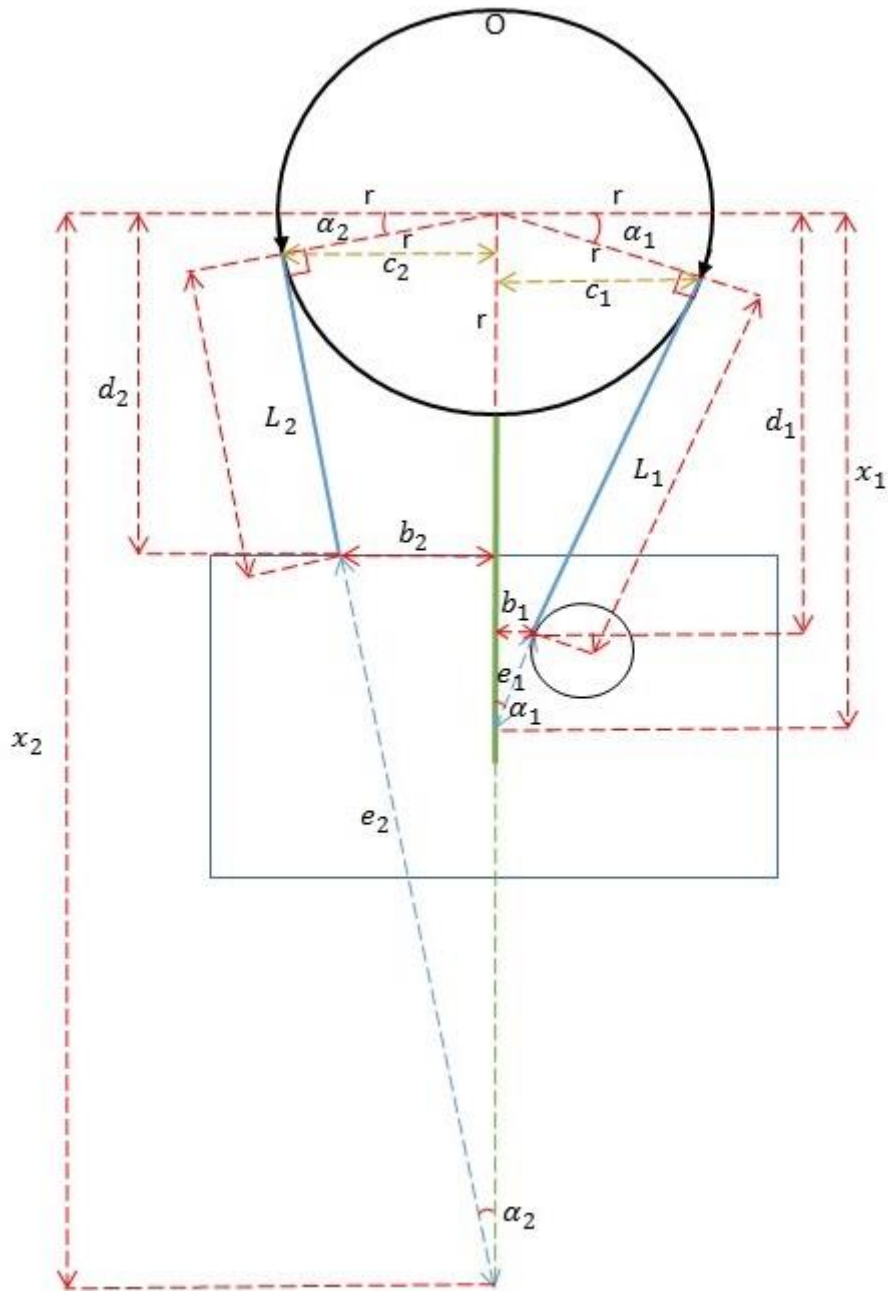
Figure 9-4 Belt tightened against pole.

Figure 9-4 displays the static case when the belt is tightened around a pole (blue and black lines) while the arm is extended and holds against the pole (green line). The total belt length used to fasten the belt to the pole is the sum of the lengths L_1, L_2 and O. The belt is statically fastened at the cog that feeds the belt into the machinery at the beginning of L_1. The belt length L_1 runs up to the start of the circumference for the belt

around the pole. The circumference length for the belt around part of the pole is O and it ends where the belt lets go of the pole again. At this point L_2 represents the belt length from the pole to where it is statically fastened by a hook to the plate that holds all the machinery.

Also seen in figure 9-4 are the constant lengths d_1, d_2, b_1 and b_2. From a helping line, drawn in parallel with the robot through the center of the pole, the lengths d_1 and d_2 represents length to fastening points for the belt sides. Lengths b_1 and b_2 represents the distances from the center of the moving arm (the toothed rack) to the fastening point for the belt sides. These lengths were gathered, before the prototype was built, from the 3D-model. When the prototype is finished these will still be the same and are displayed in table 9-1.

Table 9-1 Measured lengths used in calculations.

d_1	145 mm
d_2	130 mm
b_1	7.3 mm
b_2	29 mm

Helping lengths in figure 9-4 are c_1, c_2, e_1 and e_2. These lengths enables the use of triangle uniformity. Firstly this triangle uniformity is used in equations 9.22 and 9.23.

$$\frac{x_1 - d_1}{x_1 - rsin(\alpha_1)} = \frac{b_1}{c_1} = \frac{b_1}{rcos(\alpha_1)} \; (Eq.\,9.22)$$

$$\frac{x_2 - d_2}{x_2 - rsin(\alpha_2)} = \frac{b_2}{c_2} = \frac{b_2}{rcos(\alpha_2)} \; (Eq.\,9.23)$$

Two more equations is needed to find α_1 and α_2. Equations 9.24 and 9.25 are found with trigonometry.

$$\tan(\alpha_1) = \frac{b_1}{x_1 - d_1} \; (Eq.\,9.24)$$

$$\tan(\alpha_2) = \frac{b_2}{x_2 - d_2} \; (Eq.\,9.25)$$

To solve equations 9.22-9.25 in Matlab, condition 9.1 and 9.2 are used (the Matlab code can be found in appendix H).

$$Condition\ 9.1 : l_1 < x_1$$
$$Condition\ 9.2 : l_2 < x_2$$

With α_1 and α_2 solved equation 9.26 and 9.27 are made.

$$(L_1 + e_1)sin(\alpha_1) = c_1 = rcos(\alpha_1) \leftrightarrow (L_1 + e_1) = \frac{rcos(\alpha_1)}{sin(\alpha_1)} \; (Eq.\,9.26)$$

$$(L_2 + e_2)\sin(\alpha_2) = c_2 = r cos(\alpha_2) \leftrightarrow (L_2 + e_2) = \frac{r cos(\alpha_2)}{\sin(\alpha_2)} \ (Eq.\ 9.27)$$

Again the triangle uniformity is used to make equation 9.28 and 9.29. Equations 9.26 and 9.27 are also inserted into these equations.

$$\frac{e_1}{L_1 + e_1} = \frac{b_1}{c_1} \leftrightarrow e_1 = \frac{b_1 \frac{r cos(\alpha_1)}{sin(\alpha_1)}}{r cos(\alpha_1)} = \frac{b_1}{\sin(\alpha_1)} \ (Eq.\ 9.28)$$

$$\frac{e_2}{L_2 + e_2} = \frac{b_2}{c_2} \leftrightarrow e_2 = \frac{b_2 \frac{r cos(\alpha_2)}{sin(\alpha_2)}}{r cos(\alpha_2)} = \frac{b_2}{\sin(\alpha_2)} \ (Eq.\ 9.29)$$

The variables e_1 and e_2 can now be inserted back into equation 9.26 and 9.27 to solve L_1 and L_2.

The angles α_1 and α_2 are also used to solve equation 9.30.

$$O = r(\pi + \alpha_1 + \alpha_2)\ (Eq.\ 9.30)$$

The variables O, L_1 and L_2 can finally be used to calculate the belt length for a given radius, r, with equation 9.31.

$$L = L_1 + L_2 + O\ (Eq.\ 9.31)$$

With equations 9.22-9.31 different lengths needed for the belt can be calculated for different pole radiuses. The pole radius is directly connected to how far out the robot needs to push its arm to keep a constant distance to the pole center. Therefore a comparison between the pole radius and L is only needed to find transmission between arm and belt length.

The transmission used will only work in a linear way because the cogs are static in their places. Therefore a comparison between the linear and nonlinear relationship is made to see if a linear solution will be sufficiently close to a nonlinear solution for different pole radiuses.

Minimum pole radius that the robot should handle is 30 mm and maximum pole radius is 90 mm. Some extra length will be added to both d_1 and d_2 for an extra construction that gives better grip against the pole. This will not have only one contact point with the pole as calculated in figure 9-4 but this model is deemed close enough to the real model to be used for evaluation. In reality there might be some millimeters extra gap from arm to pole if two contact points is only achieved on wider poles. This is because the arm will be optimized in a round shape, see figure 8-3, for maximum contact with the smallest pole radius of 30 mm. This pole radius is when the friction is needed the most.

L from equation 9.31 is calculated for maximum and minimum pole radiuses. The linear relationship is found by inserting theses values into equations 9.32 and 9.33.

$$L_{max} = k r_{max} + m \ (Eq.\ 9.32)$$

$$L_{min} = k r_{min} + m \ (Eq.\ 9.33)$$

These equations can be used to find both k and m. With k and m solved the general linear relationship for the belt length versus pole radius can be used, equation 9.34.

$$L = kr + m \ (Eq. 9.34)$$

This relationship is plotted and compared for different radiuses for the linear and nonlinear equations. The smallest difference when selecting a linear solution from max and min values is obviously at the end points where the difference is zero. The biggest difference is in the middle at the radius 60 mm. At this point the difference between the linear and nonlinear solution is between 7-8 mm. This is deemed an acceptable margin of error during operation. The k-value from equation 9.34 is therefore chosen as the transmission needed between the belt and the arm. The k-value is found to be about 3.8. This means that the belt needs to travel 3.8 times faster than the moving arm. This is achieved by making the radius/diameter for the cog where the belt is fed in 3.8 times larger than the cog that rotates below on the same shaft that decides the speed for the pushing arm. This relationship comes from the circumference speed on a disk and can be seen in figure 9-6.
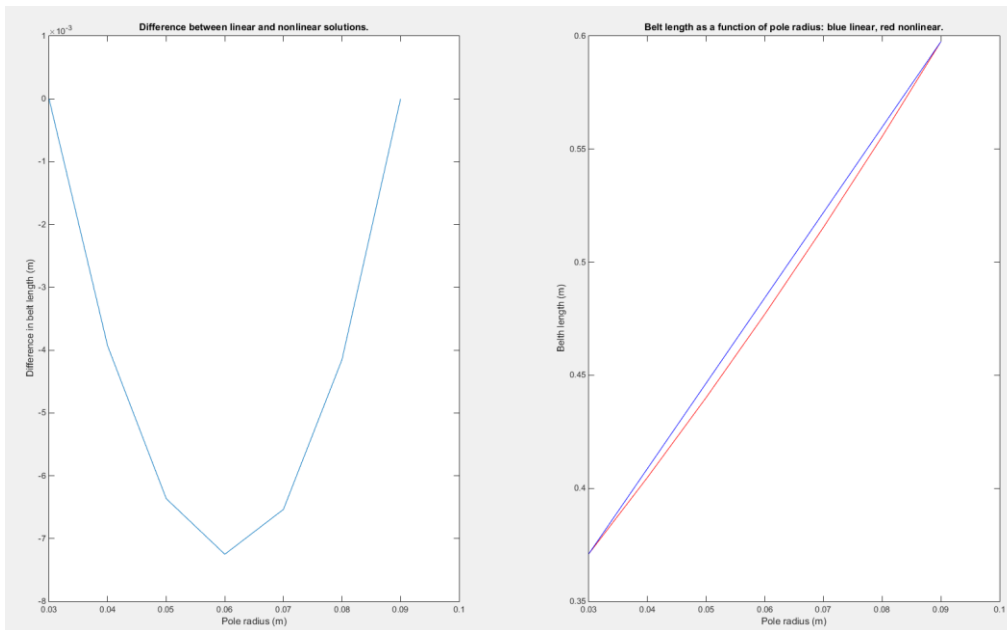
Figure 9-5 Difference between linear and nonlinear solutions.
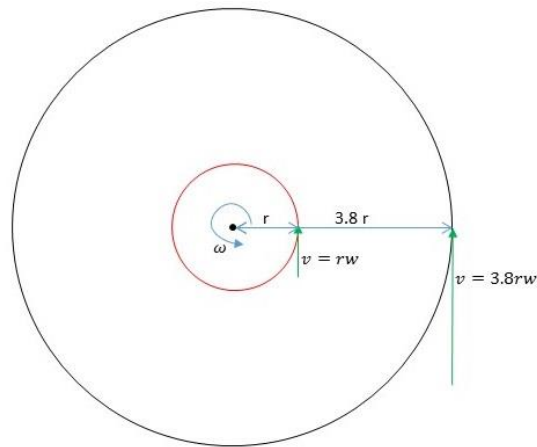
Figure 9-6 Circumference speed depending on radius.

9.3 Climbing Cycle and Motor Selection for Vertical Movement

The main climbing cycle begins with two belts tightened to the pole by the worm geared motors. By releasing the top belt while the lower belt holds the robot in place it can move the top belt up the pole with a third motor. At a certain height it will stop the motor raising the top belt and here tighten the belt at this new position. Now it can release the lower belt and raise this belt to a new higher position with the third motor. At the new position it will again tighten the lower belt and the climbing cycle is complete. Outside of the normal climbing cycle some special conditions can be considered. These are diameter changes of the pole and installation of the robot against the pole.

9.3.1 Motor Selection

With the use of Mekanex torque calculator for screw drives [13], different motors can easily be compared. By inserting linear power along the screw, required linear speed, screw pitch and efficiency, the required motor torque and speed is calculated. The formula used for motor torque is: $Md = \frac{Fp}{2000\pi\eta_s}$. Here F is linear force, p is screw pitch and η_s is the efficiency.

The formula used for motor speed is: $n = v/p * 60$. Here v is linear speed (mm/s), p is screw pitch (mm) and n is screw rotation speed in rotations per minute.

Linear force used during experimentation was chosen as: $F = mg = 100$ N. A robot weighing 10 kg will not exert a force of 100 N since the screw will not lift the part that is held against the pole with the strap. Since F will not be perfectly distributed along the screw some extra moment and friction will arise making lifting harder. F is therefore chosen to 100 N to get some extra safety margins.

Climbing the pole should be done in a reasonable time. Moving a belt up or down the pole is done sections at a time and these sections are defined as strokes. A stroke should therefore be done as fast as possible. The stroke length is chosen to 300 mm.

A reasonable time to do this in is 5 seconds. Therefore linear speed should at least be: $300/5 = 60$ mm/s.

Screw pitch is chosen to 4 mm since many trapezoidal screws have this pitch. The Mekanex torque calculator says that efficiency for trapezoidal screws vary between 0.2-0.6 depending on material, thread and lubrication [13]. Typical values often seen for trapezoidal screws are in the range 0.4-0.5 but to be on the safe side 0.3 is chosen.

Using these values in the torque calculator a motor that can handle torque of 0.21 Nm at a speed of 900 rpm is required. A motor that can handle this is found at OEM motor and is the IG-42CGM [14]. At a speed of 1400 rpm it can handle a torque of 0.22 Nm.

9.3.2 Installation Time, Climbing Time and Power Requirements

By dividing the climbing cycle into segments, time and energy for each segment can be calculated. The sum of these segments gives time and energy for a climbing cycle. By adding up climbing cycles climbing time and energy requirements to reach a certain height can be calculated.

Installation will require both belts tightened but these calculations are for just one belt. The installation time for one belt will simply be used two times for the final installation time. The belt will initially be at its outmost extended position. Motor speed for the belt is $w = 16\ rpm$ and the radius for the cog tightening the belt is: $r = 0.0192$ m. Thus circumference for the cog is: $O = 2r\pi$. Belt length for installation will for simplicity be used from calculations made in section 9.2 where minimum belt length is subtracted from maximum belt length. In reality the belt might be extended a little longer initially but this is neglected and will make a small difference in the calculations. The result is: $L_i = L_{max} - L_{min} \approx 0.2265$ m. Dividing L_i with O gives rounds the cog needs to take to tighten the belt at installation, $n_i = L_i/O$. Installation time for one belt becomes $t_i = n_i/w * 60 \approx 7.1$ s. This means that in theory it will take the user about 14.2 seconds to tighten the robot to a pole with diameter of 60 mm.

With two belts in place the climbing cycle begins. First the top belt will be loosened 40 *mm*: $L = 0.04$ m. This means the motor has to turn: $n = L/O$. Time for this is: $t = n/w * 60 \approx 1.2$ s.

With the top belt loose the screw can start turning to raise the top belt to a higher position. Turns for the screw in a stroke will be stroke length, $L_s = 0.3$ m, divided by screw pitch, $p = 0.004$ m, resulting in turns: $n_s = L_s/p$. The motor turning the screw can handle a speed of $w_s = 1400$ rpm and for simplification this speed is used for the whole stroke ignoring acceleration and breaking. Time for a stroke will therefore be: $t_s = n_s/w_s * 60\ \approx 3.2$ s.

When the upper belt is at the top of the stroke the belt will yet again be tightened to the pole. The next part will be to untighten the lower belt. Both these times are assumed to be the same as for the first belt untightening, t.

The screw will now be turned in the other direction to raise the lower belt. Time for a stroke is assumed to be the same in both directions, t_s. When the lower belt reaches the end of the stroke it can be tightened at time t and one climbing cycle is complete.

A typical height to climb is approximated to 5.1 m which is both a reasonable climb height and uses an even number of climbing cycles to reach. By dividing climbing height with stroke length number of climbing cycles is found as: $c_{nr} = 5.1/L_s$. To get the total climbing time, t_{tot}, the number of climb cycles is multiplied with the added times for the different parts that makes a climbing cycle. Finally the installation time is also added for two belts. The result becomes: $t_{tot} = (4t + 2t_s)c_{nr} + 2t_i \approx 3.5$ min.

With the times in place it is also easy to calculate required energy for climbing. The motors for tightening the belts will require 4 A at 12 V when operating at a torque of 2 Nm [12]. This means they will use 48 W during maximum load. For simplification this number is used even when the belts are not in direct contact with the pole, where the motors actually require less power.

The motor connected to the screw has a maximum power rating of 41.3 W and this number is used for calculations. By dividing the times above with 60 they are translated into hours. Multiplying the different times the motors are used during a typical climb with the watts used required watt hours is found as: $E = \frac{(4t*48+2t*41.3)nr+2ti*48}{3600} \approx$ 2.57 Wh. Assuming climbing down takes the same time and energy total energy required is: $E_{tot} \approx 5.15$ Wh.

9.4 Battery Selection

Motors selected both handle voltages between 12-20 V, so the battery should preferably use a voltage in this range.

The restriction is set that only one motor will be run at a time. This will make current measurement for the motors easier and decreases maximum current used, which decreases heat in conductors and components on the circuit board. The battery should therefore be able to provide a current of about 5-6 A, 4 A for one motor and about 1-2 A for the rest of the electronics (it is hard beforehand to know exactly how much current is needed for the rest of the electronics so some overhead room is implemented to be able to handle higher currents). It is also possible that a higher current will be needed for tightening belts harder on a rainy day with slippery poles meaning even more overhead room might be needed.

Batteries that are light weight, offer high capacities and can handle high discharge rates are Lithium Polymer (LiPo) batteries [15]. Some disadvantages compared to Nickel-Metal Hydride (NiMH) or Nickel Cadmium (NiCd) batteries are shorter life span and due to fire hazard special care is needed during charging, discharging and storage [15].

Shorter life span is acceptable in a prototype but can also be acceptable in a final product. It is easy to just buy a new battery if the need arises, which probably will not be for many years. Worse is the fire hazard, even if it is a low risk. The fire hazard can be acceptable in a final product with the use of a fire-resistant container and warning notes explaining the fire risk. An example of a warning is to never leave the building during charging of the battery. Also a Carbon Dioxide fire extinguisher should be present nearby. With the use of a proper LiPo charger, charging is fairly safe. Storage should always be done in a fire-resistant container [15].

A charged battery has unstable bonds that are in pursuit of a more stable bond and this releases energy that is used for the electrical equipment. A punctured battery will lead to the lithium in the battery reacting with the air humidity and this will heat up the battery. This extra heat might excite the unstable bonds which break and release energy in even more heat. A process called thermal runaway starts where heat releases energy that generates even more heat. The result is a very hot and dangerous fire [15]. To lessen the risk of this happening the final pole climbing robot should have a proper battery holder that decreases the risk of the battery getting harmed. For the prototype tape will be used but it will also be closely monitored during every run.

The battery chosen for the robot is a 4 cell LiPo battery that has a 14.8 V charge with a 2100 mAh capacity [16]. The battery only weighs 224 g and has the required charge to power the motors. The C-rating, which determines how fast a battery can discharge, of 30 means it can supply $30 * 2.1 = 63$ A [15]. Discharging the battery this fast is still not a good idea, since it might overheat, but it gives an idea of how high currents that can be discharged. The capacity in watt hours is: $14.8 * 2.1 = 31.08$ Wh, which will easily cover the requirements, to climb up and down a five meter pole, of 5.15 Wh. The extra power means that the robot can stay in the pole for a longer time using little energy to keep the microprocessor running. It also means the pole climber can climb higher poles and do more climbs on the same charge. The extra overhead room in capacity comes at a low weight and size cost since it is a LiPo battery.

10 PCB Design

Described in this chapter is the Printed Circuit Board (PCB) design.

10.1 Components and Circuit Diagram

The electronics needed, like sensors, motors and the battery will be connected to a manufactured PCB. This PCB will in turn be connected by pins to a microprocessor that will be used to control all the components. The microprocessor used is an Arduino Due [17]. The PCB is designed to fit directly on to it with pins that mirrors the Due ports, see figure 10-1. For example pin 37 on the PCB will be in exactly the same place as the digital input/output port of pin 37 on the Arduino. This means that pins used on the Arduino will be decided already in the hardware design of the PCB.
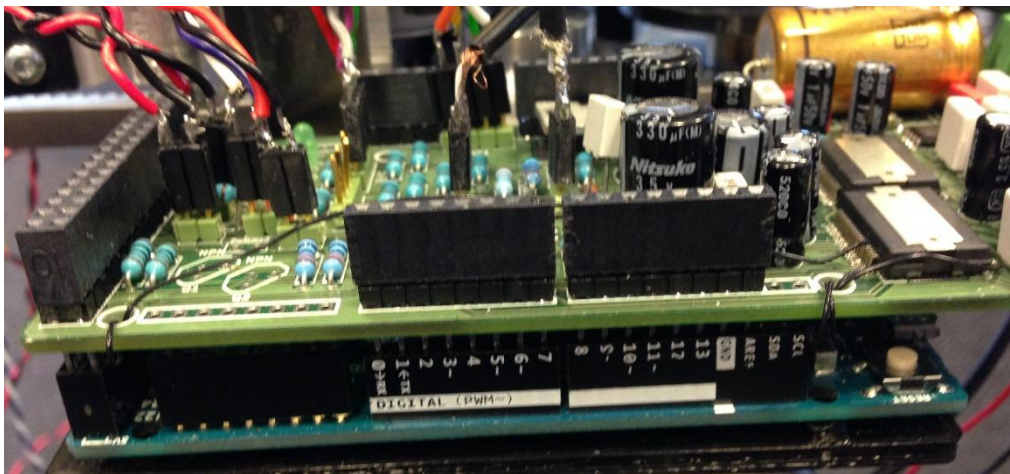
Figure 10-1 PCB mounted on the Arduino.

The Arduino Due and the H-bridges run on 12 V. Therefore the higher voltage from the battery of around 14.8 V needs to be lowered. This is done with a low-dropout regulator (LDO). Components requiring lower voltages like sensors and LEDs get their power from the Arduino ports that can supply either 5 V or 3.3 V. Circuit diagram can be seen in figure 10-2. The two large chips seen on the right are the H-bridges and on the left of them is the Arduino. Above the H-bridges is the LDO and to the right is a current measuring hall sensor along with four screw terminals used for connections to battery and motors. The higher currents will be concentrated on one side of the chip.
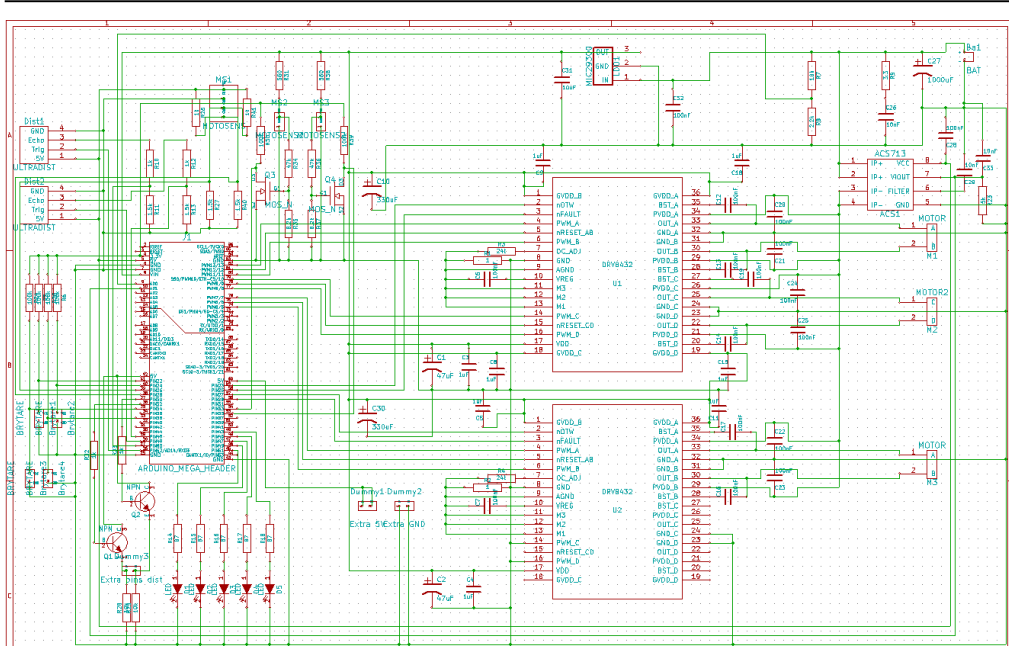
Figure 10-2 Circuit diagram for the PCB.

10.1.1 H-Bridges

The DC motors are controlled with H-bridges which has MOSFET transistors connected in an H-shape with the motor in the middle. By turning on the top left and bottom right transistors the current can pass in one direction through the motor. Closing these and opening the top right and bottom left will let the current pass through the motor in the other direction. When the motor is operational the potential between the drain and source on the active MOSFETs will decrease. The lack of difference in potential will turn off the gate. Therefore a bootstrap capacitor is connected to the gate which raises the gate voltage above the drain voltage and the MOSFET can stay open. When the MOSFET is off (depending on the PWM cycles) the bootstrap is charged.

The H-bridges DRV8432 DKD are used on the PCB. Except for normal H-bridge behavior these also have safety systems that protects against overcurrent, overheat and undervoltage. They can be connected to two motors at a time and handle a current of 7 A for each motor. The data sheet gives details for dimensioning of surrounding capacitors (like bootstrap capacitors) and resistors needed to operate and to get rid of disturbances [18]. The main circuit diagram can be seen in figure 10-1 and a portion of this displaying an H-bridge connection can be seen in figure 10-3.
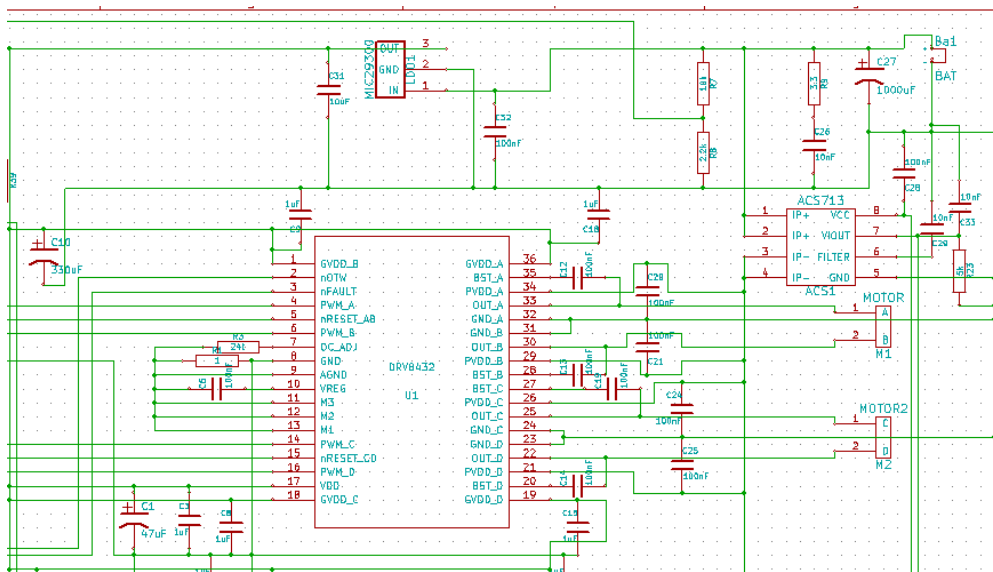
Figure 10-3 H bridge and Hall Effect sensor for current measurement.

10.1.2 Current Measurements

Current measurement to the motors is done with the current measuring Hall Effect sensor ACS713ELCTR-20A-T. The connection on the PCB is done according to data sheet [19] and can be seen in figure 10-3. The choice for current measurement stood between a shunt resistor and a Hall Effect sensor. Since the Hall Effect sensor measures magnetic field around the conductor, and therefore is non-intrusive, it was chosen as the preferred method. Current measurement is done because the worm geared motor torque is proportional with the current according to figure 10-4 from OEM motor [20].

10.1.3 Voltage Measurements

To measure battery voltage a voltage division is used where the lower voltage is measured on one of the microprocessor's analog input ports. With known resistors the voltage on the battery can be calculated. This voltage is used to know when the battery is starting to run. Five LEDs with different colors on the PCB symbolizes battery voltage status. A final market ready product will require a better system that transmits battery status down to the user on the ground. The resistor used for the voltage division can be seen between battery input and the LDO in figure 10-3.

10.1.4 Motor Connections

The torque for the worm geared motors at a given current and with the constant voltage of 12 V can be seen in figure 10-4 found at OEM motor [20]. No exact torque calculations will be made because proper tightening force through current measurement can be found with trial and error. Current measurement is done in only one place that leads down to all the H-bridges and motors. Therefore only one motor will be run at a time to get accurate current measurements. Smaller currents in the PCB, by using one motor at a time, also means less heat generation. Heat is an unwanted energy loss in

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the system and heat loss from current in conductors is called joule heating. This heat loss is proportional to the square of the current [21].
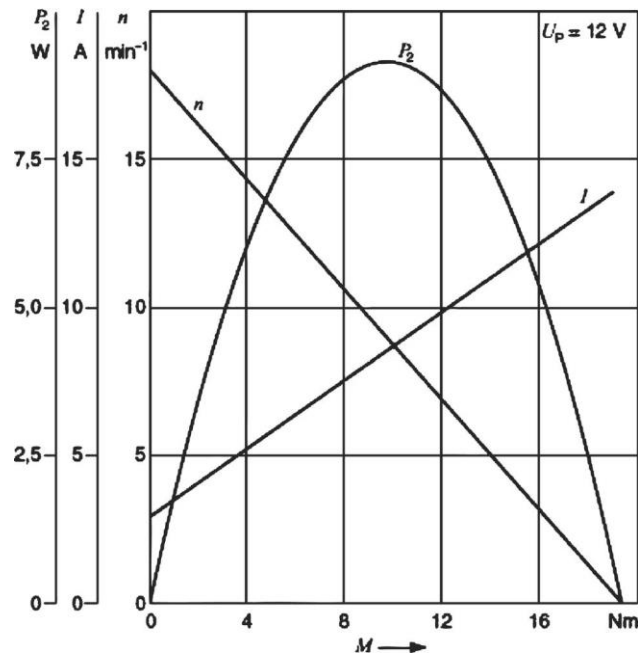
Figure 10-4 Power and current curve for worm geared motors. [20]

10.1.5 Motor Sensors

Sensors used can be seen connected around the Arduino in the circuit diagram from figure 10-2. Each motor has a Hall Effect sensor to monitor revolutions it has taken. The screw motor sensor runs on 5 V and just needs an external resistance of 1 kΩ for each of the two sensor channels. The signal from motor to Arduino comes back at 5 V. Since the DUE only can handle maximum 3.3 V on the inputs a voltage division with resistors is made before the signal is measured.

The worm geared motor sensors have a trickier connection and calculations were made to keep the voltage for the sensors between 5-10 V in the motors. The connection can be seen in figure 10-5. A gate opens and closes in the Hall Effect sensor in the motors that pulls the voltage high or low between 5-10 V. This voltage is divided down to 0.75-1.5 V that fits the gate specifications on an n-type MOSFET. The pulses in the motor thus opens and closes the MOSFET. Connected to the drain and source side of the MOSFET is 3.3 V, 100 kΩ resistor and ground. This will act as an inverted signal from motor to Arduino. When the MOSFET is triggered the Arduino gets a low signal and when the MOSFET is off the Arduino will get a high signal.
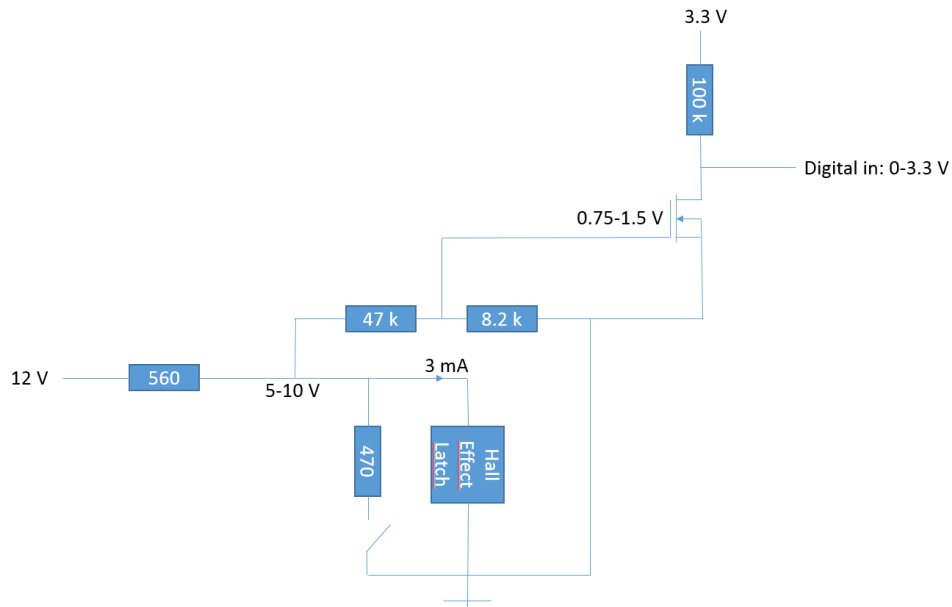
Figure 10-5 Worm geared motor sensors

10.1.6 Other Sensors

The motor turning the screw will be monitored with hall sensors but if the sensors have missed some pulses it is important that the motor stops rotating before the bushing reaches the end of the screw. Two switches connected at the ends of the stroke for the vertically moving bushing will provide this safety feature. These will stop the screw motor immediately if they are triggered.

A distance measurer is used to measure distance to the pole to determine if there is a diameter change. This is a safety measure so the belts are not tightened on a diameter change. Tightening on a diameter change gives smaller contact points and the extending arm and belt will probably slip. This means the whole robot will slant and the climbing procedure will be less controlled. An ultrasonic distance sensor is used for the prototype. This kind of method for distance measurement fits the prototype build since it is an easy and cheap solution that works outdoors in sunny conditions, has a reasonably good accuracy and can be made small and light weight.

Finally an IR-sensor is connected to the board to enable a user to control if the robot goes up or down. Apart from this some extra power ports and ground ports have been added along with some zero ohm resistors to be able to correct possible faults in the design.

10.2 Physical Layout

The Circuit diagram was made in the open source program KiCad [22]. With a finished circuit diagram the next step is to associate every component with what it will look like in real life. This is done by finding appropriate foot prints for each component.

The PCB will have through-hole mounted components for all components except for the H-bridges, current measuring Hall Effect sensor and the two MOSFET transistors. The physical layout in KiCad can be seen in figure 10-6.
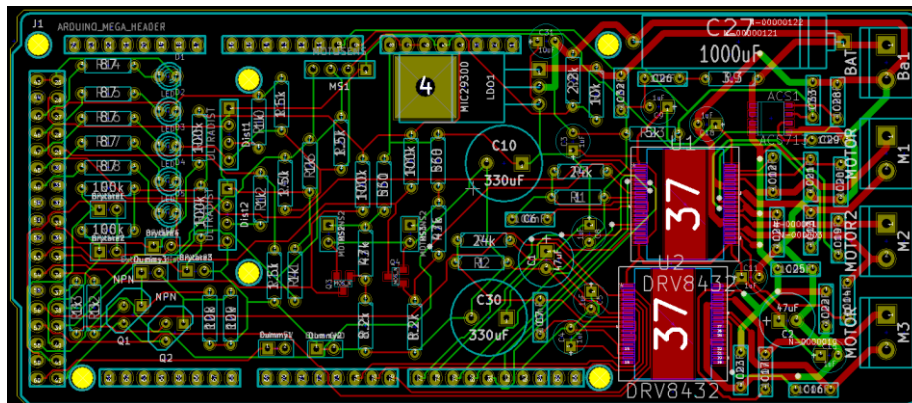
Figure 10-6 Physical layout in KiCad of the PCB.

On the right in figure 10-6 can be seen thicker conductors. This will allow higher currents to pass in the conductors without them getting too hot. A large 1000 µF capacitor can be seen in the top. This is closely connected to the high voltage conductors to even out current spikes. More conductors are used around the PCB for the same reason. Mainly these were placed because of recommendations from data sheets for different components.

The board was sent to Cogra for production [23]. The components were soldered on by the authors. The final product can be seen in figure 10-7.
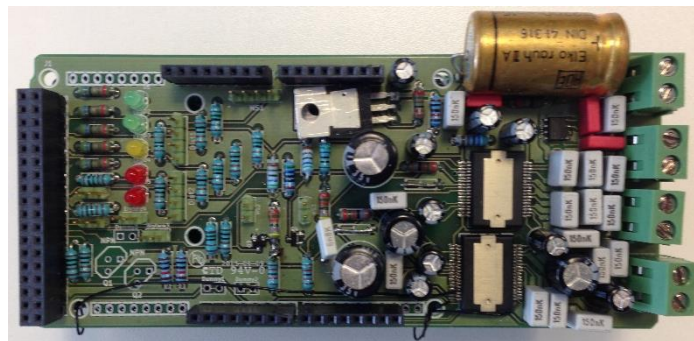
Figure 10-7 The final PCB.

11 Software Design

The programming language used is a variant of C and C++ that Arduino has made easier to use by implementing their own library. This chapter will give an overview of the program code.

11.1 Hardware Connected to Software

The voltage and current measurement along with distance measurement, rotation measurement, IR and motor driving operations are developed in separate test classes. These classes will become different methods in a final class that combines all the hardware.

11.1.1 The Motors

The screw motor is different from the worm geared motors both in how the sensor work and how the motor works. Therefore the different motors are treated differently and are controlled in different methods in the final class. Both motors need to be ramped up and down to desired speed, otherwise the H-bridge safety systems will shut down operations. This is probably due to too large current spikes.

The screw motor rotates fast and has many pulses per rotation. The only way to keep up with it at full speed is by using interrupt based sensors. A software filter is also implemented since disturbances on the sensor occurs when the motor is running. The filter is a combination between the ordinary methods and interrupt methods. The interrupts are triggered by changes on one of the two channels from the rotary encoder in the motor. In the interrupt methods is a combined counter. The counter is incremented only if both channels are high or both channels are low and last increment both channels had the opposite TTL logic level. When the motors are started an initialization of sensor starting point is done in the ordinary methods.

The worm geared motors create a lot of disturbances but the sensor values need not be updated as fast as for the screw motor. The easiest way of implementing the sensors for these motors is therefore by polling the sensor value during motor drive. This is done by initializing a first value and during motor drive check every loop for the sensor value. If it is low a small delay is made and after this the value is checked again with the added requirement that the last (or initial) value was high. If it still is low it is not a disturbance and a counter is incremented. This means every loop the sensor value is checked and saved for comparison in the next loop.

11.1.3 The Sensors

To use the IR sensor, objects are created from an imported IR sensor program. These objects give access to functions that returns the IR signal as an integer. The functions use a timer to discern the wave length of the IR signal. Different wavelengths of high and low represents 1 or 0 and a series of 1's and 0's are stringed together to make a unique pattern for the IR signal. This identifying pattern is compared with saved values for IR signals to know which button on the remote is pressed.

The distance sensor sends out an ultrasonic sound and starts a timer. When the sound returns the time it has taken can be used in combination with knowledge of the speed of sound to calculate the distance.

Current and voltage measurements are done on analog input pins for the Arduino. Both measurements gives a voltage on the analog input pins which is translated from analog to digital value as 0 to 3.3 V becomes 0 to 4095 bits.

The switch values are checked with polling when used in the climbing sequence for the screw motor. A low value means the switch is pressed and the screw motor speed is ramped down as fast as possible without triggering the H-bridge safety systems.
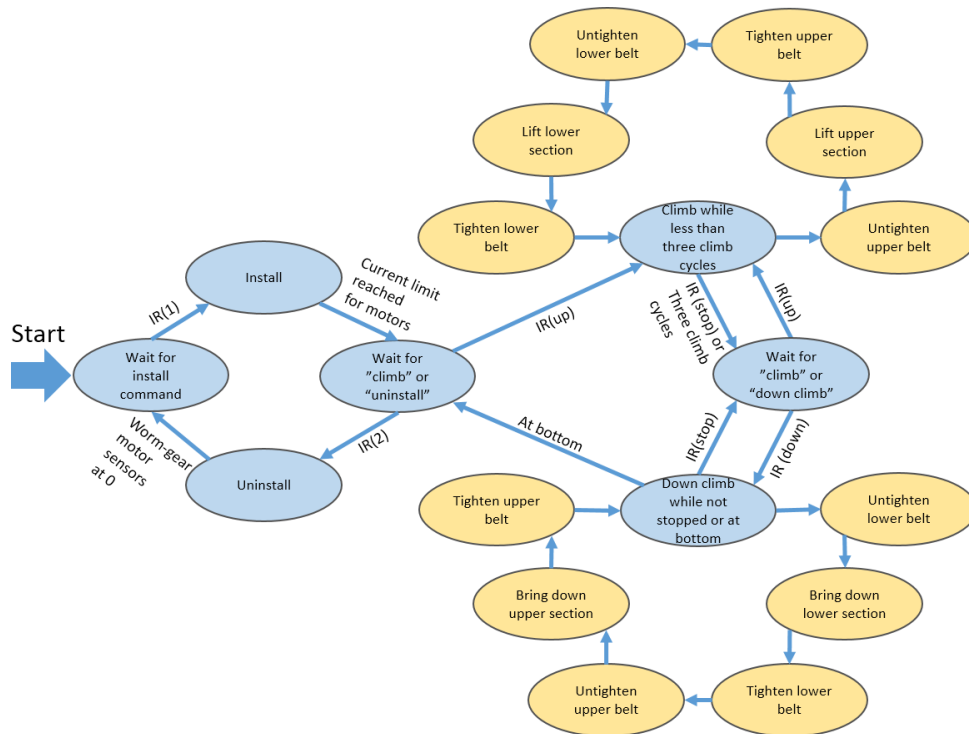
11.2 Main Program

Figure 11-1 States for the main program

The main program is a state machine with seven different main states, seen in the blue bubbles in figure 11-1. Initially the robot is at rest and awaits installation. In this state

manual adjustments for the starting position can also be made to all the motors. Motor direction is controlled by pressing one of two switches. By pressing different buttons on the IR remote different flags are set that are used to determine which motor is adjusted. Diodes are used to signal which motor is in use and the default mode for these diodes is to display the battery status where five lit diodes displays a fully charged battery and one diode a poorly charged battery. When the user presses the IR button for installation the program will move on to the installation state. The worm geared motors will start tightening the belts as long as the user holds down the same switches that is used for manual adjustments in the initial state. Holding down these switches is a safety feature so the user does not get stuck with hands inside of belts or cogs.

The motors are done tightening when they have reached a certain current. The program can move on to the next state which is another waiting state. The user has two options in this state, either begin the climb cycle or uninstall the robot again. If the user presses the up button the robot moves on to the climbing state. During climbing the robot will stop if the stop button is pressed or if it has made three climbing cycles. When this is done it reaches another waiting state. In this stage the user has two options, keep climbing or climb back down again. If the user presses the down button the robot will automatically climb down the exact path it has climbed up and stop at the bottom where it returns to the waiting state for uninstallation or climbing again. If uninstallation is chosen it reaches its last state where both worm geared motors untighten themselves to their initial position. Lastly the program will move back to the starting state.

11.2.1 Climbing Cycle

The climbing cycle is a state machine in itself. The first state untightens the upper belt by backing up its current sensor count with a constant value. Then the screw motor lifts the upper plate as long as the sensor counter is below a pre-defined value. An initial distance is calculated to the pole and if it changes a pole diameter change is present. The motor will then stop and back up a little. The sensor count is saved both if the motor reaches the end of the screw or a pole diameter change. When the upper plate has stopped the worm geared motor can tighten the belt and this sensor value is saved for later down climbing. The lower worm geared motor now releases its belt in same manner as the upper motor did. The screw motor is activated again but in the other direction and the sensor counter is counted back down to zero to return the lower plate just under the upper plate. Here the lower belt is tightened and the sensor value is saved. The climbing cycle is completed and a climbing cycle counter is incremented. This is done so the sensor values can be saved in arrays with sensor values for each climb cycle. These sensor values are used to mirror the climbing cycle when the robot is climbing down. Therefore a distance sensor looking for diameter changes on the pole is only needed during climbing.

11.2.2 Down Climbing Cycle

The down climbing cycle is also a state machine but with different order. First state is to untighten the lower belt. This is done by looking at the saved tightening value for the belt at its lower position and untighten the belt some more. The reason for this is that the belt will in some cases have to pass from a smaller pole diameter to a larger

and then needs to untighten more. Time is saved by not untightening the belt too its outer limits in every step during down climb. A shorter belt will also help stabilize the robot in case wind destabilizes the robot while only one belt is tightened.

The screw motor will back the lower plate down the plate with the help of saved sensor values from up climb. As the lower belt is tightened the upper belt can be untightened in the same manner as the lower and the screw motor backs back the counter to zero. Finally the upper belt can be tightened to its current limit and the down climb cycle is completed by decrementing the counter for current climb cycle.

12 Assembly and Prototype Manufacture

This section gives a detailed overview of the different parts and how to assemble the climber.

12.1 Manufacturing of Mechanical Parts

Cogs, timing belt pulleys, worm geared motors, toothed racks, linear motion guide and the bearing supports have been ordered directly from the manufacturers. The rest of the mechanical parts are manufactured.

12.1.1 3D-Printing

The 3D-printer at the company was used as much as possible to manufacture the parts that are complex and do not require a high yield strength. Advantages with this is not only a structure with lower weight, but also a cheaper and shorter manufacturing time. An internal honeycomb pattern of the 3D-printed parts enables them to be both light weight and still have a relatively high yield strength. Two types of plastics are used, ABS (yellow) and PLA (black). ABS is used for the components that need some extra strength and PLA for the rest.

12.1.2 Metalworking

Parts that require more strength is manufactured in metal and especially in aluminum (because it has a low density in proportion to its yield strength). Most of the metallic parts are designed in such a way that they can be laser cut from one sheet of metal and then bent to the required shape. These parts are ordered from a local company that works with metal cutting. To further simplify production most of these parts are ordered in 2 mm sheets to enable for easier manufacturing since they then can be cut in one setup of the laser cutter.

Some other parts were milled from blocks of aluminum to the required shape. The last type of manufacturing was for the shafts in the climber that were lathed from brass and steel. Most of this work was made by the authors to minimize cost and delivery time.

12.2 Assembly

The assembly can be divided into two main steps. One step is to assemble the parts used for driving the vertical movement and the other step is assembly for the belt tightening parts.

12.2.1 Assembly for Components Driving Vertical Movement

In figure 12-1 the first parts are fastened. The brace for the upper gripper's plate is reinforced with brackets because the brace is bent to its shape from sheet metal, which is thin.
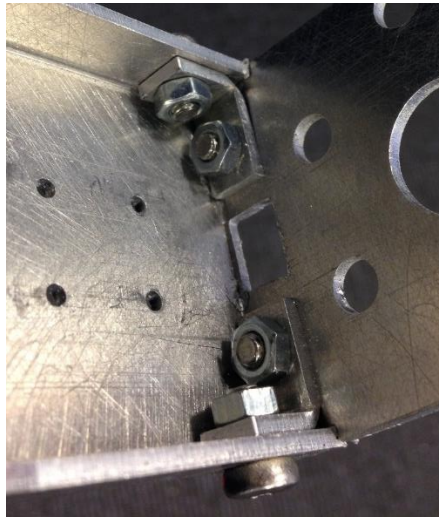
Figure 12-1 Brackets reinforcing the linear movement brace for the upper gripper's plate.

Thereafter the linear guide rail is attatched to a bearing block that later the trapezoidal threaded screw is fixed in, see figure 12-2. The connection part between the guide rail and the bearing block was made in aluminum. When the trapezoidal threaded screw rotates at a high speed the bearing block will have to handle a large force. Furthermore the connector was designed in two pieces, instead of one, which resulted in two very simple rectangular shapes with holes in them, easy and cheap to manufacture.
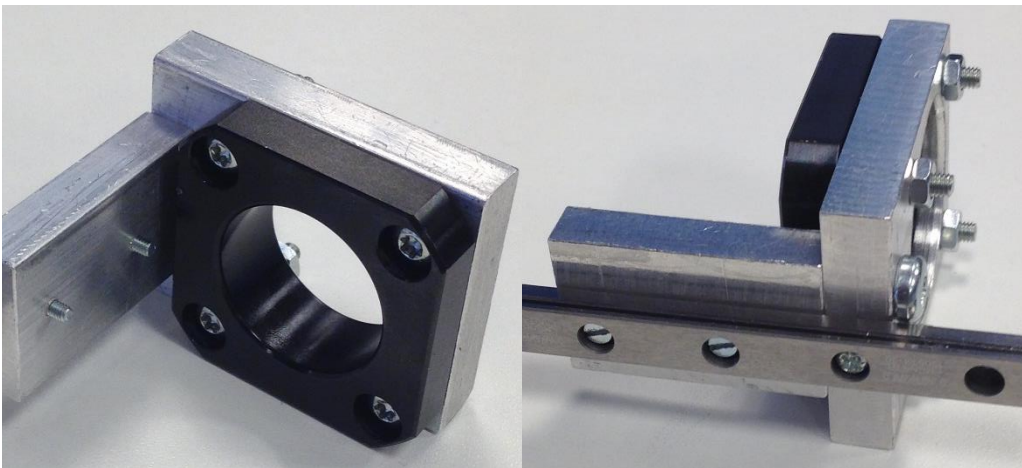
Figure 12-2 Bearing block fastened to the linear guide rail.

After the upper bearing block has been connected, the guide rail is attached to the upper gripper's brace with four screws that are fastened on a cart that slides along the rail, figure 12-3. This cart will move along the rail and guide the bushing up and down as the screw rotates. The upper gripper's brace follows this movement and is attached to the bushing and cart as seen in figure 12-4.
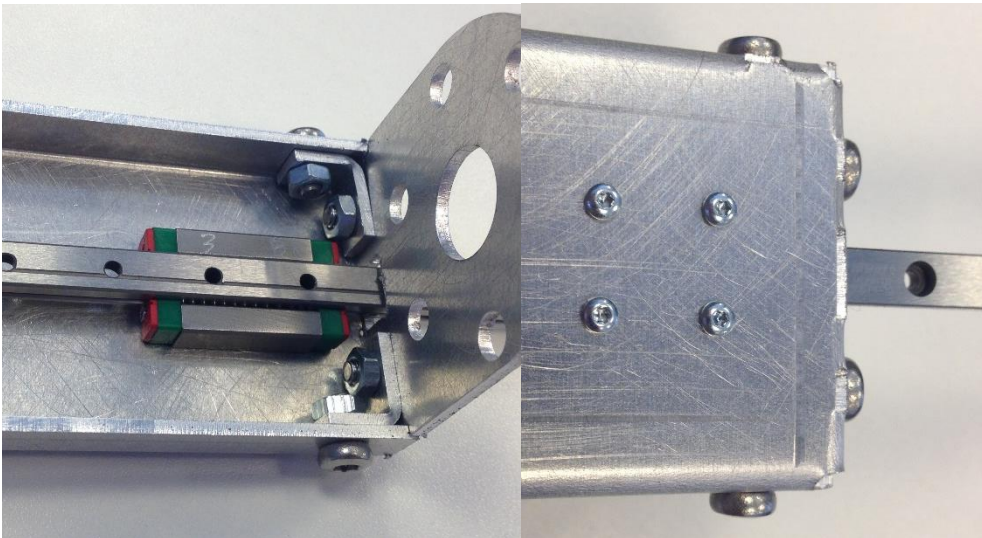
Figure 12-3 Connection between the upper gripper's brace and the linear guide rail.

The next step is to attach the trapezoidal threaded screw. It is attached to the bearing block in the top and the trapezoidal threaded bushing is attached to the lower side of the upper gripper's brace, see figure 12-4.
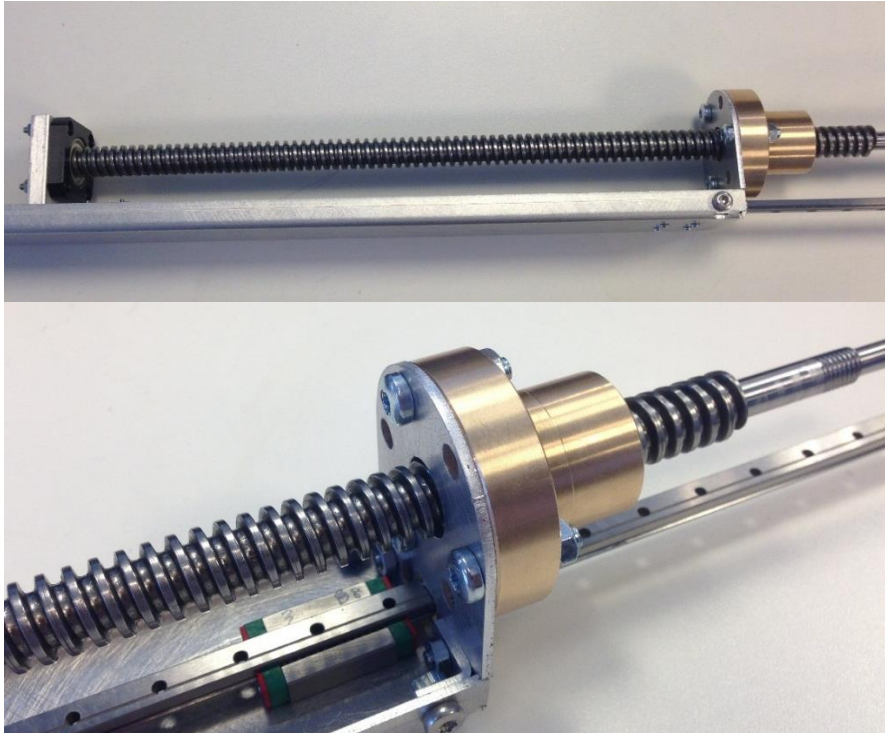
Figure 12-4 Assembly of the trapezoidal threaded screw and the rest of the linear unit.

The trapezoidal threaded screw has to be fixed in both ends and therefore another bearing block is fastened to the linear guide rail, see figure 12-5. This is a robust block that can take the forces from the trapezoidal threaded screw as it rotates. As with the upper bearing block it is made of aluminum to cope with forces that arises when the screw rotates. Also fastened to the screw is a timing belt pulley. This enables the 12 V motor to drive the screw by transferring power through a cog belt, figure 12-6.
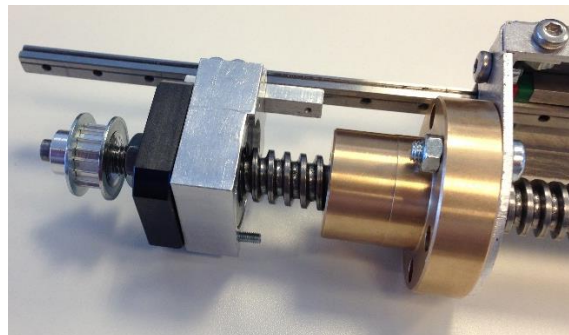
Figure 12-5 Bearing block for the screw.

Lastly the motor is assembled to the bearing block. This is done with the help of a motor bracket that positions the motor shaft in the correct level for both the timing belt pulleys. The cog belt is AT3 which means that it has a standard profile with 3 mm between cog sections. The cog belt is reinforced with steel wire and is of the smallest size available for delivery from the manufacturer. The small size is an advantage as there is a shortage of space.
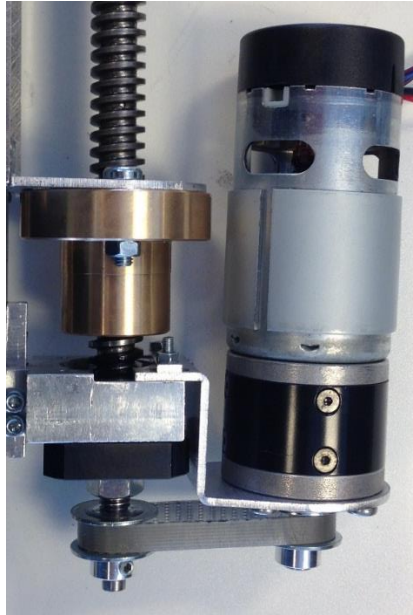
Figure 12-6 Motor fastened with bracket and cog belt drive.

12.2.2 Assembly for the Belt Tightening Parts

Assembly for the belt tightening parts is presented as one installation but it is done twice. The only difference is how they attach to the linear unit, where the top plate is fastened to the brace that is connected to the trapezoidal threaded bushing while the lower plate is attached to the guide rail's lower part. In figure 12-7 all parts necessary for a gripper is presented except for the cog belt and screws needed.
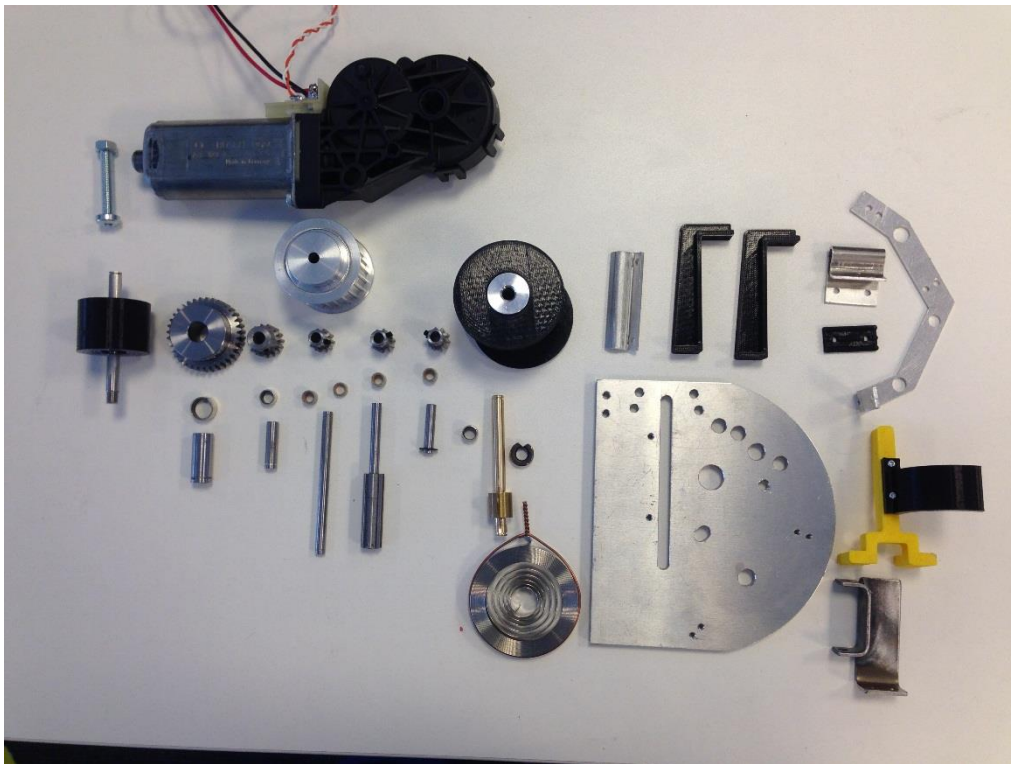
Figure 12-7 Overview of the parts in the gripper except for the cog belt and screws.

The first assembly step is to press the plain bearings in their respective location as seen in figure 12-8. These help strengthen the structure against forces from the shafts and makes the shafts rotate easier as they have a thin layer of Teflon thus reducing the friction.
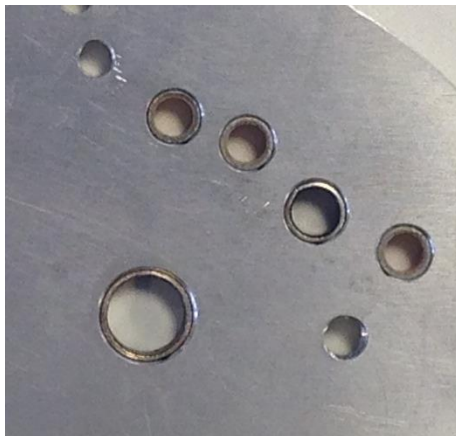
Figure 12-8 Plain bearings mounted in their respective holes.

Thereafter all the shafts get a locking washer so they do not slip out of their shaft holes, figure 12-9.

Figure 12-9 Shafts fitted with locking washers.

The shafts are fitted in the holes together with their respective spur gears, figure 12-10. Shafts subjected to the largest forces will later be connected with a top shaft support. The other spur gears only transfer force between cogs and not to shafts. Therefore the spur gear shafts for these spur gears are only connected in one point. This hade the benefit of less parts, weight and complexity for the tightening unit.
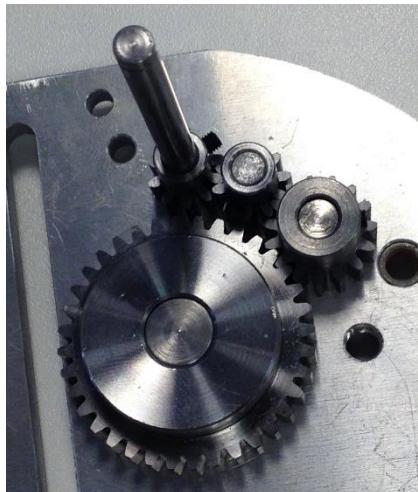
Figure 12-10 Spur gears and shafts mounted on the base plate.

After the spur gears have been fitted a wheel for holding the cog belt against the timing belt pulley is fitted on its shaft, see figure 12-11. To make it rotate easy it spins on ball bearings and therefore its shaft can be stationary and is screwed to the base plate. This wheel is there to ensure that the cog belt does not slip against the timing belt pulley and to make sure that the timing belt pulley always transfers its moment to the cog belt. The ball bearings that the wheel is installed on are chosen to be small and to ensure that minimum friction appears.
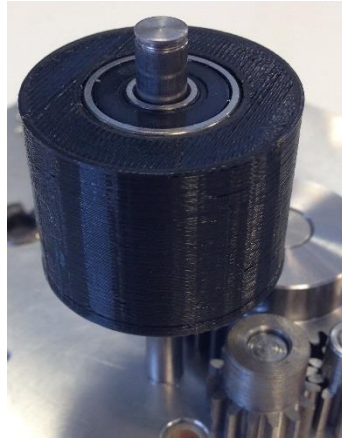
Figure 12-11 Wheel to hold the cog belt on the timing belt pulley.

Now the timing belt pulley used for rolling up the cog belt is installed in its position, as shown in the figure 12-12. This was chosen at a reasonably small size to save weight and space. A smaller size with less cog teeth might have broken the steel reinforcement in the cog belt as it gets bent in to a smaller radius. Flanges were attached to the shaft that holds the timing belt pulley. This helps hold the belt in place, around the timing belt pulley, as the belt is rolled up.

Figure 12-12 Timing belt pulley for collecting the cog belt.

The timing belt pulley used for pulling in the belt is connected in figure 12-13. This was chosen to a diameter of about 38 mm. Since the cog beneath has a diameter of 10 mm the cog belt will move 3.8 times faster than the extending arm used for self-centering to the pole. Calculations for this are found in section 9.2.

Figure 12-13 The timing belt pulley for the cog belt drive seen on the left.

Next step in the assembly is to put the cog belt in its place around the driven timing belt pulley. The cog belt used is of the AT5 standard (5 mm between cog sections) with a width of 25 mm. This was selected because it can take large loads and a wide belt is less likely to tangle itself. Thereafter the overhanging shaft support is assembled as shown in figure 12-14. The support comprises of 3D–printed legs and a laser cut aluminum bracket. In the bracket two plain bearings are pressed into place. The curved black 3D-printed part is a guide for the cog belt to reduce the risk of it slipping on the timing belt pulley.
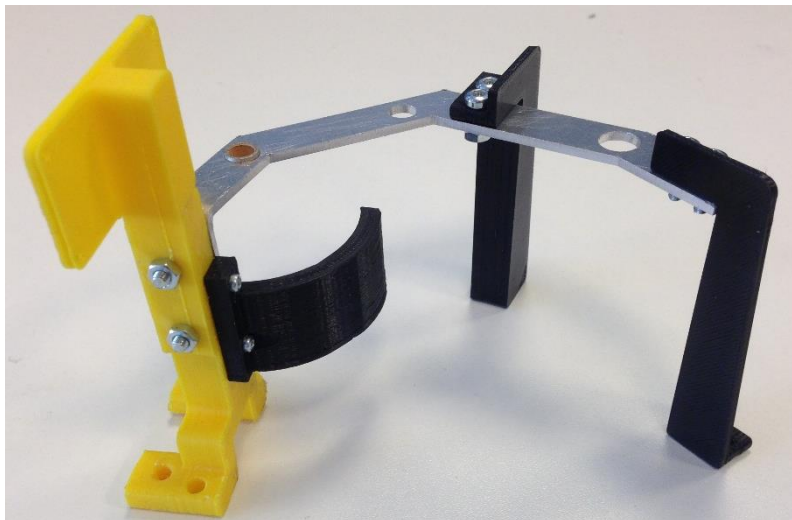
Figure 12-14 Assembled shaft support.

The shaft support can now be mounted to the base plate with respective shaft in their holes, figure 12-15. The many plastic parts seen in figure 12-15 are subjected to smaller loads. Time, weight and manufacturing cost is reduced by 3D-printing these in plastic instead of making them in metal.
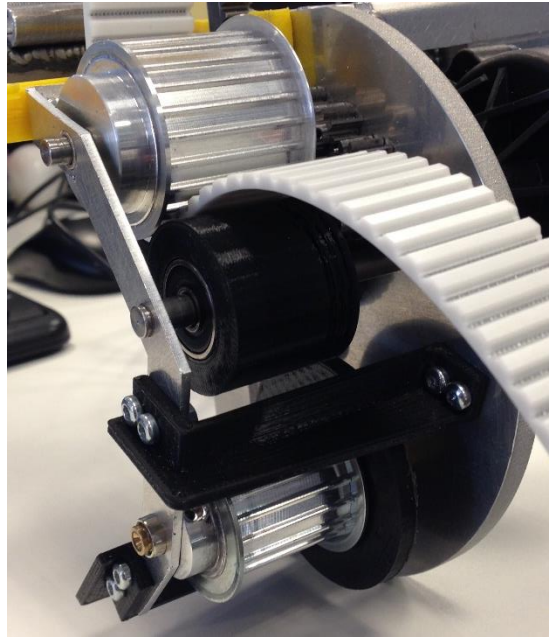
Figure 12-15 Overhead support fastened to shafts and base plate.

Afterwards the cog belt fastener is attached in its palace on the base plate, as presented in figure 12-16. This fastening mechanism is manufactured in steel from two pieces welded together, as steel is easier to weld than aluminum. The shape could not be bent from one piece while milling the part would have been more expensive and time consuming.
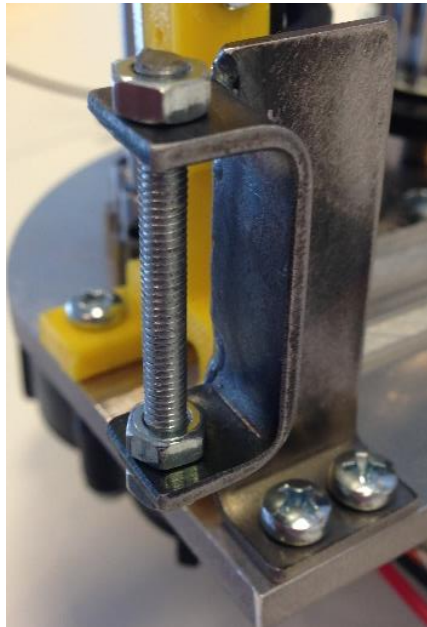
Figure 12-16 Cog belt fastener on the base plate.

To enable the cog belt to be fastened in the cog belt fastener a hook is screwed on the end of the cog-belt, figure 12-17. These hooks are made of aluminum and then secured to the cog belt with a 3D-printed profile that has the counter profile of the cog belt. This gives a good screw joint.
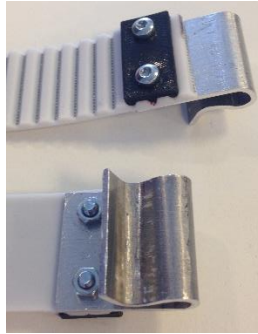
Figure 12-17 Hook fastened to cog belt.

Assembly of the counter arm now begins. This is the arm that will be used to keep a constant distance to the pole's center for both grippers. Firstly the counter block gets a high friction surface glued onto it, thereafter the toothed rack is screwed into its place. Lastly the toothed rack is slotted in its place on the base plate and fastened with a bended aluminum plate that guides the rack during its movements. These steps are shown in figure 12-18.
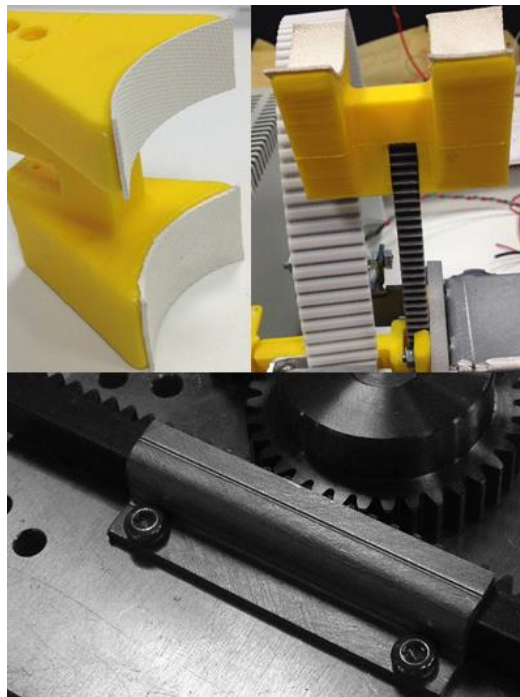
Figure 12-18 Three steps to fasten the counter arm. Glue the friction material on the holder, screw holder to the toothed rack and fasten finished arm on the base-plate.

12.2.3 Assembling the Complete Unit

With both grippers assembled they can be attached at the top and bottom of the screw unit. This is done by installing the upper gripper with four screws at the top of the brace connected to the bushing and installing the lower gripper with three screws on the bottom of the rail. After the mechanical assembly is completed only the wiring is left. As the PCB is mounted on the bottom gripper, while the battery, upper motor and ultrasonic distance sensor is on the top gripper, some wires have to connect them. These wires are taped together in two different groups where one group is for larger currents, from motor and battery, while the other is for smaller currents, from sensors. The final assembly can be seen in figure 12-19.
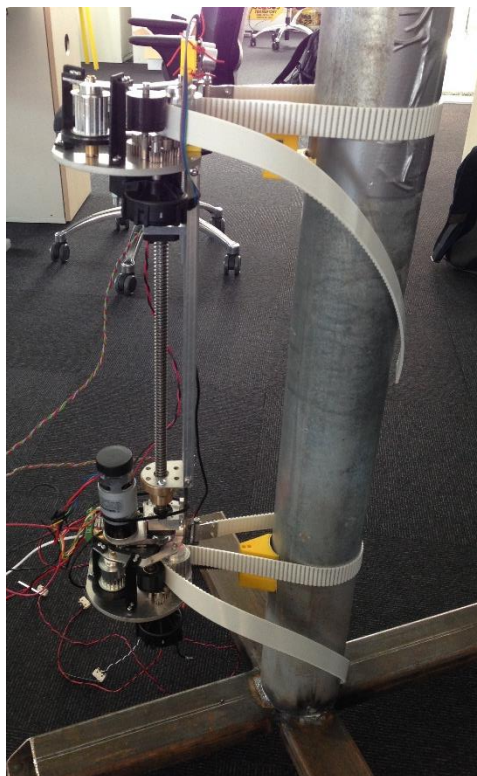
Figure 12-19 Finished prototype mounted on a pole.

13 Results

This chapter will present the results of the thesis work.

13.1 Looking Back at the Project Aims

This section will go through the project aims point by point and clarify the results.

13.1.1 Investigate Functions Needed

The first point in the project aims is to investigate functions needed for a pole climbing camera. This was done through a pole study and by following the product development process described in Ulrich & Eppinger [1].

In the pole study minimum requirements of handling different pole diameters was set. It would be beneficial if the climber could handle signs but this never became a requirement largely because of time constraints. Instead a solution was preferred that felt robust and trustworthy.

From the product development process customer statements were gathered and these were translated into interpreted needs. Concept generation led to many concepts and the interpreted needs led to a concept screening round to filter out some farfetched concepts. Feasibility for the concepts in the second round was discussed and compared through calculations and modelling. Finally a concept scoring table decided the winner. From concept scoring it was decided that the product should be lightweight, simple to install, climb fast, have a simple solution and robust top hold.

13.1.2 Investigate Different Types of Poles to Solve the Problem for

The pre-study consisted of a pole study where the conclusion was that minimum diameter requirements should be between 60-180 mm. For a final market ready product it is a bonus if the climber can negotiate not only signs but also climb on drainage pipes or house walls since many city areas have no poles at all.

13.1.3 Investigate Possible Solutions for a Pole Climbing Camera

Point two in project aims is to investigate possible solutions for a pole climbing camera. In chapter seven the concepts are divided into three main categories. These are wheel type climbing, leverage type climbing and gripping type climbing.

13.1.5 Describe a Few Concepts to Solve the Problem

The concept scoring round had two three wheeled type concepts that could drive up and down the pole and negotiate pole diameter changes by pushing in the wheels when needed. Same principle was also used in a two wheeled pole climber.

Two leverage type climbers were also considered in the final concept scoring round. These would hold on to the pole with leverage where the two wheeled type used the weight of the camera and battery as leverage to squeeze its wheels inwards towards the pole while the three wheeled type used springs as a kind of leverage.

The grippers used different types of gripping arms to hold on to the pole. The principle is the same as for the prototype where one gripper holds on to the pole while the other is raised to later hold while the other gripper can be raised.

13.1.6 Evaluate the Best Concept

Evaluation was done with calculations, modelling and discussions. The discussions were held mainly between the project authors but also with the project supervisors [8]. These discussions led to the final criteria in the concept scoring. The winner in the concept scoring round was the concept with belts for gripping the pole. Mainly it won due to its robust top hold and light weight. The concept scoring can be found in appendix E.

13.1.7 Investigate Installation Time and Ease of Installation

Calculations for the installation time can be found in section 9.3. To climb a pole of 5.1 meter will take about 3.5 minutes and installation to the pole takes about 14.2 seconds. For this prototype installation to the pole requires lifting the robot without a handle which can be cumbersome.

13.1.8 Manufacture a Prototype and Test the Performance

Building procedure of the prototype can be found in chapter 12. The concept works but the finished prototype has a weak structure and unbalanced center of gravity. This means it tightens its belts crooked which compromises both grip and structural integrity. In section 13.2 some mechanical improvements are described that improves the initial prototype seen in figure 12-19.

The PCB design works but when the motors use more energy disturbances appear giving faulty sensor readings. This is filtered out in the software. Due to the leaning the distance sensors cannot be used because distance is measured behind the pole.

One climbing cycle for the final prototype is seen in figure 13-1. The climbing cycle is:

1. Let go of top belt.
2. Raise top section by turning the screw.
3. Tighten top belt.
4. Loosen lower belt.
5. Raise lower section by turning the screw.

6. Tighten lower belt.
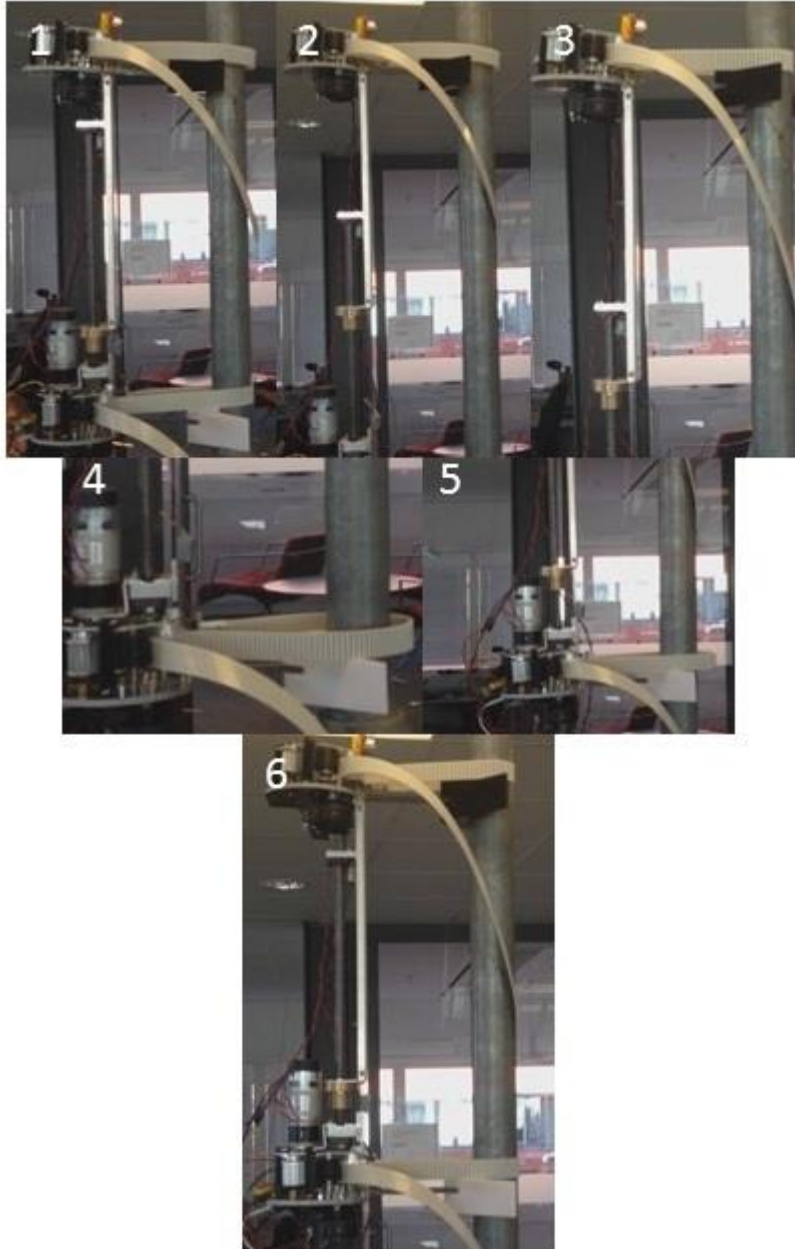
Figure 13-1 One climbing cycle for the final prototype.

13.2 Mechanical improvements

When the pole climber holds itself with just the lower belt it leans. Therefore the counter arms are made wider to catch the pole while tightening. The friction surface is skipped to enable the arms to slide into a centered position. A new counter arm can be seen in figure 13-1.

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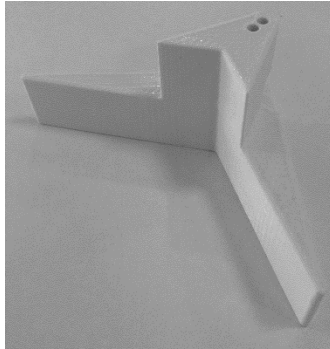
Figure 13-2 New counter arm.

To get a lighter structure and to shorten production time some cogs on the belt plates were initially connected on one end only. This had the effect that they wobbled from the applied pressure. Unevenly applied forces on the cogs meant one side got worn down more and during testing one motor shaft got raised slightly too high and destroyed both itself and its neighboring cog. To solve the problem both belt plates were re-designed to fit a plate that holds the cogs statically in place and stops the wobbling. This new plate can be seen in figure 13-3.
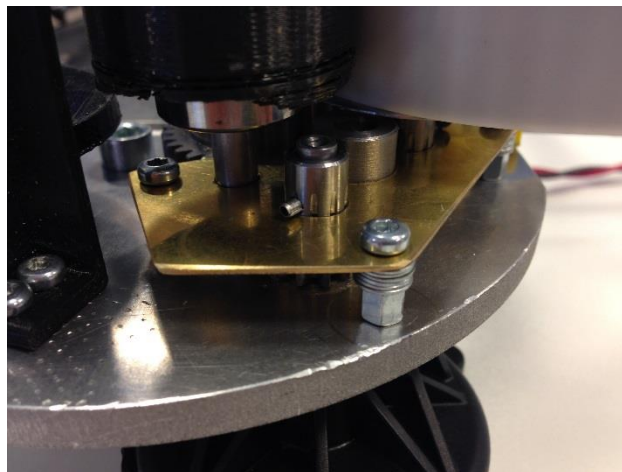
Figure 13-3 Plate that stabilizes the cogs.

14 Discussion

This chapter concludes the report with a discussion regarding the thesis, improvements and further work that can be done in the future.

14.1 General

The authors feel very pleased with the result of the project given the time constraints. With more time a more improved design could have been achieved in all areas of the prototype.

14.2 Mechanics

When the model is made in CAD everything fits perfectly but when parts are produced and fitted together this is not always the case. Clearances and glitches appear during production and suddenly parts that are only supposed to be close to each other actually collide as tolerances and material flexing is hard to determine from CAD models. With more experience in the area these tolerances would have been accounted for in an earlier design stage. The solution for the prototype was manually modifying these errors.

The first trapezoidal threaded screw ordered had calculations and was well thought through. As the screw arrival time was set at seven weeks which was unreasonable, a replacement was hastily found. Unfortunately a gamble was made on a screw that could arrive quickly. Research into all specifications for this screw was not made and when it arrived it was so bent that it had to be manually adjusted to get it straighter. This improved straightness but not perfectly. The result is plenty of vibrations when the climber uses the screw.

The linear guide rail with cart that guides the screw should be replaced with a bigger one. During component selection everything was chosen to make the product light weight and the linear guide rail is no exception. It can withstand the forces without breaking, as calculated for, but the screws that connect it to the rest of the structure are only M2x6 which cannot be properly tightened without breaking. A tilt originating from these screws is the result when the robot extends during climbing. A future improvement should therefore have a thicker rail with larger cart and screw holes.

The robot also tilted around the toothed rack for the arms that are pushing against the pole. The toothed rack could be fastened harder to the base plate with screws but since there is no sliding rail it also means that the worm geared motors have to work harder to move it as friction will increase.

The mechanism for rolling up the belt was sound in theory but when the belt arrived it was too stiff to fit on the timing belt pulley. A future improvement to this is to use a larger timing belt pulley which would give the belt a larger radius to roll itself around. A less stiff belt would also help but have the downside that the belt drops down more when loosened from the pole. This drop means the belt gets tightened at an angle which gives less friction and an uneven force distribution on the gripping mechanics.

14.3 Printed Circuit Board

The PCB was designed with the open source program KiCad which worked well. All electrical components operated fairly correct in the end but some modifications had to be made.

The lower side of one H-bridges was not used and therefore not connected in the PCB design. This was a mistake since it turned out that this side was needed for operation for the other side and therefore wires were connected to the appropriate ports.

A misunderstanding occurred of the required voltage levels on the gates for the MOSFET transistors connected to the worm geared motor sensors. By changing the 8.2 k resistor, seen in figure 10-4, to 12 k resistors voltage limits for the gates were raised to 0.9 and 1.8 V instead, and the problem was corrected.

The biggest problem in the PCB design was the conductor routing. Every time the motors started using more energy errors occurred on sensors. With the use of an oscilloscope it could be seen that the ground signal was not stable. The ground and larger voltage conductors for the motors were connected on a separate part of the board. Wide conductors went straight from the battery input for these larger currents. In another direction from the battery input went the conductors leading to the LDO. From the LDO the rest of the components were connected together. A better routing might have been to again separate the different ground signals in a star shaped pattern so the ground signals from the different parts of the PCB only met in one place on the battery input. A future PCB design should also have more space on the board to get capacitors for the H-bridges closer to target ports. A larger PCB would also have the added benefit of more space for wider conductors and a larger gap between the motor currents and sensor currents. There was not enough time to redesign and order a new PCB though, so these problems had to be handled in some other way. Larger capacitors were placed on the board in the hope of filtering more noise. In the end software filters solved the problem.

The PCB routing was not the only reason for faulty sensor readings. Some sensor wires picked up disturbances in the air from the motors. These wires were changed into coaxial cables as they shield the sensor signals from disturbances.

One of the motors had such large current spikes that the H-bridge immediately stopped the motor from operation. By reducing motor cable size and winding it around a ferrite ring this problem was solved.

The H-bridges often stopped operation due to overheating or fault signals indicating either too low voltage or too high currents. These faults were solved in software by trial

and error and finding optimal conditions for motor operation. In the final program the error signal handling was turned off completely since this also created bugs.

14.4 Software

The big savior for all the error signals from the PCB became the software. With software filters the error signals could be corrected. Lots of tweaking had to be made though.

Code that worked for the worm geared motors while the cogs were not connected had to be rewritten when cogs were added and the forces on the motors changed. When this worked adding the belts changed the applied forces again and the code had to be modified yet again. If the worm geared motors did not run at a high speed the H-bridges overheated. Therefore they always worked at max speed.

Changing motor speed for the screw motor meant that both ramp up and ramp down procedure had to be changed. Small changes in delays played a vital role for how well the robot executed a climb cycle. Too much delays and there is a risk that the robot reacts too slowly to sensor readings while too short delays made ramp up and ramp down too fast.

The ultrasonic distance sensor used an initial distance to the pole and compared this with new distance measurements during operation. This function worked well during pre-climb testing but when the robot climbed it leaned so much that the sensor missed the pole. This meant distance was measured behind the pole and the whole program had to wait for a response from the ultrasonic sound. At the mean time the motors kept running at full speed until the robot ran into a switch that triggered but also had to wait for the program loop to reach it. Therefore the bushing ran into the end of the screw.

If the switch had been interrupt based this might have stopped the robot but interrupt based switch picked up too many disturbances from the motors. With a more trustworthy mechanical design some kind of filter could perhaps have been made to make interrupt based switches work but due to the time constraints distance measurement was skipped all together which eliminated this problem. Recommended for a future design is to measure distance with something physically touching the pole. This would also have the added benefit of supporting the robot during climbing.

14.5 Usability Analysis

A final product that is appealing to use should be light weight and easy to install to a pole. The prototype is light weight and fairly easy to install to a pole. Installation to a pole for the prototype consists of holding the robot while the belts are attached in their hooks and then pressing a button to tighten the belts. The procedure in a final product can be made easier by fastening a carrying belt to the climber. During the time the cog belts are tightened to the pole the user holds the robot's weight with the whole body. When the robot is tightened the carrying belt can be unhooked from the robot and the robot can begin climbing.

Further improvement for the installation procedure is that two buttons, for belt tightening during installation, should be placed so the user is forced to use both hands

to press them. This reduces the risk of getting hands inside of belts. The buttons should be placed on handles, like in figure 14-1. Handles also have the added benefit of making lifting of the climber easier. The prototype has no handles and only one belt tightening button is implemented to show the function.
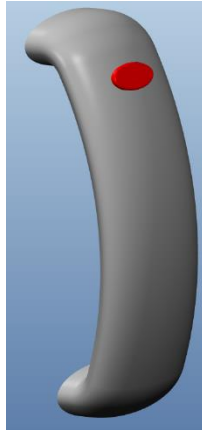
Figure 14-1 Handle with installation button.

A future design should have an autonomous climbing system. Either a sensor is used to determine when the robot has reached the top of the pole or the user pre-programs a certain height the robot should climb to. For the prototype a basic system was implemented but not used. It consists of an ultra-sonic sensor to watch upwards and determine if something (like a lamp) comes close. The system did not become good enough to trust and time constraints stopped further development and testing.

In the prototype the battery status is indicated on LEDs. This does not help much when the climber is high on a pole and therefore a final product should also transmit voltage on the battery down to the user. Transmission back and forth should be done with a system that supports outdoor use. The prototype uses an IR sensor (which is easy and cheap) to receive commands. This system only allows for one way communication and IR works bad on sunny days with disturbing sunlight. The final product should have both receiver and transmitter for communication and use for example blue tooth instead of IR that works in sunny conditions.

A power supply where it is easy to cut the power is recommended. In case of an error the power needs to be cut quickly and the battery cables are fitted tightly. Pulling these apart during operation with large currents can be hazardous. Therefore a proper switch should be implemented between battery and PCB to easily cut the power.

A case that might occur is that the battery runs out on the pole during operation. If this happens the rods that the belt hooks hold on to can be dismounted by unscrewing fastening nuts. If it happens on a pole the user will need a ladder or similar to reach the climber.

14.7 Further Work

A future product needs to be water resistant and more durable. A proper housing can help keep rain and other damaging materials out of vital machinery. If the police is to use such a product during riots the housing should be able to withstand rocks being thrown at it. The housing should also have an appealing design. A design which gives a big presence might frighten the rioters due to the fact that they are monitored but it will also draw attention to the camera leading to it being vandalized more. From the interviews conducted in the surveillance company a discrete design seems to be best. This is because the product will lose its purpose if the police have to protect the unit.

14.7.1 Future Casing

The casing of the robot is limited in that it has to cover the mechanism of the robot to protect it from weather and un-careful handling. Therefore a certain base shape has to be there to enable all the components to move unhindered and still be protected. When encapsulating the robot the electric systems are the most important thing to protect as water and dust can shorten the circuits and thus make the robot useless. The casing should be made from corrosion free materials to make it operational in different climates. It should also protect from dust and grit to minimize wear on the mechanical components.
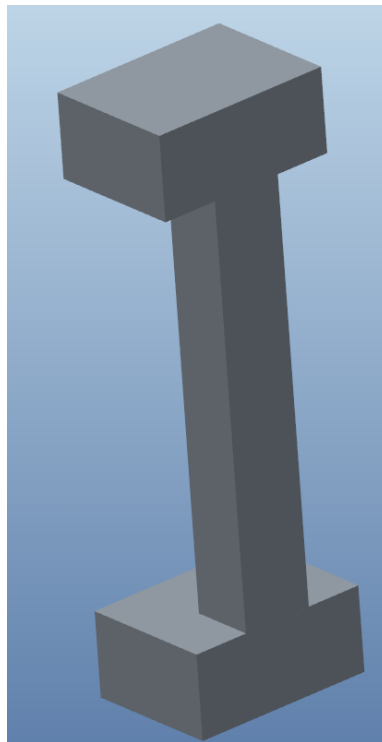
Figure 14-2 The climbers casing in a simple shape.

The robot can be divided into simple shapes with two identical cuboids for the belt sections and another cuboid, for the screw section in the middle, which is very long in

regard to its cross section. The simple shape can be seen in figure 14.2 and this is used to create a more attractive and suitable shape that fits the company's design guide seen in figure 14-3. The top is rounded so rain water and other particles do not gather on the robot's top surface. The rounded shapes also fit well with other products in the company's product portfolio.

Figure 14-3 Possible future design for a pole climber.

14.7.2 Other improvements

The climbing procedure should be fool proof. With a really rigid structure climbing can be done linear with the pole. All cogs should be fastened at both ends so they don't move around and risk breaking during tightening.

Redesign for the PCB is recommended to reduce electrical disturbances. Many components are through-hole mounted for the prototype and this can be changed to surface mounting to save space.

The worm geared motors are over dimensioned for the prototype climbing conditions, which mostly is done indoors. For a final product this might not be the case since climbing then have to be done in bad weather conditions. Slippery surfaces and strong winds might need this power for safe climbing.

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Appendix A: Time Plan

Vecka	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Planering	×																			
Initiell research online	×	×																		
Research med intervjuer/enkäter	×	×	×	×	×	×														
Sammanställa inhämtad research		×	×	×	×	×														
Mission statement			×																	
Kundbehov			×	×																
Sammanställa tekniska specifikationer			×	×																
Skapa koncept	×	×	×	×	×															
Konceptval med "concept screening och scoring"					×	×														
Förfina koncept/bärkning och dimensionering						×	×	×												
Patent-research						×	×	×												
Ritningar							×	×	×											
Komponentlösning							×	×	×											
Inköp/produktion									×	×	×	×								
Programmering							×	×	×	×	×	×	×	×	×					
Bygga												×	×							
Produkttestning												×	×	×	×					
Slutkorrigering/säkerhetstid																×	×	×	×	×
Slutrapportskrivning																×	×	×	×	×
Dokumentation	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×

Pre-study and concept development was made in collaboration. During product development Julius Lindahl focused more on the design and construction development aspects while Erik Jorde focused on programming and electronics. Collaboration between the different areas was also done.

Appendix B: Interviews

Daniel Skölde. Genomförd 2014-12-09

Intervju genomförd med Daniel Skölde. Har tidigare jobbat 10 år inom försvaret och varit säkerhetskonsult på 2secure. Även då jobbat lite med crowd control.

Kommer detta vara en intressant produkt?

Ja.

Vad tror du behövs för funktioner?

God field of view. Kunna se rakt ut men även rakt ner längs stolpen. Interna tester för vibrationer och vibrationsdämpning som EIS. Termisk kamera hade varit intressant åt brandkår.

Kan du tänka dig att det finns någon annan uppgift än att filma för en sådan här produkt?

Väderdata, vinddata, tryck, temperatur.

Hur högt bör den klättra?

Behöver det finnas någon gräns? Det är bra att kunna justera höjden kontinuerligt. Över 12 meter ger god överblick men identifikation på långt håll sker på 4 meter.

Finns det något bra system för motljus, är WDR bra?

Ja. I alla situationer kan man inte sätta upp kameran optimalt. Färg kan vara viktigt vid identifikation även i lågt ljus, light finder. Vid identifikation kan man exempelvis leta efter någons jacka. Intressant hade ett projektet varit som ger möjlighet att byta optisk sensor beroende på situation.

Hur vandaltålig ska den vara?

Man kommer antagligen försöka kasta sten på den. Polis ska inte behöva skydda kameran för då tappar den sitt syfte. Inga sladdar. Den bör hänga över 4 meter så den är svåråtkomlig

Vilka yrkesgrupper tror du kommer ha nytta av denna produkt?

Myndigheter, polis, brandkår.

Hur kompetent är användaren?

Kompetent användare. De får utbildning.

Hur snabb ska den vara?

1 minuts installationstid antagligen OK. Används en PTZ-kamera kommer den behöva 2 minuters uppstart. Kameran ska alltså inte användas under initial klättring. Man hade även kunnat tänka sig att den har 4 enklare kameror runt hela stolpen.

Har du någon uppfattning om vilken prisbild produkten får ligga inom?

Myndigheter inte priskänsliga. Då handlar det mer om vad det kostar för samhället att inte göra en effektiv insats mot kravallerna. För byggföretag och andra användare är det viktigare vad den kostar. Byggföretag behöver använda kameran under längre tid. För crowd control kan två timmar räcka medan för byggföretag hade längre användning varit intressant. Då hade man velat dra upp en sladd.

Något att tänka på vid designen?

Liten enhet som kan användas i pellet case. Poliser kan skapa plats i bil för detta om det behövs. Skärma kåpa för ljus, som en keps. Ljusreflektioner stör bilden.

Anders Eweström – Genomförd 2014-12-12

Anders Eweström installerar kameror och testar tekniken i fält. Data används för att hjälpa sälj-ingenjörer.

Kommer detta vara en intressant produkt?

Ja. Flexibel för temporära installationer är bra. I fält gör jag videoinspelningar och då hade detta varit en intressant produkt då jag slipper annan tung utrustning (hänvisar till stativ som fälls upp på 5 meter). Stativet har en tung grund för att minska gungning i masten som märks mycket på 5 meters höjd. Det hade då varit praktiskt med en klättrande kamera.

Vad tror du behövs för funktioner?

Styra var man ser som med PTZ. Man borde kunna ställa vy från början så rotation kring stolpe är kanske inte jätteviktigt. Funktioner är ju dock alltid bra!

Kan du tänka dig att det finns någon annan uppgift än att filma för en sådan här produkt?

Väderstation, antennförstärkning, trådlös repeater, lampa.

Hur högt bör den klättra?

På 5 meters höjd kan man få en hyfsad översikt på torg med min Q6000. Sen kan man markera vart man vill se så kan PTZ:an zomma ditåt. Som referens fungerar detta på parkering vid Center Syd.

Finns det något bra system för motljus, är WDR bra?

Motljus är svårt. Då är höjd bra för att titta neråt. WDR fungerar men är inte perfekt lösning, särskilt svårt vid identifiering

På natten fungerar IR. Avstånd är cirka 20-30 meter. Man skulle även kunna lägga till ljus med IR-lampa eller riktig lampa.

Hur vandaltålig ska den vara?

Den ska vara robust och klara transport.

Vilka yrkesgrupper tror du kommer ha nytta av denna produkt?

Polis, brandkår, byggföretag. Drifttid ungefär halv dag för poliser.

Hur kompetent är användaren?

Har inte så mycket erfarenhet med poliser, men teknik är inte deras kärnkompetens så produkten bör vara lätt att använda. För byggföretag kan tänkas finnas någon elektriker eller liknande som har en mer teknisk bakgrund och har större kompetens för tekniska produkter.

Hur snabb ska den vara?
Montering till användning kan få ta mellan 1-10 minuter, tror inte det är så viktigt. Om man tar brandkåren som exempel börjar de nog med att släcka. Kameran kan sedan användas som uppföljande brandövervakning.

Har du någon uppfattning om vilken prisbild produkten får ligga inom?

Ingen aning

Något att tänka på vid designen?

Robust, tål att transporteras, lätt att montera. Lätt att ladda och att byta batterier. Ska vara diskret.

Övriga tips för utvecklingen av en sådan här produkt?

Sladd bör även kunna sättas i för övriga kundgrupper än poliser.

Appendix C: Concept Screening Matrix

Selection Criteria/Concept	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Flexible climbing system																				
Can handle signs	+	0	+	+	0	+	+	+	+	-	+	+	-	+	+	-	+	-	0	+
Can climb drain pipes	0	0	0	-	-	0	0	0	0	-	0	-	-	0	+	0	0	-	0	-
Can climb building corners	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-
Heavy lifter	+	-	0	0	+	0	0	0	0	+	0	0	0	-	-	-	0	+	-	-
Construction																				
Durable	+	-	-	-	0	0	0	0	-	+	0	-	-	+	-	-	-	+	-	-
Climbs fast	+	-	+	0	-	0	0	0	0	0	0	0	0	0	+	+	0	0	0	0
Can turn around the pole	-	-	-	-	-	+	+	+	-	+	0	+	+	0	-	-	-	0	-	-
Simple construction	+	+	0	0	-	-	-	-	-	+	+	+	0	-	0	0	-	+	-	-
Light weight	-	+	-	-	+	+	+	+	+	+	+	+	+	0	+	+	-	0	0	-
Compact solution	-	-	-	-	-	+	+	+	+	+	+	-	0	+	0	-	0	+	0	0
Low battery comsumption	+	+	+	+	+	0	0	0	0	0	0	0	0	-	-	0	-	0	-	-
Cheap construction	-	+	+	+	0	-	-	-	-	0	0	-	+	-	-	-	-	+	-	-
Use																				
Simple and fast installation	-	-	-	-	-	+	+	+	+	+	+	+	+	+	+	-	0	0	0	0
Can easily adjust height continuously	-	-	0	0	-	+	+	+	+	+	+	+	+	+	-	-	+	+	0	+
Sum +'s	6	4	4	3	3	6	6	6	5	8	6	6	5	5	5	2	3	6	0	2
Sum 0's	2	2	4	4	3	5	5	5	4	3	7	3	5	4	2	3	6	4	7	3
Sum -'s	6	8	6	7	8	3	3	3	5	3	1	5	4	5	7	9	5	4	7	9
Net Score	0	-4	-2	-4	-5	3	3	3	0	5	5	1	1	0	-2	-7	-2	2	-7	-7
Rank	5	7	6	7	8	2	2	2	5	1	1	4	4	5	6	9	6	3	9	9
Continue?	No	No	No	No	No	Comb.	Comb.	Comb.	No	Yes	Yes	Comb.	Comb.	No	No	No	No	Yes	No	No

Appendix D: Concept Weights

Part	DC-motor	Wheel	Structure	Gripper	Strap	Small DC-motor	Total weight (g)	Concept	Score
Weight (g)	400	400	200	400	200	200			
Grippers									
Straps	3				2		1600	A	5
Robot fingers	3			2			2000	B	4
Spinners	3			2			2000	C	4
Spring hold	3			2			2000	D	4
Clamp	3			2			2000	E	4
Leverage									
Leverage 2 wheels	2	2				2	2000	I	4
Leverage 3 wheels	3	3				1	2600	Ref	3
Wheels									
3-wheeler straight	3	3				3	3000	F	2
3-wheeler scewed	3	3				3	3000	G	2
2-wheeler	3	2				1	2200	H	4

Appendix E: Concept Scoring Matrix

Selection Criteria/Concept	Weighting	Grippers A	Grippers B	Grippers C	Grippers D	Wheels E	Wheels F	Wheels G	Leverage H	Leverage Ref.
Important criteria										
Light weight	0,15	5	4	4	4	2	2	4	4	3
Simple installation for one person	0,25	2	4	4	4	3	3	2	4	3
Fast climber	0,2	1	1	1	1	3	2	3	3	3
Simple solution	0,1	3	2	1	2	2	2	2	4	3
Robust top hold	0,3	5	4	4	4	4	4	3	2	3
Sum		3,25	3,2	3,2	3,1	3,2	3,05	2,85	2,8	3,2	3
Rank		1	2	2	3	2	4	6	7	2	5
Continue?		Yes	No	No	No	No	No	No	No	No	No

Appendix F: Customer Needs

Situation	Customer Statement	Interpreted Need
Interviews	Should see straight ahead but also straight down along the pole.	- The product has a good field of view and has Pan Tilt Zoom (PTZ) capabilities. - The product can be turned around the pole.
	Internal tests for vibration and vibrational damping.	The product has Electronic Image Stabilization (EIS).
	Thermographic camera would be interesting for the fire department.	The product has infrared camera.
	Over twelve meters give a good overview and identification at a distance can be done at four meters.	The product can adjust height continuously.
	People will probably try and throw stones at it. It should be installed more than four meters above ground.	The product will climb higher than four meters and be durable to resist vandalism.
	One minute installation time is probably OK.	The product will be installed faster than one minute.
	For construction companies and other such users, price will be more important.	The product will have a reasonable price.
	Small unit that can be used in a pellet case.	The product will be compact.

	Light reflections disturb the picture.	The product housing will be shielded for light reflections.
Office discussions	What happens if the pole has a sign?	The product has a flexible climbing system.
	What happens if the battery runs out?	The product has a smart battery system making this unlikely and can in worst case scenario be taken down with ladders and a mechanical opening system.
	How fast should it climb?	The product climbs reasonably fast.
	How much should be automated?	The product climbs automatically to the top of the pole.
	Is there enough time to make a complex product?	The product has a simple construction.
	What happens if it's night or if the camera has backlight?	The product can handle different kinds of lighting.
	Does looks matter?	The product looks good.
	How much can it lift?	The product can lift heavy cameras.
Environmental studies	It becomes apparent that a lot of lighting is hung on wires between buildings instead of on lamp poles. In these situations mounting places for the product includes houses, trees and the wire between houses.	The product can climb more than light poles.
	Diameter of poles varied between 60 and 250 *mm*.	The product can climb poles of different diameters and also adapt to changing diameter during climb.

	When it comes to open areas as parks and market squares often the best alternative in Lund is a flag pole. The magnet does not stick to this surface.	The product can climb different types of materials and surfaces.
Project aims	Manufacture a pole climbing camera that is easy to install and use.	- The product is lightweight. - The product is small sized.
	Investigate functions needed.	The product accommodates sensors, batteries, camera and other required components.
Competition	Sherpa technology can be employed to mount Wi-Fi access points to create short distance hot-spots for secure communication, while the deployment of 3G routers enables the rapid relay of all types of data anywhere in the world.[3]	- The product should be able to communicate wirelessly. - The product should have internet connection.

Appendix G: Calculations for Leverage Type Climber With Two Wheels

In figure G-1 forces acting on the structure and its parts can be seen. Forces and lengths used for calculations are presented in table G-1.

**Table G-15-1** Forces and lengths used for leverage concept calculations

S_1, S_2	Force from mass acting on rod one and two.
H_1, H_2	Force from mass acting on wheel one and two.
K	Force from mass acting on camera and batteries etc.
N_1, N_2	Horizontal (normal) force acting on wheels from the pole.
F_1, F_2	Vertical (friction) force acting on wheels from the pole.
l_1, l_2	Rod lengths.
$r_1=r_2=r$	Radius for wheels.
A_{1y}, A_{2y}	Vertical force acting from wheel center
A_{1x}, A_{2x}	Horizontal force acting from wheel center
d	Pole diameter
$x=2r+d$	Horizontal distance between wheel centers.
$y = \sqrt{l_2^2 - x^2}$	Vertical distance between wheel centers.
θ	Angle from horizontal line for rod one.
μ	Friction coefficient

The rods connected to the two wheels and camera, battery etc. can be seen as one structure. This is pictured on the top in figure G-1. The rods holding everything together can be seen on the bottom in figure G-1 and equation 7.1 is the vertical force acting on the rods, equation 7.2 is the horizontal force acting on the rods and equation 7.3 is the moment on the rods acting around the center of wheel one.

$$Equation\ 7.1: A_{1y} + A_{2y} - K - S_1 - S_2 = 0$$

$Equation\ 7.2{:}\ A_{2x} = A_{1x}$

$Equation\ 7.3{:}\ Kl_1\cos(\theta) + \dfrac{S_1 l_1\cos(\theta)}{2} - A_{2x}y + A_{2y}x - \dfrac{S_2 x}{2} = 0$
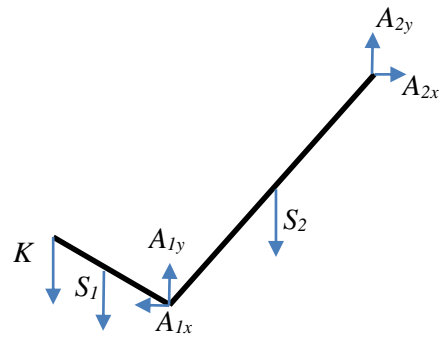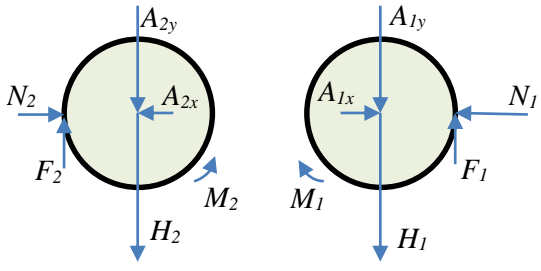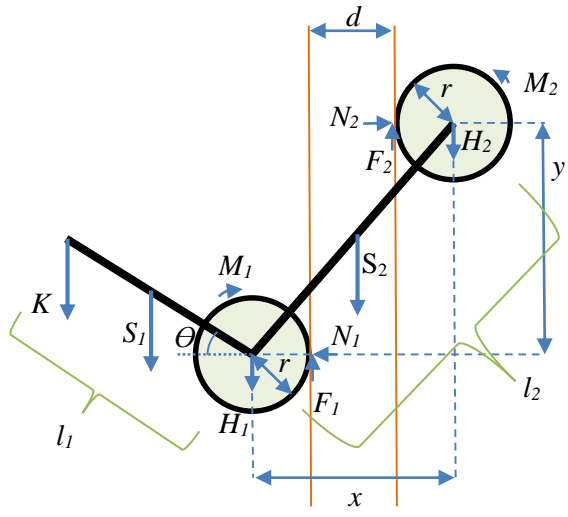
Figure 15-1 Forces and distances on the leverage concept.

The same structure is used for equation 7.4-7.6 and 7.7-7.9 that are the equations representing how forces act on each wheel. Equation 7.4 and 7.7 represent vertical forces on wheel one and two, 7.5 and 7.8 horizontal forces, 7.6 and 7.9 is the moment around the center point of wheel one and two.

$$Equation\ 7.4: F_1 = A_{1y} + H_1$$
$$Equation\ 7.5: N_1 = A_{1x}$$
$$Equation\ 7.6: M_1 = F_1 r$$
$$Equation\ 7.7: F_2 = A_{2y} + H_2$$
$$Equation\ 7.8: N_2 = A_{2x}$$
$$Equation\ 7.9: F_2 * r = M_2$$

Conditions for a statically at rest system that does not slip is that the friction force is smaller than, or equal to, the friction coefficient times the normal force [11, p. 109]. This means that no slippage requires:

$$Condition\ 7.1: F_1 \leq \mu N_1$$
$$Condition\ 7.2: F_2 \leq \mu N_2$$

Finally assumptions regarding the moment on the wheels is done. One assumption is that torque will be the same on both wheels during drive leading to assumption 7.1.

$$Assumption\ 7.1: M1 = M2$$

Another possible assumption is that all the drive will be on the lower wheel. This leads to assumption 7.2.

$$Assumption\ 7.2: M2 = 0$$

By choosing reasonable values for *K, l1, l2, r, d, θ* and μ in MATLAB and comparing the results for the different assumptions feasibility for the climber can be determined. If F_1 is smaller than μN_1 and F_2 is smaller than μN_2 the wheels are not slipping meaning that moment M_1 and M_2 can statically hold the robot at this position. Assumption 7.2 quickly became unfeasible with lower friction and therefore assumption 7.1 was chosen for further investigation.

Using the friction coefficient *μ*=0.3 [11, p. 109], which is a typical friction coefficient for rubber against metal it was found that in order for conditions to hold l_1, which is the arm the camera is mounted on, has to be made longer than l_2, which is the arm that connects the wheels. The worst case was for the smallest pole diameter at 60 *mm*. For this case some different masses were tried. Making the rods and wheels heavier quickly made the case unfeasible but at normal weights it could work. A big impact was made using l_1 at least three times larger than l_2. This often led to the force *μN* being well above the force *F* in condition 7.1 and 7.2. The biggest problem was when the friction coefficient was lowered to *μ*=0.1 which is the friction coefficient for rubber against ice [11, p. 109]. To make a two wheel drive solution work in icy condition l_1 had to be made about 5.5 times longer than l_2. This is not a feasible solution because l_2 had to be larger than the pole diameter plus the wheel radiuses for the two wheels. With a pole diameter of 240 *mm* and wheel radius of 70 *mm* l_2 had to be more than 380 *mm*. This means that l_1 becomes over 2 *m* long.

Appendix H: Matlab Code for Comparing Linear and Non-Linear Relationship Between Belt Length and Pole Radius

Code for the main running program in Matlab:

```matlab
%Maxradie
rMax=0.09;
rMin=0.030000000000001;
%Centrum till inlöp för rem
b1=0.0073;
b2=0.029;
%Utstickande för v-hållare från struktur till stolpe (vid maxbredd då arm
%är helt inmatad)
v=0.04;
%Avstånd vägg till mitt av stolpe rMax + v-hållare
D=rMax+v;
D1=D+0.015;
D2=D;


%LuMax och LuMin skapas med r=rMax=0.09 och r=rMin=0.030000000000001
%Matar in vektorer med värden i funktion LuCalc2 som löser ut obekanta och
%beräknar LuMax samt LuMin

valuesMax=[rMax,b1,b2,D1,D2];
valuesMin=[rMin,b1,b2,D1,D2];
LuMax=vpa(LuCalc2(valuesMax))
LuMin=vpa(LuCalc2(valuesMin))



%Konstanten m beräknas enlig linjärformel
m=LuMin-(LuMax-LuMin)/(rMax-rMin)*rMin;

%Snyggar upp formel
A=(LuMax-LuMin)/(rMax-rMin);

%Beräkna mellan min och maxradier
```

```
x=[0.030000000000001:0.01:0.1];
y=[];
for i=1:length(x)
  rad = x(i);
  val=[rad,b1,b2,D1,D2];
  y(i)=LuCalc2(val)-(A*rad+m); %Skillnad mellan olinjärt och linjärt
förhållande
  y2(i)=LuCalc2(val); %Olinjära värdet
  y3(i)=A*rad+m; %Linjära värdet
end
%Plottar skillnad mellan linjär och icke linjär lösning
subplot(1,2,1);
plot(x,y)
title('Difference between linear and nonlinear solutions.');
xlabel('Pole radius (m)');
ylabel('Difference in belt length (m)');
hold on
%Plottar linjär och icke linjär med remlängd vs radie
subplot(1,2,2);
plot(x,y2, 'red')
title('Belt length as a function of pole radius: blue linear, red
nonlinear.');
xlabel('Pole radius (m)');
ylabel('Belth length (m)');
hold on
plot(x,y3, 'blue')
```

Code for the function LuCalc2:

```
%Mata in radie, r, bredd från centrum av kuggstång till remingång, b, samt
avstånd
%från remingång till centrum av stolpe, D
%Dessa finns i vektorn values
function Lu = LuCalc2(values)

%Måste döpa om variabler av någon anledning
r2=values(1); %r
b3=values(2); %b1
b4=values(3); %b2
D3=values(4); %d1
D4=values(5); %d2
%Då reminfästning och remingång hamnar på olika ställen utförs samma
%beräkningar men med olika värden. Vänster sidas beräkningar läggs
%ihop med höger sidas beräkningar i slutet till Lu.
syms x3 x4 alpha3 alpha4 a3 a4  L3 L4 %e3 e4

%Låter Matlab lösa ekvationerna
```

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```matlab
S1=solve( (x3-D3)/(x3-r2*sin(alpha3))==b3/(r2*cos(alpha3)),
tan(alpha3)==b3/(x3-D3) , x3>=D3 );
alpha3=vpa(S1.alpha3);
S2=solve( (x4-D4)/(x4-r2*sin(alpha4))==b4/(r2*cos(alpha4)),
tan(alpha4)==b4/(x4-D4) , x4>=D4 );
alpha4=vpa(S2.alpha4);

%Hypotenusa i triangel som ska bort
e3=b3/sin(alpha3);
e4=b4/sin(alpha4);

%Ta bort lilla triangels hypotenus för L3 och L4
L3=r2*cos(alpha3)/sin(alpha3)-e3;
L4=r2*cos(alpha4)/sin(alpha4)-e4;

%Omkrets omslutning av stolpen
O3=vpa(r2*alpha3);
O4=vpa(r2*alpha4);
O=r2*pi+O3+O4;
%Remlängd utanför struktur
Lu = O + L3 + L4;
end
```