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Industrial Electrical Engineering and Automation

Autonomous static charging of electric vehicles

using ElOnRoad's electric road technology

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Preface

This master thesis was performed at the department of industrial electrical engineering and automation at the faculty of engineering at Lund university. The main goal of the project was to develop and build an automated charging device for electrical vehicles. Our hopes are that this project can help ElOnRoad and IEA to develop the next generation of electrical vehicles and its required infrastructure for a more sustainable society.

We would like to thank our examinator Mats Alaküla for proposing and making it possible for us to do this interesting project. We are also very greatful for the valuable input of our supervisors Bengt Simonsson and Dan Zethraeus. The most time consuming and difficult part was to build and implement our concept and this would never have been possible if it was not for Svante Bouvin, Ryszard Wierzbicki and Mikael Hörndahl at Production and materials engineering. They have all helped us a lot with manufacturing and workshop practice. Acknowledgment also goes to Getachew Darge and Johan Björnstedt that have helped us with the electronics and embedded programming and also Aventics in malmö and especially Stefan Berg helped a lot with design of the pneumatic system.

Abstract

The scale at which greenhouse gases are produced by human activities is a global problem, and as such it is being targeted broadly both by political means as well as technologically. One of the major contributors to the emission of green house gases globally, as well as in Sweden, is the transportation sector. This poses an opportunity for technologies that aim to reduce impact of the transport sector in this aspect. ElOnRoad's ambition is aligned with this opportunity with their electric road system which could help alleviate some of the ramifications that comes from the largely fossil fueled vehicles of today.

The specifications were written from a set of requirements provided by the supervisor at ElOnRoad. These specifications and case studies of other similar solutions were the basis for the concept generation. One concept was selected to be built and tested in a lab environment. Since it is a multifaceted system the mentioned process was done for each subsyste, and for each, numerous concepts were generated. The final concept was a combination of each of the selected subsystem concepts. To a large extent the final design have been built by the authors to reduce costs.

The results were satisfying even though all of the specifications were not met. By the use of multiple sensors and actuators the device is able to perform its tasks fully automated. The next step for the system would be to build a full scale prototype and make it work as intended underneath a vehicle. Another possibility is for either single or more subsystems that the device consists of can be implemented in other similar designs.

Contents

Nomenclature

ERS - Electric Road System
Rail - Electrified rail which is a central part of the ERS. Supplies power to the vehicle's batteries.
Pickup - Part which moves in a vertical movement, anchored to the cart. Consists of the contact house and struts.
Cart - Part of the structure which is suspended on the racks.
Contacts - Parts that physically connects to the rail
Contact house - Part which the struts and contact is mounted on
Contact device - One full contact system. This includes racks, cart, contacts and contact house.
Static charging - Charging of batteries while the vehicle is at a standstill
Dynamic charging - Charging of the batteries while the vehicle is moving
PCB - Printed Circuit Board
Drive shaft - Shaft which is used to drive the cart forward and connected to the motor on the cart.
IC - Integrated Circuit
Contact cycle - All of the required movements the contact device has to achieve to charge the vehicle and go back in waiting mode
X-direction - across the vehicle
Y-direction - along the vehicle
Z-direction - perpendicular to ground
FSM - Finite state machine
Drive shaft - Shaft which is connected to the belt pullet and cogwheels

1 Introduction

1.1 Thesis outline

This thesis has been divided into seven different main sections. The introduction section is the first section and it describes the problem which this thesis project intends to solve together with information of the project objective. The following sections is in the same order as the work flow of the project. Firstly the concept phase is described, secondly the design phase and lastly the test phase. The report is concluded with a brief discussion of interesting topics of how the system can be improved and future work.

1.2 Background

How to lower our dependency of fossil fuels to stop the earth's climate change is a major challenge. The usage of fossil fuels results in an increase of greenhouse gases in the earth's atmosphere and causes a rise in temperature on the earth's surface. This will eventually worsen the living conditions for humans, animals and many other lifeforms on the planet in a variety of ways. In 2012, 80% of the world's energy consumption was based on fossil fuels [1] and sustainable alternatives to fossil fuels are necessary to solve this problem. By using renewable energy the emissions of greenhouse gases could be reduced, but to be able to use renewable energy new technical and innovative solutions must be provided.

One of the areas were renewable energy could make a meaningful impact is in the transport sector. In Sweden during 2012 92% of all transports were done using vehicles which ran on fossil based fuels and 5% used bio fuels. Only 3% were based on electricity and most of these were transports mainly carried out by trains [2]. There is much to gain from an environmental and sustainability perspective if more transports could be made using electricity since the it could be produced using renewable energy sources. But to go from conventional fuels to electricity for trucks and cars for example in and of itself creates even more challenges. There are however many commercial actors on the market who drive this development forward. One example would be Tesla in the automotive industry which have developed electric cars that can run in excess of 500 kilometers on a single charge [3]. Practically all commercial solution to this problem are based on static charging. By only charging the batteries when at a standstill after they have been fully drained will require a lot of time before the batteries are fully charged again. To charge the batteries continuously while the vehicle is driving on the road or do many small charges during brief stops could be potential solutions.

ElOnRoad is a Swedish company that develops and builds electrified roads. The idea behind these roads is to develop sufficient infrastructure to provide dynamic charging possibilities for vehicles. It also provides an opportunity for intermittent charging when vehicles are at a standstill above the electric road system. The purpose of this master thesis is to provide such a system for electrified buses that will charge when the bus are at a standstill. Ideally would be to be able to charge the bus while it is stopped to let passengers enter and exit. Such a system requires a fast, autonomous connection between the vehicle and the ERS and safety functions due to the high power in close proximity to passengers. Today there exist no such commercial solution, neither any standard. Standardized connectors for manual connection exist, like Combo2/CCS, but these are limited in power at AC charging and not suitable for automatic connection. Simultaneously, conductive electric road systems are developed with automatic connection. An opportunity arises for using all or parts of an ERS technology for automatic static conductive charging.

1.3 Objective

The project objectives was developed together with Dan Zethraeus from ElOnRoad, Supervisor Bengt Simonsson and examinator Mats Alaküla.

- Define a minimum subsection of the ElOnRoad ERS system to be used for static charging
- Define requirements for a charging system to fit both cars and buses
- Develop a mechanical design suitable for automated static charging
- Build and demonstrate automatic static charging with the exception of vehicle position control.

2 Prestudy

A prestudy was conducted in order to analyze the performance related requirements needed in order to establish more detailed technical specifications for the prototype. The prestudy was largely based on an outline provided by Dan Zethraeus from ElOn-Road. It also involves a few experiments regarding the cleaning procedure in order to evaluate the effectiveness of using brushes to ensure a sufficiently clean surface for connection between vehicle and contact.

During the prestudy process other solutions for automatized charging was analyzed in order to gain a deepened understanding of how such a system could work in practice. The two commercial solutions that have been most significant for this project were Siemens eHighway [4] and Alstom's SRS system [5]. The eHighway uses a pantograph that charges truck batteries when it is in contact with wires suspended over the road. It is basically a conventional solution for trains but applied over roads instead of tracks. The SRS system is a more similar solution to the one ElOnRoad is working on. These two systems are proof that electrified roads is a viable alternative to combustion engines for vehicles.

2.1 Project plan

A project plan was created to get an estimate of how much time and resources each necessary activity would take. The time plan is in form of a Gantt chart and is divided into activities and weeks. The project plan is an important tool for project control and to ensure that every deadline is met. The project plan can be found in Appendix A.

2.2 Requirements

The requirements of the system were established by ElOnRoad and are based on their assumptions of what the system should sustain. Due to the complexity of the system the requirements have been separated in three different categories: geometrical/physical, environmental and electrical requirements. The requirements can be found in Appendix B.

2.3 Limitations

The limitations have been largely dictated by the budget of the project as one of the directives given for the development of the prototype was to limit the cost to the extent possible. Because of this several cost reducing compromises regarding the acquisition of components and scale of the prototype. Instead of a full prototype the project's goal is to design and develop a proof of concept.

There is also limitations made to the scope of the project as regarding the conditions under which the prototype is intended to operate. The stated purpose of the cleaning operation is not to handle large objects which could interfere with the connection such as rocks, but rather to be able to remove smaller objects such as gravel or leaves.

2.4 Analysis of ElOnRoad's ERS

The Electric Road System from ElOnRoad consists of an electrified rail which is supposed to lie in the middle of the road. The rail consists of one meter long, metal segments. Between each segment there is $15cm$ of plastic insulation. Whether it is dynamic or static charging a three point contact is always made between the vehicle and the rail. The three point contact ensures that there always exist contact with the positive part and the pickup as well as ground and pickup. Because of the insulation between each segment a third contact point must exist in order to ensure contactation.

One of the objectives was to decide a minimum subsection of ERS that could be used for static charging. This problem is slightly separated from the rest of the project as it is not part of the contact device. Information acquired from ElOnRoad states that the minimum distance between the outer contact points would be $1400mm$ and that the minimum length of the contacts should be $20mm$. Using this information the minimum subsection is calculated to be the same as the minimum length of the entire pickup in it's shortest form, $1480mm$ (minimum distance between contacts plus two minimal contacts). The shortest every contact section could be on the ERS is calculated to be $394mm$.

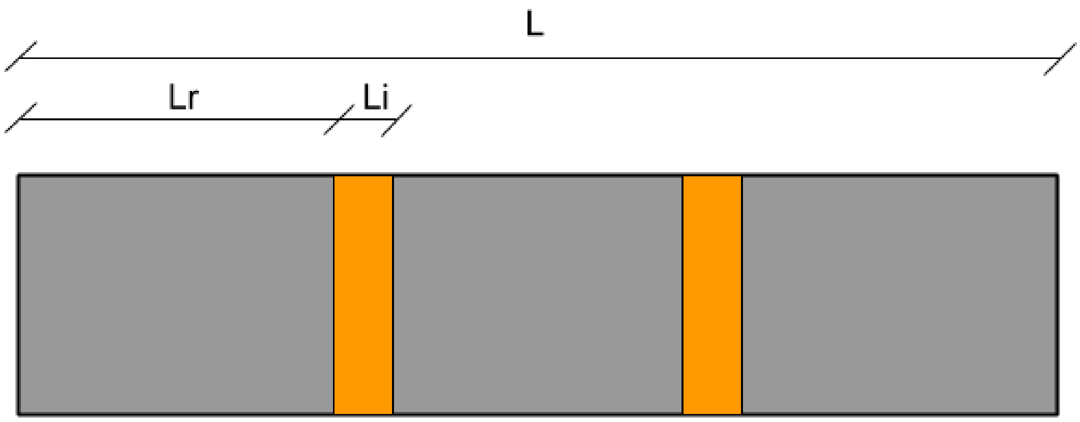


Figure 1: Schematic image of the ERS seen from above

This minimum subsection is not suitable to use since it is deemed to not be very practical as it leaves no room for, even slight, positioning errors. Instead the subsection of the ERS that is used is the length of two whole sections, where one is divided in half for the outer contact points and one undivided section for the middle contact point. This is illustrated in figure 2. The used subsection has a total length of $2300mm$.

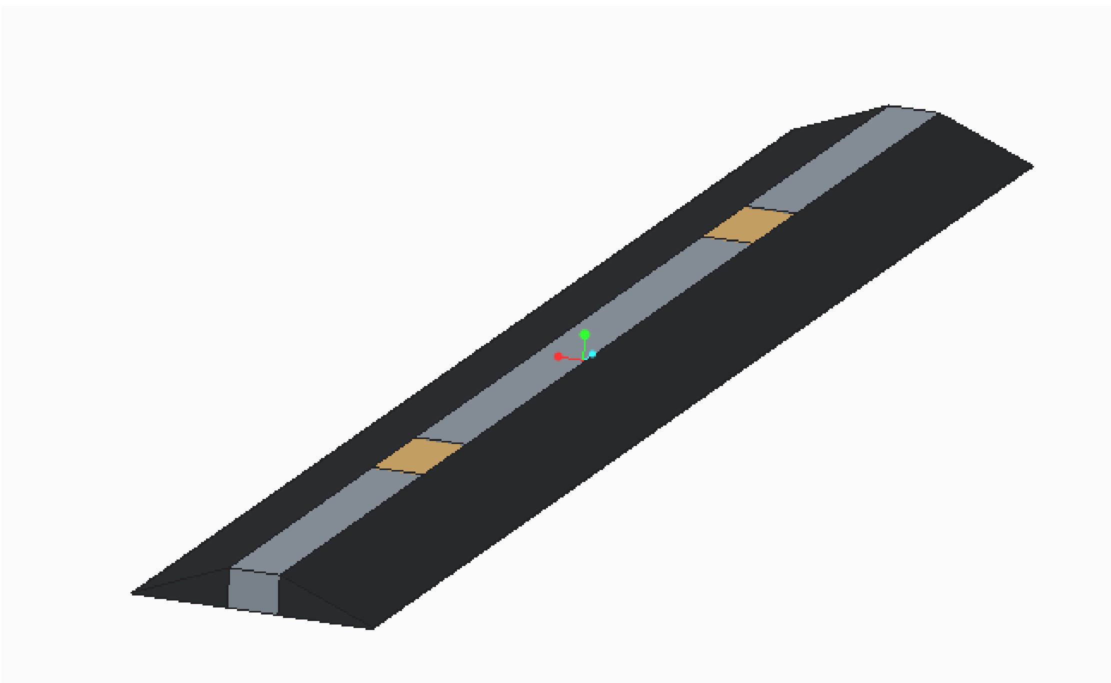


Figure 2: One whole segment and two half segments for static charging

2.5 Specifications

The specifications are made by quantifying the requirements stated above. Each specification is written in such a way that it has a measurable value and unit of measurement. The specifications are made as thoroughly as possible because it simplifies the whole concept generation process and detailed design by having clear goals. It also makes the testing procedure a lot easier since the whole process can be verified against the specification. When all of the specifications are met, all of the objectives have been accomplished. The full list of specifications can be found in Appendix C.

2.5.1 Acceleration, speed and movement specifications

The dimensions and movement specifications of the pickup is established by the use of the analysis of the ERS. ElOnRoad's demand regarding contact time is 2 seconds. The contact time along with the linear movement requirements gives the minimum speed and constant acceleration which the pickup must achieve to meet the requirements. ElOnRoad's demands regarding the movement of the pickup is 150 to 400 mm in the Z-direction, 800 to 1200 mm in the Y-direction and 0 to 500 mm in the X-direction. The calculation for minimum acceleration and speed is given below. Figure 3 shows the different directions relative to the vehicle.

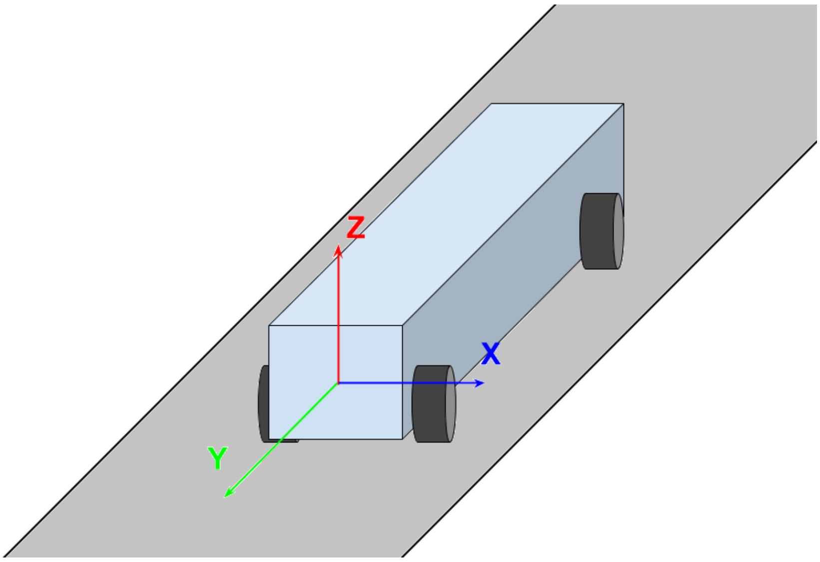


Figure 3: Definition of X-, Y- and Z-axis relative to the vehicle

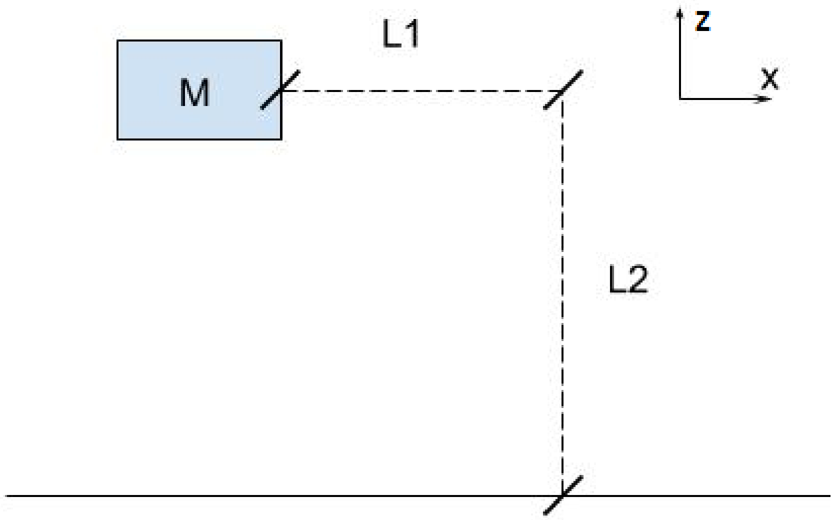


Figure 4: The worst case required movement of the pickup before contact with the rail

Figure 4 describes the horizontal and vertical movement of the pickup in the worst case scenario (this is when the pickup must travel the furthest possible distance).

$$
\begin{gathered}
F_0 = m\ddot{x} = mx_0 \\
\ddot{x}_0 = F_0/m = a_0 \\
\dot{x} = a_0 + v_0 \\
x = x_0 + v_0 + a_0 t^2/2 \\
x_0 = 0, v_0 = 0
\end{gathered}
$$

$$x(t) = a_0 t^2/2 \tag{1}$$

If the acceleration of the pickup is presumed to be linear, equation 1 can be used to find the acceleration needed to meet the time specification. Equation 1 is also used for the distance in the Y-direction even though it would be different because of gravity. Another assumption is that it would take longer for the pickup to travel the horizontal distance in the X-direction than the vertical Z-direction. Since the maximum time for the pickup to contact the rail is two seconds, the contact time has been divided as 1.5 seconds for the horizontal movement and 0.5 seconds for the vertical movement.The last assumption is that the pickup is able to start and stop instantaneously.

$$
\begin{gathered}
\sum t_{final} = t_x + t_z = 1.5 + 0.5 = 2s \\
L_x = a_0 t_x^2/2 \\
L_z = a_0 t_z^2/2
\end{gathered}
$$

$$t_{final} = \sqrt{\frac{2L_x}{a_0}} + \sqrt{\frac{2L_z}{a_0}} = \sqrt{\frac{2}{a_0}}(\sqrt{L_x} + \sqrt{L_z}) \iff a_0 = \frac{2}{(\frac{t_{final}}{\sqrt{L_x}+\sqrt{L_z}})^2} \quad (2)$$

$$a_0 = 1.493 m/s^2$$

The speed specifications are calculated by assuming that the velocity of the pickup is linear. The velocity in the Y-direction is considered to be 0 since this is the forward direction of the vehicle and thus not needed.

$$v_x = \frac{L_x - W_x}{t_x} = \frac{1200-250}{1.5} = 633 mm/s$$
$$v_z = \frac{L_z - H_z}{t_z} = \frac{400-50}{0.5} = 700 mm/s$$

The rotational movement of the pickup along the Z-axis is set to 49°. This ensures that the pickup can charge the batteries even if the vehicle is not directly parallel to the rail.

2.5.2 Dimension specifications

By establishing a minimum length of the rail to ensure sufficient contact the dimensions of the contact could also be established. The minimum length of the rail was determined to be 2.3 meters (one full section plus two halves and two insulation sections). The dimension of the contact needs to ensure that the most of the contact surface on the rail is covered but at the same time not be too big to give enough contact pressure.

The dimensions requirements of the pick up were given by ElOnRoad and stated that the contact and pick up should have the following dimensions:

- Width: 60 to 500 mm
- Length: 140 to 300 mm
- Height when in upward position: 10 to 50 mm
- Distance between contacts: 400 to 700 mm
- Three or more contacts
- Volume for the control unit on the pick up: 100x200x15 mm
- Contact length: 20 to 50 mm
- Contact width: 50 to 400 mm
- Contact height: 5 to 15 mm

2.5.3 Contact specifications

There are not any real standards for contact pressure for applications as in this project but there are a few guidelines. According to the supervisor Bengt Simonsson and examinator Mats Alaküla the contact pressure should be approximately "10 Kg on a surface around the size of the palm of a hand", the palm of a hand is estimated to be 2 dm^2. This gives the contact pressure 5 kPa according to 3.

$$P_{contact} = \frac{mg}{A} = \frac{100}{0.02} = 5000kPa \tag{3}$$

The temperature near the contact and the rail cannot exceed 70°C. This requirement is needed to protect the contact, rail and environment surrounding the contact.

2.5.4 Electrical specifications

The electrical specifications are written after analyzing the electrical requirements which were given by ElOnRoad. These requirements stated that the contact and cables should be able to work during heavy loads (600 V, 300 A), that the contact must be insulated from the body of the vehicle and that the system must verify that the connection between pickup and rail is sufficient.

To verify the connection between the contact and the rail a resistance specification has been set. This specification was set by experiments done by ElOnRoad. These experiments were conducted in a lab environment using a carousel with a electrified rail surrounding the edges and a contact which with the help of a motor moves along the rail. The idea was that this would simulate the dynamic and static charging. The value of 0.0022 Ω was the highest resistance measured when the contact was at a standstill.

3 Concept development process

The concept development process was largely based on Ulrich & Eppingers method for concept development [6].

3.1 System decomposition

To get a clear overview of the system, a system decomposition is made. The system decomposition is a schematic figure and it describes the relationships and dependencies of the different subsystems.

A "Black box model" helps establish the different signals, material and energy what the system would require in order to operate properly. The material which is moving is the pick up and contact and when it is first activated it will move vertically and horizontally against the ERS. When the process is finished the pick up will move away from the rail. The energy that will flow through the system is from the rail to the contact and into the batteries. The first signal which initiates the system is some form of "begin" signal and the signal which is set when the process is finished is the "End" signal. The black box model is shown in figure 5. The black box model provides early feedback on what the systems should be able to do as well as an clear overview of the input and output signals.

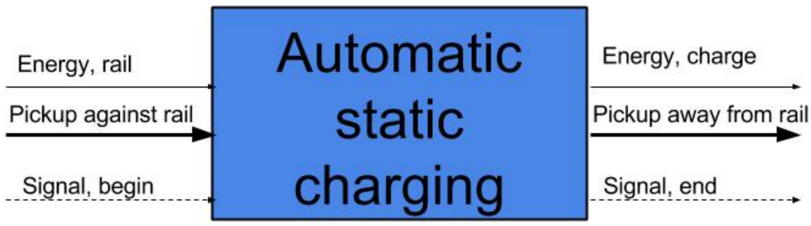


Figure 5: Black box model of the system

From the black box model a system decomposition is made which an extension of the black box model. While the black box only shows the inputs and outputs of the system, the decomposition shows how the inputs are handled by each subsystem. The system decomposition is shown in figure 6.

The decomposition shows that the quality of the physical connection needs to be checked before the power in the rail is turned on. It also shows that the system needs to verify that nothing interferes with the charging or the system while it is active for the power to remain on. If the quality of the contact would not be good enough the system would have to trace back and clean the rail again.

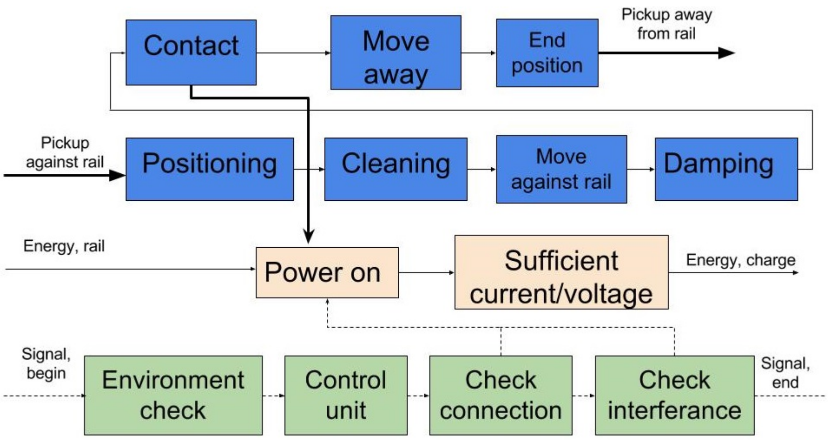


Figure 6: System decomposition

3.2 Concept generation

The subsystems identified in the system decomposition serve as the basis of the concept generation phase. The decomposition of the system is made with the intention to divide the system into subsystems which are to the largest extent possible decoupled from each other in order to be able to handle their respective concepts separately.

3.2.1 Positioning

The task of the positioning subsystem is both to align the pick up with the rail, as well as to achieve contact between these. Several concepts were developed with varying principles of movement and configuration of the contacts.

- Rotating frame: By suspending the pickup in a frame structure all of the required movements could be accomplished by the use of four actuators. The frame itself is rotating around the Z-axis by the use of a cogwheel structure mounted along one of the short sides of the frame.

- Static frame: The required movement along the X-axis is accomplished by the use of two linear actuators connected to the shorter sides of the pick up. Rotation around the Z-axis is performed by moving the shorter sides away from one another with the help of the actuators. The whole device would be suspended in a frame that can be moved up and down along the Z-axis with the use of a third linear actuator.

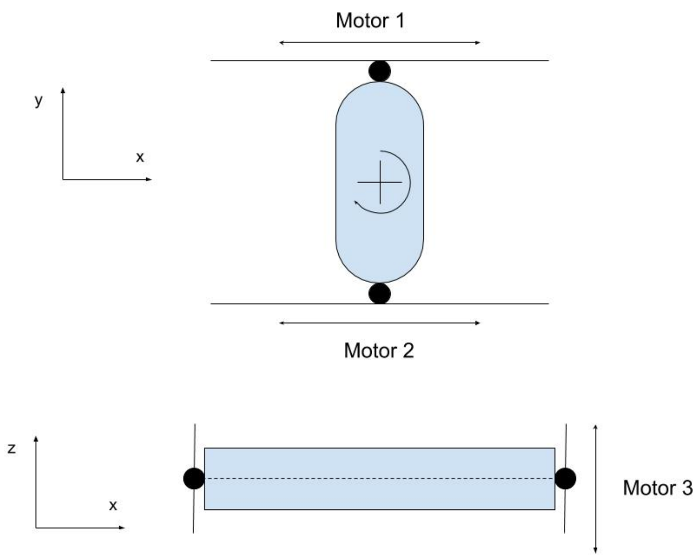


Figure 7: Static frame concept

- Claw crane: A claw crane is an arcade game were the player has to move a claw in two linear movements and then lower the claw to grip a prize. Like a claw crane, the pick up in this concept would be moved linearly along the X-axis and then lowered along the Z-axis. Between the connection of the crane structure and the pickup an actuator would be placed to allow rotation around the Z-axis. The claw crane would use three actuators in total.

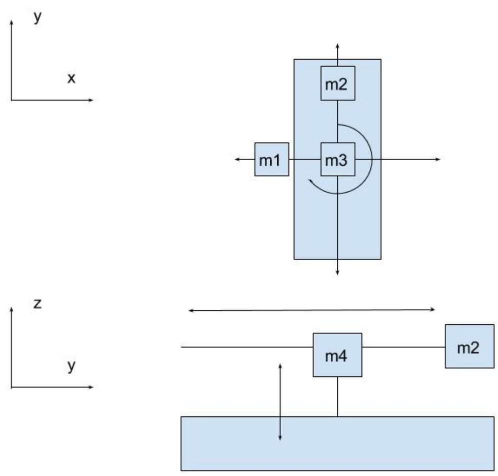


Figure 8: Claw crane concept

- Angled struts: Struts with adjustable length would be mounted in each corner of the pick up. By adjusting the length of each of the struts and mount them using ball joints the pick up can be moved and rotated in any plane. This concept would use four actuators in total and it would not need any type of frame structure to suspend it.

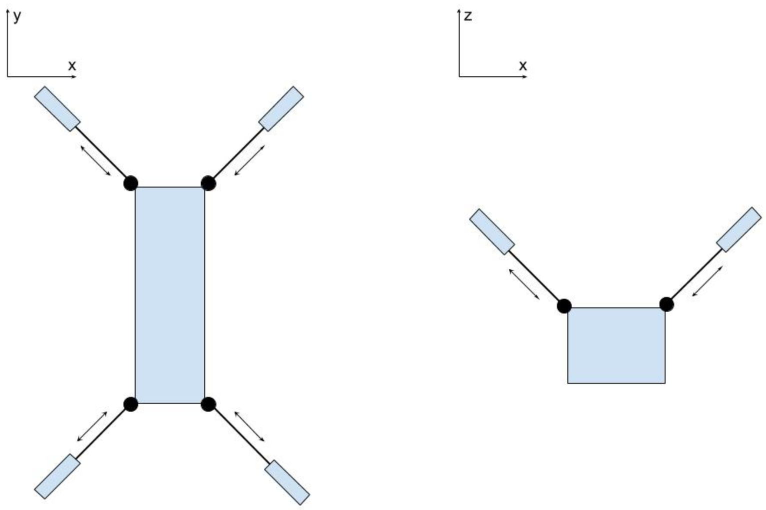


Figure 9: Angled struts concept

- Separate contacts: Individual movement of the contacts can be achieved by splitting the pick up into three identical parts. Every contact would have to have its own actuators for movement along the X- and Z-axis, but the rotation along Z would be accomplished by moving the contacts differently along X. This concept would use six actuators in total.

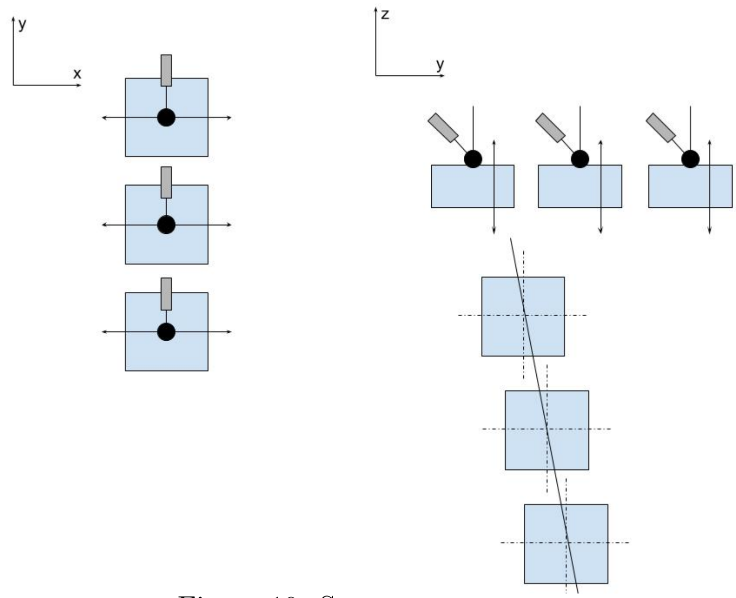


Figure 10: Separate contacts concept

- Hammock: The next concept is inspired by an ordinary hammock. The pick up's short sides would be connected to one linear actuator each. This allows for movement along the X direction and rotation along the Z-axis, very much like concept A. The main difference are the added struts of adjustable length between the actuator and the pick up. By changing the length of these struts linear movement along Z and rotation along X could be accomplished.

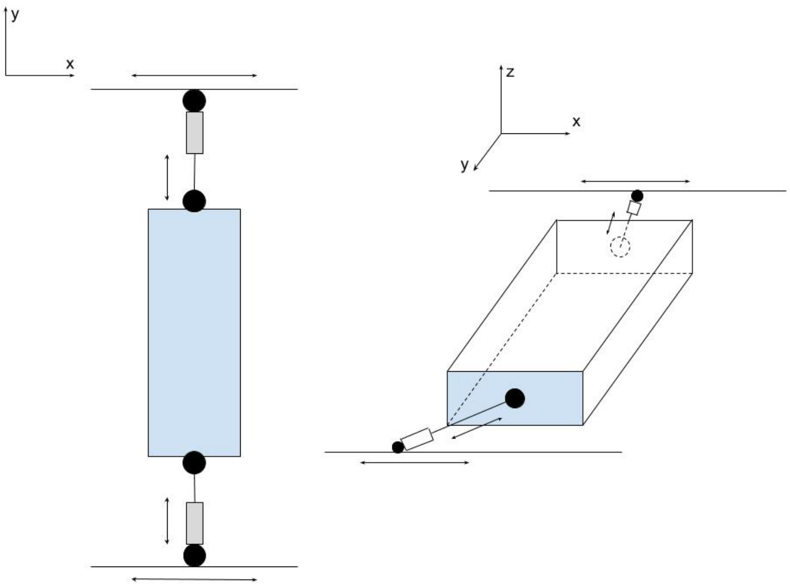


Figure 11: Hammock concept

3.2.2 Cleaning

The task of the cleaning system is to prepare the contact surface of the rail prior to applying the pickup in order to achieve a sufficiently low electrical contact resistance. An auxiliary goal of the cleaning subsystem is to be as simple and robust as possible due to the harshness of its intended environment of operation. The concepts that were generated and subsequently considered are presented below.

- Static brushes: Non-actuated brushes that are attached to one or more of the contact's surface in order to use the same actuators used to position the contact for cleaning the rail.

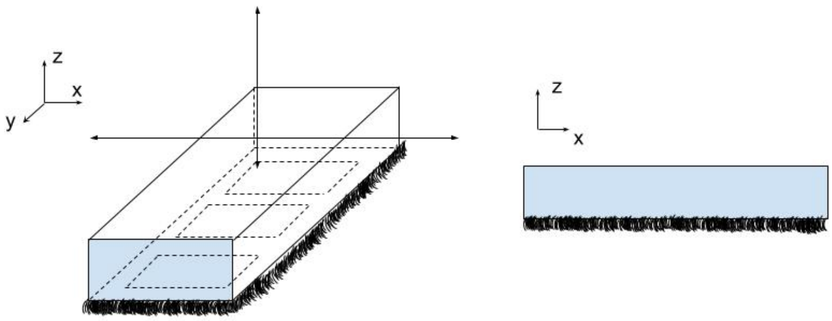


Figure 12: Static brushes

- Internally retractable rotating brushes: Rotating brushes which are retractable into the contact itself as to not interfere while the contacts are in the process of charging the vehicle.

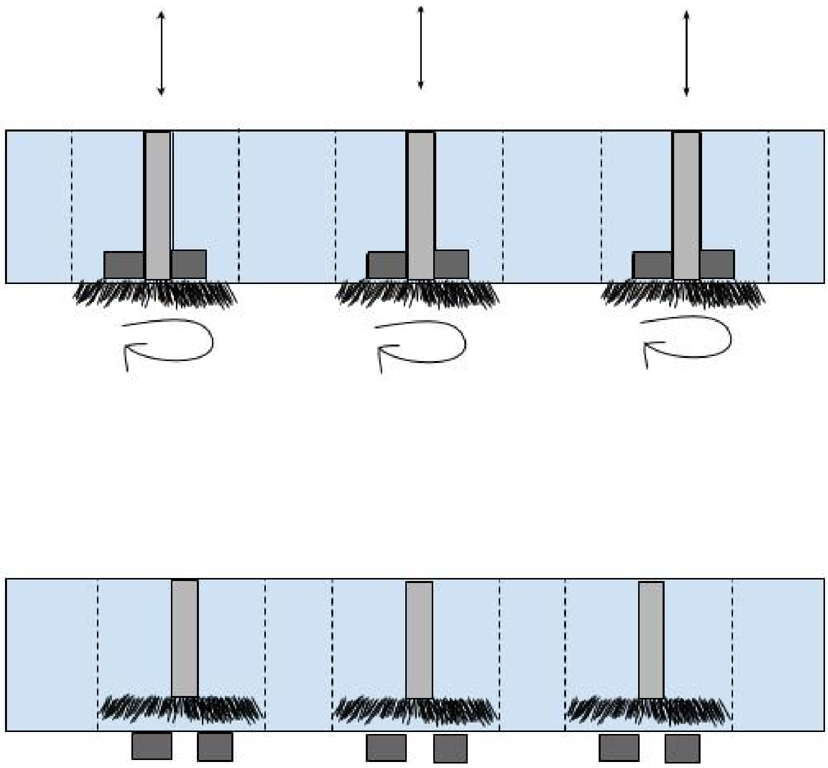


Figure 13: Internally retractable rotating brushes

- Rotating brushes, movable: A similar approach as described in the point above, but with a different pattern of movement. The rotating brushes are lowered to the sides of the contact and clean the surface as the contact positions itself above the rail.

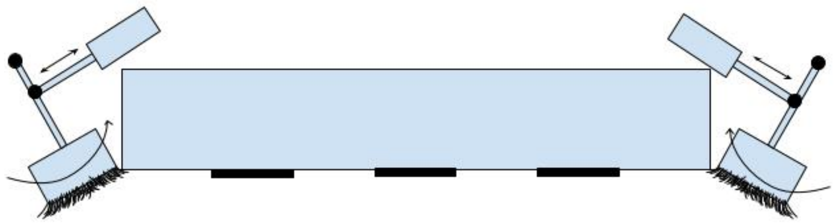


Figure 14: Rotating brushes, movable

- Car wash type brushes: The brushes are cylindrical in shape and span the width of the contact. The brush is in turn mounted on a hinge which is able to move in a guide rail which allows the brush to not interfere with the charging by positioning itself on the top side of the contact.

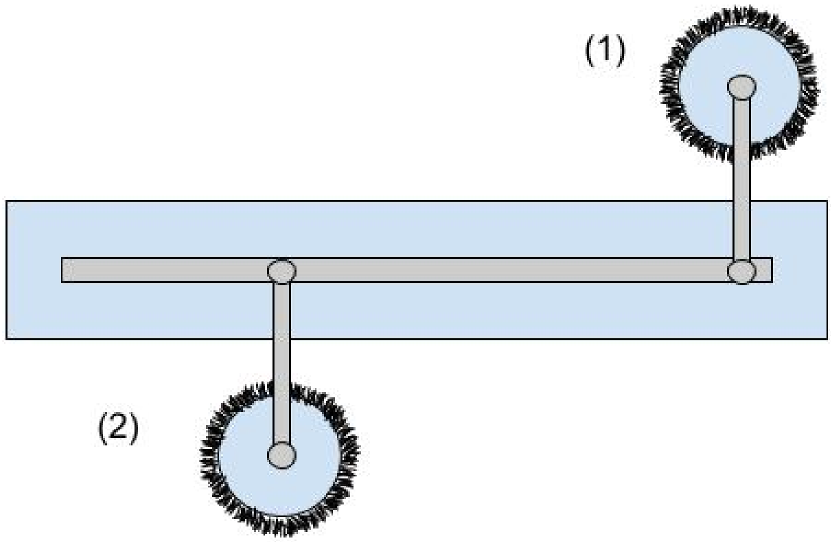


Figure 15: Car wash type brushes. (1) shows the concept in its upright position and (2) its position and movement when activated

- Rotating brushes, fixed position: One or several brushes clean the rail as the contact positions itself above the rail, they are placed on the sides of the contact in order to not obstruct the contactation between the rail and the contact.

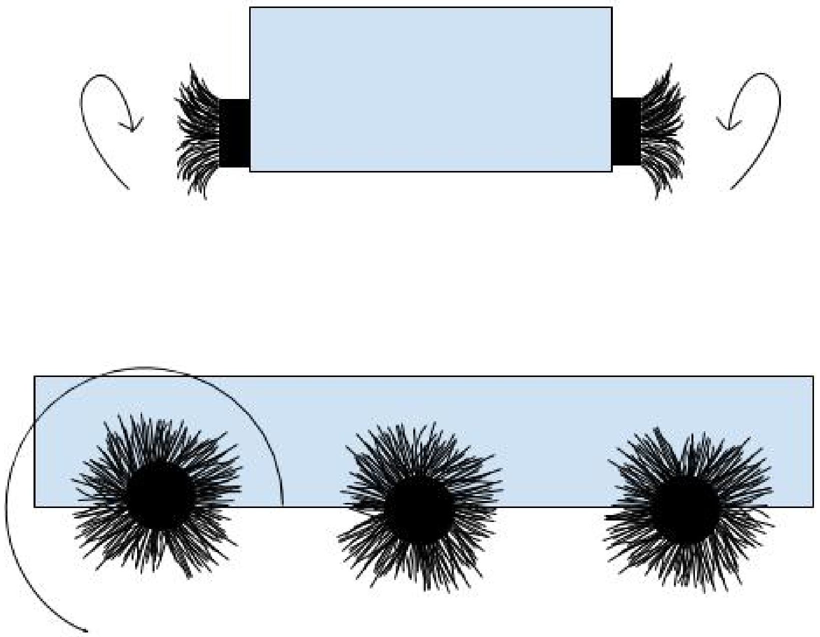


Figure 16: Rotating brushes, fixed position

- Air pressure: Since many of the concepts regarding the positioning of the contact involve some form of pneumatic actuator the may be an opportunity to utilize the pressurized air in order to blow some of the contaminants off of the rail. In this concept this is done using one or several nozzles mounted through the contact.

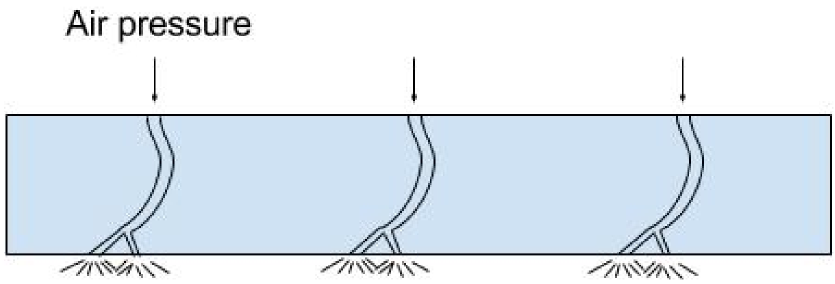


Figure 17: Concept for cleaning with air pressure

- Plow: More severe obstructions on the rail might be too heavy or too adhered to the rail for brushes or pressurized air to be able to remove them with a satisfying result. For such events a sort of plow might be better suited. The plow in this concept is a simple wedge shape which uses the movement of the actuators that positions the contact in order to remove such obstructing elements.

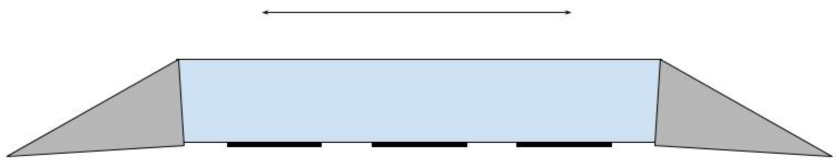


Figure 18: Plow concept

3.3 Concept selection

To select which concept to move forward with a structured method of concept selection is needed. The reason for selecting a final concept in a structured manner is to ensure that there are as many aspects as possible of the design and system considered. The selected method is described in [6] under the section "Concept selection". The movement subsystem is selected using the method described in [6] and the cleaning subsystem is selected by using an experimental approach.

3.3.1 Selection criteria

For the movement subsystem different selection criteria are established. These criteria are given an individual weight to give them different level of importance. The criteria for each the movement subsystem are listed below.

- Number of actuators - The number of actuators should be as few as possible.
- Height in upright position - The design should be as low as possible in an upright position.
- Degrees of freedom
- Robustness
- Movement speed
- Size
- Estimated price - A rough estimation of the price is considered.
- Implementation difficulty - The concept should be possible to implement.

3.3.2 Selection matrix

The selection matrix is created by putting each selection criterion as a row and each concept as a column. For each criterion the concepts are given a score between one and six since there are six different concepts to consider. The concepts with the lowest score are the ones which are further investigated. These are shown in the matrix (figure 19). The weight of the criterion has a total sum of 100 and these weight points are distributed among the different criterion depending on how important they are deemed for the design. Robustness, price and height are considered as the most important design aspects and have been given high weights. The importance of the different criterion have been set by analyzing the environment were the product is suppose to act and the whises of ElOnRoad. The product is supposed to be beneath a vehicle and it was decided that the most important feature is robustness so that it cannot damage or make the vehicle unsafe. One demand from ElOnRoad is for the product to have a very small height to ensure that it can fit under any type of vehicle and the height criterion is thus given a high weight. The size criterion is strongly connected to this and is also given a relative high weight. The last important criterion is cost and this is another demand from ElOnRoad that the costs are to be as low as possible for the product.

Critierion	Weight	Static frame	Claw crane	Angled struts	Seperate contacs	Hammock	Rotating frame
Number of actuators	4	1	1	2	3	2	1
Height	18	2	1	3	1	3	2
Degrees of freedom	2	2	2	1	2	1	2
Size	12	4	1	6	2	5	3
Implementation difficulty	4	3	1	6	2	5	4
Price	20	3	1	6	2	5	4
Robustness	40	3	2	6	1	5	4
Score		**284**	**142**	**520**	**146**	**444**	**336**

Figure 19: Selection matrix

As seen in figure 19 the concept "Claw crane" and "Separate contacts" got the lowest score and considered for final selection. The final selection is made based on which concept is thought to be the most robust since this was the most crucial design aspect. Thus the concept "Separate contacts" is chosen as the final concept. The separate contacts and claw crane were deemed to have the same height and many of the other scores are equal. It should be stated that the final choice of concept between the two were largely based on the authors subjective feelings on which of the concepts were more likely to succeed. Because of this it is difficult to tell whether or not the chosen concept really is the best one.

3.3.3 Selection of cleaning subsystem

The selected movement subsystem allows a modular approach of the cleaning subsystem. Meaning that the concept can be modified to fit any of the cleaning subsystem concepts. It can use multiple cleaning concepts. Static brushes was considered as the most simple and easy to implement of the cleaning subsystem concepts. Because of this the static brushes are selected as the base cleaning system which would be added to the final concept. To verify if the static brushes would be sufficient as cleaning system or if another cleaning system would have to be added to the design, experiments were conducted to test it's capability.

The experiments are carried out using a simple brush operated by hand in a brushing pattern that simulate the movement of the contacts, two pieces of metal and a digital multimeter. Dirt consisting of leafs and mud are spread out across the piece of metal which simulate a section of the ERS. The other piece of metal which acts as the contact is pressed against the first one and the resistance between them is measured with the multimeter. The contact is then removed and the ERS is cleaned by brush. After the removal of dirt the contact is yet again pressed against the ERS and the resistance between them is measured. The results of the experiments indicate that the method of cleaning is sufficient without the use of further cleaning systems.

3.4 Final concept

The figures below shows one contact from the final concept as it was initially designed. The numbers in the figures refer to crucial parts of the concept.

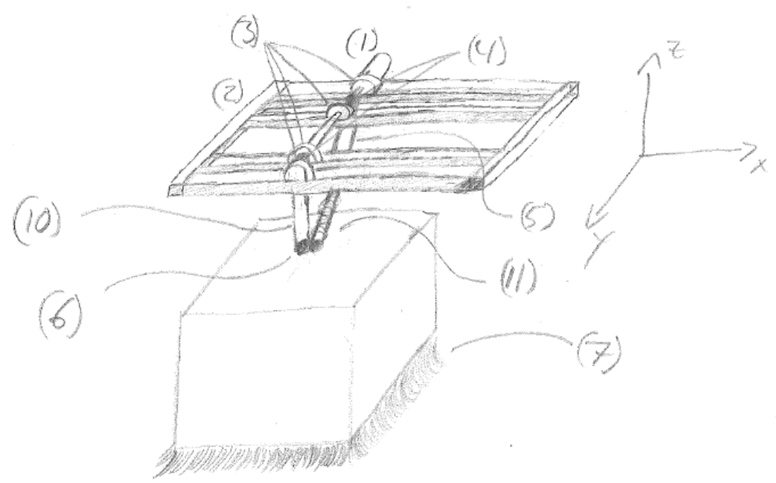


Figure 20: Sketch made by hand of one contact

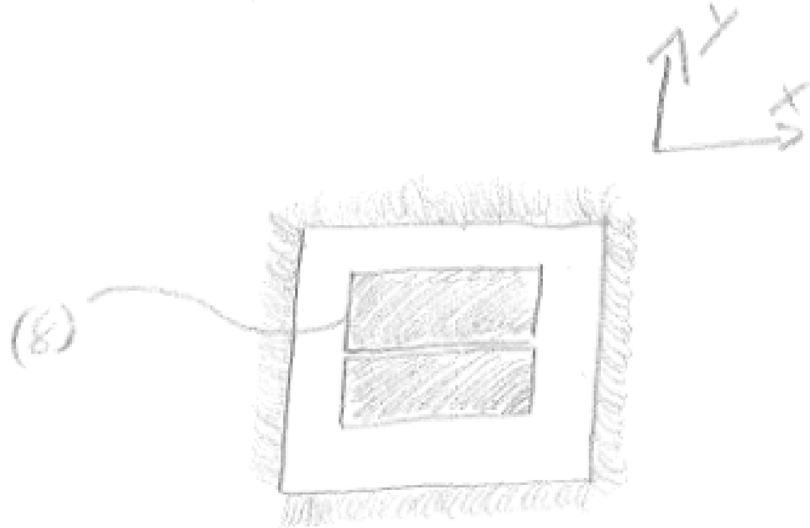


Figure 21: One contact seen from underneath

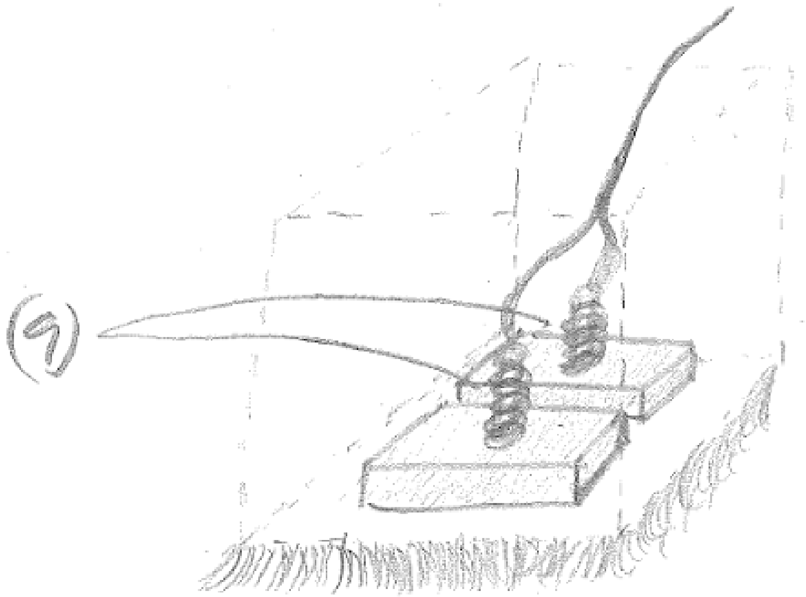


Figure 22: A wireframe view of the contact house showing the cables and contacts

1. DC motor for movement in the X-direction
2. Rail on which the contact is suspended
3. Bearings on suspension rail
4. Connection for struts and actuator
5. Pneumatic cylinder for lowering the contact towards the rail
6. Brushes for cleaning
7. Contacts for charging. Divided into two parts.
8. Damping of contacts
9. Struts for stability
10. Damping of the contact house

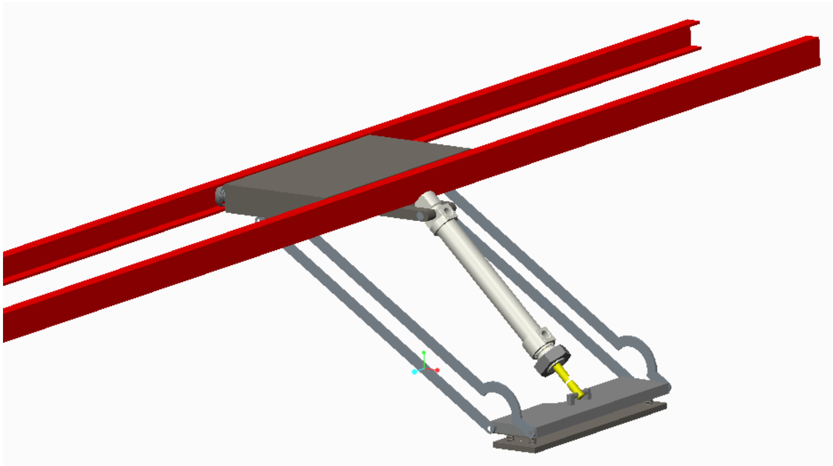


Figure 23: One contact in the final concept as a CAD model

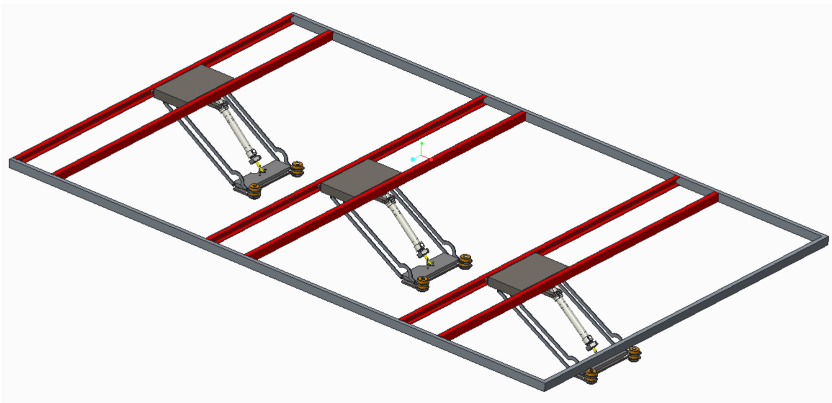


Figure 24: The final concept shown as a CAD model

4 Detailed design

One of the goals for the mechanical design is that it should not include components that can not be either manufactured without external involvement or bought off the shelf in order to reduce the cost of the prototype. Based on this intention a few components, critical to the function of the prototype, are selected and subsequently the rest of the design is made with simplicity in mind in order for it to be easily manufactured.

4.1 Geometry of the lowering mechanism

In order for the lowering mechanism to function properly the struts and the pneumatic cylinder need to be mounted relative to each other in such a way that as much of the length of the cylinder rod is utilized while also maintaining angles that allow for the cylinder rod to exert enough force on the contact. In order to evaluate different configurations in a quick manner, a Matlab script is used which plots the length of the pneumatic cylinder as a function of the angle of the struts while allowing the parameters regarding the cylinder and struts positions to be tweaked to see how it affects the graph. In figure 25 such a graph is displayed.

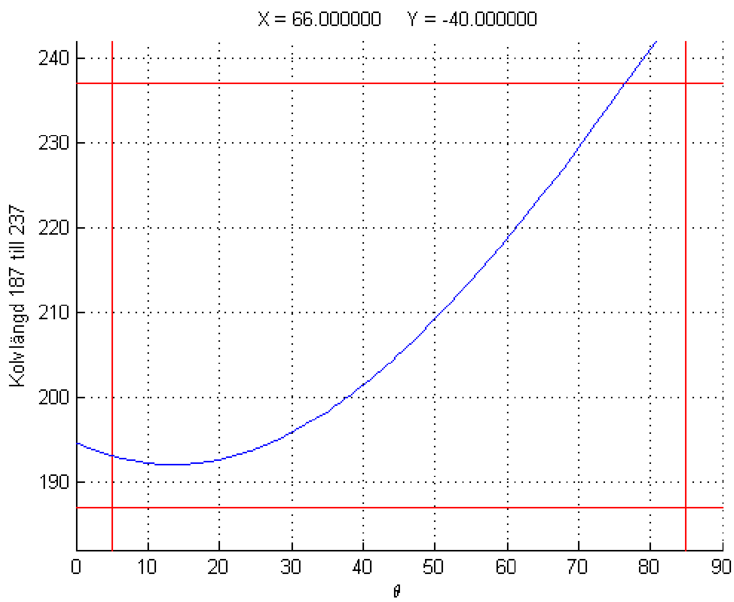


Figure 25: Length of the pneumatic cylinder as a function of the strut angle measured from a folded position. The horizontal red lines indicate the end positions of the cylinder and the vertical ones indicate 5° and 85°

With the configuration shown in figure 25 most of the cylinder's length is utilized and the struts are able to move in the range of approximately 15 °and 75 °. However, to achieve this the cylinder would have to be mounted around $40mm$ below the cart. This would make the design take up more vertical space than what is desired.

4.2 Pneumatic

A draft is made for the pneumatic subsystem containing only the main components needed for the principal functionality of the system. The only component which is explicitly chosen is the cylinder so that its measurements can be utilized in the design of the mechanism controlling the contact. The selected cylinder is double acting, has a stroke of 100 mm and a threaded cylinder rod.
In order to select appropriate components for the rest of the pneumatic system invaluable assistance was provided by Stefan Berg at Aventics in Malmö, who also provided a good portion of the auxiliary components needed to assemble the system. Several decisions regarding design and functionality had to be made before a complete list of components could be assembled, decisions such as how many different pressure levels would be utilized and their magnitude as well as how many different states would be needed from the valves. The full schematic of the pneumatic system can be found in appendix D

4.3 Components

This section describes all of the components that were either bought or manufactured during the project.

4.3.1 Transmission components

To meet the required speed, power and acceleration in the X-direction a 96 W DC motor with brushes is used. The motor which is a 775 For Johnson motor is chosen because of its high power density and low price. The motor can achieve a speed of 18000 rpm according to the supplier. In reality this number is probably slightly less. The motor was bought online through Ebay and as a result the documentation is limited. By comparing the motor with other Johnson Electronics motors, the torque and speed of the 775 could be estimated and was considered to be enough. To ensure sufficient torque a transmission was used between the motor shaft and drive shaft. A compromise had to be made because of the size of the belt pulleys and thus the gear ratio could not be higher than 3/2. The weight of the whole structure was assumed to be 8,8 Kg. By assuming what type of materials will be used the weight is estimated by using the analysis tools in Creo Parametric. The following calculations are used to to verify that the motor and a 3/2 gear ratio is enough to drive the contact device forward and give it the necessary acceleration:

The necessary rotational speed, ω, and torque, M_{Da}, of the drive shaft to meet the specifications:

$$V_x = \omega * D_0 * \pi \iff \omega = \frac{v_x}{D_0 * \pi} \text{ , } \omega = 1273rpm$$
$$M_{Da} = F_x * r_0 \text{ , } M_{Da} = 0.18Nm$$

The force F_x which acts on the gears by the end of the drive shaft is calculated from the estimated weight and acceleration. This force is calculated to be 13.11 N but because of friction and other loses the force is estimated to be 30 N. This is to ensure that the contact device gets the required acceleration.

The maximum rotational speed of the motor is 18000 rpm and is well above the critical speed. The torque is harder to predict if it is enough since there is no documentation regarding the motor's rated torque. Other 100 W motors normally have a rated torque of 0.5 Nm and it is estimated that the 775's torque would be sufficient with added gear ratio. All of the transmission components were acquired at Kedjeteknik AB in Malmö.

4.3.2 Sensors

Within the scope of the project, is it necessary to be able to react to certain external events. To this end several sensors are utilized, the most prominent of these is an inductive proximity sensor. This sensor from Omron is called E2B-M12KN08-M1-B1 and has a detection distance of $8mm$. It is used to detect the ERS in order to determine whether the contact is correctly positioned in relation to the rail. The choice of inductive proximity sensors for this application is based on a academic paper where the authors have used these kind of sensors to build a system for automatic charging of electric vehicles [7]. In order to have a reference point for the incremental encoder to relate to as well as to be able to stop the cart from moving past its end position hall effect sensors (Hamlin 55140) are placed on the ends of the device and corresponding magnets in the end positions.

4.3.3 Other electrical components

The contact is moved across the vehicle using a DC motor which is driven by means of a motor drive circuit based on a VNH2SP30 H-bridge IC which is controlled by a control circuit containing a PIC16F1939 microprocessor. The control circuit also handles all the external inputs given by the sensors. The incremental encoder is also connected to the micro controller via the PCB, although its functionality is not implemented.

A schematic of the PCB used to control the system can be seen in figure 26 as well as the corresponding circuit diagram in figure 27. The PCB has two separate sections, one relating to the H-bridge circuit which controls the motor and one related to the micro controller, sensors and pneumatic valves. These are galvanically isolated by means of optocouplers and each has their own separate ground plane in order to protect the more sensitive components from the higher voltages and back EMF from the motor side. A few sections of the board has been framed and numbered in figure 26, these are described below.

1. Transistors operated by the micro controller which actuate the solenoids in the pneumatic valves.

2. In circuit programming interface, to be able to program the micro controller without removing it from the board.

3. Input channels from the different sensors to the micro controller.

4. Output channels from the micro controller to the H-bridge circuit in order to control its operation. Galvanically separated via optocouplers bridging the gap between the two ground planes.

5. A MAX232 IC for serial communication with a PC, this is used to extract data as well as to send commands to the micro controller.

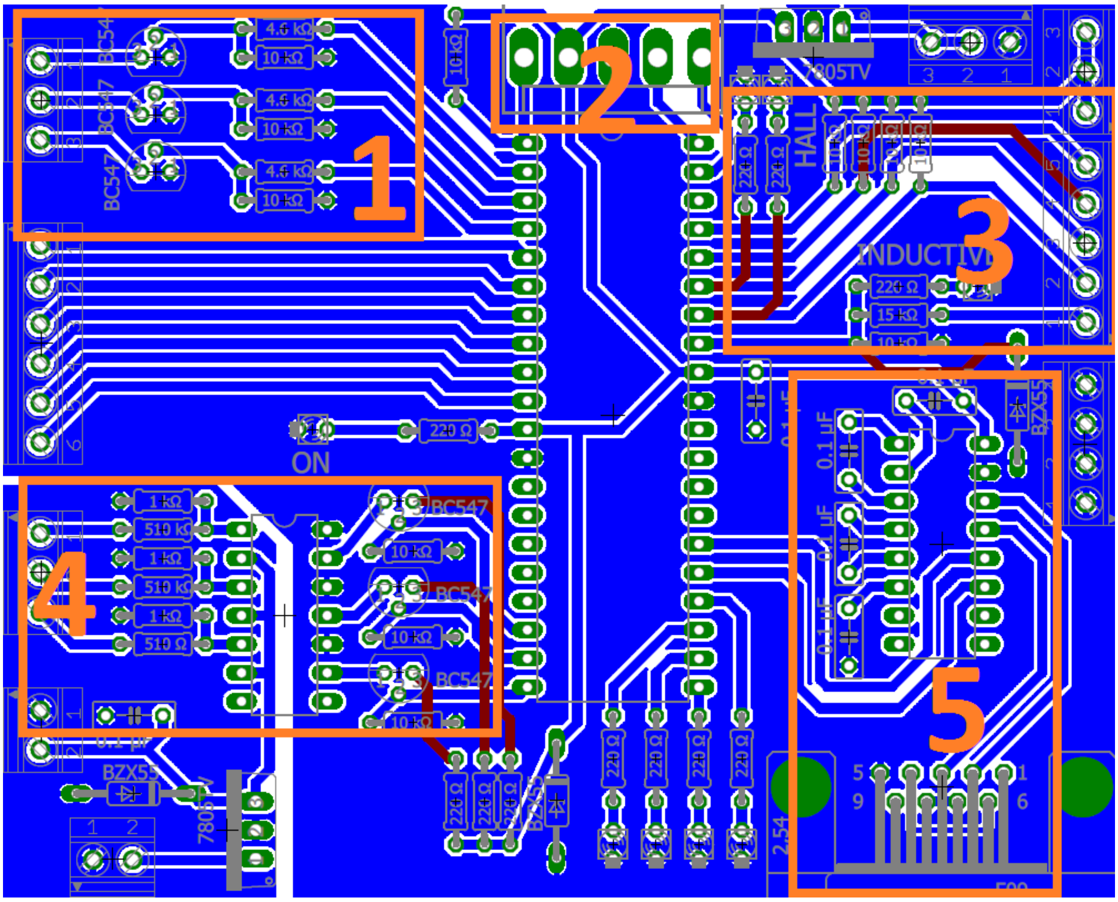


Figure 26: Printed Circuit Board for the controller circuit

The design of the PCB changed over a few iteration as the need for improvements and additions became evident. The last of these iterations were sent to be made by a PCB manufacturing company.

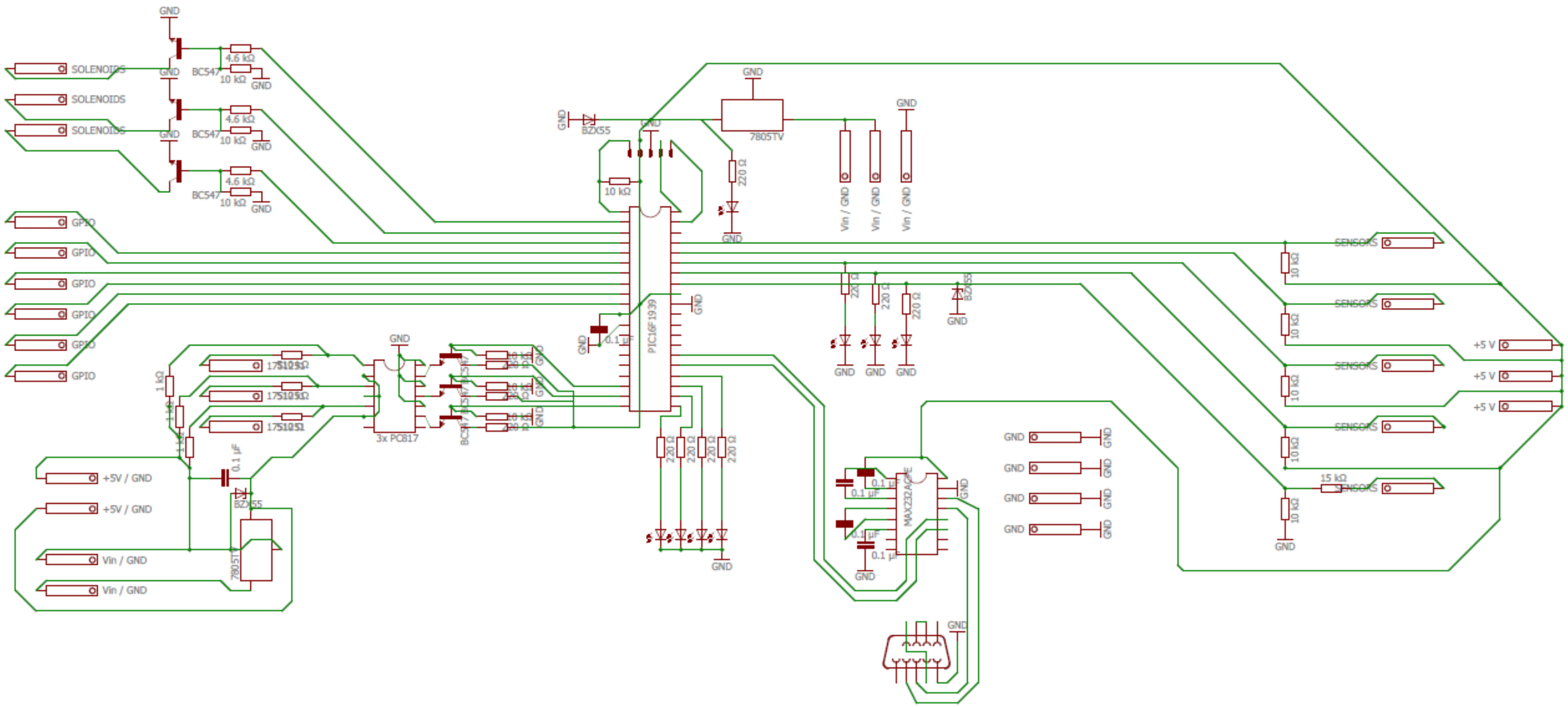


Figure 27: Circuit diagram of the controller circuit

4.3.4 Software

The software involved in this project mainly consists of an interrupt driven FSM. Relying on input from the inductive- and hall sensors, as well as input from the user. Its purpose is to position the pick up so that it may make contact with the ERS. A graphical representation of the software can been seen in figure 28, which should be viewed along with tables 1, 2 and 3.

The operation of the FSM is such that upon powering up it enters state S0 and remains there until a certain command is sent by the user at which point it proceeds to state positionCal. In state positionCal the cart is moved to the left until it reaches the left hall sensor, which acts as a limit switch, it then proceeds to the idle state. The software remains in the idle state until a specific user input is supplied, in a more realistic application this input could instead be supplied automatically when the vehicle is stationary above a charging rail. From the idle state the FSM enters the goRight state, the pick up is lowered and the cart starts moving to the right until it either detects the rail by means of the inductive sensor, at which point the next state is railFoundRight, or until it reaches the right hall sensor and proceeds to the goLeft state. The goLeft state carries out a similar operation as the goRight state only in the other direction, if the rail is detected by the inductive proximity sensor the software proceeds to the railFoundLeft, otherwise, if the left hall sensor is triggered it enters state railNotFound. The railNotFound state counts the number of attempts made to find the rail and either makes a new attempt or resets the FSM.

The states railFoundRight and railFoundLeft states pushes the pick up downwards toward the rail with increased force in order to make a satisfactory connection before proceeding to the charge state in which the charging current is intended to be switched on to charge the batteries until a end command in issued by the user at which point the FSM resets. In a more realistic application the end command could be issued by a number of different sources, such as that the vehicle begins to move or that the batteries are fully charged. The STOP state raises the pick up and brakes the cart, the STOP state is reachable from any of the other states via user input.

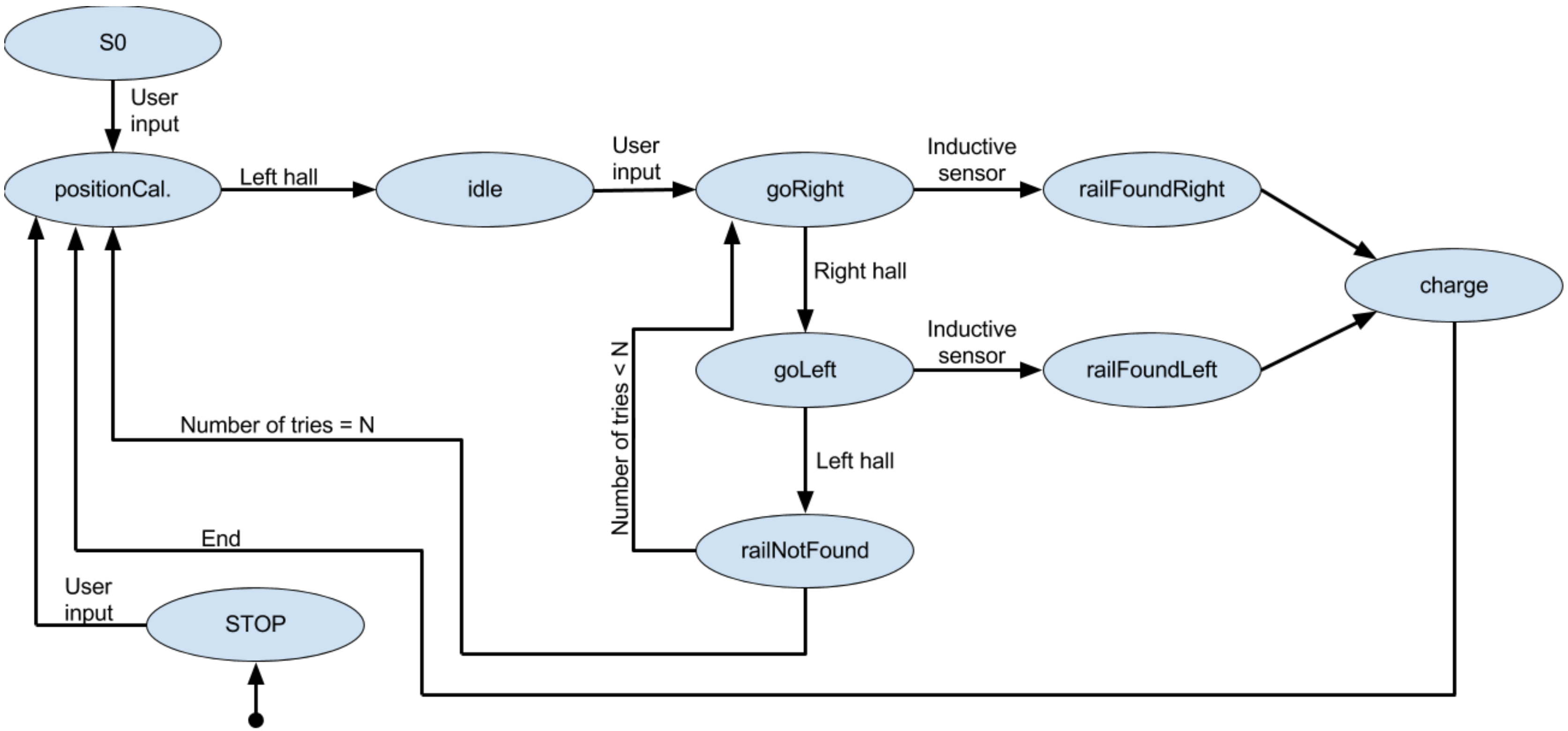


Figure 28: A graphical representation of the software used in the project.

State	**Output**
S0	HPU, brake
positionCal	HPU, left
idle	HPU, brake
goRight	LPD, right
goLeft	LPD, left
railNotFound	LPD, brake
railFoundRight	HPD, brake
railFoundLeft	HPD, brake
STOP	HPU, brake

Table 1: The states and their related output signals

Output	**Description**
HPU	High pressure up, pneumatically raises the pick up
HPD	Pushes the pick up down with a enough force to make contact with the rail
LPD	Low pressure down, lowers the pick up with a small force
left	Moves the cart to the left
right	Moves the cart to the right
brake	Actively stops the cart by applying voltage to both terminals of the motor

Table 2: Description of outputs

Triggering condition	**Description**
User input	Triggers on button presses
Left hall	Triggered upon reaching left limit
Right hall	Triggered upon reaching right limit
Inductive sensor	An inductive proximity sensor indicating that the rail has been detected
N	The number of tries to find the rail the system makes before giving up

Table 3: Descriptions of triggering conditions

4.4 Components manufactured during the project

All schematics of the manufactured parts can be found in appendix G.

4.4.1 Box

The box which contains the motor and control system consists of a $1.5mm$ sheet of steel which has been cut, punched, bent and welded to achieve the desired form. The box is also fitted with turned steel rods on which the struts are hinged. In addition to this, four 3D-printed supports with bearings are glued to the walls of the box in which the shafts on which the gears which move the box are mounted. On the back side of the box a bracket which holds the pneumatic cylinder is mounted.

4.4.2 Struts

The struts which connect the contact with the box each consist of two turned steel collars which are hinged on the box and the contact and connected to each other with a threaded aluminum rod. The struts are hinged in a corresponding configuration on the box and the contact in order to keep the contact parallel with the box.

4.4.3 Contact insulation

The contact house is the part which encapsulates the contacts and acts as insulation from the rest of the structure. The contact insulation is made from Polyoxymethylene (POM) and was manufactured by milling and drilling a solid block of POM into the desired geometry. The design was made in plastic because of its insulating capabilities and ease of manufacture.

4.4.4 Contacts

The contacts are designed to be able to be damped against the contact surface and slightly angled along the X-axis. This offers a better chance of sufficient connection since the system can withstand more obstacles on the rail. The contacts are designed to be able to tilt 2.86° around the X-axis.

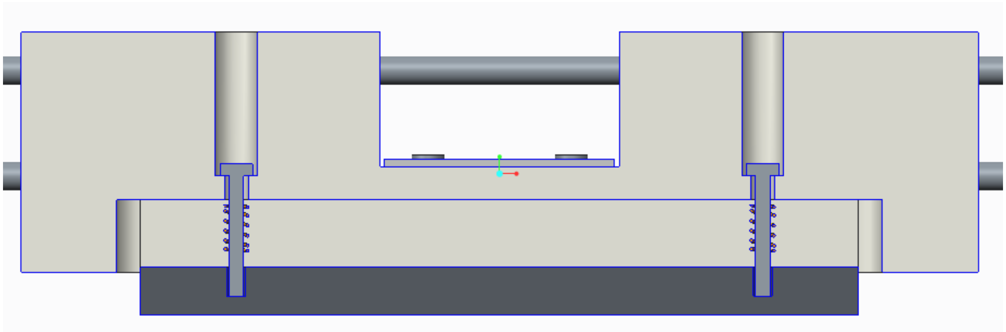


Figure 29: A cross section of the contact surface showing the contact together with its springs

4.5 Overview

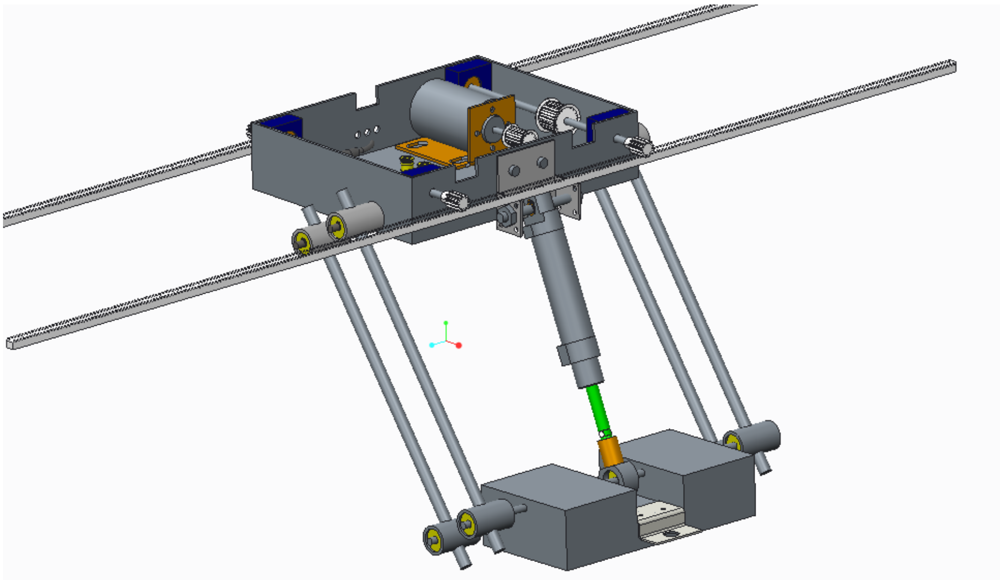


Figure 30: The final design in charging position

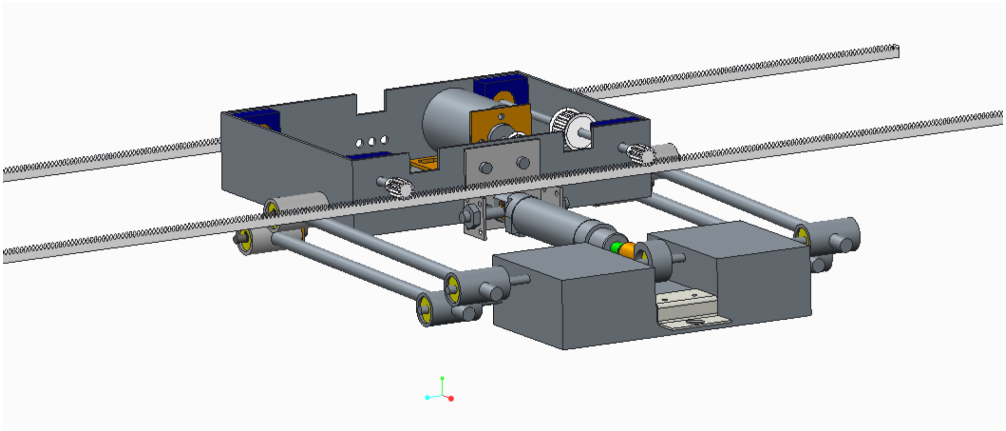


Figure 31: The final design in upward position

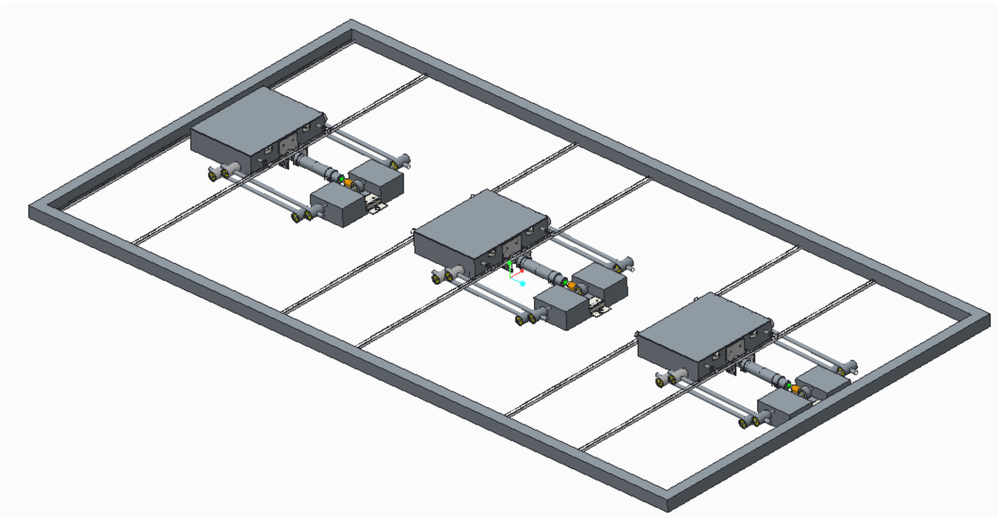


Figure 32: Finished design

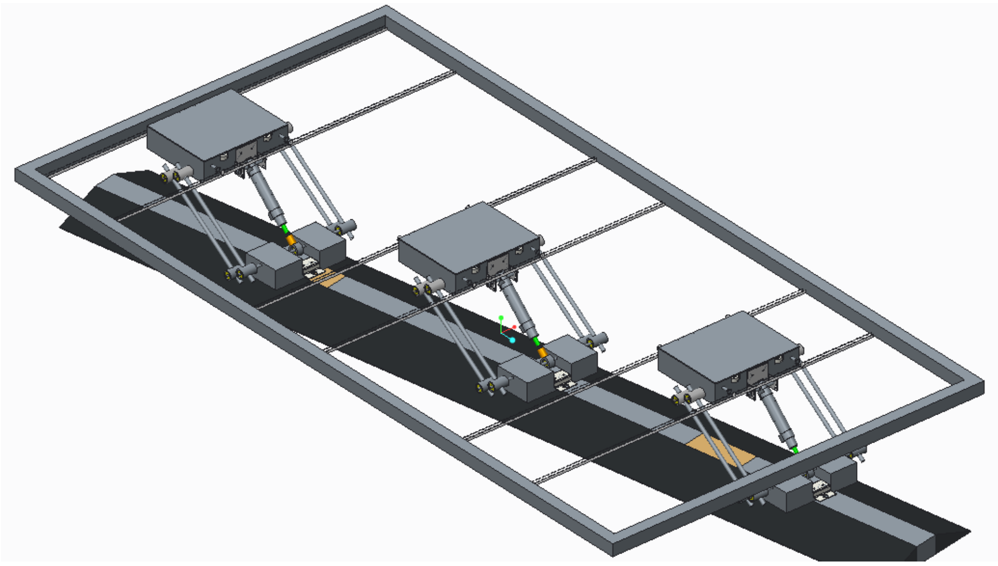


Figure 33: Finished design with ERS

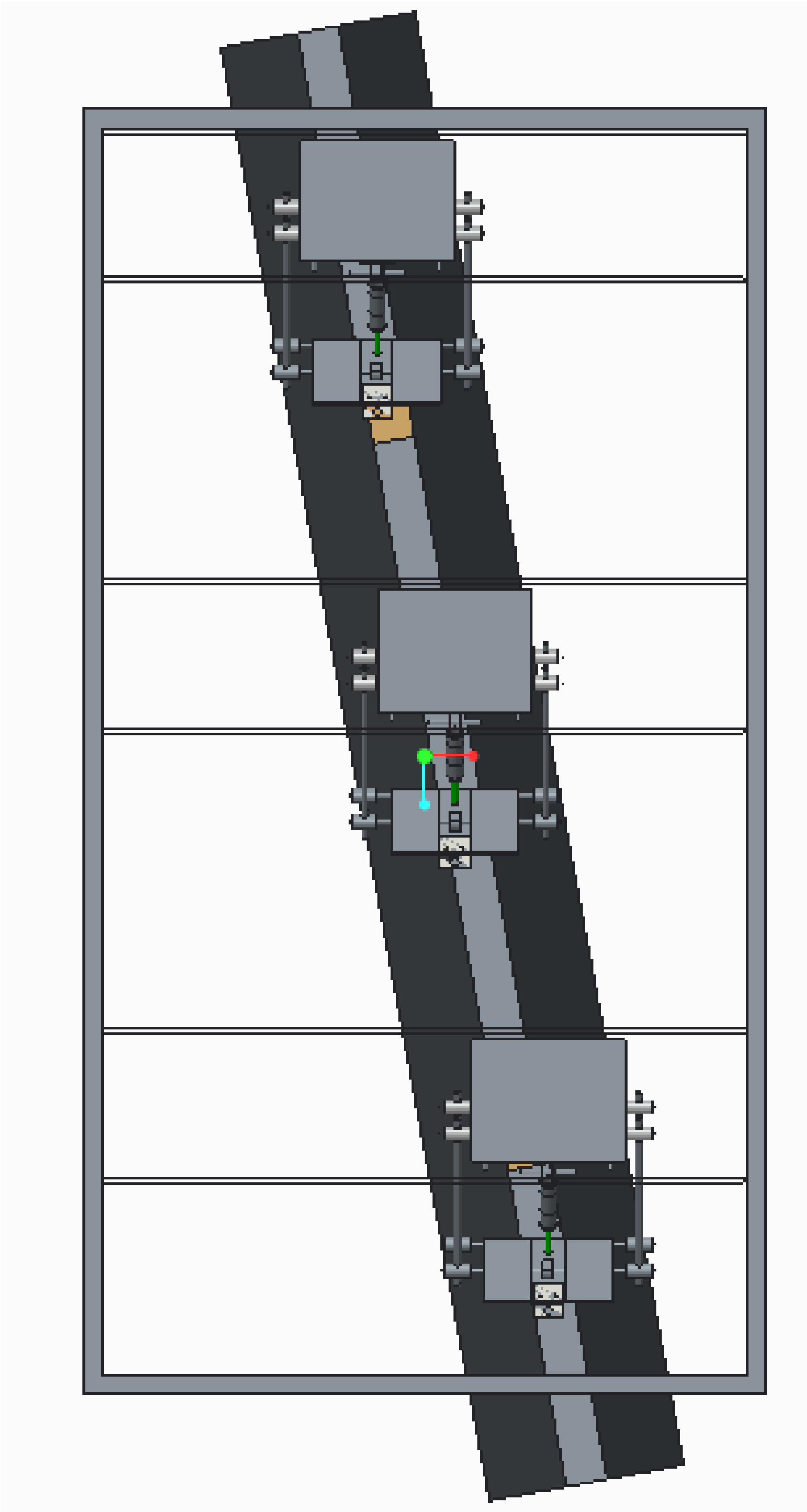


Figure 34: Finished design with ERS seen from above

Figure 35: Finished design with ERS seen as a rendered image mounted underneath a bus

5 Testing and verification

Since the project was scaled down, certain parameters could not be tested. Tests were done to assess the average speed in the X-direction, linear acceleration in the X-direction, resistance between the contact and ERS and that the contacts are isolated from the rest of the cart. Other parameters were disregarded since there are no purpose in testing them on this scaled down version of the system. These include average speed and acceleration along the Z-direction, number of contacts, rotational movement along the Z-axis, electrical capacity of charging cables, pick up position measurement resolution and temperature due to of charging.

5.0.1 Method

The testing and verification methods were altered from the initial idea of testing the system against each and every one of the specifications on one test setup. This was not possible since a total verification against the specifications was based on the assumption that a full scale prototype was to be built. Instead more general tests were made on the overall system on one larger setup and the subsystems were tested individually on setups of their own. All of the tests were made in a lab environment.

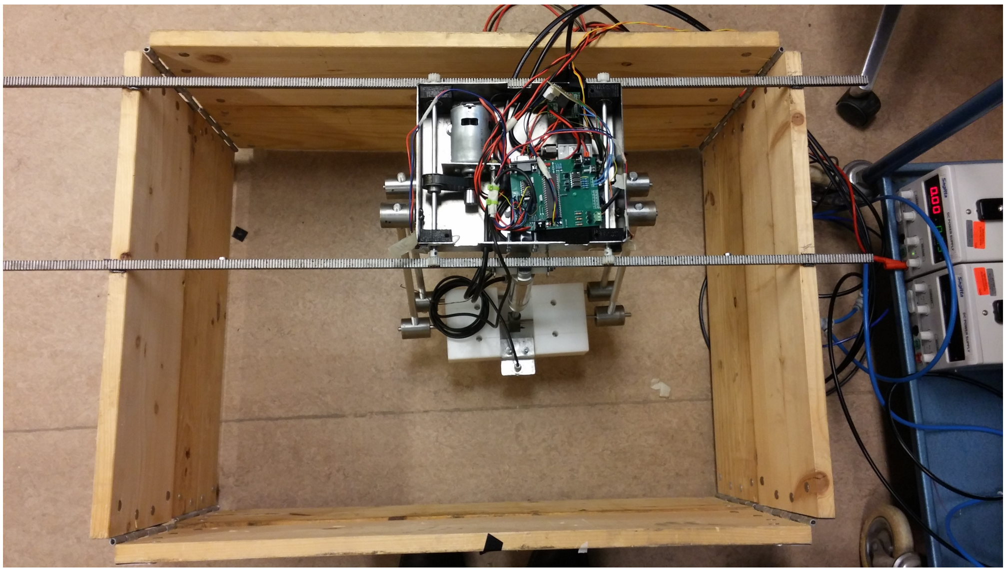


Figure 36: The final design mounted on the larger test setup.

The larger setup mostly used for testing the functionality of the overall system was made by using wooden pallet collars with the racks suspend on the edges of the topmost pallet collar. This setup is shown in figure 36. With this setup it is possible to do a full position calibration and charge movement test as the state machine in figure 28 describes. The individual subsystem tests were carried out by disassembling parts from the device and test them once they were off.

On the larger test setup a total system functionality test was performed by simply testing each movement and action the system was to perform during a normal charge. For the test to be successful each action in the state machine must be performed at the right time and give the right signals when it was in certain states. The horizontal speed was established by simply letting the cart move from one reference point to another as fast as it could and measure the time it took. To get a precise result this test was performed three times and the average speed was considered as the verified speed. From this data the linear acceleration could be calculated as well.

By removing the contact insulation the contacts was tested by using the specified 5 KPa pressure against a metal surface that would simulate the ERS. The voltage drop over the contact was measured at different constant currents. A test series of eight different currents were used. This test was performed by the use of digital multimeters and a general purpose DC output power supply. The test was made using $2Kg$ weights on top of the contact house that would simulate the cylinder pressing down on the contact against the ERS. Tests were also performed when the contact house stood on top of the ERS without any added weight. The tests of the contact is shown in figure 37. A second set of test were also carried out where the simulated ERS was covered in a thin coating of dirt.

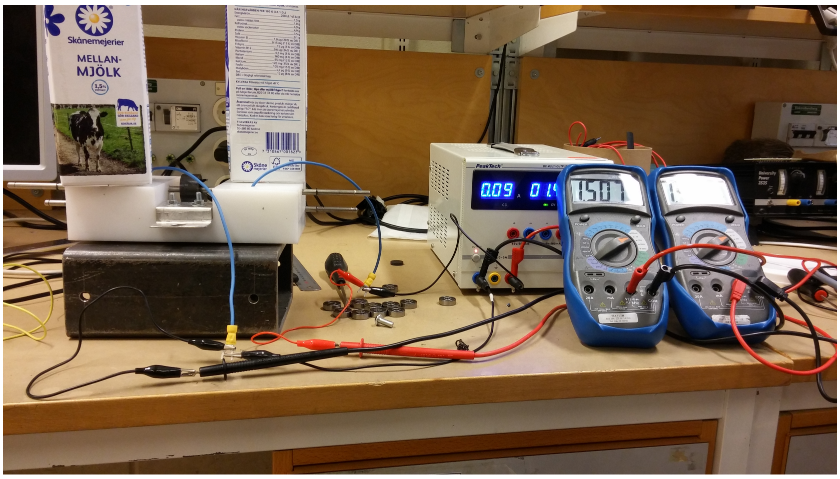


Figure 37: Test of the contact connection capability with added weights to get sufficient working pressure against the used metal surface

6 Results

Description of the achieved results in relation to the expected results.

6.1 Overview

In figure 38 a view of the disassembled system is presented, the components numbered are as follows:

1. The box described in section 4.4.1.
2. The struts described in section 4.4.2.
3. The 100 mm stroke, double acting, pneumatic cylinder mentioned in section 4.2.
4. The contact house described in section 4.4.3.
5. Inductive proximity sensor mentioned in section 4.3.2.
6. Pneumatic 5/3 valve for controlling the air flow to the cylinder.
7. Drive shafts with associated pulley.
8. For Johnson 775 motor mounted in a bracket, mentioned in section 4.3.1.
9. Incremental encoder mentioned in section 4.3.2.

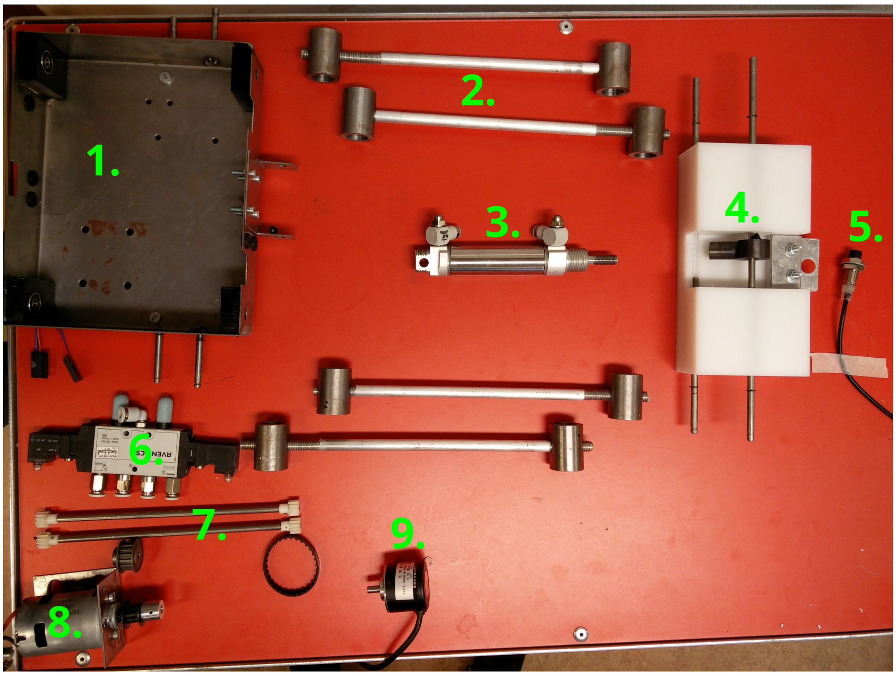


Figure 38: Disassembled view

6.1.1 End result of built design

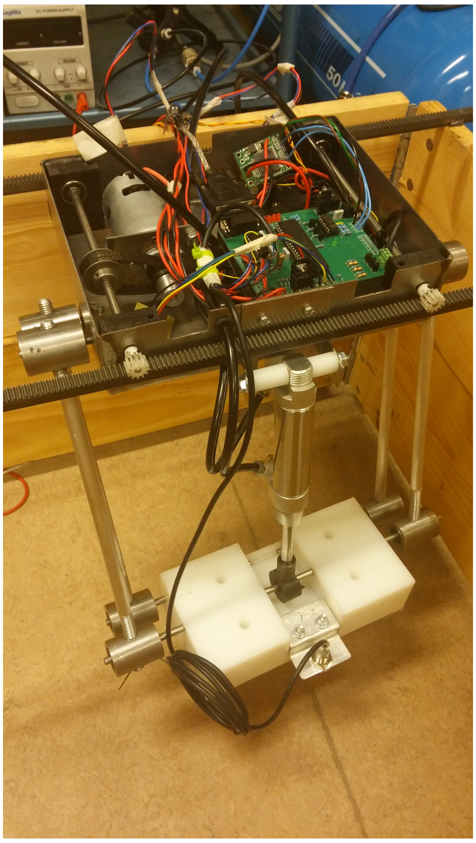


Figure 39: Built design when it is in its charging position

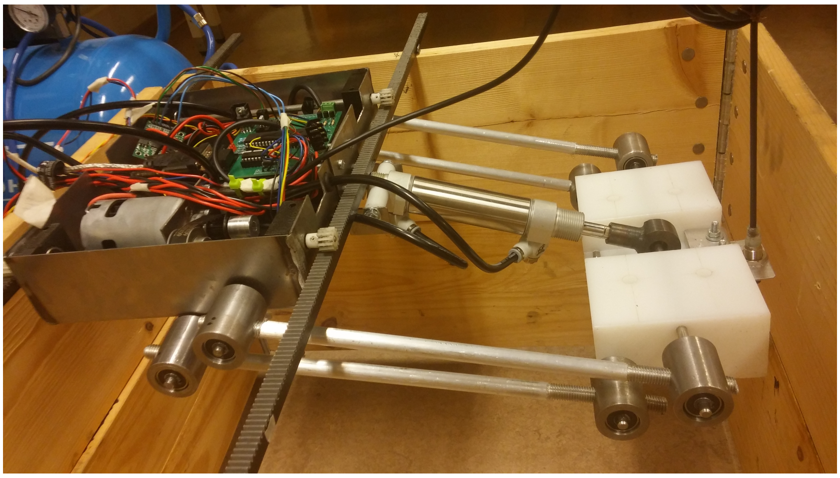


Figure 40: Built design when it is in its upright position

6.2 Results compared to specifications

Criteria	Specified value	Achieved value	
Linear movement Z-axis	150 - 400 mm	209	✓
Linear movement X-axis	0 - 500 mm	N/A	N/A
Width (X-axis)	60 - 500 mm	335	✓
Length (Y-axis)	140 - 300 mm	500	×
Height (folded)	10 - 50 mm	244	×
Distance between contacts	400 - 700 mm	N/A	N/A
Number of contacts	≥ 3	N/A	N/A
Contact tilt (along X-axis)	$1° < x < 5°$	2.86°	✓
Contact length	20 - 50 mm	15 mm	×
Contact width	50 - 400 mm	150 mm	✓
Contact height	5 - 15 mm	10 mm	✓
Time before contact is achieved after stop	0,5 - 2 s	4 s	×
Achievable contact pressure	$\geq 5kPa$	$\geq$ 5 kPa	✓
Linear speed Z-axis	$\geq$ 700 mm/s	$\geq$ 700 mm/s	✓
Linear speed X-axis	$\geq$ 633 mm/s	201 mm/s	×
Linear acceleration X- and Z-axis	1.49 m/s^2	1,14 m/s^2	×
Rotational movement Z-axis	$\leq 49\ °$	N/A	N/A
Resistance between contact and ERS	$\leq 22\ m\Omega$	50 $m\Omega$	×
Pick up position measurement resolution	$\leq$ 1 cm	N/A	N/A
Cables connecting to the vehicle capable of	300 A, 600V	N/A	N/A
Connection measured with resolution	$\leq 1\ m\Omega$	N/A	N/A
Temperature because of charging	$\leq$ 70°C	N/A	N/A
The pick up is isolated from the chassis	Yes	Yes	✓

Table 4: Results compared to specifications

6.3 Design

A description of the resulting design of each part of the project divided into their respective fields.

6.3.1 Mechanical

In essence the resulting mechanical design is functioning as intended, although there are some aspects which could be improved.

Many of the components involved are made of steel, and to a lesser extent aluminium as opposed to for example plastic. This makes the design quite mechanically rigid which is desirable as it reduces strain on wires, ensures a better contact for the driving gears and allows the motor and drive shaft to have a fixed relative distance which is necessary for the cog belt to function properly. The mechanical rigidity is also of importance as there are several sensors which interact with external sources, it is therefore necessary to know the positions of the sensors in order to be certain of where the external interactions occur. In addition the sensors have a limited sensing distance and were they to be displaced they might not be able to detect properly.

The contact itself, apart from the steel conductive surfaces, consists mainly of polyoxymethylene this is done with weight and insulation in mind. The contact, however, is not as light as would be desirable in order for the pneumatic cylinder to function optimally as it is unnecessarily large due to a desire to keep its complexity of manufacture low. The way this effects the cylinders operation is that it warrants a higher operating pressure in the pneumatic system which leads to a quite jerky actuation of the cylinder, this jerkiness can be mitigated to a degree by adjusting the dual flow control valve to allow for a smoother actuation. The conductive surfaces has been designed to be able to tilt along the X-axis. The geometry of the holes for the screws that hold the steel conductive surfaces and its springs would not allow more than $2.86°$ of tilt.

6.3.2 Electrical

The electrical side of the project consists mainly of the PCB, the solenoids as well as the motor and its peripheral components. Even though not all the functionality that was intended for the electrical system was implemented, the parts that were implemented function as intended. As can be seen from the resulting electrical system, priority was given to the components themselves and less effort was devoted to their interconnections as well as their external connections. The effect of this on the end result is a sort of disarray of wires which can be seen in figure 41.

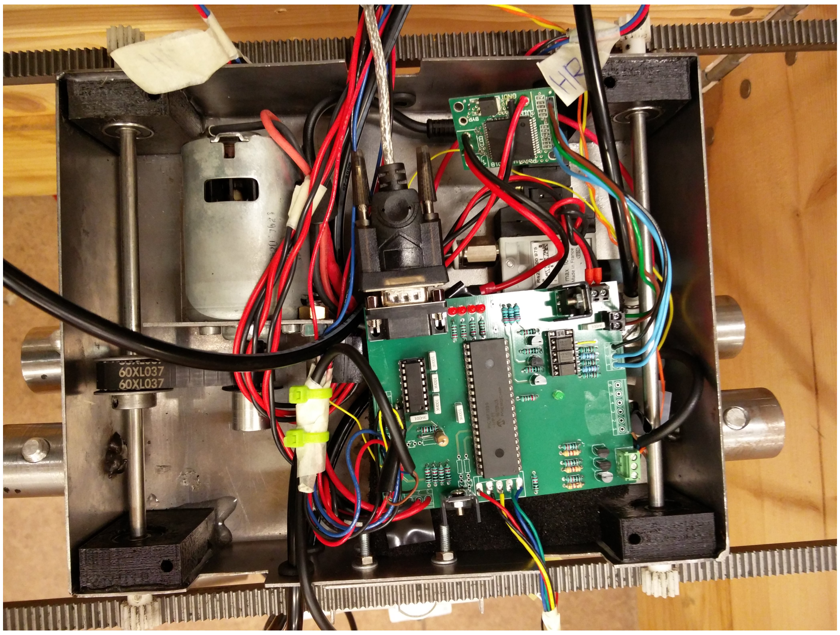


Figure 41: Interior of the cart as seen from above.

6.3.3 Software

The software as described in section 4.3.4 is identical to the final software so further description is superfluous in this case. The software as a whole is perceived to be very responsive in regard to external inputs such as sensor triggers and user input. It seems that the interrupt service routine upon which the software is based is written sufficiently short to not be a problem regarding responsiveness. The software is, in short, working as intended.

6.4 Performance

The quality achieved by the system while performing its different tasks.

6.4.1 Positioning

The positioning system in regards of the sideways motion gave satisfying results. As mentioned in section 4.3.2 the distance the detection distance for the Hall effect sensors is 8 mm. By using ordinary general purpose permanent magnets this detection distance was verified by testing the sensors on the test setup.

The velocity of the cart was evaluated in a few trial runs and is displayed in table 5.

Time [s]	**Distance** [mm]	**Average velocity** [mm/s]
1,32	265	201
2,07	362	175
1,83	349	191

Table 5: Result of the velocity test

The result of the velocity test indicate that the average velocity decreases when evaluated over longer distances. This may be a result of the omission of some sort of system to ensure a correct distance between the box and the rack. This results in that the cart skews during operation and comes into contact with the rack which slows it down to some extent. This indicates that the velocity, assuming correct distance to the rack, would be closer to the velocity of the trial conducted over 265 mm. The PWM signal controlling the velocity of the motor is limited in the software to a duty cycle ratio of around 85% due to limitations in the optocouplers (PC817), at the frequency the PWM is operating on the optocouplers handle duty cycle ratios above this poorly.

6.4.2 Cleaning

The cleaning was initially intended to be done with brushes mounted on the contact insulation which would brush off any contaminants as the cart moved to contact over the ERS (the cleaning concept mentioned can be seen in figure 12) but because of lack of time and funds the cleaning concept was never implemented. The cleaning principle was however tested by using the same cleaning pattern which the cleaning system would have used but with a simple brush operated by hand. When dirt and gravel was applied on the test metal surface shown in figure 37 the cleaning concept proved not to be sufficient to provide enough contact with the ERS when the test was performed.

6.4.3 Connection capability

In this section the results from the tests described in section 5.0.1 regarding the connection between the ERS and the contact are presented. As figure 42 and 43 shows resistance between the ERS and the contact is around $50m\Omega$.

There are not much difference when contacting the ERS using high or low pressure. This shows that contact pressure does not do very much for the charging contact quality. Except for tests using 5 and 6 A without dirt on the ERS the results are very similar. Tests using less than 2 A should be considered as failed because the results are not reliable. In figure 43 the graph shows that the result for these tests have a negative resistance, which is not possible. In section 7.2 a brief discussion is made regarding what can be done to improve the contact quality using different texture on the contact surface.

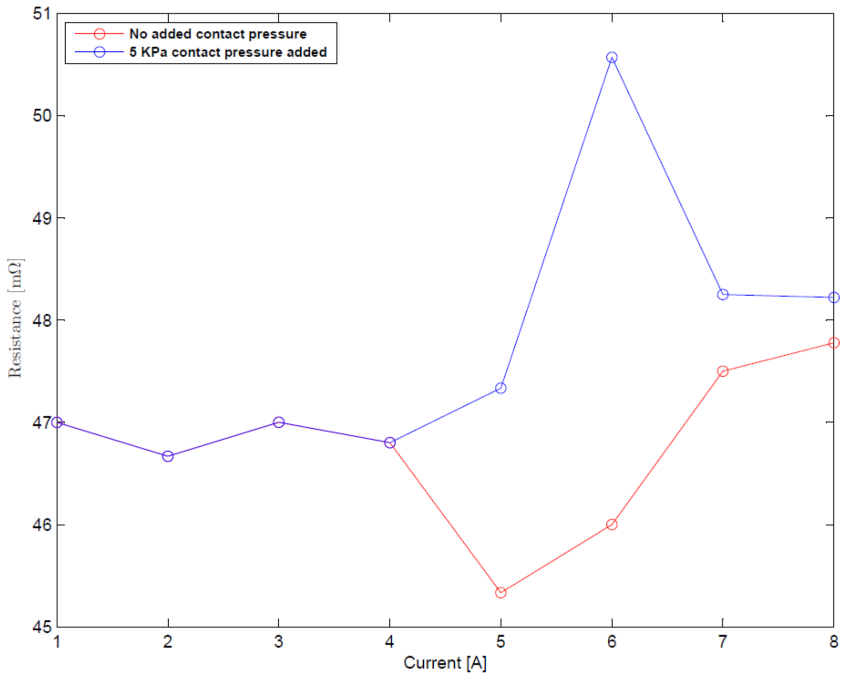


Figure 42: Resistance between the contact and ERS without dirt on the ERS.

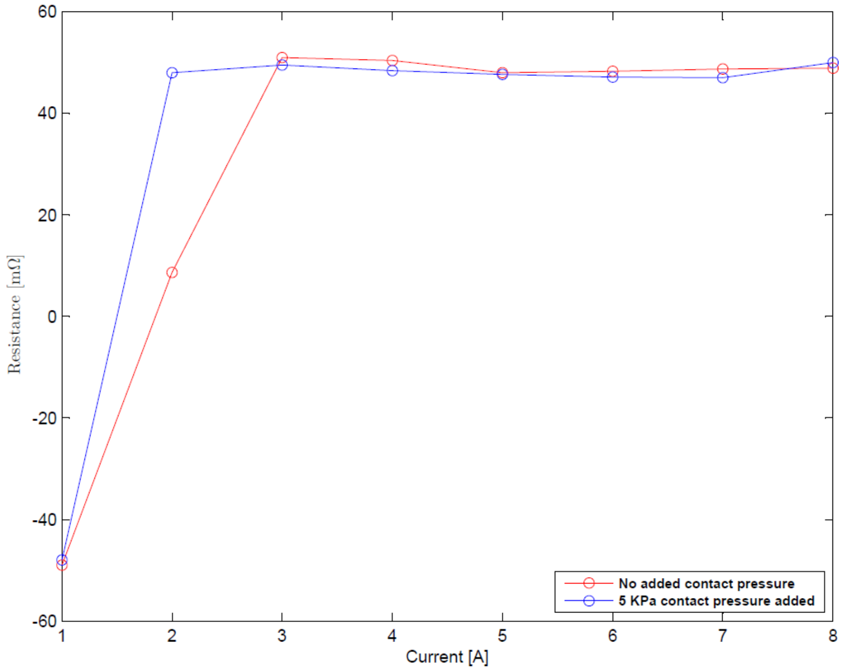


Figure 43: Resistance between the contact and ERS with dirt on the ERS.

7 Discussion and conclusions

This section describes which challenges presented themselves during the course of this project. Future work and what parts and knowledge that can be used from the result of his project when ElOnRoad develops a new automated contact. The section is ended with a brief conclusion of the project.

7.1 Trade-offs

During the course of this project there has extensive trade-offs has been made in order to keep the cost low and in order to be able to reach a conclusion within a reasonable time span.

This is quite prominent throughout the entirety of the components which has been manufactured in the project, as these are all made of salvaged materials to some extent. This has to a great impact on the design of several of the components as they are designed with what materials are available in mind. The design of the contact insulation is largely based on the fact that a brick of polyoxymethylene was available. The insulation's size could have been reduced, but as it was made in one of the later stages of the project and thus other tasks were deemed more pressing.

A similar point can be made regarding the struts which are made of steel collets linked together by threaded aluminium rods. This is in no respect an optimal solution as the threads gives the aluminum rods room to rotate a bit which causes the pick up to flex, however these materials were the most readily available and as a consequence the cheapest alternative.

Some trade offs were of a more omissive nature as was the case of the incremental encoder that was intended to be used in order to verify and control the position of the cart. However since the brushes were not implemented there was no need for precise position control as this was meant to be used mainly when brushing in order to know how far to move the cart. Thus, the encoder got a low priority and was, in the end, omitted entirely. All the trade-offs are shown if one would compare the requirements with the specifications. The requirements are demands that a fully working product should sustain while the specifications are this project's objectives.

7.2 Improvements

The pick up would likely had been more rigid and less prone to flex if the connecting rods instead consisted of pipes welded or soldered to the collets, although compelling this design was left untested due to time considerations. Another approach could had been to use carbon fiber tubes and plastic collets similar to the ones in figure 44, however this approach was deemed too expensive.

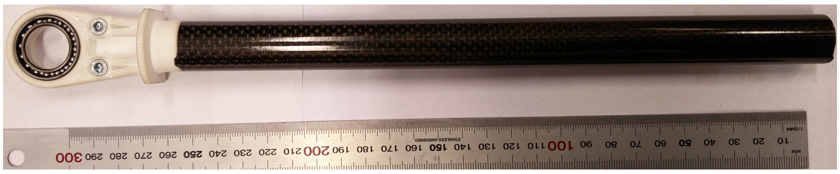


Figure 44: Carbon fiber tube with a nylon collet.

As is shown in figure 42 and 43 there is no discernible difference between any of the cases of dirt/no dirt pressure/no pressure. This is in all likelihood due to the contact surface being smooth as opposed to having some sort of texture. As such the contact is unable to properly utilize the added pressure to make a more solid connection with the ERS. This also led to there having to be a very small amount of dirt on the ERS during the test in order for the contact to be able to connect at all which could explain the lack of difference between the case where there is dirt on the ERS compared to when there is no dirt. In order to make better use of the pressure supplied by the pneumatic cylinder as well as to have a more dirt resistant contactation some sort of surface texture should be added to the contact surface. One example of this texture could look like is shown in figure 45.

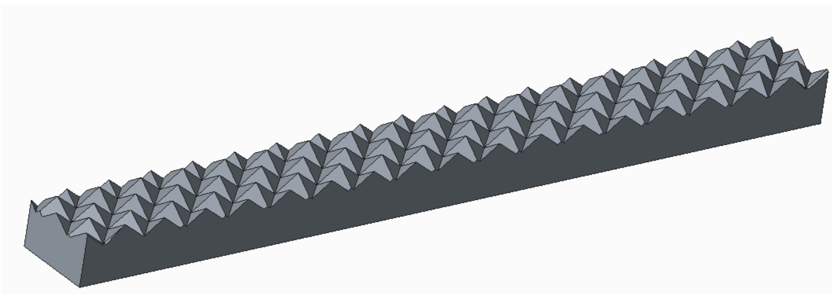


Figure 45: Suggestion of contact texture

In the case of the cabling there are quite a bit of room for improvement, as mentioned in section 6.3.2 as it in its current state is quite cluttered. An approach that in an earlier stage of design takes into account the different connections that need to be made and plans the usage of space accordingly is advisable.

An alteration which potentially could decrease the height of the system in its folded state, as well as help smooth its vertical movement would be the addition of torsion springs. These could be added to the struts in order to apply torque to help pull the pick up upwards.

7.3 Future work

This section describes what can be done for future development of the concept.

7.3.1 Safety functions

In order for a application similar to the one described in this project to be viable, great consideration will have to be taken to the safety of both users and surroundings. Since the power transmission from the ERS to the vehicle is intended to be large, it is critical that proper precautions are in place to ensure that at no point will a person or object be able to come into contact with the energized rail. This issue could be mitigated by the use of, for example, ultrasonic sensors monitoring the vehicle's perimeter and shutting of the ERS in case of a breach, as well as by physically covering the electrified parts of the ERS. In addition there may also be a potential hazard as the vehicle leaves the ERS at which point the ERS will be exposed and could potentially be hot. In order to minimize the heat it is important to verify that the contaction between the ERS and the vehicle is of a sufficiently resistance.

There should also be some way for the pick up and cart to measure their respective loads in order to be able to stop, should they come into contact with something in their surrounding.

7.3.2 Full prototype

To fully verify if this concept could achieve all of the said requirements a full scale prototype would have to be built. A full prototype would need two more identical contact devices, a frame for suspension underneath a vehicle, cables with electrical capabilities to sustain the specified voltage and current, position control and software that makes it possible for the contact devices to interact with each other.

7.3.3 Speed and positioning control

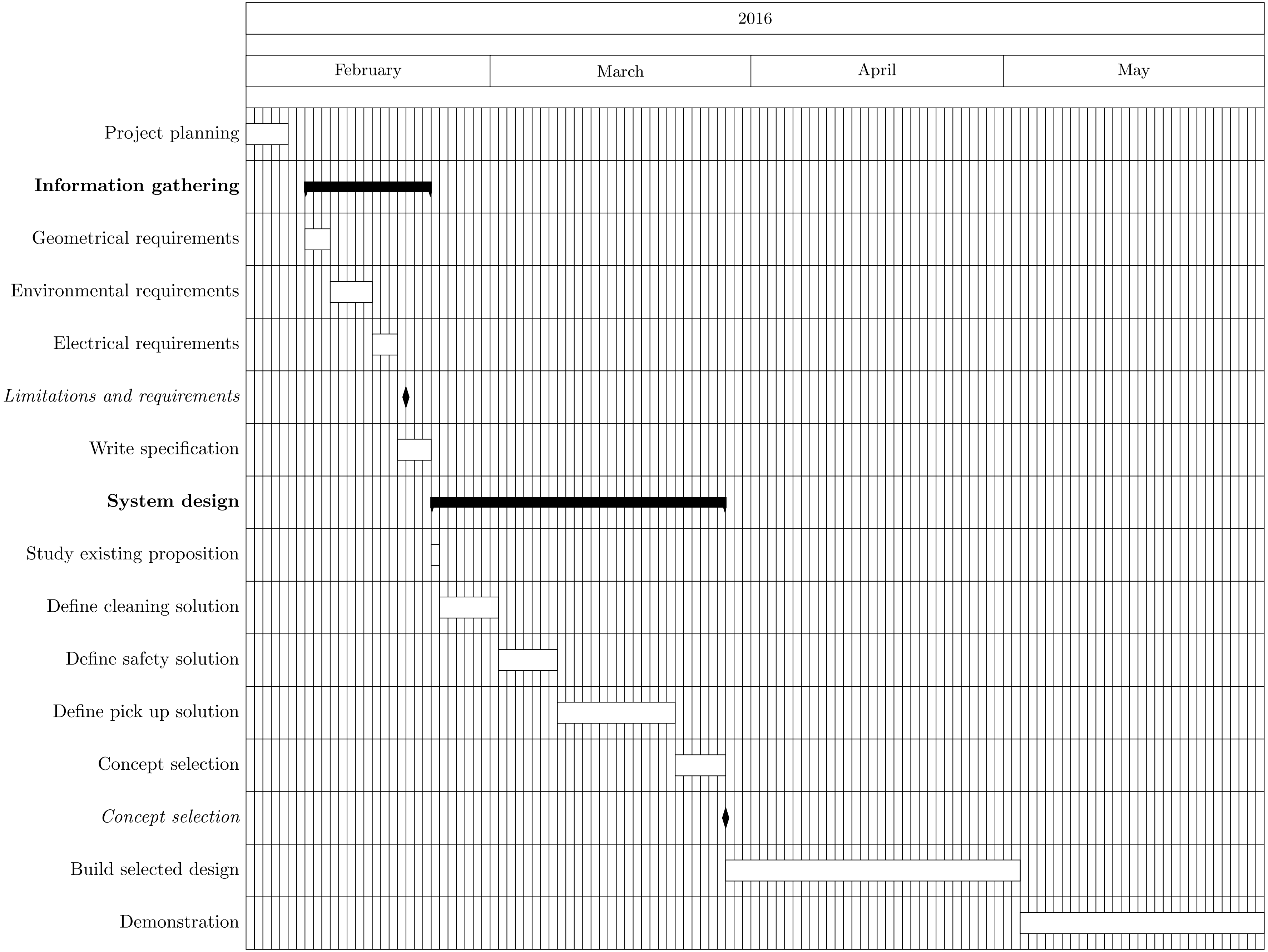
Speed and position control are not crucial in this project since there are only one contact device. If there would have been more than one contact device position control would be needed for the rotation along the Z-axis specification. With speed control it would probably be possible to minimize the time for one contact cycle. The incremental encoder which was acquired for the project could achieve this with modifications to the software.

7.4 Conclusions

The project did not achieve all of the specifications but still gave valuable knowledge of how an automated charging system could be designed. With more time and more funds most of the requirements could probably be achieved using this concept. Certain requirements however could probably not be achieved if not special and very expensive parts would be used. The geometrical requirement of a folded height of $50mm$ would be one major problem using this approach. This is due to the size of the motor that would have to be much smaller and the small down angle the contact device has when it is in its upright position. This down angle is very difficult to decrease since this is directly proportional to the leverage the cylinder has to be able to make the vertical movement of the pick up. If the cylinder is parallel with the cart it will not be able to apply any force in the Z-direction.

Certain specifications are met using this concept and more specifications could probably have been as well if other parts had been used. This shows that there are ideas and subsystems from the concept that can be used in the future. There are a lot of challenges when a complex product like this is to be implemented in form of a prototype or a product ready for launch. Hopefully this project can be used for future reference when ElOnRoad develops their automated contact for either static or dynamic charging.

Appendix A - Project plan


2016
February
March
April
May
Project planning
Information gathering
Geometrical requirements
Environmental requirements
Electrical requirements
Limitations and requirements
Write specification
System design
Study existing proposition
Define cleaning solution
Define safety solution
Define pick up solution
Concept selection
Concept selection
Build selected design
Demonstration

Appendix B - Requirements

Geometrical/physical requirements

- (At least) 3 DoF movement of pick up. Linear X, linear and rotational Z.
- Should work for a wide range of heights.
- Should work for different vehicles.
- Dimension of pick up must match dimension of rail.
- Pick up must have at least three contacts.
- The contact pressure should be adjustable or damped against rail.
- The contact should be able to tilt along the X-axis.
- The control unit must fit on the pick up.
- The contactation must be fast enough.

Environmental requirements

- The rail need to be free from dirt, gravel, snow and any other type of object that might interfere with the connection.
- The power must be switched off if any object is or moved under the vehicle during the charging process.
- The power must be switched of when there is interference with the contact
- There should be some way to determine whether the pick up is positioned correctly.
- The temperature in the contact and it's surrounding cannot be too hot

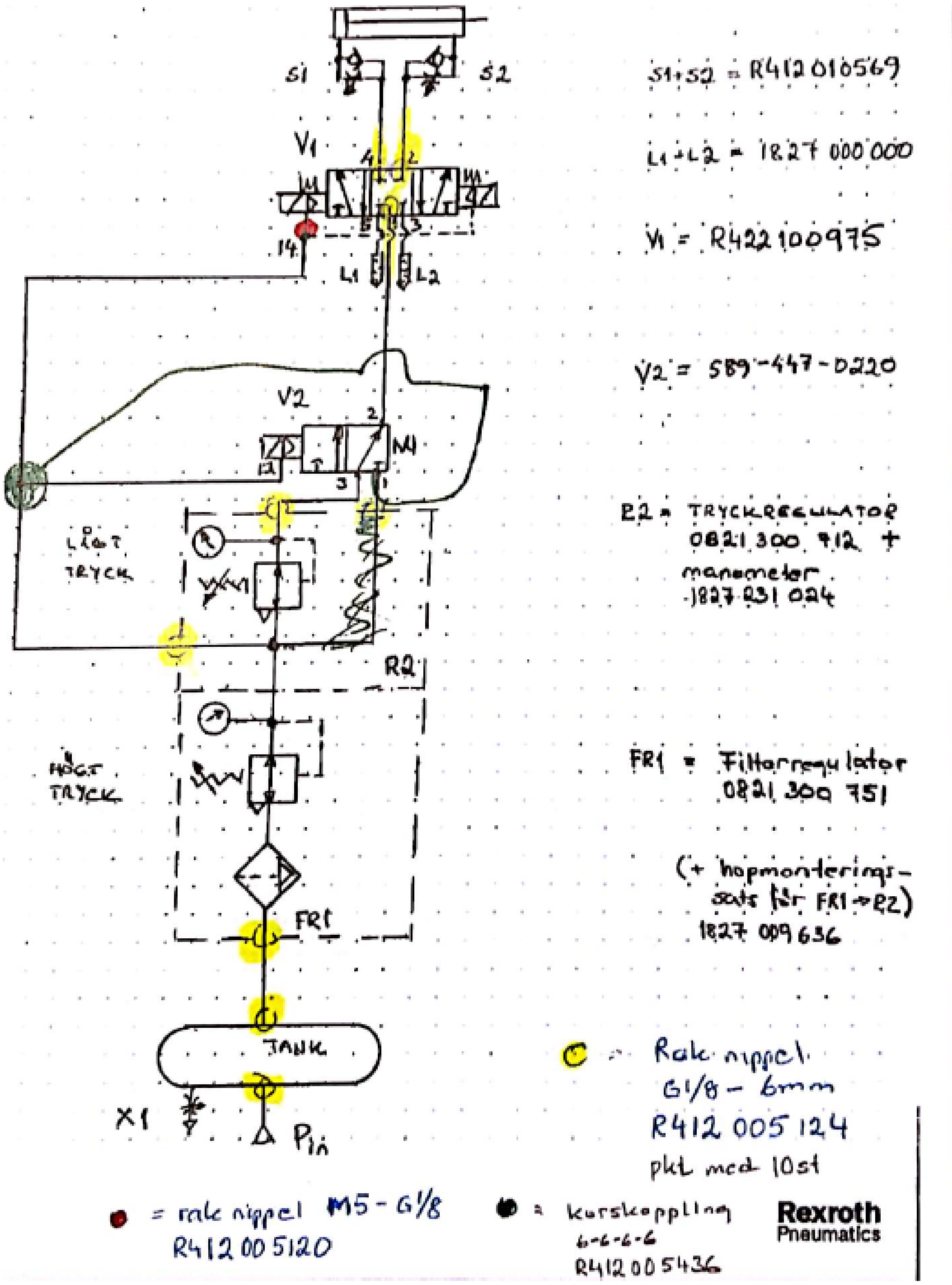
Electrical requirements

- The cables connecting to the vehicle should be capable of 300A, 600V.
- The pick up is isolated from the chassis.
- The system should in some way verify that the connection is sufficient.

Appendix C - Specifications

- Linear movement Z-axis(perpendicular to ground): $150mm < x < 400mm$
- Linear movement X-axis(across the vehicle): $0 < x < 500mm$
- Width: $60mm < x < 500mm$
- Length: $140mm < x < 300mm$
- Height (folded): $10mm < x < 50mm$
- Distance between contacts: $400mm < x < 700mm$
- Number of contacts: $x \geq 3$
- Contact tilt (along x-axis): $1° < x < 5°$
- Contact length: $20mm < x < 50mm$
- Contact width: $50mm < x < 400mm$
- Contact height: $5mm < x < 15mm$
- Time before contact is achieved after stop: $0,5 < x < 2s$
- Achievable contact pressure: $\geq 5kPa$
- Linear speed Z-axis: $x \geq 700mm/s$
- Linear speed X-axis: $x > 633mm/s$
- Linear acceleration Z- and X-axis: $1.49m^2/s$
- Rotational movement Z-axis: $x \leq 49°$
- Resistance in the contact: $x < 2.2m\Omega$
- The temperature because of the charging cannot exceed: 70°
- Pick up position measurement resolution: $x \leq 1cm$
- The cables connecting to the vehicle should be capable of: 300 A, 600 V.
- The connection is measured with a resolution of: $1m\Omega$
- The pick up is isolated from the chassis.

Appendix D - Pneumatic schematic



Appendix E - main.c

```
// PIC16F1939 Configuration Bit Settings
// 'C' source line config statements
#define _XTAL_FREQ 4000000
#define HALL_L  IOCBFbits.IOCBF1
#define HALL_R  IOCBFbits.IOCBF2
#define INDUCTIVE   IOCBFbits.IOCBF0

#define A LATCbits.LATC3
#define B LATDbits.LATD0

#define LED1 LATCbits.LATC4
#define LED2 LATDbits.LATD3
#define LED3 LATDbits.LATD2
#define LED4 LATCbits.LATC5

#define threeTwo LATAbits.LATA2
#define fiveThree_1 LATAbits.LATA1
#define fiveThree_2 LATAbits.LATA0

//Number of attempts to find the ERS
#define N 2

//States
#define S0              0
#define positionCal     1
#define w8              2
#define goRight         3
#define goLeft          4
#define railFoundRight  5
#define railFoundLeft   6
#define railNotFound    7
#define charge          8
#define STOP            9

#include <xc.h>
#include <pic16f1939.h>
#include "uart.h"

// #pragma config statements should precede project file includes.
// Use project enums instead of #define for ON and OFF.

// CONFIG1
#pragma config FOSC = INTOSC    // Oscillator Selection (INTOSC oscillator:
     I/O function on CLKIN pin)
#pragma config WDTE = OFF       // Watchdog Timer Enable (WDT disabled)
#pragma config PWRTE = OFF      // Power-up Timer Enable (PWRT disabled)
#pragma config MCLRE = OFF      // MCLR Pin Function Select (MCLR/VPP pin
    function is digital input)
#pragma config CP = OFF         // Flash Program Memory Code Protection (
    Program memory code protection is disabled)
```

```
#pragma config CPD = OFF        // Data Memory Code Protection (Data memory
     code protection is disabled)
#pragma config BOREN = OFF      // Brown-out Reset Enable (Brown-out Reset
    disabled)
#pragma config CLKOUTEN = ON   // Clock Out Enable (CLKOUT function is
    disabled. I/O or oscillator function on the CLKOUT pin)
#pragma config IESO = ON        // Internal/External Switchover (Internal/
    External Switchover mode is enabled)
#pragma config FCMEN = ON       // Fail-Safe Clock Monitor Enable (Fail-
    Safe Clock Monitor is enabled)

// CONFIG2
#pragma config WRT = OFF        // Flash Memory Self-Write Protection (
    Write protection off)
#pragma config VCAPEN = OFF     // Voltage Regulator Capacitor Enable (All
    VCAP pin functionality is disabled)
#pragma config PLLEN = OFF       // PLL Enable (4x PLL disabled)
#pragma config STVREN = ON      // Stack Overflow/Underflow Reset Enable (
    Stack Overflow or Underflow will cause a Reset)
#pragma config BORV = LO        // Brown-out Reset Voltage Selection (Brown
    -out Reset Voltage (Vbor), low trip point selected.)
#pragma config LVP = OFF         // Low-Voltage Programming Enable (Low-
    voltage programming enabled)

volatile double duty = 0;       //Duty cycle ratio
volatile unsigned char data;    //Serial input data
unsigned short temp;            //Variable used in calculations
unsigned short K;               //Constant related to setting duty cycle
    ratio
volatile unsigned char STATE;
volatile unsigned char tries = 0;//Maximum number of attempts to find ERS
```

```
void IO_Setup(void){
    //Solenoid control outputs
    TRISAbits.TRISA0 = 0;
    TRISAbits.TRISA1 = 0;
    TRISAbits.TRISA2 = 0;
    ANSELAbits.ANSA0 = 0;
    ANSELAbits.ANSA1 = 0;
    ANSELAbits.ANSA2 = 0;

    //Sensor input pins
    TRISBbits.TRISB0 = 1;
    TRISBbits.TRISB1 = 1;
    TRISBbits.TRISB2 = 1;
    ANSELBbits.ANSB0 = 0;
    ANSELBbits.ANSB1 = 0;
    ANSELBbits.ANSB2 = 0;

    //Motor control pins
    TRISCbits.TRISC3 = 0;
    TRISDbits.TRISD0 = 0;
    ANSELDbits.ANSD0 = 0;

    //LED outputs
    TRISCbits.TRISC4 = 0;
    TRISCbits.TRISC5 = 0;
    TRISDbits.TRISD2 = 0;
    TRISDbits.TRISD3 = 0;
}

//High pressure, up
void HPU(){

    threeTwo = 1;
    fiveThree_1 = 1;
    fiveThree_2 = 0;
}

//High pressure, down
void HPD(){

    threeTwo = 1;
    fiveThree_1 = 0;
    fiveThree_2 = 1;
}

//Low pressure, up
void LPU(){
    threeTwo = 0;
    fiveThree_1 = 1;
    fiveThree_2 = 0;
}
```

```c
//Low pressure, down
void LPD(){

    threeTwo = 0;
    fiveThree_1 = 0;
    fiveThree_2 = 1;
}

//Shut both openings in the 5/3 valve
void springMode(){
    threeTwo = 0;
    fiveThree_1 = 0;
    fiveThree_2 = 0;
}

//Sets the PWM duty cycle in order to regulate motor speed
void setPWM(double duty){
    temp = duty*K;
    CCPR4L = temp >> 2;
    CCP4CONbits.DC4B1 = temp >> 1;
    //CCP4CONbits.DC4B0 = temp; //Tenth bit of CCPR4L, unused as PR4 = 249
}

//Rotate the motor counter-clockwise
void left(){
    setPWM(duty);
    A = 1;
    B = 0;
}

//Rotate the motor clockwise
void right(){
    setPWM(duty);
    A = 0;
    B = 1;
}

//Stop the motor
void brake(){
    setPWM(duty);
    A = 1;
    B = 1;
}

//Apply no input to the motor
void freeRoll(){
    setPWM(0);
    A = 0;
    B = 0;
}
```

```
void InterruptSetup(void){
    RCIE = 1;
    PEIE = 1;

    //Interrupts generated on rising andfalling edges for the Hall sensors
        and on rising edges for the inductive sensor
    INTCONbits.IOCIE = 1;
    IOCBPbits.IOCBP0 = 1;
    IOCBNbits.IOCBN1 = 1;
    IOCBNbits.IOCBN2 = 1;
    IOCBPbits.IOCBP1 = 1;
    IOCBPbits.IOCBP2 = 1;


    INTCONbits.TMR0IE = 0; //timer0 interrupt, disabled

    //Resetting interrupt flags and enabling global interrupts
        IOCBF = 0;
        IOCIF = 0;
    GIE = 1;
}

//Setting up the timer for use with the PWM generation
void timerSetup(void){
    OPTION_REGbits.TMR0CS = 0;
    OPTION_REGbits.PSA = 0;
    OPTION_REGbits.PS0 = 1;
    OPTION_REGbits.PS1 = 1;
    OPTION_REGbits.PS2 = 1; //1:256 prescale => f=15625 Hz t= 64 us

}

void PWMSetup(void){
    TRISDbits.TRISD1 = 0;
    ANSELDbits.ANSD1 = 0;
    PR4 = 249;  //9 bit resolution PWM, period=(PRx+1)*4*TOSC*prescale,
        TOSC=1/FOSC=2.5*10^-7 s, PWMt = 1ms     PWM period = (PR2+1) *
        prescaler * Tcy = 1ms
    CCP4CONbits.CCP4M3 = 1;
    CCP4CONbits.CCP4M2 = 1;//PWM mode: PxA, PxC active-high; PxB, PxD
        active-high
    T2CONbits.T2CKPS0 = 0;
    T2CONbits.T2CKPS1 = 0;
    T2CONbits.TMR2ON = 1;
    K = 4*(PR4+1);
    CCPR4L=0;
    CCP4CONbits.DC4B1 = 0;
    CCP4CONbits.DC4B0 = 0;
}
```

```
void interrupt ISR(void){

    //Recieve data over the UART connection
    if(UART_Data_Ready()){
        data = (unsigned char)UART_Read();
        UART_Write(data);
    }

    //Write which hall sensor triggered on if it was a rising or falling
       edge on the seral port
    if(HALL_L){
        UART_Write('L');
        if(RB1 == 0){
            UART_Write('n');
            LED1 = 1;
        }else if(RB1 == 1){
        LED1 = 0;
        UART_Write('p');
        }
    }

    if(HALL_R){
        UART_Write('R');
        if(RB2 == 0){
            LED2 = 1;
            UART_Write('n');
        }else if(RB2 == 1){
            LED2 = 0;
            UART_Write('p');
        }
    }

    //Increment or decrement pulse width
    if(data == '+'){
        if(duty <= 0.75) duty = duty + 0.05;
        data = 0;
    }else if(data == '-'){
        if(duty >= 0.05) duty = duty - 0.05;
        data = 0;
        }
```

```
//FSM transition handler
if(data == 'X' || data == 'x'){
    STATE = STOP;
    }else if(STATE == S0 && data == 'G'){
            STATE = positionCal;
    data = 0;
    }else if(STATE == positionCal && HALL_L && RB1 == 0){
            STATE = w8;
    }else if(STATE == w8 && data == 'G'){
            STATE = goRight;
    data = 0;
    }else if(STATE == goRight && INDUCTIVE){
            STATE = charge;
    }else if(STATE == goRight && HALL_R && RB2 == 0){
            STATE = goLeft;
    }else if(STATE == goLeft && INDUCTIVE){
            STATE = charge;
    }else if(STATE == goLeft && HALL_L && RB1 == 0){
            STATE = railNotFound;
    }else if(STATE == railNotFound && tries < N){
            STATE = goRight;
    }else if(STATE == railNotFound && tries >= N){
            STATE = w8;
    }else if(STATE == railFoundRight){
            STATE = charge;
    }else if(STATE == railFoundLeft){
            STATE = charge;
    }else if(STATE == charge && data == 'G'){
            STATE = positionCal;
    data = 0;
    }else if(STATE == STOP && data == 'G'){
            STATE = positionCal;
    data = 0;
    }
```

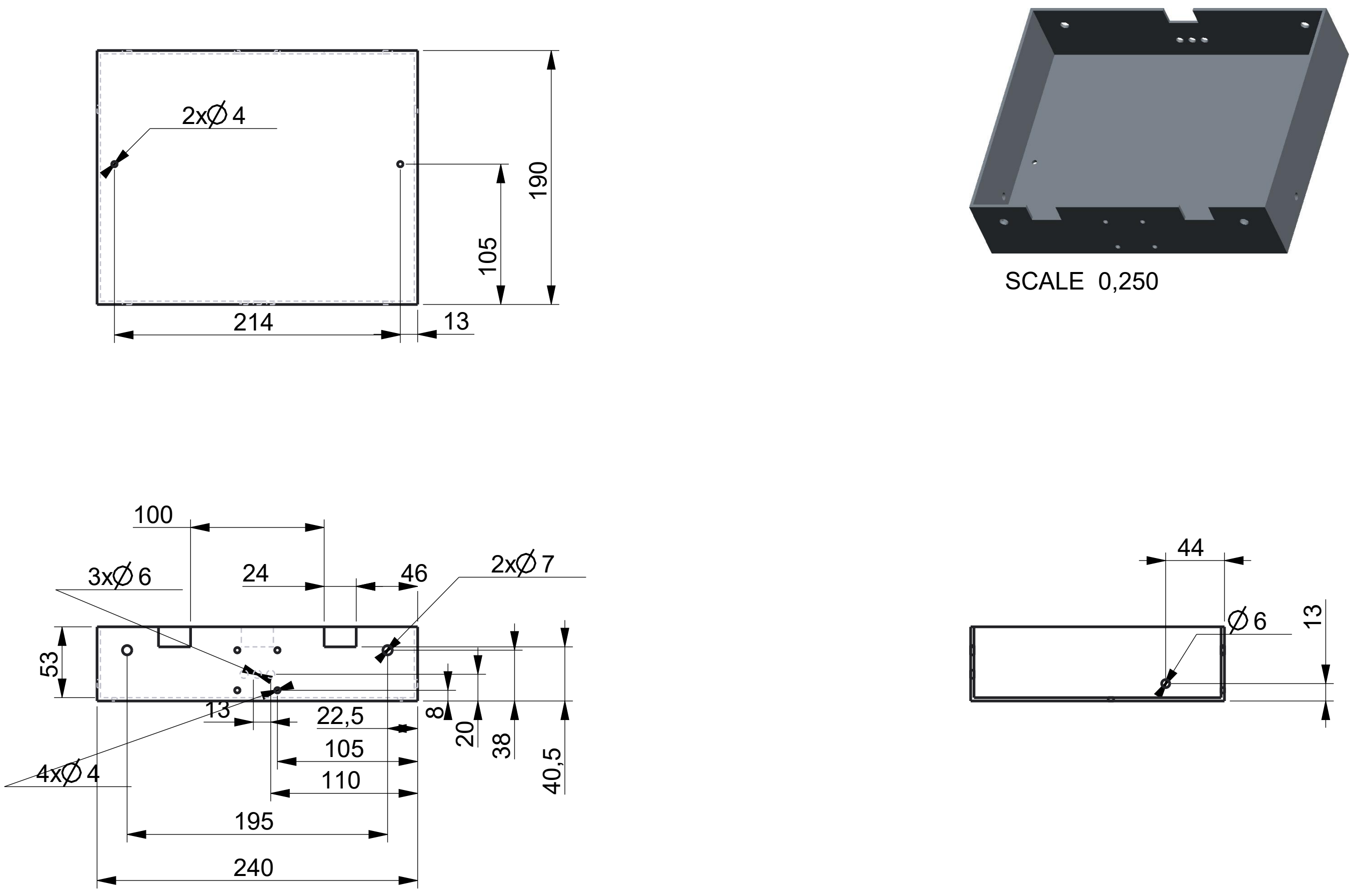
```
//FSM output generation
    if(STATE == STOP){
            brake();
            HPU();
    UART_Write('9');

    }else if(STATE == positionCal){
            HPU();
            left();
    UART_Write('1');

    }else if(STATE == w8){
            brake();
            HPU();
            tries = 0;
    UART_Write('2');

    }else if(STATE == goRight){
            LPD();
            right();
    UART_Write('3');

    }else if(STATE == goLeft){
            LPD();
            left();
    UART_Write('4');

    }else if(STATE == railFoundRight){
            brake();
            LPD();
    UART_Write('5');

    }else if(STATE == railFoundLeft){
            brake();
            LPD();
    UART_Write('6');

    }else if(STATE == railNotFound){
            brake();
            LPD();
            tries++;
    UART_Write('8');
    }else if(STATE == charge){
            brake();
            HPD();
    UART_Write('7');
    }
```

```
    //Reset interrupt flags
        HALL_L = 0;
        HALL_R = 0;
    IOCBF = 0;
        IOCIF = 0;

}

void OscillatorSetup(void){
    OSCCON = 0b01101010;
}

int main(void){

    GIE = 0;
    OscillatorSetup();
    UART_Init(2400);
    IO_Setup();
    STATE = S0;
    PWMSetup();
    setPWM(0);
    springMode();
    InterruptSetup();

    while(1);
}
```

Appendix F - uart.h

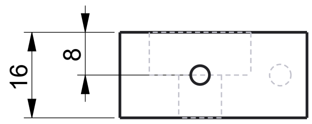
```
char UART_Init(const long int baudrate)
{
        unsigned int x;
        x = (_XTAL_FREQ - baudrate*64)/(baudrate*64);

        if(x<256){
        BRG16 = 0;
        BRGH = 0;

        SPBRGL = x;
        SYNC = 0;
        SPEN = 1;


        TRISC7 = 1;
        TRISC6 = 1;
        CREN = 1;
        TXEN = 1;
          return 1;
        }
        return 0;
}

char UART_TX_Empty(){
  return TRMT;
}

char UART_Data_Ready(){
   return RCIF;
}
char UART_Read(){

  while(!RCIF);
  return RCREG;
}

void UART_Read_Text(char *Output, unsigned int length){

        for(int i=0;i<length;i++)
                Output[i] = UART_Read();
}

void UART_Write(char data){
  while(!TRMT);
  TXREG = data;
}
```

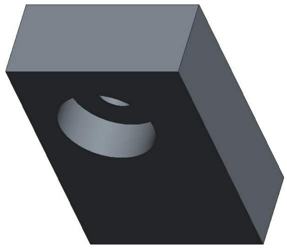
Appendix G - Schematics

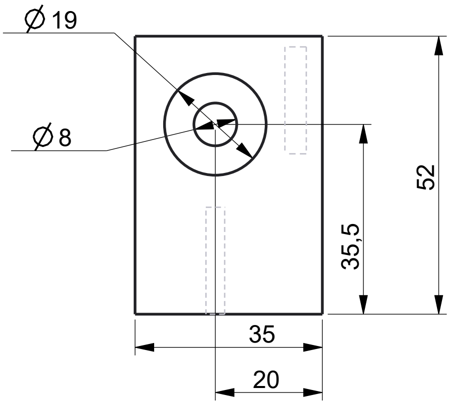


2x∅ 4
190
105
214
13
SCALE 0,250
100
3x∅ 6
24
46
2x∅ 7
53
13
22,5
8
20
38
40,5
105
110
4x∅ 4
195
240
44
∅ 6
13

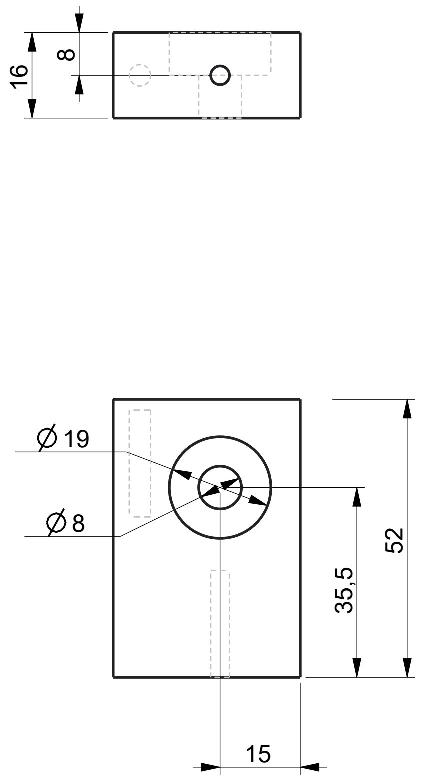
Part:	Box

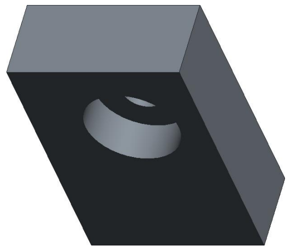




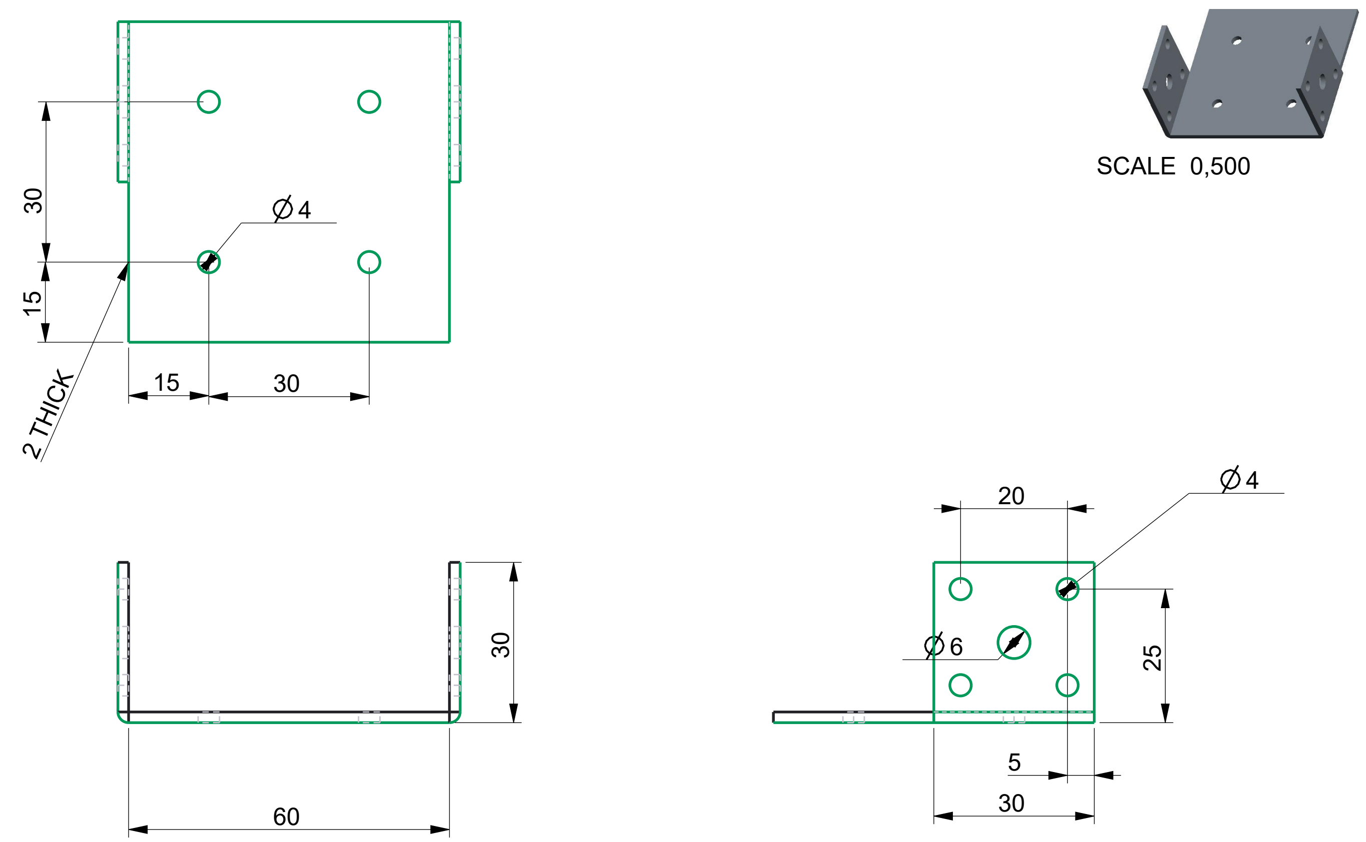


Part:	Support A

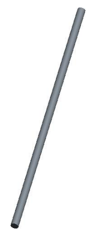




Part:	Support B



Part:	Front holder



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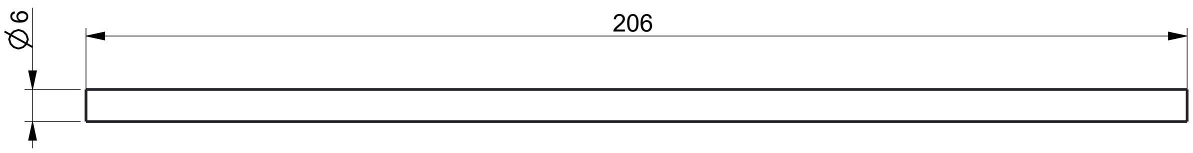
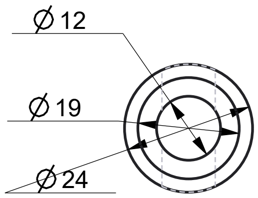
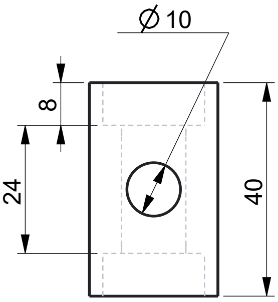


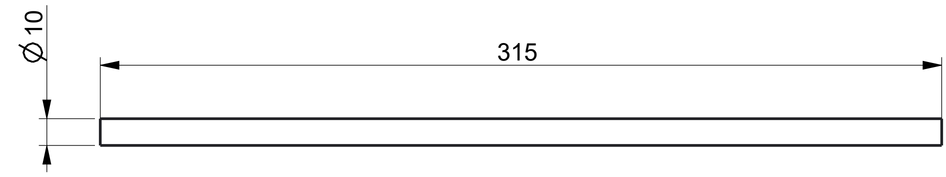
Part:	Drive shaft



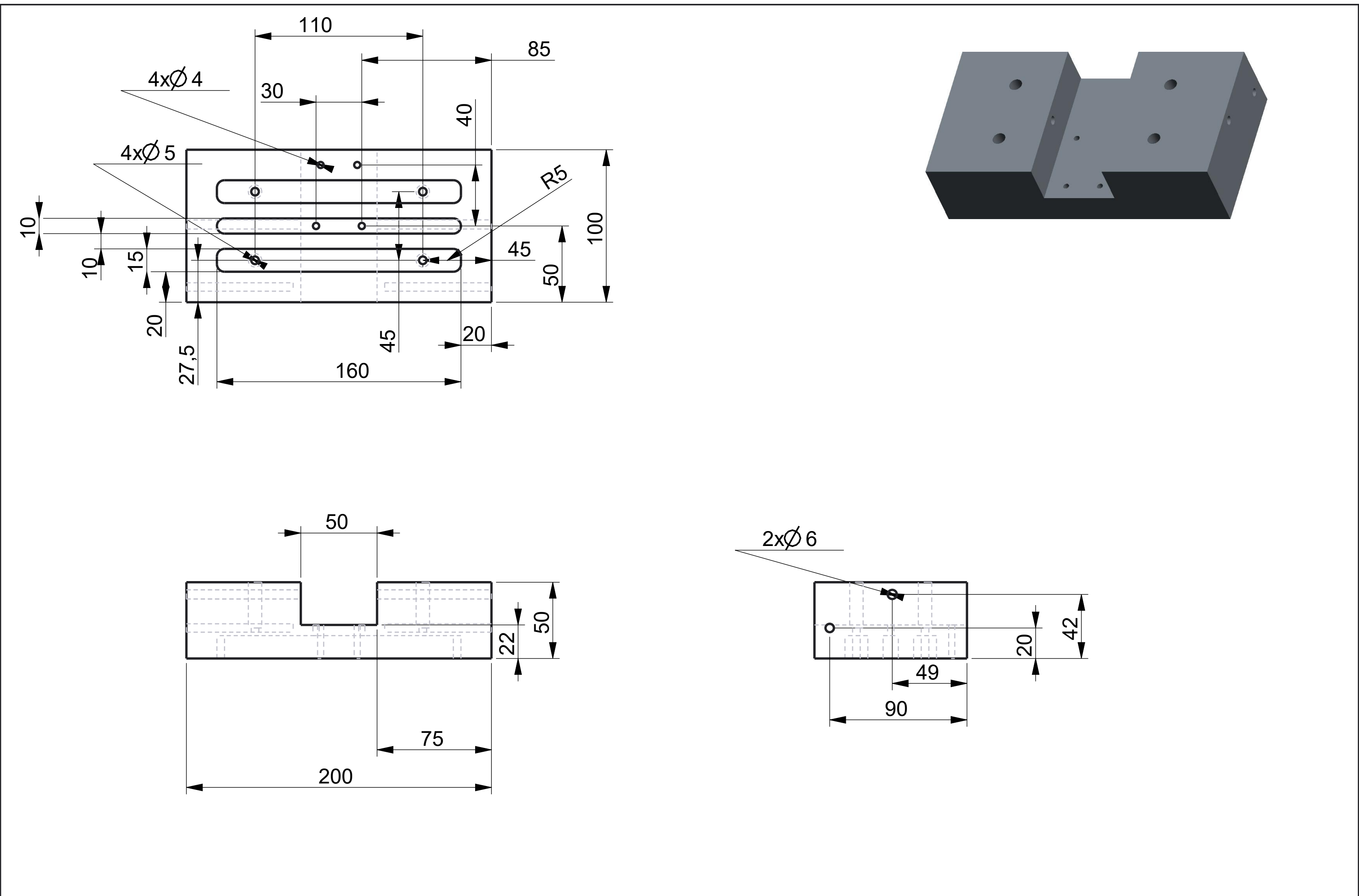


Part:	Rodend house

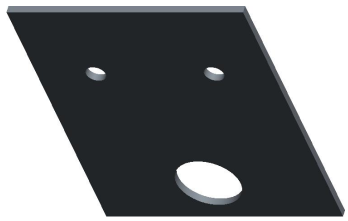
SCALE 0,250

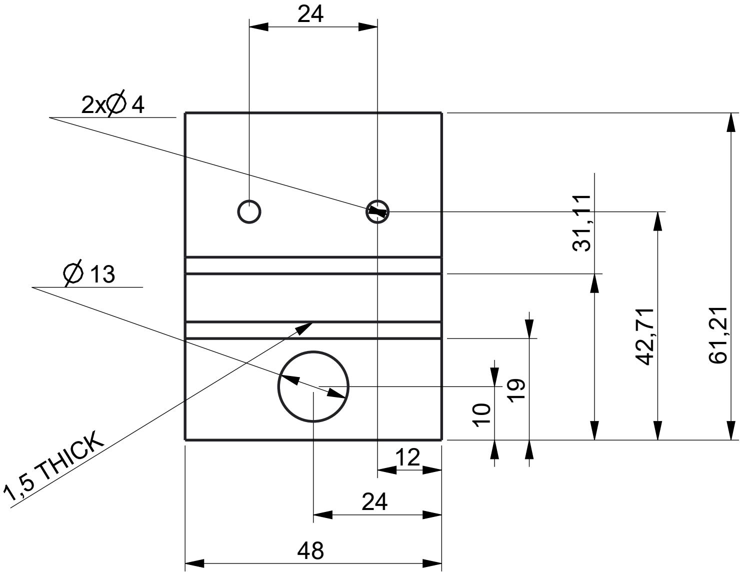


Part:	Strut

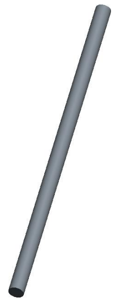


Part:	Contact house





Part:	inductive sensor holder



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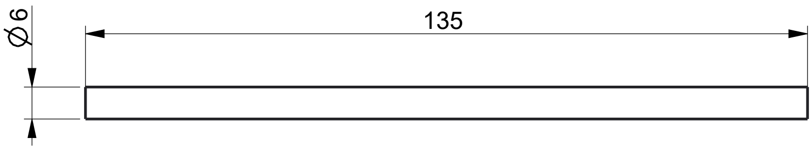
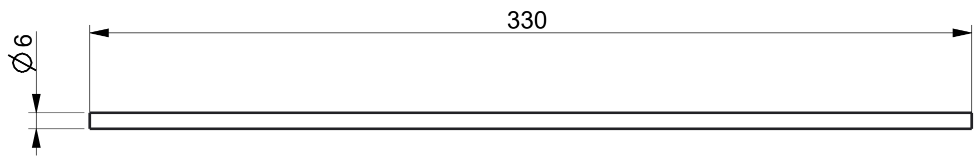
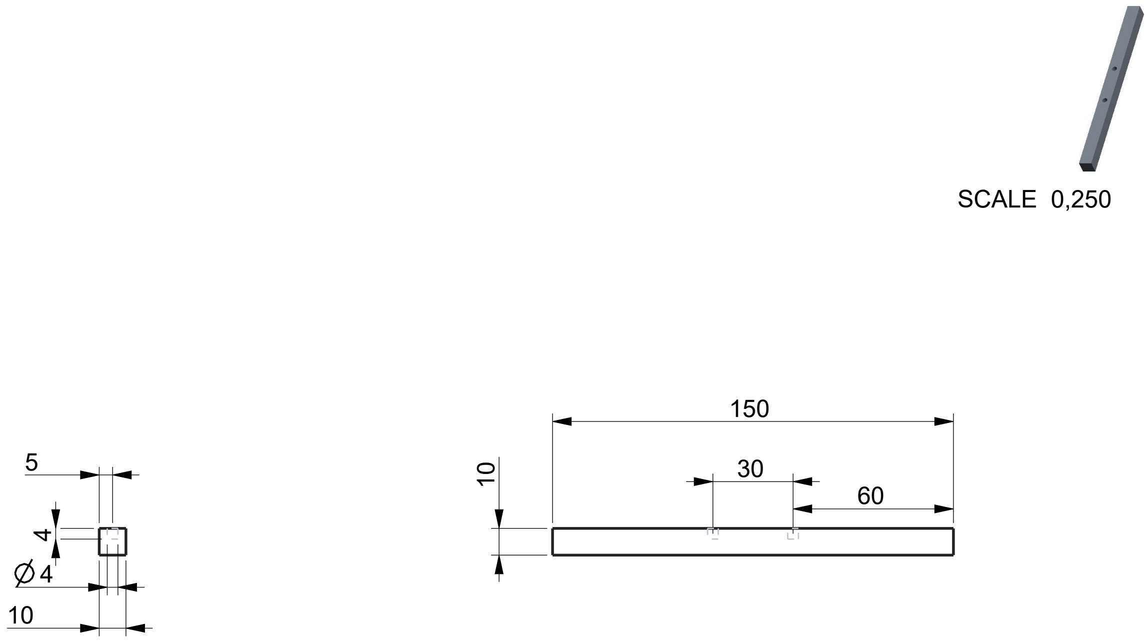


Part:	Lower contact shaft

SCALE 0,250

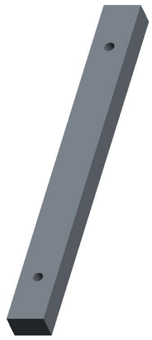


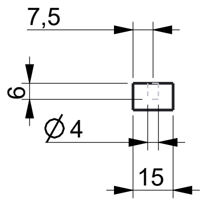
Part:	Upper contact shaft

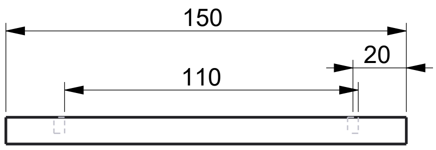


SCALE 0,250

Part:	midlle contact







Part:	Side contact

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