CHALMERS
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Development of an Undercarriage for a Mobile X-Ray Device

Master's thesis in Industrial and Material Science

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Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

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Abstract

The master thesis was performed to further develop a mobile x-ray device and to evaluate if it is possible to expand the x-ray device's range of operation. Today these units are limited to be used within hospitals. This thesis explores the opportunity to bring the x-ray device outside the hospitals, out to temporary visits at smaller health care centres and retirement homes, for examination closer to the accidents. For this purpose, the device's handling over surfaces outside the hospitals had to be investigated and improved.

The thesis is based on the work of a previous thesis which covered the customer needs mapping for the new model, resulting in this thesis focusing on solving these identified customer needs. The work performed in this project initiated with the establishment of specifications for the device, followed by identification of desirable functions, technological benchmarking and research of relevant literature. Based on these, a concept generation was performed, which by using various decision methods, resulted in a final concept for further development. The outcome of this development was a final prototype used to evaluate the fulfillment of established requirements.

The developed prototype have been considered a success, with the introduction of stronger motors and more effective suspension with only 5.7 % increase in cost of the undercarriage. However, it is still an early design only suitable for testing and would require further development in order to enter the competitive market.

Keywords: Mobile, X-Ray, Undercarriage, Off Road, Medical, Hospital, Health Care

Acknowledgements

We would like to thank Johan Malmqvist who have been our supervisor throughout this thesis, with his help both with feedback on our work and the report.

We would also like to thank Solutions For Tomorrow AB, firstly for giving us the opportunity to do our master thesis in collaboration with them, and also for the continuous support during the different testing phases and providing us with a x-ray device to the test various solutions. Additionally, we would like to thank our company supervisor, Mattias Guldstrand and our primary company contact, Jan Bååt.

Finally, we would like to thank the company Esta Oscillation for providing suspension elements free of charge for testing and evaluation purposes.

Ola Delfin, Marcus Sandberg, Gothenburg, August 2017

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1
Introduction

This section of the report covers the fundamental information regarding this master thesis and provides an understanding of the value created during the project. Moreover, the section includes a description of what is expected to be evaluated as well as which limitations have been set to the execution of the project.

1.1 Background

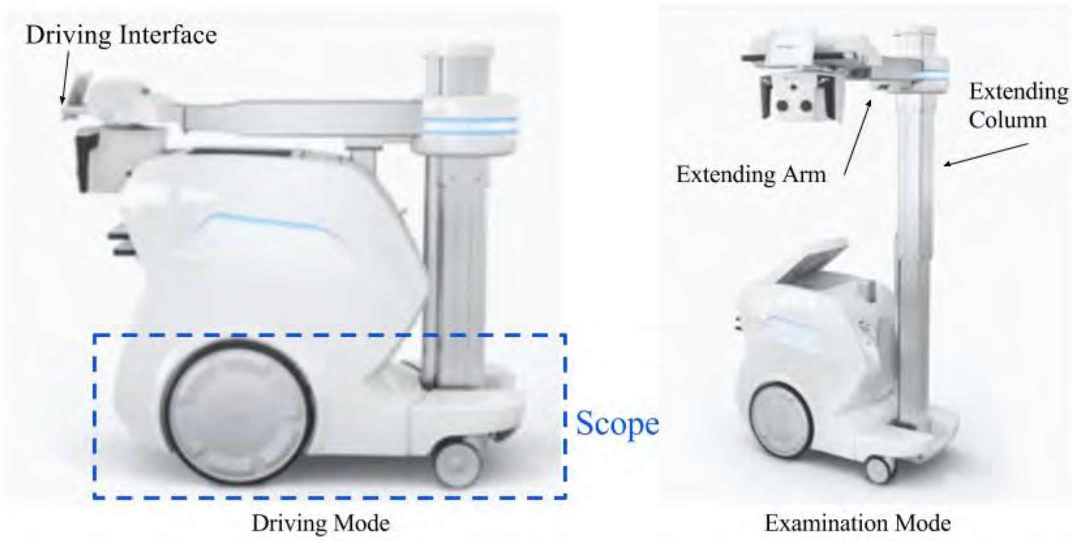


Figure 1.1: Scope and illustration of the device (Solutions for Tomorrow AB, 2017)

X-ray examinations are today most often performed in specific x-ray rooms located inside hospitals equipped with the necessary instruments. Performing the examinations at the hospital have some drawbacks since the patient needs to be transported from the place of the accident to this specific room, which in certain cases even can be harmful to the injured person. Therefore, a solution where the x-ray equipment instead is moved to the injured patient has the potential of increasing the level of comfort, lower the risk of additional injuries and simultaneously shorten the total waiting time for the patient.

Figure 1.2: Mobile x-ray scenario

The thesis have been performed in collaboration with Solutions for Tomorrow AB, further on called SFT in this report. SFT was founded in 2011 and is a medical technology company that has developed a vision of creating a mobile x-ray device. SFT's current model, shown in Figure 1.1, was released in early 2016 and is primarily developed to operate in hospital environments.

The idea behind this thesis is to evaluate if it is possible to move the machine outside of the hospital to people in need of x-ray examinations. The operating procedure of this type of machine could be that the machine is transported inside a van, for example, to a retirement home. Once there it will be driven, by its own power, from the vehicle to the location of where the examination will be performed, see Figure 1.2. A limitation of today's mobile x-ray devices is their ability to handle different surfaces, and the possibility of loading them into a transportation vehicle. A previous master thesis was performed assessing the different requirements needed for this type of product (Weidenmark, 2016). That thesis was used as the primary source for establishing requirements during the development process. One of the main findings in this thesis was that further improvements on the undercarriage of the machine, concerning suspension, wheels and propulsion, will have to be performed to achieve a well-functioning machine that is easy to transport.

1.2 Purpose

The purpose of this master thesis is to increase the ability to transport SFT's current mobile x-ray machine to environments outside of hospitals. Therefore, the x-ray machine will need to overcome the varying terrain conditions that may occur when it is driven from the transportation vehicle to the location of the x-ray examination.

1.3 Objectives

In this project, there are a number of objectives that needs to be considered, both specified by SFT but also through the previously performed master thesis evaluating the requirements of SFT's next model. The primary objectives identified for this project are as follows:

- Increase ability to transport the device across different surfaces and obstacles
- A CAD model of the prototype

- A tested prototype for future pilot use
- The machine shall be able to drive up a ramp angled 14.5°
- The machine shall be able to drive up a 25 mm threshold from standing still
- Minimize risk of tipping the device during examination
- Minimize cost

1.4 Scope

The thesis will be limited to the development of an undercarriage for the x-ray machine, this means that components related to the other sub-systems of the machine will not be altered. However, the effect which the new undercarriage might have on the other sub-systems and components will be analyzed. The reasoning behind keeping changes to the rest of the machine minimal is to avoid expensive design changes to the product layout as the existing product is considered to have an effective layout already. Systems surrounding the machine will not be investigated, such as suitable vehicles or ramps. The x-ray machine is designed to have similar dimensions as motorized wheelchairs and will use the same methods and standards for securing it inside transportation vehicles.

The existing product is driven by electrical motors which are controlled by pressure sensing handles. It is desirable to keep this system in the new version as it has been proven to be an effective way of driving the device and the interface for driving the device should not change in complexity. Although changes will be introduced to the undercarriage and driving characteristics of the device, it is desirable to ensure that the operational capacity of the x-ray functions remains the same as on the current device.

The developed prototype will be used for pilot testing and demonstration of its capabilities according to the scenario described in Figure 2. Therefore it will not necessarily be ready for series production without additional design alterations.

The requirements which the undercarriage needs to fulfill will primarily be based on a previous master thesis written for SFT at Chalmers (Weidenmark, 2016). This thesis evaluated requirements for the new version of the mobile x-ray, however it investigated entire product. Therefore, only requirements related to the undercarriage will be extracted from the requirements. No further customer visits will be performed since this has been done to a large extent already, and would most likely not lead to the identification of new customer needs.

In order to obtain a certification on the product, it is required to fulfill the standards related to the certification. The standard which has to be considered in the development of this undercarriage is IEC 60601-1 Medical electrical equipment. This standard will put additional constraints and requirements on the finished product, which needs to be considered during the development process.

Knowledge possessed by the team members might be a limiting factor in some regards. For example, if it turns out that the solution requires a level of programming too advanced for the programming skills of the team members. If this is the case, the project will be limited to more basic programs if at all necessary. Similar aspects also apply to areas such as simulations, if they become too advanced, the simulations could get simplified to match the capability of the team members. Another alternative is to consult experts in the field regarding the particular simulation.

Other limitations which might occur is related to the work flow during the first part of the project. Regularly, a master thesis will use 40 hours per week for each team member over a 20 week period. However, as this project is performed at a 50 % workload during the spring semester of 2017 and further into the summer period, parallel to another project course. Therefore, the work sessions could get disrupted by mandatory activities or other scheduled sessions in the parallel project.

Since half of this master thesis reached over the summer of 2017, the Swedish industrial holidays interfered with the delivery of components. Therefore, some of the components had to be ordered based on early design drafts of the product in order to finish the prototype in time. Since the prototype is intended to demonstrate the functions and verify the requirements, this was considered acceptable.

1.5 Outline of the Report

The report has been divided into different chapters that cover the process from gathering data to finalizing the prototype and presenting the results. In Figure 1.3 the chapters are presented with a short introduction to each of the different segments.

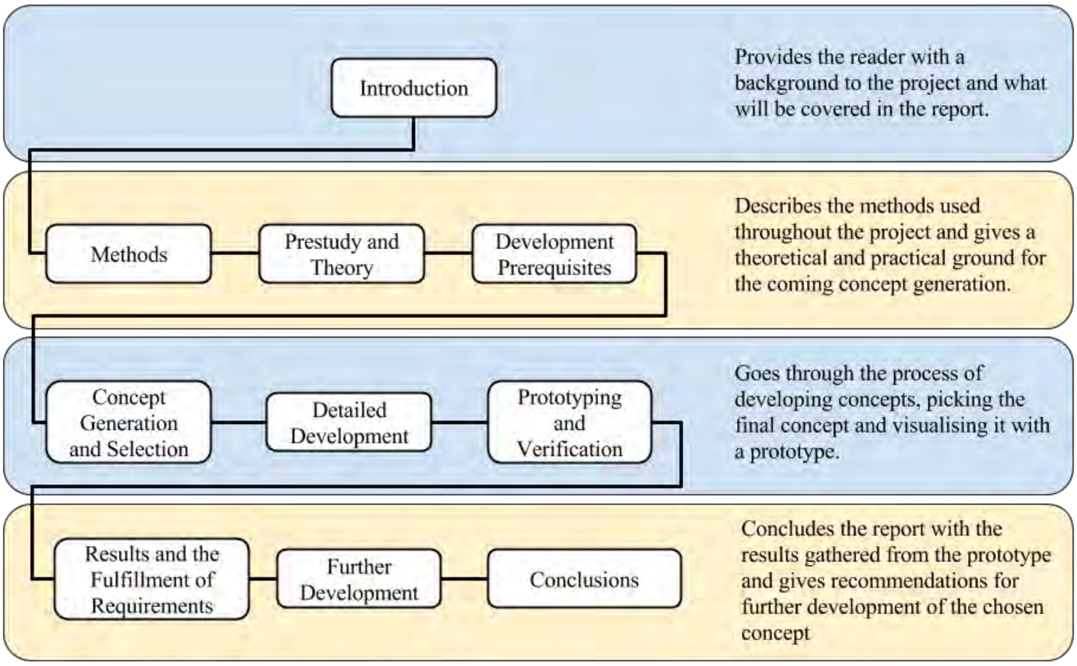


Figure 1.3: Outline of the report

2
Methods

During the course of this master thesis, a number of methods have been utilized in the development of the undercarriage. These have been used as they provide a systematic approach to the development process and decisions are easier to justify. In this chapter, the used methods are described, not only in their general form of the use but also how they are applied to this particular project. The process is visualized with a flowchart in Figure 2.1 below.

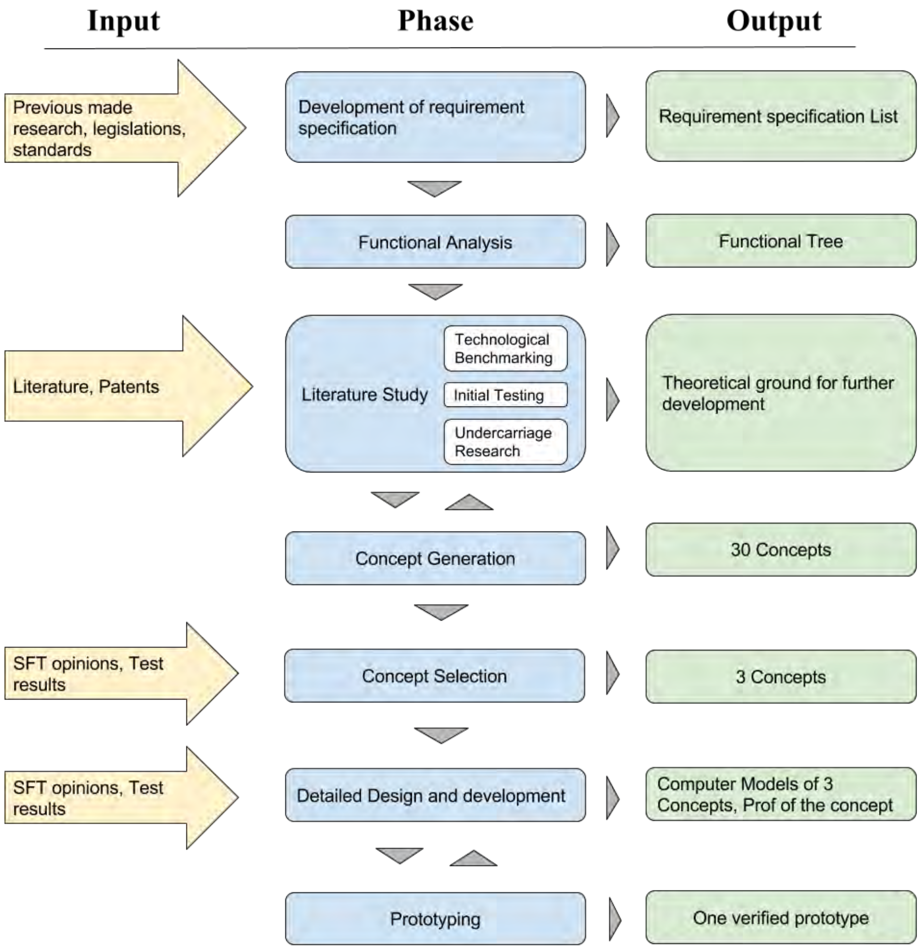


Figure 2.1: Flow chart covering the different phases

In Figure 2.1 the different phases of the project are connected to various inputs, shown to the left, and to its output shown to the right in the Figure. The process flows from the top, down to the bottom of the Figure with a number of iterations included.

2.1 Develop Requirements

When developing a product, it is important to establish a Specification of Requirements. The specification enables the development team to acquire an overview of the expected performance of a product. A requirement is a text describing what a product is supposed to do. It is formulated in a solution neutral language, meaning that the requirement does not state precisely how the product fulfills the requirement (Hull et al., 2005). Therefore, it will allow for a wide range of possible solutions that fulfills the requirements.

In the list of requirements conducted for the thesis, requirements of different types have been established. A number of the requirements have exact measurable values, for example *Maximum propulsion required on a hard flat horizontal surface of 200 N.* Others describe if the machine has a specific property or function, for example *The system shall be standing still and braked when not in operation.* Both examples have been extracted from the conducted Specification of Requirements seen in Appendix A.

The requirements can be divided into demands (D) and wishes (W). A demand is a requirement that the device has to fulfill to accomplish its purpose. Wishes are similar to demands, with the primary difference that they do not necessarily have to be fulfilled. It is however beneficial to do since it will provide a greater customer value (Hull et al., 2005).

The generated Specification of Requirements consists of requirements from a number of different sources. The primary part of the requirements were extracted from a previous master thesis written at Chalmers on behalf of SFT (Weidenmark, 2016). In the previous thesis, a Specification of Requirements was conducted for an x-ray machine developed to be brought outside the hospitals for temporary visits to people in need. Since the scope of this project covers the development of an undercarriage for the new product version, irrelevant requirements had to be filtered out as they did not influence the development of the undercarriage.

During the course of the previous project, a variety of customer visits and tests on the existing product were performed to identify customer needs and requirements. A number of these were covered by video recordings and were once again analyzed in this project to reduce the risk of leaving any important needs behind. In addition to the video analyses, further tests on the current machine have been performed with the potential to identify requirements which might not have been covered by the first iteration of tests.

The next major source of requirements is the industrial standard for medical electrical equipment IEC 60601-1, (International Electrotechnical Commisson, 2012). A large proportion of the standard involves various durability tests which the device has to pass in order to achieve certification. Finally, the specification contains requirements related to assembly and additional requirements established on request by SFT.

2.2 Functional Analysis

To find a solution to fulfill the requirements set for the product, it is important to identify functions that the finished product should possess. The identification was primarily performed by the creation of a hierarchical function tree which decomposes the complete solution into smaller sub-functions. It provides a greater overview of the important sub-functions that should be included in the complete solution.

The sub-functions that should be included in the undercarriage have been established early on, primarily based on sub-systems present in the current version of the device. Moreover, undercarriages for other types of vehicular products were investigated to identify certain sub-functions which might not be present in the current x-ray model. These possible absent sub-functions could be beneficial to include into the functional tree for further investigation.

2.3 Literature Study

As this project covers the development of an undercarriage for the new version of SFT's x-ray device, additional knowledge regarding vehicle undercarriages and their configurations was required. Therefore, a literature study covering this field of knowledge was conducted early in the project. This was done to ensure that the generated concepts, as well as the evaluation and development had a higher quality.

2.3.1 Technological Benchmarking

To obtain inspiration for new concepts while developing a new product, a technological benchmarking was performed. Benchmarking is an external search method with the purpose of identifying existing products on the market that have similar functionality as the product being developed, (Ulrich & Eppinger, 2012). By investigating products similar to the one being developed, or even products in other markets with similar functionality, it is possible to give the developing team another perspective on the problem and could lead to further ideas.

The benchmarking covered the most important sub-systems of the undercarriage and were taken from the functional analysis. The benchmarking was not performed on other types of propulsion systems than electrical motors, since it was decided early on that this was the system to use. The only varying aspect would be the specifications of the motor which were specified at the detailed design of the undercarriage. The primary benchmarking effort was instead aimed at finding different configurations of chassis configurations, suspension and movement facilitators for the undercarriage.

2.3.2 Undercarriage Research

The result of the literature study includes, to a large extent, inspiration for solutions as well as extended knowledge regarding the elements involved in an undercarriage. This theory includes collection of information regarding how the current product is configured, as well as relevant calculations performed in order to ensure that the requirements are fulfilled.

2.3.3 Study of Current Design

To gain a greater understanding of the problem, initial testing of the machine was performed. This testing has been used as a complement to the previously made market research. During the testing, the behaviour of the current model was evaluated regarding transporting capabilities and overall maneuverability. Videos were taken to provide further material in the development process.

2.4 Concept Generation

To maximize the chances of finding a suitable solution which solves the problem, a number of potential concepts have been generated. The identified functions that the undercarriage should possess were used as the foundation for a number of brainstorming sessions. Many different concepts were generated during these sessions, covering different levels of maturity, technology, and complexity. Therefore, some concepts was inevitably less promising than others, both in terms of relevance and in which level that they can be realized into real products. Furthermore, before combining solutions for the different sub-functions, it is important to eliminate concepts not fulfilling the requirements.

Sub-functions which can not immediately be disregarded were combined to create a number of concepts covering the entire system. The system, in this case, refers to the undercarriage of the x-ray machine. The activity was performed by utilizing a Morphological matrix (Pahl et al., 2007), providing a systematic approach to generating concepts that might solve the existing problem.

2.5 Concept Selection

The process of choosing a final concept for this product took a considerable amount of time in this project to maximize the potential of choosing a well-suited solution. It is desirable to keep the evaluation as systematic as possible while simultaneously using rational reasoning.

Initially, an Elimination matrix (Pahl et al., 2007) was utilized to eliminate concepts not able to fulfill the established requirements. An Elimination matrix is a systematic method of evaluating whether concepts are fulfilling the main function, if they fulfill the requirements in the specification, if they are feasible or within the budget (Pahl et al., 2007). The Elimination matrix is regularly displayed in tabular form. By eliminating all concepts not suitable for the task, the number of concepts will be reduced to a manageable number for further evaluation.

The remaining concepts, following the elimination, have been evaluated using Pugh matrices in a number of iterations. The use of a Pugh matrix (Lindstedt et al., 2003) is a method used to compare how different concepts performs in relation to each other based on a number of criteria. This will give an indication of where the different concepts are better suitable and where improvements can be done to the ones performing worse. Concepts which appears to be performing considerably worse than others could also be subject to elimination. By switching reference concepts in between iterations, the evaluation of the concepts can be done with different perspectives (Lindstedt et al., 2003).

The results of the Pugh matrices were presented to SFT to get additional decision grounds. The reasoning behind consulting SFT was to give them the opportunity to provide their input on the thought processes. The concepts might need modifications to have a better potential of succeeding, or even be eliminated based on what SFT thinks of them.

Concepts remaining from this process were subject for further evaluation. Parts of the solutions for certain functions required additional testing in form of basic prototypes. These tests were used to confirm whether the concepts are feasible at all, and how well they potentially could perform their task.

Based on the results of the prototyping, the concepts were once again evaluated in a systematic way through a Kesselring matrix, to rate their performance with regards to important criteria. A Kesselring matrix is a concept scoring method, where different criteria are weighted on a scale of 1 to 5, based on their importance. Depending on how well each concept fulfills the different criteria, they are given a score between 1 and 5. After each remaining concept has been evaluated on each criteria, the scores are summed up and compared. This gives an indication of which of the concepts are most suitable for further development (Lindstedt et al., 2003). As with the results from the Pugh matrices, this evaluation was presented to SFT to gain their input as further grounds for the decision making.

2.6 Detailed Design and Development

Three promising concepts remained from the concept selection process. By creating 3D-models and further develop these concepts, it allowed for either initial Finite Element Analysis or prototyping. The tool used when performing the Finite Element Analysis was Autodesk Inventor. Moreover, the models were used for cost approximations regarding standard components as well manufactured components to get an understanding of which solution that would be most cost effective. By using these initial analysis methods, it was possible to get a better understanding of how well the concepts fulfills the requirements. It also became apparent which concept is most suitable to select as the final concept. Based on the development of the three concepts, a more detailed testing phase was be performed where all concepts were tested on the current model, either through prototypes or simulations. The tests were based on requirements that the machine is required fulfill on a daily basis.

With a final concept chosen, further effort was put into detail design of this concept. This time, proper dimensions and materials were chosen to create the final CAD-model of the undercarriage. A Failure Modes and Effects Analysis (Carlson, 2012) was conducted to get an understanding of where the main risks of the product are. Based on the analysis, changes could be made to lower the risk in the most problematic areas. A higher precision will be acquired in the Finite Element simulations as well as cost assessments for the final CAD-model.

2.7 Prototyping

A prototype (Ulrich & Eppinger, 2012) has been built and installed on an existing machine in order to verify that the final product fulfills all requirements and that the functions intended are present. It will also be subject for future pilot testing to determine how well it works when used for real scenarios. The prototype is based on the design created in the detail design phase, where components for the construction were purchased or manufactured in the workshop either at Chalmers or SFT.

Testing of the finished prototype was based on requirements stated in the Specification of Requirements. Moreover, most of the testing was carried out in collaboration with SFT. The outcome of the prototype testing resulted in some adjustments to obtain a satisfying device.

3

Prestudy and Theory

Theory related to components and systems commonly used to make various vehicle move is presented in the following section. This theory section also consists of information regarding how these systems are incorporated in the current version of the x-ray device. The theory section is a result of the performed literature study which was conducted to obtain additional knowledge regarding the included systems.

From the Specification of Requirements in Appendix A, a number of performance requirements were found describing which driving modes the machine would be exposed to. The different terrains the machine will need to handle includes gravel roads, asphalt of varying condition as well as loading and unloading from the transport vehicle. The x-ray device will also require a method for securing the machine inside the vehicle, for example, anchoring points for safety straps. Moreover, the machine is required to handle thresholds inside buildings as well as different elevation ramps effectively. Elevation ramps are primarily used as means of loading the x-ray device into transportation vehicles or to get it into buildings. These ramps are assumed to be included in the transportation vehicle or implemented into the buildings, therefore the machine needs to be versatile enough to handle the inclination of the ramps.

3.1 Undercarriages for Vehicles

The term undercarriage in this thesis represents the supporting structure for the x-ray device. For this product, the undercarriage primarily includes the x-ray's chassis, the suspension and wheels. Moreover, the overall performance of the maneuverability of the x-ray device is highly dependent on the stability of the device. The stability can be altered by changing a number of different criteria (Young, 1998), where the most prominent criteria are:

- The location of the centre of gravity of the system
- The number, size and mechanical properties of the wheels
- The presence and configuration of suspension elements and/or components preventing the device from turning over

3.1.1 Chassis

In the vehicle industry, a chassis is the primary structural component, with the task of providing stability and robustness to the vehicle. It is also the structure upon which other components related to the movement of the vehicle are attached. The used definition of a chassis refers to a separable chassis, where the chassis and the body of the vehicle are joined together after both components have been manufactured. Therefore the entire product relies on the sturdiness of the chassis (Giancarlo et al., 2014).

The same definition for chassis is used in this thesis as the goal is to install the existing components of the x-ray device directly on top of the developed undercarriage. The chassis of SFT's current x-ray device consists of a solid steel plate positioned in the bottom of the machine with all components attached. The reason behind making the bottom plate solid is primarily to keep the centre of gravity low. Otherwise the machine would likely turn over while driven on larger slopes due to heavy top mounted components. Therefore, the new version of the x-ray device was desired to have the same center of gravity.

3.1.1.1 Design Requirements

The existing chassis has a number of support systems which are required to be included in the new chassis. This includes attachment points for straps used to secure the device in transport. It also includes attachment points for the components, which today are directly connected to the chassis. These are components such as the generator, the telescopic arm and the frame, to name a few. These components had to be taken into consideration while configuring the layout of the new chassis. The required weight of the chassis had to be considered as well in order to make sure that the centre of gravity is located at a satisfying position.

3.1.1.2 Ground Clearance

Since the chassis is the structural mounting platform for many of the device's components, this also includes the mounting points for the device's wheels. The placement of these mounting points, together with the wheel dimensions will determine the ground clearance, c_g. Ground clearance is the shortest distance between the ground and the lowest part of the device. Since the machine is required to climb ramps with an angle set by the Specification of Requirements, the ground clearance needs to be high enough to avoid the device getting stuck. The required ground clearance also depends on the wheel base, w_b, being the distance between the front and rear wheels of the device, illustrated in Figure 3.1.

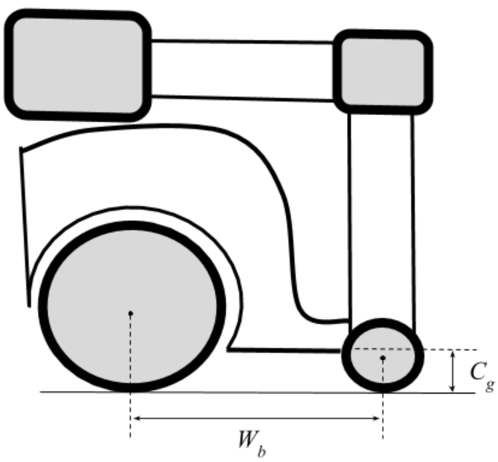


Figure 3.1: Ground clearance and wheelbase

To estimate the required ground clearance to climb ramps, the problem has been illustrated in Figure 3.2. The minimum clearance allowed before the device becomes stuck is calculated. The angle of inclination α is the maximum angle the device is required to climb, obtained from the Specification of Requirements.

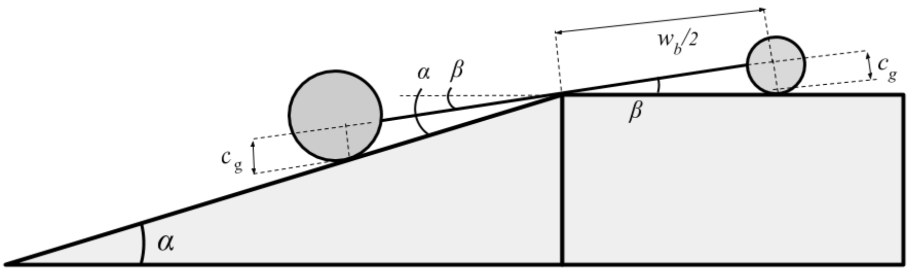


Figure 3.2: Estimation of the required ground clearance

It is assumed that the distance from the ground to the bottom of the device is the same for both the front and rear of the device, due to the placement of the wheels. Therefore, the assumption can be made that the device will become stuck in between the wheels, when the front wheels have covered a distance of $w_b/2$ past the edge of the ramp. As a result, the angle β can be assumed to be $\alpha/2$. With the angle β and the distance from the edge known, the ground clearance can be estimated with the following equation.

$$\tan\beta = \frac{c_g}{w_b/2} \tag{3.1}$$

By solving for c_g and inserting the value for β, the required minimum ground clearance can be estimated as follows.

$$c_g = \frac{w_b}{2} \tan\left(\frac{\alpha}{2}\right) \tag{3.2}$$

3.1.2 Vehicle Suspension

The suspension handles the relative movement between the wheels and the vehicle by utilizing systems as for example tires, shock absorbers, springs and linkages (Goodarzi & Khajepour, 2017). Its main functions are to minimize the vibrations that occurs when the vehicle is in motion, and also to provide a good handling of the vehicle. Therefore, the suspension always tries to keep the wheels in contact with the ground. In this particular case, an important aspect is to dampen the impacts transferred to the vehicle and its medical equipment while driving over thresholds and other obstacles.

The existing solution have similar designs for both the front and rear suspension, see Figure 3.3. They have rubber dampers mounted between the base frame and the motor mount which minimizes the vibrations on the machine.

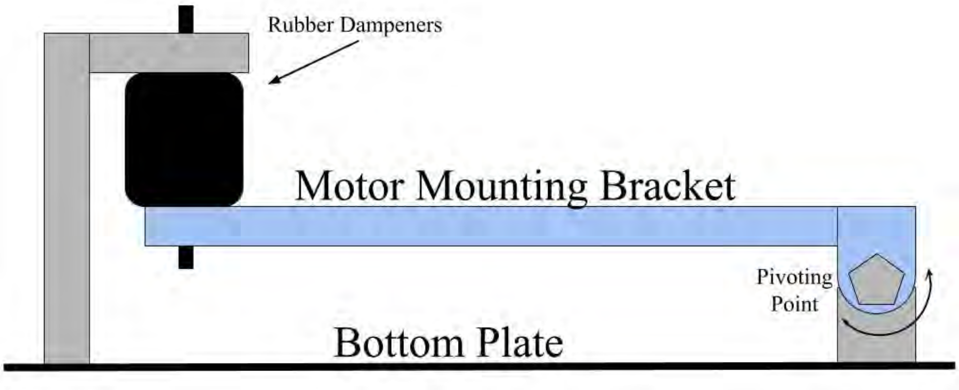


Figure 3.3: Suspension layout currently used

3.1.3 Brakes

There are several ways of stopping the machine and according to the Specification of Requirements in Appendix A, it is required to have the machine braked when it is not in use. SFT's current machine has its brakes mounted directly on the motors and they are bought together with the motor. Other ways of utilizing brakes is to have for example disc brakes or drum brakes (Reif, 2014). These types could work sufficiently in this application but would increase the complexity.

3.2 Wheels

The primary task of the wheels is to transform the rotating motion from the drive unit down to the ground to create movement of the device. Wheels are relying on the friction between wheels and surface to enable movement in a controlled way (Dixon, 1996).

Wheels used on the current product are of two different types with regards to the front and rear. The front wheels are plastic casters, these provides a good turning radius as they are double axis wheels. One of the axes is for rotating the wheel and one for changing direction. The wheels have different angle properties which are important for the overall behavior of the device. The angles can increase the stability of the device and also change the handling of the device. There are foremost two angles that have an impact on this master thesis, being caster and camber angles.

3.2.1 Caster Angle

The caster is the angle created when the steering pivot axis is tilted either forward or backward from the vertical axis, when looked at from the side (Dixon, 1996). By increasing this angle the straight line stability of the device will increase, but will simultaneously increase the steering effort required. This mechanism is used in the front wheels on SFT's current product, when the device is pushed forward the steering axis drags the front wheels and aligns the wheels with the driving direction. The distance between the steering axis and the point where the wheel is in contact with the ground is called trail, a greater trail will increase the force required to turn the wheel. These dimensions are visualized in Figure 3.4. In this thesis, the trail will also alter the stability of the device since the wheels can be positioned in ways that is unfavourable for the stability.

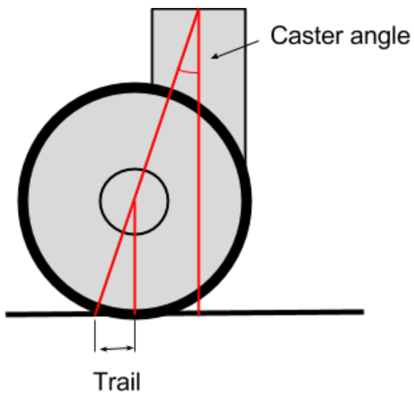


Figure 3.4: Caster angle

3.2.2 Camber Angle

Camber is the angle the wheel have relative to the vertical axis, when looked at from either the front or the rear (Dixon, 1996), see Figure 3.5. In car applications this angle is important for the handling of the car, since this angle will change in corners due to the weight transfer on the suspension. In this project this phenomena will be much more limited, since the weight transfer in the speeds that the x-ray device will travel are not as significant. Although, it could be beneficial for the stability of the device to have some degree of camber angles.

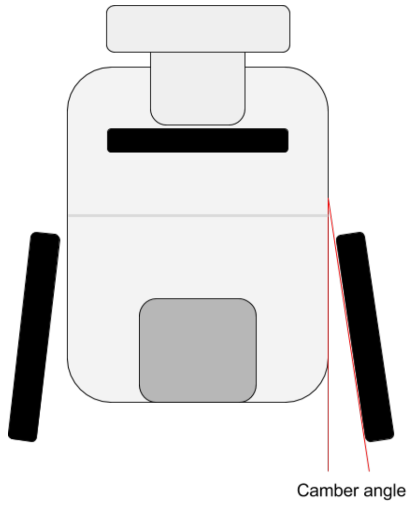


Figure 3.5: Camber angle

The rear wheels are regular single axis wheels made out of cast aluminum with a surrounding layer of rubber for traction. In this case the rear wheels are powered, which requires them to have sufficient amount of traction to move the device forward. The rear wheels of the device have a relatively large diameter compared to the front wheels. Large wheels are beneficial as they enable the device to traverse over thresholds and other obstacles. However larger wheels requires a higher amount of torque, putting additional requirements on the drive units.

3.2.3 Wheel Dimensions and Motor Specifications

The dimensions of the wheels together with the capabilities of the motors were important aspects to take into consideration during development. As previously mentioned, the x-ray device is required to be able to traverse various obstacles, including thresholds and ramps. The estimated specifications will inevitably be varying for the two types of obstacles. It was therefore important to estimate the required performance of the motors, and size of the front wheels to make sure that the device would get across. Results from both types of estimations had to be taken into consideration while establishing the final specifications.

For these calculations, it is assumed that the rear wheels are powered and the front wheels are not.

3.2.3.1 Thresholds

As the rear wheels will have a certain diameter, the force which the rear wheels will push onto the threshold will depend on the output torque of the motors. Therefore the required motor torque will be estimated. With an assumed radius of the rear wheels of r_R and an output torque of M, the force driving the device forward can be derived from Figure 3.6 and calculated as follows.

$$F = \frac{M}{r_R} \tag{3.3}$$

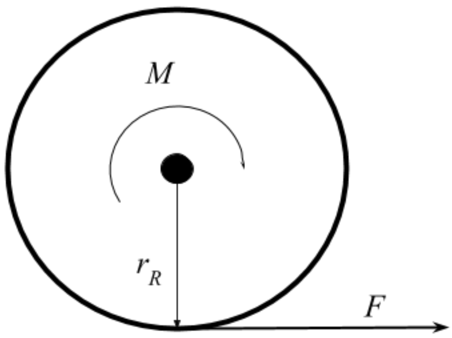


Figure 3.6: Force Forward

For the wheel to be able to climb up a threshold, there has to be an moment equilibrium at the pivoting point A at the edge of the threshold seen in Figure 3.7.

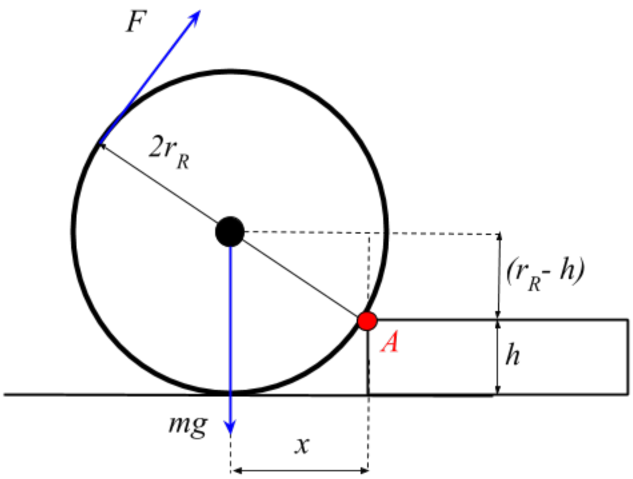


Figure 3.7: Estimating the required output torque of the motors

In Figure 3.7, h is the height of the threshold, specified in the Specification of Requirements. m is the mass which is applied to the rear wheel together with the wheel itself, and r_R is the radius of the wheel. To find the distance x, a right-angled triangle can be identified with the radius of the wheel as hypotenuse. Therefore x can be calculated using Pythagoras theorem.

$$r_R^2 = x^2 + (r_R - h)^2 \tag{3.4}$$

With the distance calculated, the equilibrium equation for the moment around A can be established.

$$F \cdot 2r_R - mgx = 0 \tag{3.5}$$

By inserting the expressions for F and x, the required motor torque as a function of the rear wheel radius, is obtained as follows.

$$M = \frac{mg}{2}\sqrt{2r_R h - h^2} \tag{3.6}$$

Solving the equation for the minimum allowed torque of the motors M from equation 3.6, with the given rear wheel radius r_R, the force F pushing the device forward can be obtained and further used to estimate the required dimensions for the front wheels. This estimation is done in a similar way as for the rear wheels, with a few modifications to the problem. The setup for the front wheels can be seen in Figure 3.8. The primary difference is that this time, the wheels are not powered, instead the driving force is the force F estimated that the rear wheels produces, located at the centre of the front wheels.

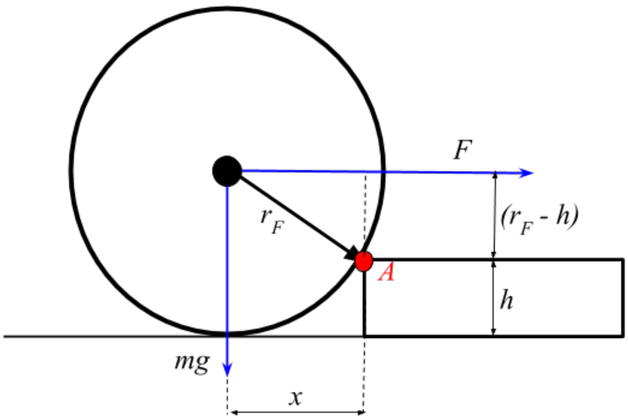


Figure 3.8: Estimating minimum allowed dimensions for the front wheels

This time, r_F is the radius to be estimated. To be able to conduct the equilibrium equation for the moment, the distance x is calculated the same way as for the rear wheels. With this setup, the equilibrium equation around the pivoting point A looks as follows.

$$F \cdot (r_F - h) - mgx = 0 \tag{3.7}$$

By inserting the expression for the distance x and solving for F gives the following equation.

$$F = mg\frac{\sqrt{2r_F h - h^2}}{r_F - h} \tag{3.8}$$

From this equation, the minimum allowed radius r_F of the front wheel, given the rated torque of the selected motor, can be obtained.

3.2.3.2 Ramps

The ramps were another obstacle to consider when estimating the motor specifications. These ramps includes those built into buildings for wheelchair access and those implemented in the transport vehicles. The required output torque of the motors was estimated similarly as for the thresholds. Once again, the radius of the rear wheels are assumed to be known as r_R. This problem is illustrated in Figure 3.9 and is used to calculate the required force F_R, which also gives the required torque of the motors.

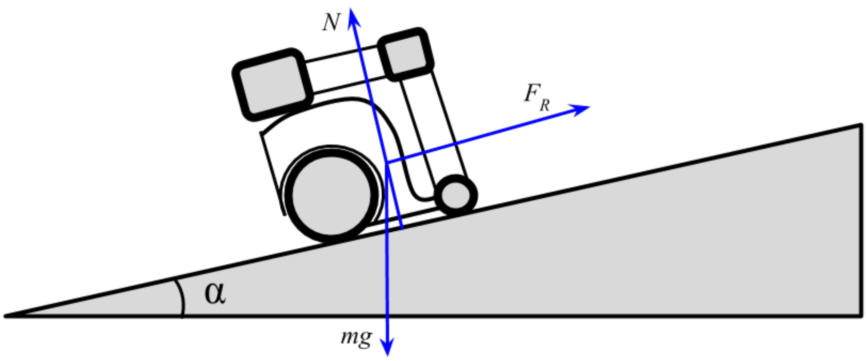


Figure 3.9: Estimating the Force required to ascend ramps

The force calculated is the force required in order for the system to stay in equilibrium. This means that a greater force will make the device move forward, and will therefore be considered the minimum force required. To obtain an estimate of the force, the equilibrium equation in the direction of the force F_R, perpendicular to the normal force N is established as follows.

$$F_R - mg\sin\alpha = 0 \tag{3.9}$$

m represents the mass of the entire device. By solving for the force, the following expression is obtained.

$$F_R = mg \sin \alpha \tag{3.10}$$

Since the x-ray device has two motors, the minimum force required to move the device is divided in two. Therefore, the torque which each motor needs to provide is expressed with the following equation, using the same principles as in Figure 3.6.

$$M = \frac{F_R r_R}{2} \tag{3.11}$$

By inserting the expression for F_R from equation 3.10, the required torque M can be estimated as follows.

$$M = \frac{mgr_R \sin \alpha}{2} \tag{3.12}$$

3.3 Drive Train

The drive train of the unit consists of the components responsible for making the wheels on the device rotate with satisfactory speed. Today, the drive train consists of two electrical motors combined with a transmission to provide correct torque output to the wheels.

3.4 Test Phase 1

Even though this thesis is based on results from the previous thesis conducted for SFT (Weidenmark, 2016), it is important to create a deeper understanding of the problems present in the current version of the device. Moreover, additional measurement data was desirable to collect to explain the behavior of the system. The data was acquired through initial tests performed on the existing model.

3.4.1 Drive Tests

Initially, a number of tests labelled drive tests were performed in order to gain perception of the device's behaviour. The drive tests included driving the machine over various surfaces to observe how it behaves when exposed to these types of environments. Surfaces included in the tests were those that the machine is likely to encounter, such as asphalt, grass and gravel. Important to note is that these different surfaces were not constantly horizontal, which means that the surfaces in combination with slopes and bumps could have impacted the device's driving capabilities.

While driving the machine over asphalt, it became apparent that the current version is able to handle this surface without major issues. The only concern was with the front casters, these caused rather loud noise and vibrations while driving.

Driving across grass did not go as well as on asphalt. Due to small contact area of the rear wheels, the machine sank down into the grass under its own weight. While attempting steering, the front casters positioned themselves in a disadvantageous position, as seen in Figure 3.10a, causing them to dig down into the grass. This phenomena further increased the power required to drive forward, power which the device does not possess. Therefore, the machine did not have enough power to start rolling without assistance.

(a) Disadvantageous position of the front casters

(b) Trail from the casters when changing direction

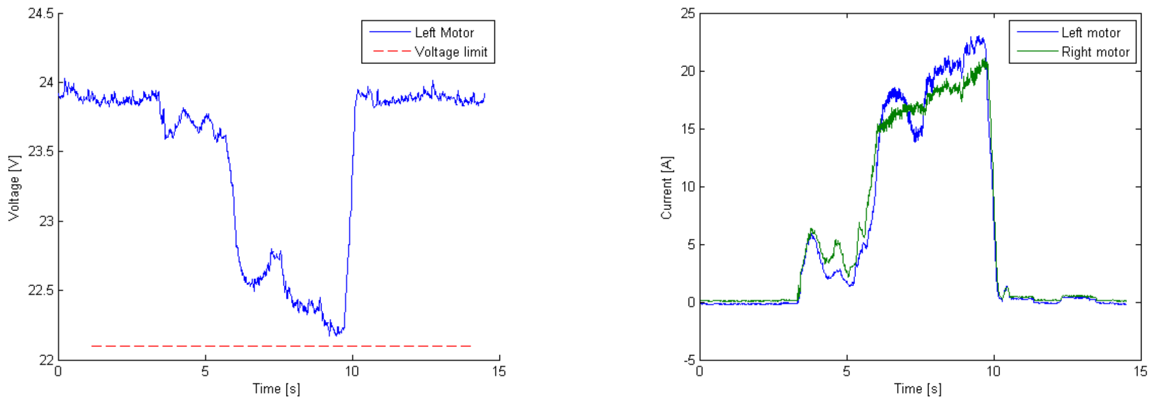
Figure 3.10: Tests made on grass

Driving on gravel roads further highlighted issues with the front casters. Due to the surface being uneven, the casters had a tendency to lift from the ground as seen in Figure 3.11. This left the rest of the device to balance on three wheels, distributing the load onto the remaining wheels. The front casters also easily filled up with dirt, resulting in them getting stuck. The overall drive across gravel was rough, indicating that the current suspension is under-performing in this application.

Figure 3.11: Gravel driving

3.4.2 Measurements Electrical System

Even though performing the drive tests gave an understanding of the issues of the device, it was also desirable to collect measurements of how the electrical system behaves under load. As reported in the previous master thesis (Weidenmark, 2016), the device has issues driving up steep inclines. To understand this problem, a thorough investigation of the electrical system was required, where measurements on both voltage and current was collected. Figure 3.12a illustrates the behaviour of the system when the device drives up a slope that it is able to handle.



(a) Voltage curve for left motor

(b) Current curve for both motors

Figure 3.12: Electrical measurements when driving on a 10° slope

Driving on slopes causes high amount of load on the system, requiring the drive units to provide a higher current to compensate, as seen in Figure 3.12b. The drive units are the components responsible for conveying and regulating power from the power supply into the motors. When the current surging through the drive units increases, the voltage simultaneously drops, as illustrated in Figure 3.12a. If the voltage drops below a certain limit, the drive unit will turn off as a safety measure. Turning of the drive units means that the motors will not receive any current, resulting in a bad behaviour of the device. Such behaviour could for instance be that the device makes rapid uncontrollable turns and stuttering movements.

The current configuration of the machine was able to drive up a slope of maximum 10°. Inclines steeper than this would require a larger amount of current passing through the drive units which the device was not able to provide. To be able to drive up steeper slopes of 14.5°, as specified in Appendix A, the output torque from the motors needed to be increased. It could be done either by increasing the current surging into the motors, or by mechanically increasing the torque output through various measures.

3.4.3 Summary of Tests

After performing various tests on the device, it became apparent that the issues are located at certain sub-systems of the machine. The most prominent issues identified are listed below with a brief description of what requires improvements.

- **Overall Suspension:** Became most prominent while driving over gravel, but the issue was also present on the other surfaces. An improved suspension, both in the front and rear would ensure a smoother ride over the surfaces. It would also provide a better balanced product since all four wheels would be forced to be in contact with the ground over uneven surfaces.

- **Front Casters:** Since the front wheels are made out of hard plastic, they caused a lot of noise while driven over uneven surfaces, they also caused a high amount of vibrations throughout the device. The construction of the casters enabled dirt to enter and get stuck, requiring disassemble to clean.

- **Power Output:** The issues regarding power output identified in the driving tests and confirmed in the electrical tests indicated that this issue had to be addressed in the development of the new version. By resolving this issue the device will be able to cross the various difficult surfaces and obstacles it is required to handle.

- **Torque Output:** Even though the power output of the device was an identified issue, the machine would also need a higher torque output to overcome the various obstacles it will encounter. From the tests, it was discovered that the current motors have a torque output of approximately 52 Nm. This torque was not enough to drive across soft surfaces such as grass, which caused the device to get stuck.

In addition, the device is intended to be driven in speeds of approximately 5.5 km/h, however it was able to manage 9.7 km/h with the current setup. The tests did not reveal new requirements for the device, but rather that it does not fulfill requirements currently existing for the new version of the device.

4

Development Prerequisites

To understand the product that SFT needed for their application, a closer investigation was made regarding the Specification of Requirements. This chapter also covers the creation of a functional tree, dividing the components of the machine into sub-categories. These categories were then used as a base for a technical benchmarking, performed to obtain more inspiration from different solutions available.

4.1 Specification of Requirements

The layout of the specification is as follows. If the requirement is an extraction from the previous thesis (Weidenmark, 2016), there is a describing background to why the requirement exists under *Observation*. These originates from customer visits performed during the thesis. Stated secondly in the specification is the criteria, followed by whether it is a requirement or a wish. Each criteria has a method of how they will be verified. These are either one of the following.

- **Engineering Test:** Testing of the created prototype.
- **CAD Assessment:** Design choices, the criteria have been controlled in the CAD environment

Finally, each criteria has a reference which tells where the requirement or wish originates from. If it is the customer studies, the industrial standard, or other sources. The complete Specification of Requirements can be seen in Appendix A.

The most important requirements from the specification are those concerning overcoming obstacles, and the stability requirements regrading risks of tipping over. These requirements will be essential to fulfill for a machine intended to be used in these conditions. The tipping requirements are important to evaluate since, if not fulfilled, it can injure the person operating the machine or damage the equipment. The requirements regarding overcoming obstacles are important since if they are not fulfilled, the purpose of the new device will not be met.

4.2 Functional Analysis

The functional analysis mentioned in Section 2.2, with the purpose of identifying functions beneficial for the product to possess, have been structured in a functional tree. Visualized in Figure 4.1, it also illustrates the sub-systems which have been deemed beneficial to include in the system, and the functions relates to the sub-systems.

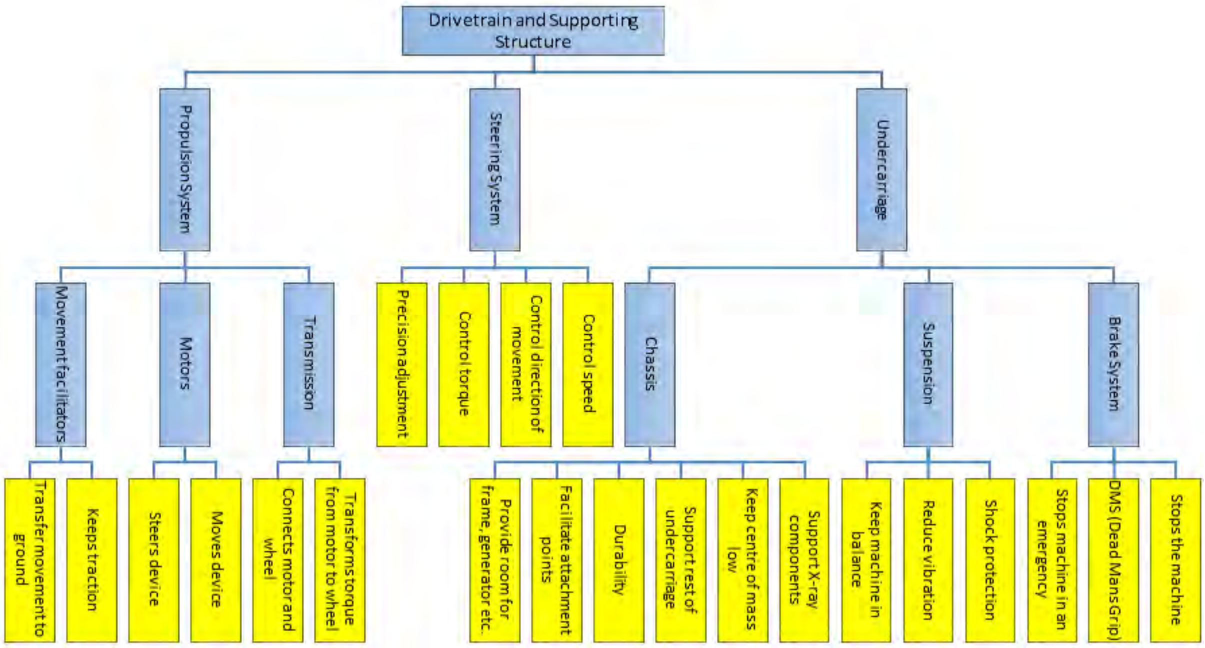


Figure 4.1: Created Functional Tree

During the creation of the functional analysis, it was realized that some of the sub-systems were beneficial to keep similar as to the current version. The current version has built in brakes in the electrical motors, which is beneficial regarding space efficiency compared to external brakes. Furthermore, this type of configuration will be able to fulfill the desirable functions covering the *Brake System* and *Motors* in Figure 4.1. A similar reasoning was applied for the transmission system of the undercarriage. Since the motors often are delivered with a corresponding transmission, it is beneficial to use these transmissions since they provide a space efficient solution for the device.

The steering system utilized in the current product will also be used in the new version since it is proven to work sufficiently. There is therefore no reason to completely redesign it, but minor changes such as a function switching between driving modes could be introduced.

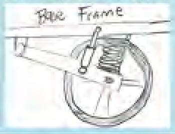
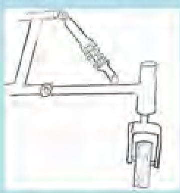
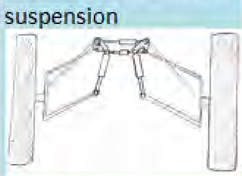
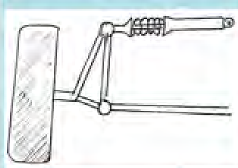
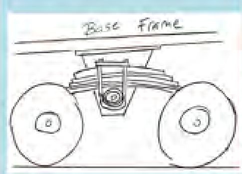
4.3 Technological Benchmarking

Performing the benchmarking for identified sub-systems, by investigating existing solutions in other product fields provided useful inspiration for the idea generation. The results of the benchmarking is divided into three different categories and visualized in tabular form. Brief comments and evaluations on relevant characteristics are present to provide an idea of the potential of the solution for this particular project.

4.3.1 Chassis Configuration

Different vehicles have various types of chassis adaptations to facilitate the suspension. Therefore these different types have been identified to find the configuration best suitable for a product of this type and size. The amount of space required for a sub-system is therefore important to investigate in the benchmarking process. The identified solutions for the configuration of the chassis are illustrated in Table 4.1

Table 4.1: Identified existing solutions on how the chassis can be configured. 1-5 (Dixon, 2009) and 6 (Lee et al., 2016).

Chassis Configuration	Complexity	Price	Space	Ability to absorb shocks/vibrations
1. Separate suspension and base frame, Twist-beam rear suspension 	Low It has few components when both wheels are connected together with the same part	Low-Medium Depending on which kind of suspension element chosen, but it have the potential of being a priceworthy alternative	Low-Medium Takes quite small amounts of space, a difficulty is that it needs to connect the two wheels where there is a limited amount of space	High Since, both wheels are connected it is a higher risk for the machine to tip over
2. Separate suspension and base frame also separate for each wheel, Trailing arm 	Low It has few components even though the wheels have separate suspension	Low-Medium Depending on which kind of suspension element chosen, but it have the potential of being a priceworthy alternative	Low Takes small amounts of space, good that the wheels dont need to be connected	High Good with independent suspension since the wheels don't interfere with each other
3. Front wheel suspension, Swing axle 	Low It has few components even though the wheels have separate suspension	Low-Medium Depending on which kind of suspension element chosen, but it have the potential of being a priceworthy alternative	Low-Medium Takes some space but could be redesigned with other suspension element to free up space	High Good with independent suspension since the wheels don't interfere with each other
4. Formula 1 suspension, Multi-link suspension 	High Many parts and connections between the wheels	High Many parts included	High takes much space since the two wheels requires connection	High Good at absorbing up shocks and vibration
5. Pushrod suspension, Horizontal suspension 	High-Medium Quite complex do to a complex linkage when transfering the dampening into the horizontal plane	Medium	Medium Requires space in the horizontal plane but saves space in the vertical plane	High Will take up both shocks and vibrations
6. Bogie suspension 	High Complex due to many parts, another question is how to connect the drive units	High	High Takes a lot of space	High Will absorb vibrations and shocks thats the machine could be exposed to

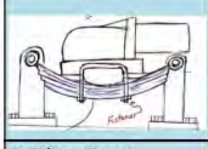
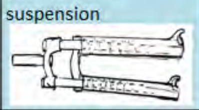
To summarize this part of the benchmarking, there are two main configuration types of chassis construction. The wheels on either side of the device could be connected to each other, making their articulating movement dependent on each other, or they have separate suspension. The later enables the wheels to move freely in spite of what the wheel on the opposite side is doing. This will provide better stability if one wheel is traversing an obstacle while the other stays on flat ground. However, by using dependent suspension the structure generally becomes less complex and more durable.

4.3.2 Suspension Elements

Similarly to the previous section where different configurations can be made on the chassis to enable for a certain type of suspension, a number of suspension elements can be used to accomplish the desirable chassis configuration. In this area, the search was not limited to vehicular configurations as there are other industries where vibration dampening and shock absorbing characteristics are used.

It turns out that there exists a large number of ways to obtain the desired dampened motion. This proved beneficial as it opens up the possibilities to utilize solutions not commonly used in vehicular products, and adapt them to the mobile x-ray. Potential solutions identified for this type of application are illustrated in Table 4.2 together with brief comments. As there are many solutions available, they were categorized in order to give a better overview of the alternatives.

Table 4.2: Identified suspension elements present in existing solutions. 1-2 (Dixon, 2009), 3 (Davie, 2011), 4 (Ding & Cooper, 2005), 5-6 (Heinrich Kipp Werk, 2017), 7 (Esta Oscillation, 2017) and 8 (Stemco LP, 2017).

Suspension Elements	Complexity	Price	Space	Ability to absorb shocks	Ability absorb up vibrations
1. Car suspension – General layout 	Medium Generally the supporting structure required to hold the elements contains quite a few components.	Low High availability in many different variants	High Requires large amounts of space as the elements requires supporting structure to be effective	High Large potential as this setup allows for significant articulation of the wheels, thereby absorbing impacts well	High The springs will absorb the vibrations well
2. Leaf spring 	Low Generally simple ways of installing, could increase if a dampner needs to be added.	Low Simple design, relatively common	High Requires large amounts of space, leaf springs are generally large themselves	High Very good articulation for leaf springs	High The springs will absorb the vibrations well
3. Bike – Front suspension 	High All elements are located internally inside the piping.	Medium-High Generally using non common components, depending on brands	Low Requires small amounts of space due to its very compact layout	High Good articulation	Medium Not focused on vibrations
4. Front Wheel, Casters with suspension 	Medium Easy to implement if acquired complete, higher complexity if built from scratch.	Low-Medium, Depends if it is built or purchased	Low Requires small amounts of space, mounted in a similar way as current solution	Low Not large articulation due to small form factor	Medium-High Depends on the dampening component built in
5. Rubber bushings, Pressure 	Low Not much supporting structure required	Low Simple design	Low Requires small amounts of space as the construction is small and not much additional support structure	Low Rubber generally does not provide significant articulation by it self	High Good vibration absorption by the spring-rubber combination
6. Rubber bushing, used under stretching force 	Low Simple installation method	LowSimple Design	Low Requires small amounts of space as it has low number of components	Low Rubber generally does not provide significant articulation by it self	Medium Due to being rubber, however based on drag motions, uncertainty regarding stretching forces
7. Rubber suspension, Torsion 	Low Easy to install as it is the whole suspension in one package	Medium It consists of a complete solution with a few internal parts	Low Small amounts of space required	High If the lever is made longer, allowing for more articulation	High The rubber construction allows for vibration absorption
8. Air cushions/Bag 	Medium Easy installation, however the air pressure needs to be calibrated for the particular product, complexity increases due to supporting structure	Medium	Medium, Lower amount of space than regular car suspension as it combines spring and dampner but still requires surrounding structure	High This setup allows for good articulation of the wheels, thereby absorbing impacts well	High Cushions will absorb vibrations well

The majority of the existing solutions uses the conventional elements found in cars and other larger vehicles, where a combination of a spring and a shock absorber creates the suspending movement. These elements can however be mounted in numerous different configurations depending on space available and complexity. These factors will inevitably have an impact on the cost, which has to be taken into consideration.

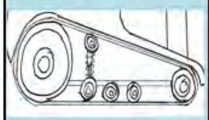
Another common category of existing elements are rubber dampeners. These generally do not have the same ability to absorb shocks or to provide wheel articulation as the conventional configuration present on larger vehicles. However, the more compact design of these components makes it easier to fit them into the already limited space inside the device. Generally the complexity of utilizing these types of solutions is low and also the cost of the solution tends to be low. In most cases regarding the rubber dampeners, they have been utilized either as torsion springs or in pure axial compression.

A number of solutions were found regarding the front casters, incorporating suspension built in to the caster themselves. These casters will provide a very compact solution but it is uncertain whether the built in suspension possesses the desirable characteristics and if they are cost effective.

4.3.3 Movement Facilitators

The movement facilitators can be describe as the units connecting the device with the ground, allowing the device to move. On SFT's current model different size and models are used in the front and rear respectively. The rear wheel has a cast aluminum rim with a solid rubber tire. The front wheels are casters which can rotate around their fastening point. Hence, the machine has a small steering radius. There are many different solutions with different benefits which all are presented in table 4.3.

Table 4.3: Identified concepts for movement facilitation. 1-2 (Batelaan, 2014), 3 (Bridgestone Americas, Inc., 2017), 4 (Dixon, 1996), 5 (Tellus Hjul & Trade AB, 2017), 6 (Loopwheels, 2017), 7 (Dixon, 1996)

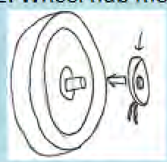
Movement Facilitators	Complexity	Price	Traction	Ability to absorb shocks/vibrations	Comment
1. Quad track 	High Very complex solution	High Many parts and hard to maintain	High Due to a greater contact surface with the ground	High Have the potential to take up the shocks that the system will meet, but will have to use a complex suspension solution	
2. Twin track 	High Complex solution	High Many parts and hard to maintain	High Due to a greater contact surface with the ground	High Have the potential to take up the shocks that the system will meet, but will have to use a complex suspension solution	
3. Airless tyres/wheels, with structure as main dampning	High Complex to model and investigate how it will function. If bought finished and tested its a good and simple solution	High	High-Medium Good traction with the ground	High-Medium Depending on the model it have high potential in taking up both shocks and vibrations.	Can make a simplification of the concept to include in the prototype, however it is hard to model the final effect it will have on the system.
4. More thread on tire for traction	Low	Low A lot of products available	High Good traction with the ground	Medium Will be slightly better to take up shocks	Can bring in more dirt to the house
5. Tyreless wheels (layer of rubber around)	Low	Low Good possibility to customize according to what is desired	Medium Depends on the design of the wheel	Low Not as sufficient to take care of shocks and vibrations	
6. Suspended wheel, all suspension fits inside the wheel 	High	High	High Good traction	High Sufficient ability to manage shocks and vibrations	
7. Air tires	Low	Low	High-Medium Depends on the design of the wheel	High Better to handle vibrations and shocks than airless tires	Need for maintenance, reinflate air in tires

The main takeaway from this section of the report is that the best solution for the device will be to use ordinary wheels, compared to the different track solutions seen in Table 4.3. These wheels can on the other hand be designed in various ways to enhance different properties. The biggest discussion here will be whether it will be better to use airless wheels with lower need of maintenance, or to use air filled tires with a higher degree of built in suspension. Different kind of rims were found which can be used together with, or instead of, suspension. Moreover, an increased threading in the tires will create better traction on different surfaces. However, it will bring more dirt into buildings, they will also become more difficult to clean and disinfect after the machine has been operated.

4.3.4 Motors and Transmission

In the scope of this thesis, it was defined that electrical motors should be used to drive the device. It can be motivated by SFT's effort to develop a battery technology, together with the argument that the battery will be used to power the x-ray equipment. To stick with electrically powered motors will therefore be the logical decision to keep the system as consistent and simple as possible. In table 4.4 different motor configurations are evaluated.

Table 4.4: Identified concepts for motors. 1 (ElectroCraft, Inc., 2017), 2 (The HEINZMANN Group, 2017), 3 (ElectroCraft, Inc., 2017)

Motors	Complexity	Price	Ease of implementation	Comment
1. Wheelchair motor 	Low Possible to purchase the complete unit	Low	High Same as the current model and therefore low effort to implement in a new system	Is used in the current machine, and a lot of knowledge about the motors characteristics is in the company already
2. Wheel hub motor 	Low	High-Medium	Low Greater effort to implement since new drive code needs to be generated, new brakes	Do not take up much place and can therefore free up space in the machine
3. Brushless motor	Medium	Medium	Low Greater effort to implement since new drive code needs to be generated, new brakes, matching motors/ transmission	

To summarize this table, it will be beneficial for SFT to use the same type of motors and transmission as today. Particularly due to SFT's knowledge about the current system, it has established suppliers and no significant effort will be required obtaining the same feeling of handling the device. There are some interesting concepts available that have the potential to reduce the size of the system even though changes needs to be done both concerning the braking and the drive units with new programming. An example of this is the wheel hub motor configuration.

4.3.5 Conclusions from the Technological Benchmarking

The technological analysis brought up interesting solutions and was used as a base for the coming phases of the thesis. The choice of movement facilitators was decided to be wheels, both in the front and the rear. This primarily due to the cost and complexity of the solutions. Moreover, depending on the final solution, changes might have to be made to the machine, reducing the possibility of using the same components for the current and new version of the product.

The chassis configuration can be designed in many different ways, and the performance of it is largely dependent on the suspension element chosen for the specific configuration. A preferable solution will be one which is both simple and occupies as little space as possible at a low cost. The suspension elements ranges both in cost and in performance, were some are better at handling vibrations while others are better at absorbing shocks. Therefore tests where different suspension elements are evaluated will be made further into the project.

As mentioned in section 4.3.4 it will be beneficial for SFT to use their current motor solution which the company already has gained knowledge about. Although, the wheel hub motors have a great potential of minimizing the total volume of the drive units and wheels.

5

Concept Generation and Selection

During the concept generation phase, a lot of new concepts and ideas were created solving the problems that the device will encounter. To evaluate these concepts and ideas, several methods can be used, most of them containing a matrix comparing the concepts regarding different criteria. Through this process the best concepts will be discovered and further improved until a final concept can be chosen. The chapter covers both the concept generation, where many different concepts were introduced, and the selection of the concepts that performs best in this application.

5.1 Concept Generation

Based on identified sub-systems included in the new undercarriage of the device, a number of brainstorming sessions were performed. Sub-systems addressed are *Rear Suspension, Rear Wheels, Motor Placement, Front Suspension* and *Front Wheels.* To provide a better understanding of where the generated solutions to these sub-systems will be positioned on the device, Figure 5.1 illustrates the bottom plate with the placement indicated on the existing product.

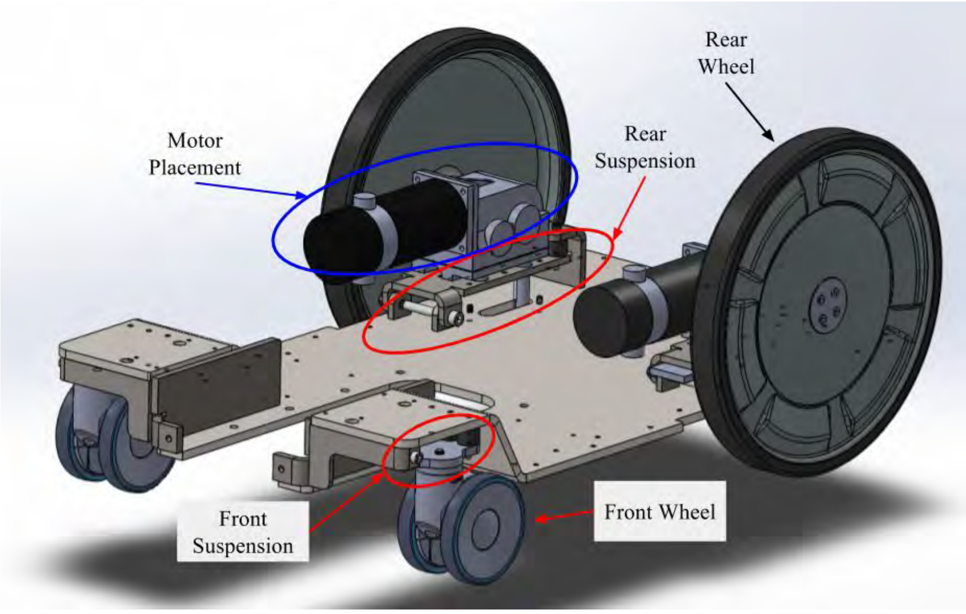
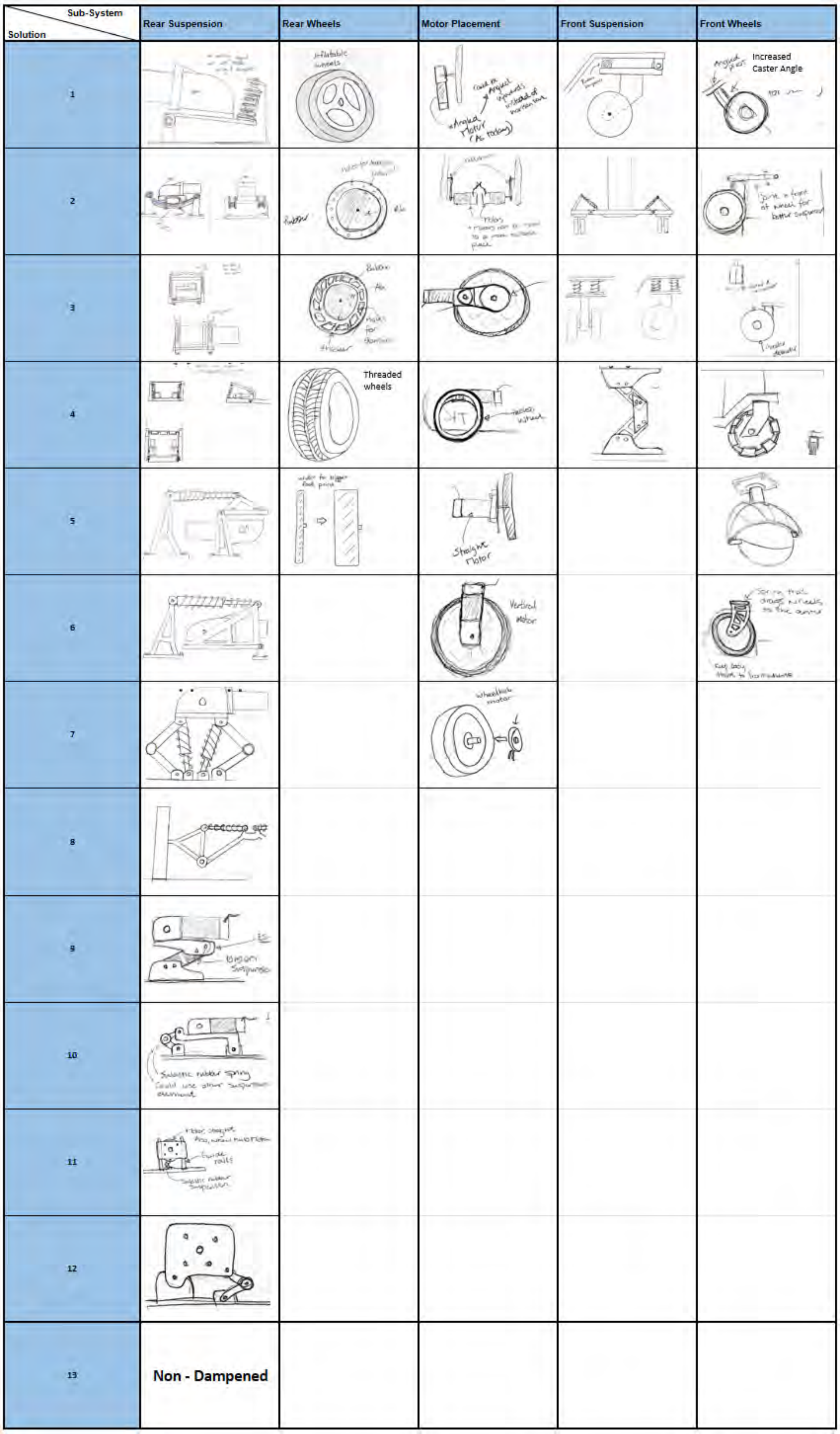


Figure 5.1: Highlighting where solutions for the different sub-systems will be located

The brainstorming sessions provided a large number of solutions which all varied in both complexity and performance, providing a base for further development. The generated sub-solutions to these categories of the undercarriage were later combined with each other to form complete solutions. This combination was done using a Morphological matrix, seen in Table 5.1.

Table 5.1: Morphological matrix for generating complete solutions



To obtain a large variety of solutions, still trying to keep the number of combinations at a manageable level, a set of distinct themes for the solutions were established. These themes indicates that the conceived solutions behaves in a certain way. For example, one theme used was *Simplicity*, indicating that the solutions should be combining sub-solutions with as simple layout and components as possible. Another theme was *Space Efficiency*, with the purpose of creating solutions as compact as possible given the generated sub-solutions. Both team members also individually combined a number of concepts each. The reason for this was to ensure that further variation is obtained without the team members influencing each other. Each of the combined concepts received their own distinctive name which will be used during further concept evaluation and development. These concepts are illustrated in Table 5.2.

Table 5.2: Combined concepts

	No.	Rear Suspension	Rear Wheels	Motor Placement	Front Suspension	Front Wheels	Name
Miscellaneous	1	9	4, 5	1	1	2, 3	Torsion
	2	10	4, 5	1	1	2, 3	Sulastic
	3	2	4, 5	1	1	2, 3	Leafy
	4	4	4, 5	1	1	3	Wheelchair
	5	9	1	1	3	3	Simple Torsion
	6	6	4, 5	1	1	1	Almost radical pushrod
Innovation	7	7	4, 5	4	3	5	Quadpod
	8	13	3	5	3	4	Tire suspension
	9	12	2	7	1	6	Wheelmotor
	10	5	1	1	2	5	Reversed motor
Shock Absorption	11	3	3	1	4	6	The bike
	12	4	2	2	1	2	Soft wheelchair
	13	11	1	7	4	6	Built in guidance
	14	7	3	1	4	6	Soft Quadpod
Space efficient	15	1	4	1	3	3	Compact Existing
	16	12	1	7	3	4	Multidirectional Wheelhub
	17	13	3	1	3	3	Ultimate space saver
Simplicity	18	1	5	1	1	3	Existing principles
	19	10	5	1	3	3	Simple Sulastic
	20	2	5	1	1	3	Simple leafs
	21	13	1	1	3	3	Spartan
Modified	22	11	2	5	3	3	Straight motor
	23	5	1	1	2	3	Reversed lawn mower
	24	11	2	2	1	2	Belt drive
	25	12	1	7	3	3	Aero hubs

5.2 Concept Selection

As there was a large number of generated concepts with varying levels of performance and feasibility, a reduction of the number of concepts was necessary. It was important to remain as objective as possible during the evaluation, which lead to a systematic approach through decision matrices.

5.2.1 Elimination Matrix

The first method used to sort out unfeasible concepts was the elimination matrix. In the matrix, all concepts gathered from the morphological matrix Table 5.2 was evaluated by the following four criteria:

- Fulfills the main function
- Fulfills all requirements
- Realistic
- Within the budget

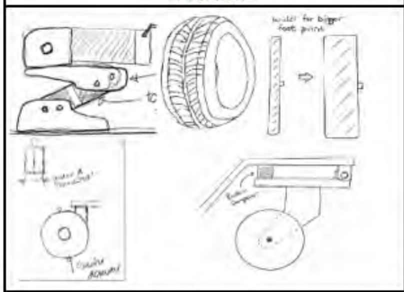
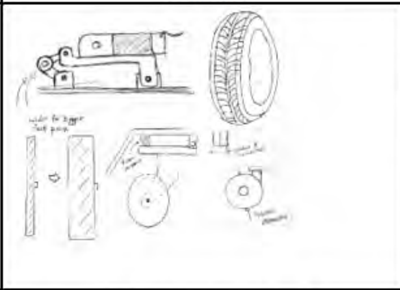
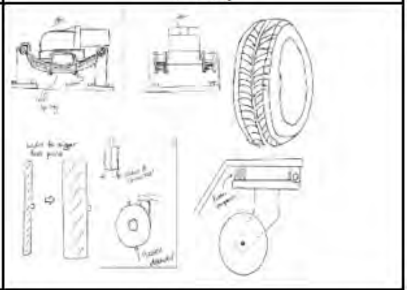
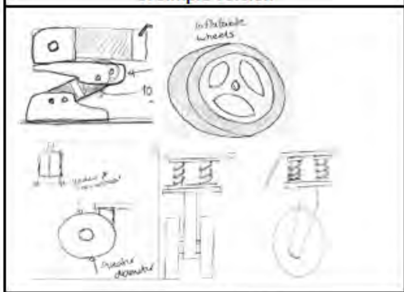
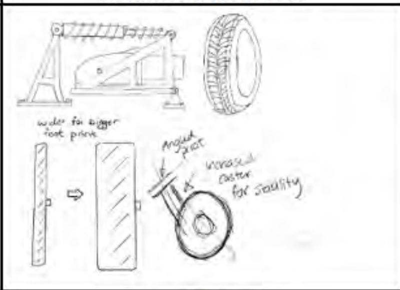
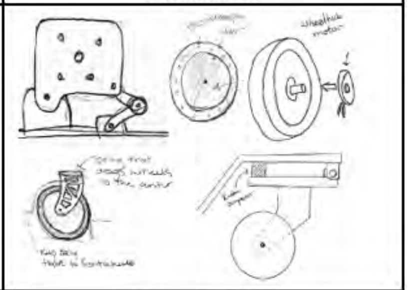
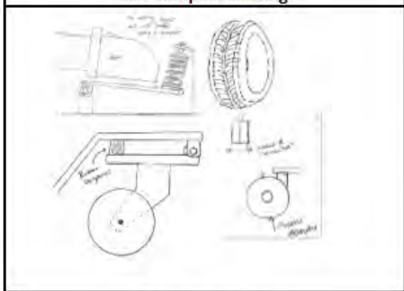
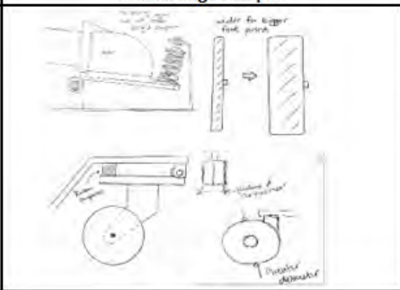
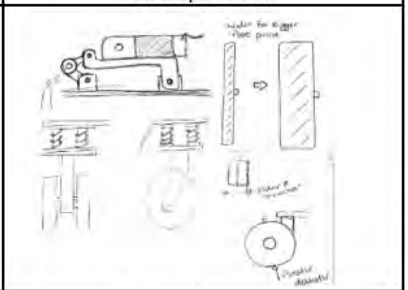
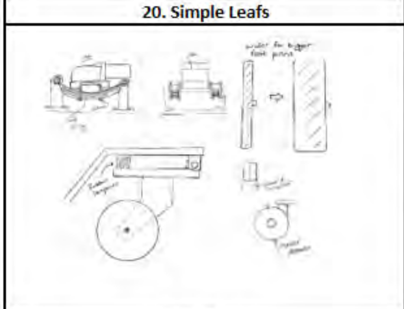
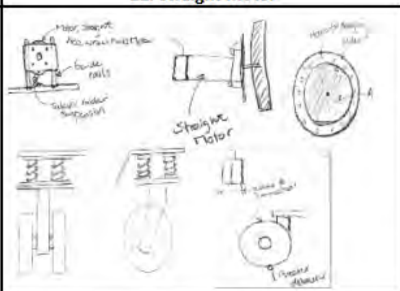
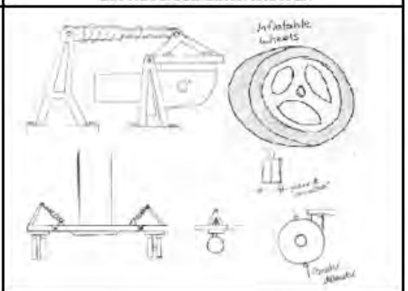
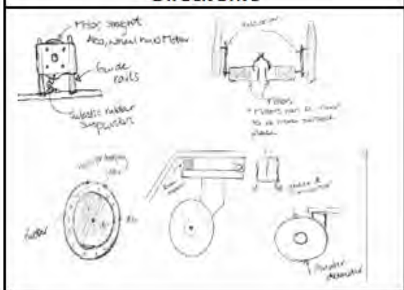
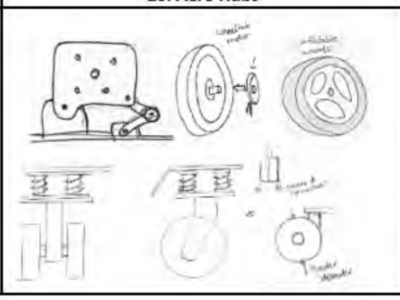
All concepts had to fulfill each criteria, if any concept did not, it was eliminated. If there were any questions or uncertainties regarding a concept, a short research was performed to fill in the knowledge gaps. Most of the knowledge gaps at this point was regarding the cost of different products.

Table 5.3: Elimination matrix

Chalmers		**Elimination Matrix for X-ray Undercarriage**					
Created by: Ola Delfin, Marcus Sandberg		Created: 2017-03-15					
		Modified: 2017-03-21					
		Elimination Criteria				Decision	
		(+) Yes				(+) Continue work on solution	
		(-) No				(-) Eliminate solution	
		(?) Additional information required				(?) Search additional information	
		A: Fulfills the main function					
			B: Fulfills all requirements				
				C: Realistic			
					D: Within the budget		
No.	**Solution**	**A**	**B**	**C**	**D**	**Comment**	**Decision**
1	Torsion	+	+	+	+		+
2	Sulastic	+	+	+	+		+
3	Leafy	+	+	+	+		+
4	Wheelchair	+	-			Stability issues	-
5	Simple Torsion	+	+	+	+		+
6	Almost radical pushrod	+	+	+	+		+
7	Quadpod	+	-			Rear suspension not sufficient stability	-
8	Tire suspension	+	+	+	-	Expensive rear wheels	-
9	Wheelmotor	+	+	+	+		+
10	Reversed motor	+	+	-		Unrealistic front wheels	-
11	The bike	+	+	-		Unrealistic	-
12	Soft wheelchair	+	-			Stability issues	-
13	Built in guidance	+	+	+	-	Too expensive combination of components	-
14	Soft Quadpod	+	-			Rear suspension not sufficient stability & Rear tire expensive	-
15	Compact Existing	+	+	+	+		+
16	Multidirectional Wheelhub	+	-			Multidirectional front wheels not sufficient	-
17	Ultimate space saver	+	+	+	-	Cost issues with rear wheels	-
18	Existing principles	+	+	+	+	The same solution as existing but improved elements	+
19	Simple Sulastic	+	+	+	+		+
20	Simple leafs	+	+	+	+		+
21	Spartan	+	-			Not sufficient suspension	-
22	Straight motor	+	+	+	+		+
23	Reversed lawn mower	+	+	+	+		+
24	Belt drive	+	+	+	+		+
25	Aero hubs	+	+	+	+		+

To make sure that no concept containing good solutions was eliminated, the eliminated concepts were reviewed a second time. As seen in Table 5.3, each of the eliminated concepts received a short comment describing why the concept got eliminated. During the elimination process, 11 concepts were removed and 14 concepts made it through to the next stage. In Table 5.4 the remaining concepts are displayed. These concepts will be compared and evaluated according to certain criteria further on in the Pugh matrix.

Table 5.4: Concepts remaining after elimination

1. Torsion	**2. Sulastic**	**3. Leafy**
		
5. Simple Torsion	**6. Almost Radical Pushrod**	**9. Wheelmotor**
		
15. Compact Existing	**18. Existing Principles**	**19. Simple Sulastic**
		
20. Simple Leafs	**22. Straight Motor**	**23. Reversed Lawn Mower**
		
24. Belt Drive	**25. Aero Hubs**	
		

5.2.2 Pugh Matrix

With the total number of concepts reduced, it became easier to make comparisons between each individual concept through the use of a Pugh matrix. Despite the fact that the elimination matrix removed a substantial amount of concepts, the number remaining was still rather high. Therefore further reduction was required.

For the first iteration of the matrix, the first concept, *Torsion* was set as the reference concept, comparing it with the rest of the concepts considering different criteria. Compared to the elimination matrix, a new set of criteria was used, more suitable for determining whether a concept performs better than another. The criteria used for this iteration along with a brief description are as follows.

- **Cost:** Which concept is estimated to cost less to implement and manufacture.
- **Complexity:** Which concept will be less complex to assemble for SFT.
- **Space Efficiency:** The concept which will occupy less space is favoured.
- **Modification:** The concept which will require less modification on the existing product to fit is favoured.
- **Durability:** Which of the concepts is more likely to withstand the most stress.
- **Maintenance:** Which concept is estimated to require the least amount of maintenance.

The comparison based on these criteria can be seen in Table 5.5 below. As desired, a result from this matrix is that a number of concepts has been eliminated. The reasoning behind the scores of the various concepts follows below, where the explanations have been split up into which concepts performs better, the same, and worse than the reference.

Table 5.5: First iteration of the Pugh matrix

Chalmers	Pugh Matrix - First Iteration													
Created by: Ola Delfin Marcus Sandberg	**Created:** 2017-03-23													
	Modified: 2017-03-27													
	Alternatives													
Criteria	1	2	3	5	6	9	15	18	19	20	22	23	24	25
Cost	Reference	+	0	-	0	-	+	+	+	0	0	0	0	-
Complexity		-	-	+	-	-	0	+	0	-	-	-	-	0
Space efficiency		-	-	0	-	+	0	0	-	-	-	-	0	+
Modification		+	-	-	0	-	+	+	+	-	-	-	-	-
Durability		0	0	-	0	0	-	0	-	0	-	0	0	-
Maintenance		0	0	-	0	0	0	0	0	0	0	-	-	-
Sum +		2	0	1	0	1	2	3	2	0	0	0	0	1
Sum 0		2	3	1	4	2	3	3	2	3	2	2	3	1
Sum -		2	3	4	2	3	1	0	2	3	4	4	3	4
Net Value	0	0	-3	-3	-2	-2	1	3	0	-3	-4	-4	-3	-3
Ranking	3	3	5	5	4	4	2	1	3	5	6	6	5	5
Further Development														

Alt.	Concept name
1	Torsion
2	Sulastic
3	Leafy
5	Simple Torsion
6	Almost Radical Pushrod
9	Wheelmotor
15	Compact Existing
18	Existing Principles
19	Simple Sulastic
20	Simple Leafs
22	Straight Motor
23	Reversed Lawn Mower
24	Belt Drive
25	Aero Hubs

- **Cost:** The concepts receiving better scores are using suspension elements which are considered to have a smaller cost than the torsion suspension, which is bought in as a finished component. These are for example rubber dampeners as well as spring and gas dampeners, due to the low number of components. The concepts that received a zero in the matrix either consist of the same kind of pre-built suspension element or utilizes components that are considered to cost the same. Finally, the concepts that got a minus are concepts with higher complexity or with many additional parts. This also includes the wheel motor concepts as these are considered more expensive to implement due to the different motor type.

- **Complexity:** The *Simple Torsion* concept is considered less complex than the reference since it uses the same suspension element for the rear wheels and a pre-built suspension element for the front wheels which makes it easy to assemble. Similar reasoning applies for concept *Existing Principles*, which fundamentally uses the same suspension layout as the existing solution, with the only difference being that the suspension elements have been changed from rubber dampeners to springs and gas dampeners, with a pre-built solution for the front wheels. The concepts that got the same score as the reference are concepts with similar complexity, which uses the same amount of pre-built suspension elements as the reference. For example, concept *Compact Existing* uses a pre-built solution for the front wheel suspension and a self assembled solution for the rear wheels. The concepts considered to be more complex are concepts which utilizes a large number of components required to be assembled by SFT. There are a high number of these in the Pugh matrix, as the reference is using a low number of components, and the ones included are considered easy to assemble.

- **Space efficiency:** The only concepts that were considered to be more space efficient than the reference was concepts *Wheelmotor* and *Aero Hubs*. The reasoning behind this was that the motor is integrated in the wheel, clearing up space inside the machine. Many concepts were considered less space efficient since they utilize more mechanical components which will take up space within the machine.

- **Modification:** The concepts requiring less modification than the reference are the ones which to a large extent can reuse existing components for the new solution. For example, concept *Compact Existing* and *Existing Principles* primarily uses the existing suspension layout, but changes the suspension element. While concept *Sulastic* and *Simple Sulastic* uses slightly modified versions of the existing suspension components, compared to the reference which introduces a new type of component. Concept *Almost Radical Pushrod* was the only concept considered to require the same amount of modifications to fit the machine. Even though it requires more space the rear suspension can be assembled as a stand-alone system and mounted to the device, comparable to the reference. The majority of the concepts required more modifications to fit the machine. For example, the leaf springs in concept *Leafy* and *Simple Leafs* might require adjustments to work as intended. The front wheel suspension in concept *Simple Torsion*, *Straight Motor*, *Reversed Lawn Mower* and *Aero Hubs* is a completely new principle of suspension, which in turn requires more modifications. Introducing new types of motors and their placement, as for concept *Wheelmotor*, *Straight Motor*, *Belt Drive* and *Aero Hubs* is also an aspect which is considered to require more modifications.

- **Durability:** A lot of concepts ended up in the same level of performance. It was mainly due to the concepts being early in the development phase making it hard to evaluate the final durability of the concepts. All concepts that was deemed less durable utilized the same front wheel design. This concept was seen as less durable since it is not as stable as the other solutions leading to a larger risk of fatigue.

- **Maintenance:** Most of the concepts require the same amount of maintenance as the reference since all of them consist of long lasting components. These components are assumed to be able to have a consistent performance for a long time. Concepts which would require more maintenance than the reference are the concepts which utilizes wheels filled with air, since these needs to be refilled periodically. It also includes the concept using a belt drive, since the belt might need increased tension or replacement with time.

Important to note is that the concepts removed were considered inferior to the rest of the concepts evaluated. The first iteration of the Pugh matrix resulted in the removal of 5 concepts. Concept 5, *Simple Torsion* was eliminated due to the fact that by changing the elements receiving bad scores it would fundamentally turn into a very similar concept to concept 1, *Torsion*. Concept 3, *Leafy* and 20, *Simple Leafs* both uses a unique type of rear suspension which is considered to have a high potential even though the concepts received underwhelming scores. Due to its potential, it was desirable to keep at least one concept using leaf springs. Since both concept 3 and 20 are very similar, the decision was made to keep concept 3 and eliminate concept 20, due to the rear wheels of concept 3, *Leafy* that were considered more favourable. Similar reasoning was used while deciding to keep concept 24, *Belt Drive*. It allows for of the motors to be placed in another location and additional gears would be easy to incorporate. By relocating the motor, space for other components could open up. Concept 25, *Aero Hubs* was eliminated since there is another similar concept with better scores, concept 9, *Wheelmotor*.

A second iteration of the Pugh matrix was performed with the winner from the first iteration used as a reference. However this iteration did not provide enough decision grounds to further reduce the number of concepts. It was realized that concept number 15, *Compact Existing* seen in Table 5.4 could be eliminated due to it being very similar, while still scoring less than number 18, *Existing Principles* which was the winning concept in the first Pugh iteration. The main difference in score was dependent on the front suspension, changing this on concept 15 would turn it into concept 18.

5.2.3 Concept Testing

In order to create a deeper understanding for further evaluation with the Kesselring matrix, testing of a number of the principles in the remaining concepts was performed. The performed tests were primarily conducted in order to clear out uncertainties regarding if these principles would work for this type of application and how realistic they are. The principles tested were as follows.

5.2.3.1 Pushrod Suspension

The test covered if the principle could be used in the restricted space available in the device, and if the principle of horizontal suspension provided enough suspending properties. It was carried out by simple paper prototypes, illustrated in Figure 5.2, the model proved the principle feasible. By moving the connection point between the suspension element and the holder along the y-axis, the suspension element would travel different distances in order to obtain the same suspension properties.

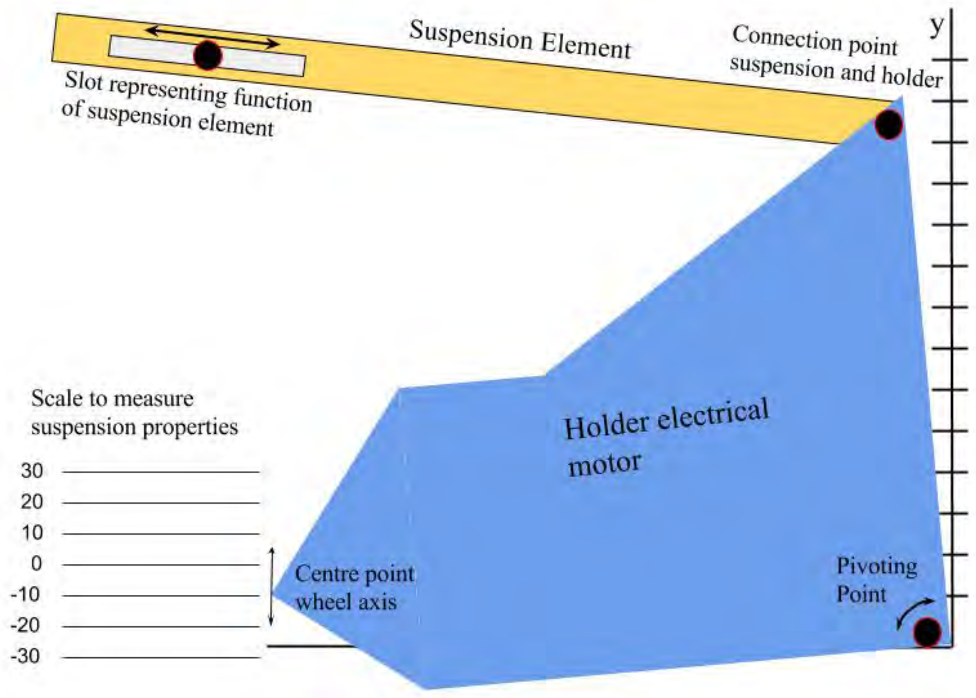


Figure 5.2: Prototype of the principles of the pushrod suspension

The outcome of the test was that the principle of horizontally mounted suspension element is feasible but it will need to be adjusted to fit into the small space available in the machine. It is however easy to change the dampening properties by just changing the dimensions of the suspension element or its placement.

5.2.3.2 Levered Rubber Dampening

The test evaluated if the principle of introducing a lever to push down on rubber dampeners will provide better vibration dampening and wheel articulation, and if it is feasible as a suspension element. This principle is represented in the concept generation and selection sections as the *Sulastic* suspension element. The prototype was created out of simple aluminum profiles, joined together with hinges to allow for a pivoting movement. In between the moving profiles, a rubber dampener was placed, which is compressed when adding a load. It is a simple principle, which means that it was implemented in a small scaled version of a chassis to test its behaviour. The prototype can be seen in Figure 5.3.

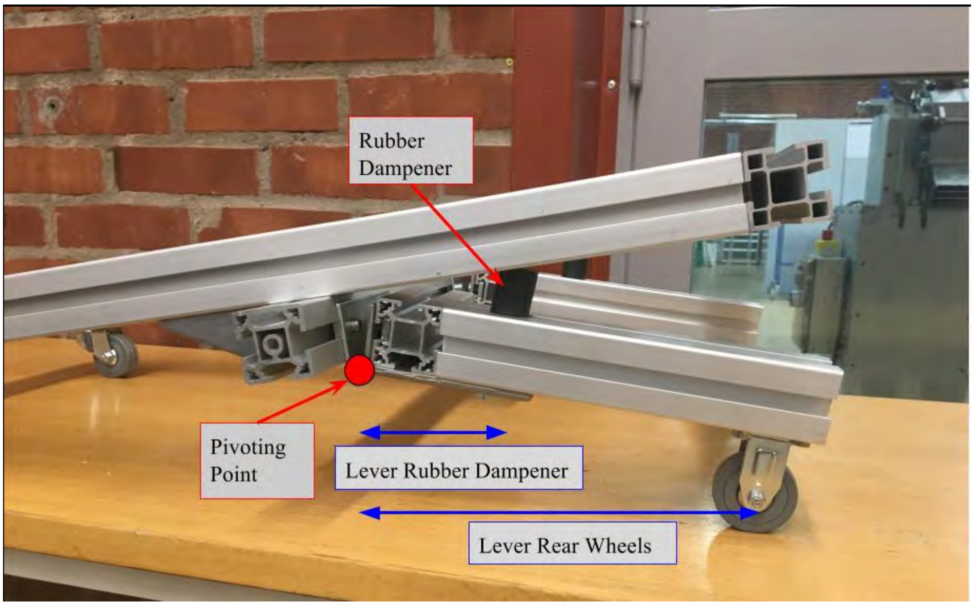


Figure 5.3: Prototype of the principles of the levered rubber dampning

This type of principle proved to be an efficient suspension element. It is a relatively inexpensive and simple construction that also provides good wheel articulation and vibration dampening. The amount of wheel articulation is possible to modify by increasing or decreasing the distance between the pivoting point and the rubber dampener. Placing the rubber dampener closer to the pivoting point puts a larger load on the dampener, compressing it more, and therefore providing more wheel articulation.

5.2.3.3 Varying the Caster Angles

To make the machine more stable when driving up ramps, a principle that makes the caster rotate around an axle that not is perpendicular to the ground was examined. By altering this angle, the machine will self align and automatically try to keep the machine moving in a straight line. As seen in Figure 5.4, the principle was tested on the same platform as the prototype for the levered rubber dampening. The reason behind this is that the caster angle can be changed simultaneously as the dampening properties of the suspension by simply changing the position of the rubber dampener, which raises or lowers the rear end of the chassis.

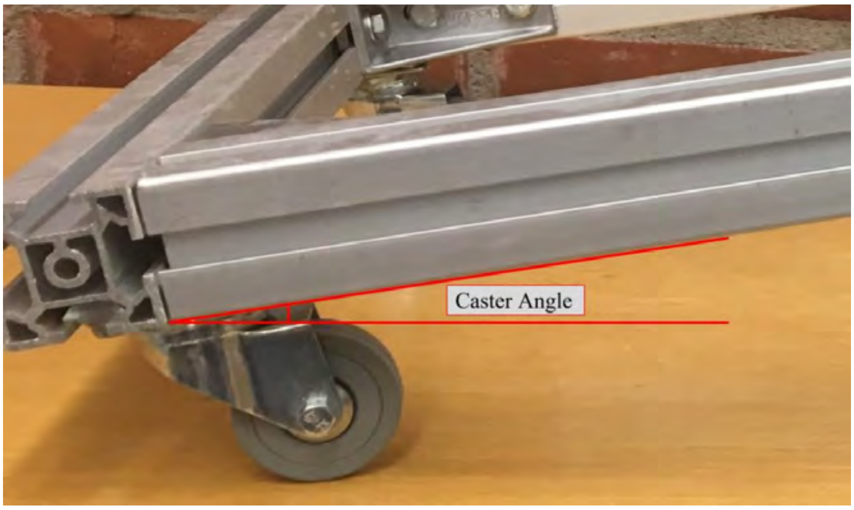


Figure 5.4: Prototype testing the effects of an increased caster angle

The principle worked as planned and always attempted to make the machine move in a straight line. The problem that occurred was that the machine became difficult to turn since the wheels needed to push the whole machine up when turning. In order to minimize this problem, the angle of the axis could be altered. On the other hand, this also minimized the effect of the self aligning properties of the principle.

5.2.3.4 Coupled Rear Suspension

The rear wheels in the prototype for the levered rubber dampener was initially independently suspended. However, it was desirable to investigate how the dampening properties were influenced if the movement of the wheels depended on each other.

The primary outcome of the comparison between coupled and independent suspensions was that the coupled suspension tends to be stiffer than the independent, since the force applied will affect both sides no matter where it is applied. The independent suspension will flex differently depending on where the load is applied. An independent suspension will try to push both rear wheels into the ground while keeping the device leveled, even over uneven surfaces. On uneven surfaces, the coupled suspension will make the device follow the movement of the suspension, even if it will make the device tip over.

5.3 Kesselring Matrix

With the acquired results and knowledge from the tests performed, a Kesselring matrix was created to further narrow down the number of alternatives. Before the matrix was conducted, concepts involving the changed caster angles on the front wheels were modified to not include these, as the tests already proven these insufficient. Therefore, there was no risk that the changed caster angle would be the cause of a concept being removed. At this stage, all concepts were equipped with larger front caster wheels than the present model as these allows for better off road capabilities. It became apparent that the main aspect differentiating the concepts was the rear wheel suspension, which is why focus has been put on this aspect during the evaluation.

The criteria used while evaluating the concepts are mentioned below, together with a brief description and explanation of their appointed weights. The criteria used are covering several important areas occurring in the Specification of Requirements.

- **Stability while driving:** How well will the undercarriage provide a stable ride across uneven surfaces. A very important criteria as it is crucial that the device does not turn over, giving it a weight value of 5.

- **Stability during examination:** How stable is the device while in examination mode, with the arm extended. Also a very important criteria as it is crucial that the device does not turn over, once again receiving a weight value of 5.

- **Shock absorption:** How well does the suspension react to sudden impacts caused by obstacles. Not as important as the device should not intentionally be driven into obstacles on a daily basis, however it should still be able to handle these, due to the lower level of importance, the criterion receives a weight of 3.

- **Vibration absorption:** How well the suspension prevents vibrations from spreading into the rest of the device. An important aspect, not only to protect the components of the device, but also to provide a pleasant driving experience, giving it a weight of 4, higher than the shock absorption criterion.

- **Maintainability:** How long time it is estimated to take in order to access and maintain components included in the undercarriage due to their configuration. A rather important aspect, however it is not crucial, therefore receiving a weight of 3.

- **Assembly:** How long time it is estimated to take to assemble the components of the undercarriage due to their complexity and placement. As opposed to the maintainability, the removal of components and reassembly is not necessarily happening on an otherwise complete product, but rather when the base plate is easily accessible. It is however an advantage, giving it a weight of 3 due to not being crucial.

- **Cost:** How much is the undercarriage estimated to cost, only applies to deviating parts of the undercarriage such as suspension elements, elements common for all configurations are not considered. The device in general is rather expensive, therefore keeping costs low is important, which is why the criterion is weighted with a value of 4.

- **Space efficiency:** How well will the new components of the undercarriage utilize the space previously occupied by the old components. There are available margins to increase the dimensions of the device if necessary, according to the Specification of Requirements. It is desirable to keep the changes in dimensions low, giving it a weight of 3 due to the possibility to change dimensions.

Table 5.6 illustrates how the score is applied to each concept based on different scales. Due to the early stage of the concepts, some of the intervals in 5.6 are rather wide since it is hard to get exact numbers regarding their performance.

Table 5.6: Scales for the Kesselring matrix

	1	2	3	4	5	Scenario/Explanation
Stability when driving	Bad	Mediocre	Acceptable	Good	Excellent	General off road driving
Stability while examination	Falls over if additional force applied	Heavy tilting	Acceptable tilt	Minor tilt	No tilting	While in worst arm position during examination
Shock absorption	Bad	Mediocre	Acceptable	Good	Excellent	Recovery from hitting an obstacle in max speed
Vibration absorption	Bad	Mediocre	Acceptable	Good	Excellent	
Mainatinability	121+	61-120	31-60	11-30	0-10	Time [min]
Assembly	121+	61-120	31-60	11-30	0-10	Time [min]
Cost	7501+	5001-7500	3001-5000	1001-3000	0-1000	SEK
Space efficiecy	Bad	Mediocre	Acceptable	Good	Excellent	

Backed up by the performed tests, both in terms of objective results and subjective understanding, the concepts were evaluated based on each established criterion. The resulting scores, rankings, and eliminations are illustrated in Table 5.7. The numbers representing the various concepts evaluated are corresponding to the numbers used in the Pugh matrix, Table 5.5.

Table 5.7: First iteration of the Kesselring matrix

Chalmers		Kesselring Matrix															
Created by: Ola Delfin, Marcus Sandberg		Created: 2017-05-02 Modified: 2017-05-02															
				Concepts													
Criteria		Ideal		1		2		3		6		9		18		24	
	w	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t
Stability when driving	5	5	25	4	20	4	20	4	20	4	20	4	20	2	10	3	15
Stability during examination	5	5	25	3	15	4	20	3	15	3	15	4	20	4	20	4	20
Shock absorption	3	5	15	4	12	4	12	3	9	4	12	4	12	2	6	3	9
Vibration absorption	4	5	20	4	16	4	16	3	12	3	12	4	16	3	12	4	16
Mainatinability	3	5	15	4	12	4	12	3	9	3	9	3	9	4	12	3	9
Assembly	3	5	15	4	12	4	12	3	9	3	9	3	9	4	12	3	9
Cost	4	5	20	4	16	4	16	4	16	3	12	2	8	3	12	4	16
Space efficiecy	3	5	15	4	12	4	12	4	12	2	6	4	12	3	9	3	9
Total		40	150	31	115	32	120	27	102	25	95	28	106	25	93	27	103
Relative total		1,00	1,00	0,78	0,77	0,80	0,80	0,68	0,68	0,63	0,63	0,70	0,71	0,63	0,62	0,68	0,69
Ranking			IDEAL	2		1		5		6		3		7		4	

To get a better view of the thought process behind the established scores in the matrix, a description of the reasoning for each criterion is illustrated below.

- **Stability when driving**
  As seen in the tests, the current solution did not perform well in off road driving. Concept 18, *Existing Principles* which has many similarities with the existing solution, with only the suspension elements differentiating. It was assumed to behave similarly, with a few differences in wheel articulation, thus resulting in a low score. Moreover, concept 24, *Belt Drive* has quite a weak mechanical structure with a low articulation giving it a lower mark in this area. The rest of the concepts have a similar performance to each other, with the potential to provide approximately the same articulation and vibration dampening. This behaviour allows them to provide a more stable ride.

- **Stability during examination**
  Concept 1, *Torsion* and concept 6, *Almost Radical Pushrod* are assumed to have a greater articulation than the rest of the concepts which is preferable when driving off road. However it will give a more unstable machine when moving the arm during examinations due to the high moment caused when extending the arm sideways. Also concept 3, *Leafy* received a lower score since the leaf springs would take longer time to settle due to movements caused by the telescopic arm. Even though concept 9, *Wheelmotor* and 24, *Belt Drive* are similar to concept 2, *Sulastic* regarding the suspension of the machine, the load from the arm will compress the holes in the rubber tires. This in addition to the suspension will cause the device to tilt even more sideways, making it more unstable in this situation. The suspension in concept 18, *Existing Principles* does not posses a large articulation leading to a stable machine, however it is still more unstable than the current version during examination due to the new suspension elements. Concept 2, *Sulastic* got a high score due to the tests revealing that the suspension is simple to adjust for good stability during stationary conditions.

- **Shock absorption**
  The low score given to concept 18, *Existing Principles* was motivated by the reasoning that in the occurrence of an impact, the low wheel articulation of the suspension would cause the entire machine to be affected by the impact. The reason to give concept 3, *Leafy* a rather low score was that even though leaf springs are likely to handle a shock well, it would put the machine into an oscillating motion due to the impact. The score given to concept 24, *Belt Drive* was due to the rear suspension layout being less robust, which would make it less effective at handling impacts, together with a belt drive where one end of the belt connection is not suspended. Concepts 1, *Torsion*, 2, *Sulastic*, 6, *Almost Radical Pushrod* and 9, *Wheelmotor* received good scores in this criterion since they all provide sufficient wheel articulation during the impact, while also having elements which can dampen the oscillating motion.

- **Vibration absorption**
  The rubber dampening in concept 1, *Torsion* 2, *Sulastic*, 9, *Wheelmotor* and 24, *Belt Drive* will provide the machine with a satisfying reduction of vibrations. This is mainly due to the material properties of the rubber that effectively absorbs these vibrations. Concept 3, *Leafy* will still manage the vibrations in an acceptable way

but the leaf springs will take longer time to settle which leads it to a lower mark. Concept 6, *Almost Radical Pushrod* and 18, *Existing Principles* utilizes a gas dampening solution where the possibility to reduce small vibrations in a longer time frame is uncertain.

- **Maintainability**
The maintainability of a concept was based on the removal and reassembly time of the differentiating components of the concept. Concept 1, *Torsion*, 2, *Sulastic* and 18, *Existing Principles* were assumed to require 11-30 minutes to maintain. The reasoning behind this is that these concepts consists of compact assemblies which are easily accessible by simply removing the side panel of the device. Due to being compact, they can be removed without disassembling surrounding components. The remaining concepts were estimated to require 31-60 minutes for maintainability for a number of reasons. Concept 3, *Leafy* and 6, *Almost Radical Pushrod* consists of a large amount of components, which would require more space to reassemble due to the various elements included Therefore requiring surrounding components to be removed as well, increasing the time of maintenance. The wheel hub motor of concept 9, *Wheelmotor* together with the mounting of this is assumed to require more time to maintain since it would require access both in front and behind the mounting plate. With restricted access inside the device, this would take more time to achieve. The belt configuration of concept 24, *Belt Drive* is also assumed to take longer time, primarily the reassembly of the belt and its components in such a restricted space.

- **Assembly**
The evaluation of the assembly time of the various concepts was done through a number of assumptions. The scores for the different concepts was the same as for maintainability, but with differentiating reasoning behind the scores. Concept 1, *Torsion*, 2, *Sulastic* and 18, *Existing Principles* received high scores due to the fact that they are utilizing a low amount of components. The components included are also simple to assemble, therefore the assembly time is estimated to only require 11-30 minutes. Remaining concepts were estimated to require 31-60 minutes. The leaf spring configuration of concept 3, *Leafy* was assumed to require a longer assembly time since the springs are required to be aligned, both in relation to each other, and mounted in place. Concept 6, *Almost Radical Pushrod*, which utilizes a horizontal spring and dampener would require more time due to the complexity of the configuration, together with the high amount of components included. The same reasoning was used for concept 9, *Wheelmotor* and 24, *Belt Drive* with regards to complexity and number of components.

- **Cost**
At this stage in the thesis, exact cost of the various concepts were difficult to establish. However, since it still is an important aspect to consider, assumptions regarding the cost range of the concept was used during the evaluation. The estimations were regarding the cost of purchasing finished solutions such as the torsion dampener in concept 1, *Torsion* or components such as rubber dampeners, the manufacturing of various components such as the holders for the rubber dampeners for concept

2, *Sulastic* among other considerations. From this criteria, concept 9, *Wheelmotor* stands out significantly as receiving bad scores. The reason behind this is that wheel motors were found to be expensive compared to regular motors present in the rest of the concepts.

- **Space efficiency**
  Since there is a limited amount of space inside the machine, concepts requiring less space received a better score. Concept 1, *Torsion*, 2, *Sulastic* and 3, *Leafy* were assumed to not require any significant modification to the surrounding components within the device, therefore receiving a good score. They still require more than the current solution, which is why they did not receive top scores. Concept 9, *Wheelmotor* received the same score with the reasoning that the major parts of a wheel motor would be mounted on the wheels, outside the device. Therefore only the mounting point for the wheels would be required to be placed inside the device. However, the mounting point would still require a certain amount of space inside due to it being required to withstand the loads of the device, giving it the same score. Even though concept 18, *Existing Principles* utilizes the same principles as the existing solution, the suspension elements would be significantly larger than the rubber dampeners currently used, resulting in a lower score. Concept 24, *Belt Drive* also received a lower score due to the belt configuration would require some modifications inside the device in order to fit. Concept 6, *Almost Radical Pushrod* stands out due to it requiring significant modifications inside the device to fit due to its size.

It became apparent from the Kesselring matrix that concept 1, *Torsion* and 2, *Sulastic* received a remarkably higher score than the rest, therefore the decision was taken that these proceeds to further development. It was however more difficult to choose a third concept, as the ones obtaining the ranks 3 to 5 got very similar total scores. Eventually, concept *3-Leafy* was chosen as the third and final concept to work further with. It was chosen as it has potential and adjustments in suspension properties could be made without significant modification by changing the number or dimension of the leaf springs. Even though the rest of the concepts had potential as well, there were some reasons for them to be eliminated. A number of motivations to why follows below.

6 - Pushrod: This concept requires a large amount of space in its conceptual configuration. It would most certainly not fit into the machine without major modification. The idea of installing the suspension element in another orientation than the conventional could prove useful in a later stage however.

9 - Wheel Motor: The introduction of a wheel hub motor into the system would require a large amount of changes, not only mechanical configuration, but also in the electric control of the device. A new type of brakes would also be necessary to be introduced. Due to uncertainties regarding whether this solution would actually save a significant amount of space, it was deemed that using the same, or a similar motor to the current one was preferable. Introducing a new type of motor would also affect costs significantly, as SFT currently has an established supplier of electrical motors. It is an interesting concept and could possibly be utilized in a future model of the device.

18 - Existing Principles: This concept received a relatively low score. Even though it has a high level of similarities to the existing solution, it would require a significantly larger amount of space to install. In addition, due to the current solution having insufficient suspension properties, it was deemed having less potential than the rest.

24 - Belt Drive: Including a belt drive system would add unnecessary complexity to the solution. However, the idea of placing the motor somewhere else inside the device is interesting and has the potential to return if later findings reveals that this is necessary.

With three concepts identified to have the highest potential in fulfilling the tasks at hand, these were subject for further development on a more detailed level to evaluate their performance.

6

Detailed Development

Out of the original 25 concepts, three concepts remained after the previous phase. These three concepts needed to be evaluated on a more detailed level to find the best solution for the desired application. Depending on the complexity of the concept, different evaluation methods were chosen. The methods used were both physical prototype tests together with simulations and fem models.

6.1 3D-Models

When evaluating different concepts it is important that they are equally developed and on the same readiness level, otherwise it could lead to an unfair comparison of the concepts. By making 3D-models of the components for each concept, this problem is minimized. Moreover, the real size 3D-models will increase the understanding of the concepts and the possibility to see if the components will fit together with the rest of the machine.

6.1.1 Leafy

The Leafy concept is based on leaf springs arranged in such way that they absorb the vibrations and shocks that will appear when driving the x-ray device. Each leaf spring assembly contains two leaf springs. The reason behind this is to increase the stability of the spring when the machine is exposed to side forces. With a larger distance between the springs, the larger side forces will the machine be able to handle. To obtain the desired articulation of the wheel, the leaf spring needed to be at least 160 mm long. However, the limited space in the machine also limited the possible length and width of the spring. When designing the thickness of the springs, several simulations were performed to find a thickness that provided a satisfying articulation. The thickness chosen was 2 mm, which gave a total wheel articulation of 20 mm calculated from an unloaded spring to a spring loaded with twice the weight of the device. This load is used since it is the estimated maximum load occurring due to impacts. The base of the leaf spring is welded onto the base plate and the motor is fastened to the motor bracket as seen in Figure 6.1

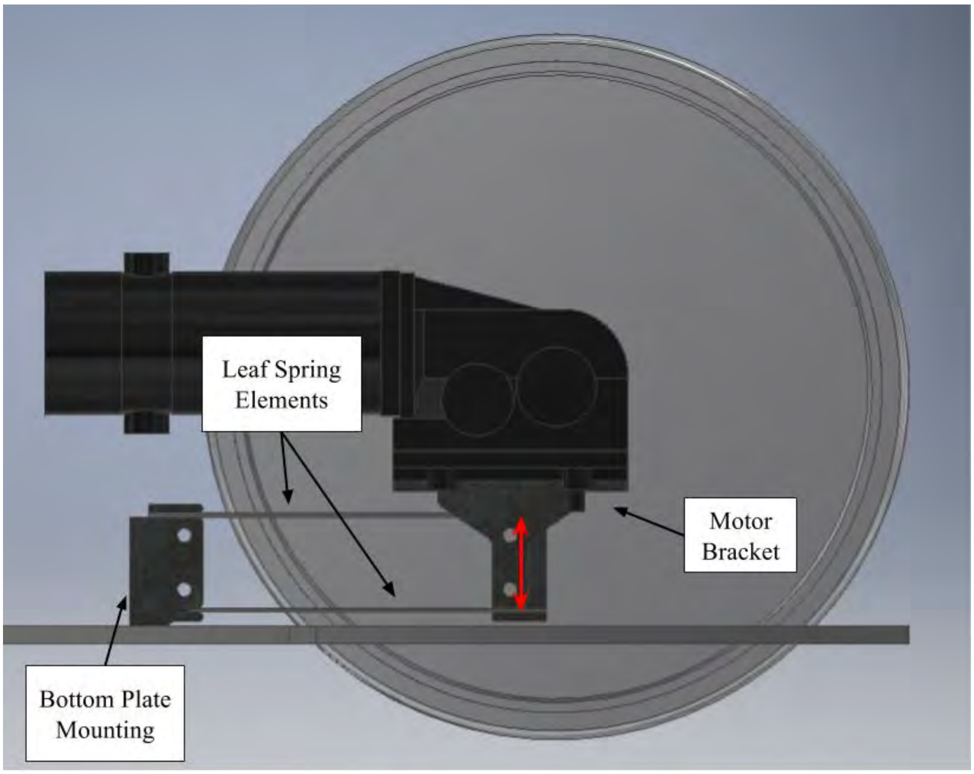


Figure 6.1: The leaf spring suspension mounted on the bottom plate

This model was later used for simulations regarding material choice for prototyping. The design was chosen to be easily manufactured and assembled by SFT as it can be installed to the device as a unit. The components included are made out of steel with simple geometries simplifying assembly.

6.1.2 Sulastic Dampener

The principles behind the Sulastic dampener is that the motors and wheels are mounted on top of a platform which is allowed to pivot around an axis. On the other side of the pivoting point are a number of rubber dampeners installed which handles the load of the device. By utilizing the lever effect, visualized in Figure 6.2, the placement of the dampeners determines how much wheel articulation the wheels will experience and how much load the dampeners are exposed to.

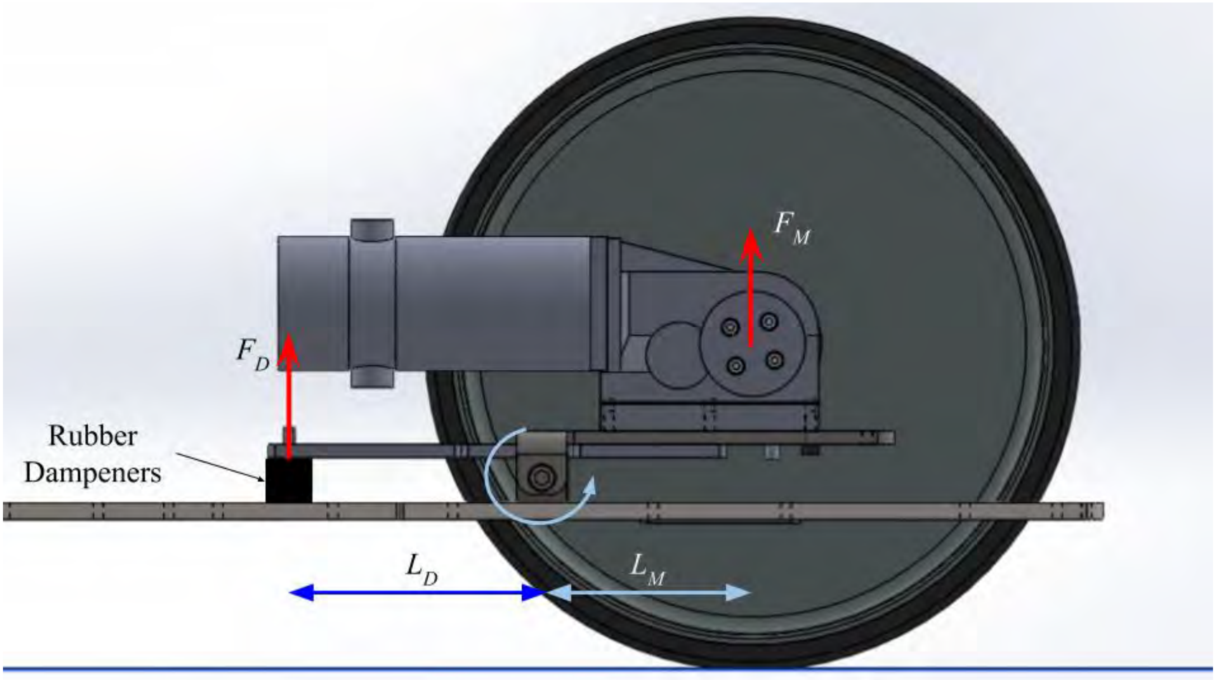


Figure 6.2: The Sulastic principles applied for the prototype

The prototype of this concept has mounting points for four rubber dampeners, designed with the intention to be able to move the dampeners closer to the pivoting point. It allowed for identifying the behaviour of the system due to different positions of the dampeners. The component created is seen in Figure 6.3. The intention was to use the threaded mounting holes on the motor to secure it to the device, enabling a fast installation without the need to modify any parts of the device.

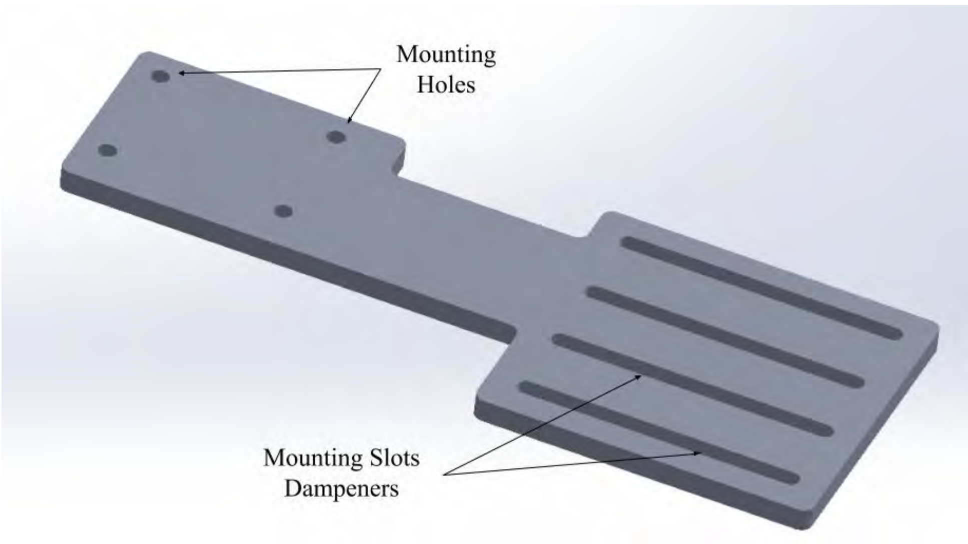


Figure 6.3: Component used to test the Sulastic concept

6.1.3 Torsion Dampening

The Torsion dampening utilizes a vibration dampener bought as an assembled unit. It is therefore easy to mount onto the existing base plate. The only modification required was a couple of holes drilled in the base plate and the vibration dampener. The dampener is designed for a load of 750-2000 N and to have a rated articulation of 19 mm when exposed to its max load. The Torsion dampener has a rubber center that combined with a square metallic structure allows the component to absorb vibrations through a pivoting movement. Figure 6.4 illustrates the principle of how the suspension element works. The basic idea is that when a force is applied on top, as indicated by F in the figure, the pivoting axes will rotate, thus compressing the component. Simultaneously, the motion is dampened by the rubber dampeners which are surrounding the pivoting axes, creating a dampened motion.

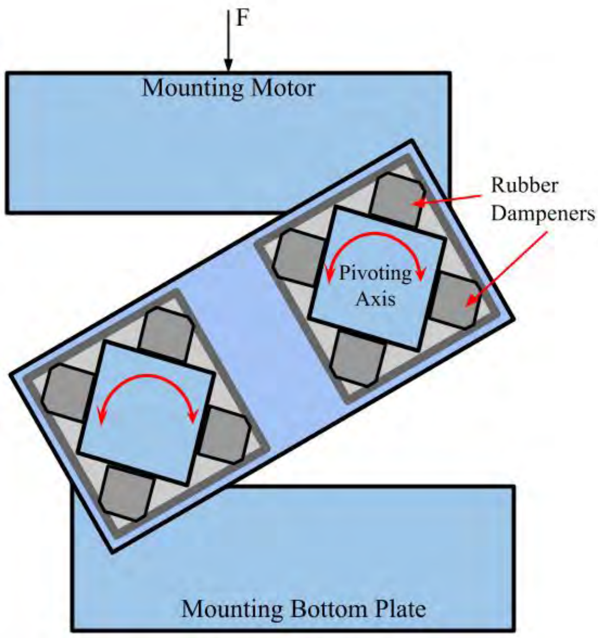


Figure 6.4: The principles of the Torsion dampening element applied for this prototype

Figure 6.5 illustrates the suspension element mounted on the bottom plate with motor and wheel.

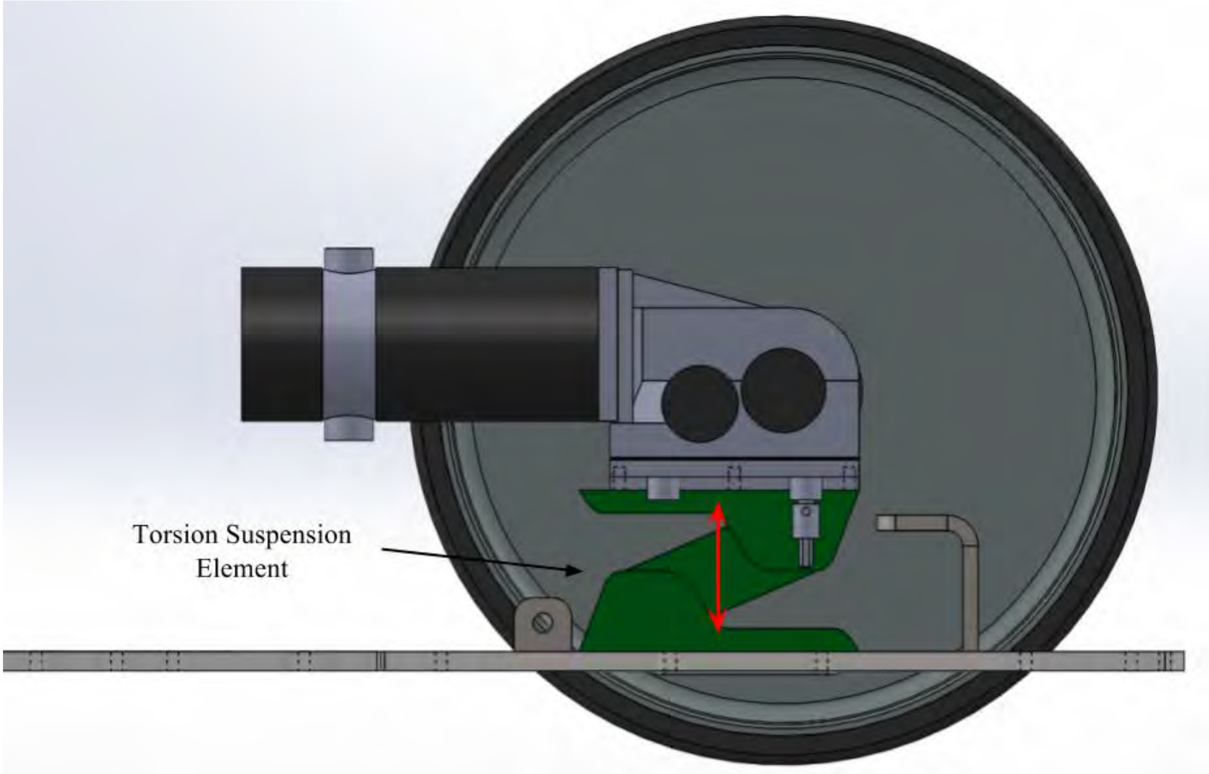


Figure 6.5: The Torsion suspension element applied for the prototype

6.2 Concept Testing

As stated above, different evaluation methods were chosen depending on the complexity of the concepts. Although it would be beneficial to test all concepts with real physical prototypes, the complexity and time needed to test the Leafy concept made simulations an appropriate evaluation method.

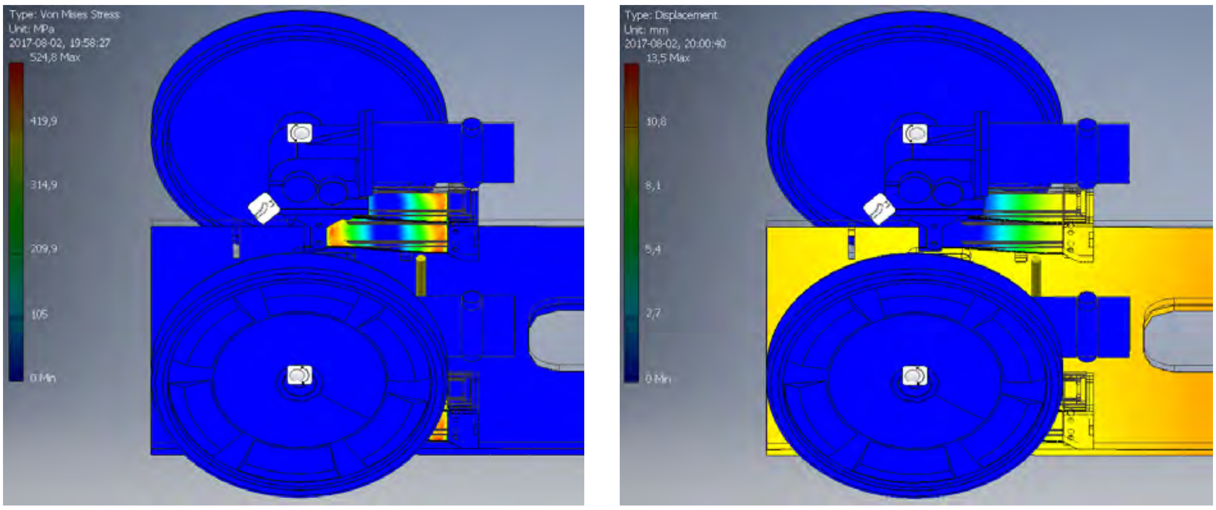
6.2.1 Simulations

Simulation is an alternative method to use when the complexity of a concept is high and therefore hard to prototype during the time frame of a project (Ulrich & Eppinger, 2012). It enables for complex stress analysis providing data for the components that can be hard to measure when using real prototypes or performing hand calculations, (Liu & Quek, 2014). The Leafy concept therefore fitted perfectly for simulations since the simulations will provide accurate approximations of the stresses inside the structure and behaviour of the structure, which can be used to evaluate the feasibility of the concept. The data of the stresses in the structure will also be used to select a material for the springs that can handle the loads.

6.2.1.1 Leafy

To obtain the desired articulation of the suspension and still fit within the device, the leaf springs had to have a certain length. If the springs are to short they will not provide enough articulation but if they are too long, they will not fit inside the device. To improve the stability of the leaf springs when encountering side forces, two springs were mounted on top of each other, with some space in between. This influenced the height of the suspension, changes would therefore be required to the base plate in order to install the suspension. The solution also requires a many components which gives it a high complexity.

The simulations were performed primarily at two different loads, the first involved a 1800 N load on the bottom plate to represent the weight which the device itself puts on the rear wheels. The second load was 3000 N to represent the load occurring due to passing over an obstacle during driving. Figure 6.6 illustrates the case with 1800 N loaded on the base plate, both the max stress occurring and the deformation of the springs. The simulations of the suspension show that the suspension would work with a sufficient amount of articulation. Although, the stresses within the springs became very high. Finding a material able to handle these stresses turned out to be a hard task and only specific high strength steel specifically designed for springs would prove sufficient. The most suitable material found was a austenitic stainless steel with EN number 1.4310. This steel has a tensile strength of 1700-2050 MPa (Sandvik AB, 2017), but due to the high stresses in the springs, the safety factor towards failure was low even with this material. As seen in Figure 6.6, with a load of 1800 N applied the maximum stresses occurring are 525 MPa. These stresses are already above or on the same level of the strength limit of regular carbon steel, being between 240 and 550 MPa (Sundström, 2010).



(a) Von Mises Stress

(b) Deformation

Figure 6.6: FEM analysis of the rear leaf suspension exposed to a 1800 N load on the base plate

The Leafy solution would need a long implementation time and further endurance tests would need to be performed. Also tests to find the right characteristics of the suspension would be required. Due to behaviour of leaf springs they would need a complementary dampening system reducing the oscillations of the springs.

6.2.2 Physical Testing

The physical testing provides a hands on experience for the developers. Therefore, it is a simple way to create an understanding of how the concept works and a way of evaluating its general characteristics, (Ulrich & Eppinger, 2012). Concepts tested with physical prototypes were the Sulastic dampening, the Torsion dampening and the front wheel assembly. The physical tests were performed with the intention to observe the general behaviour of the prototypes in order to create an understanding of how well they would perform in a finished product.

6.2.2.1 Sulastic Dampening

The installation of the Sulastic dampening prototype went easily. In Figure 6.7 it can be seen installed to a bottom plate together with a motor and wheel. Thanks to the dampener slots previously mentioned, the distance between the rubber dampeners and the pivoting point could be changed to easily achieve different behaviours of the device. This made the prototype flexible and allowed for the evaluation of different suspension properties. Due to the prototype utilizing existing components included in the suspension, the ground clearance of the device remained approximately the same. If desirable, the ground clearance was possible to be increased by simply raising the rubber dampeners, which in turn tilts the wheel down towards the ground. It could also be achieved by installing taller rubber dampeners than the ones currently used.

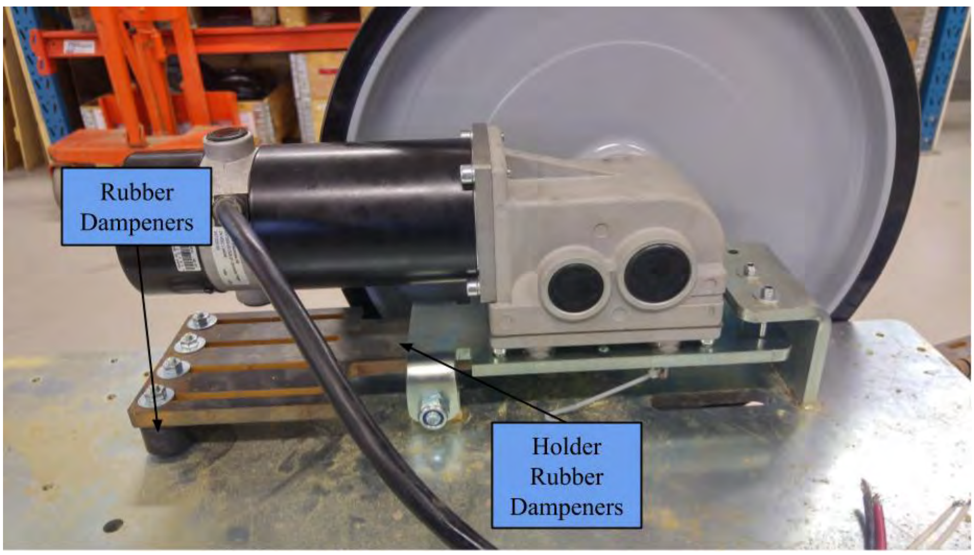


Figure 6.7: Sulastic dampening solution mounted on the bottom plate

The tests on the Sulastic dampening prototype were performed to determine its potential. The purpose was primarily to identify the behaviour when driven over various surfaces and with differently positioned dampeners. By installing the solution on top of the base plate together with a pair of front wheels, the principle could easily be tested outdoors. The setup can be seen in Figure 6.8.

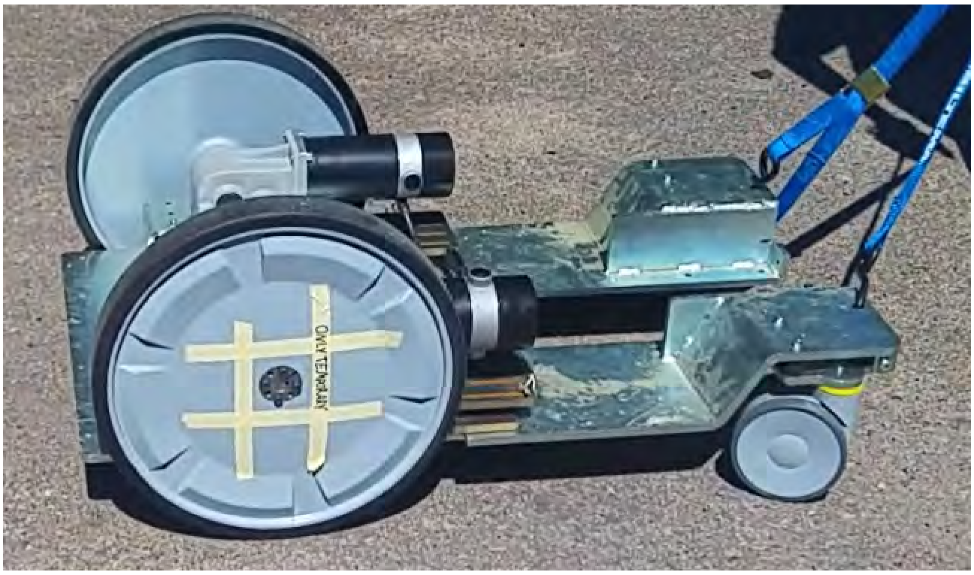


Figure 6.8: The full layout of the Sulastic dampening concept used during testing

Testing indicated that the Sulastic dampening concept provided satisfying wheel articulation and vibration absorption, it also dampens motions created due to impacts. Although the satisfying test results, further tests would be required if this concept is selected as a final concept. The tests would evaluate the final configuration of the dampeners to achieve a satisfying behavior.

6.2.2.2 Torsion Dampening

Since the Torsion dampening concept consisted of a stand alone unit, it was simple to install to the bottom plate and motor. The assembly is illustrated in Figure 6.9.

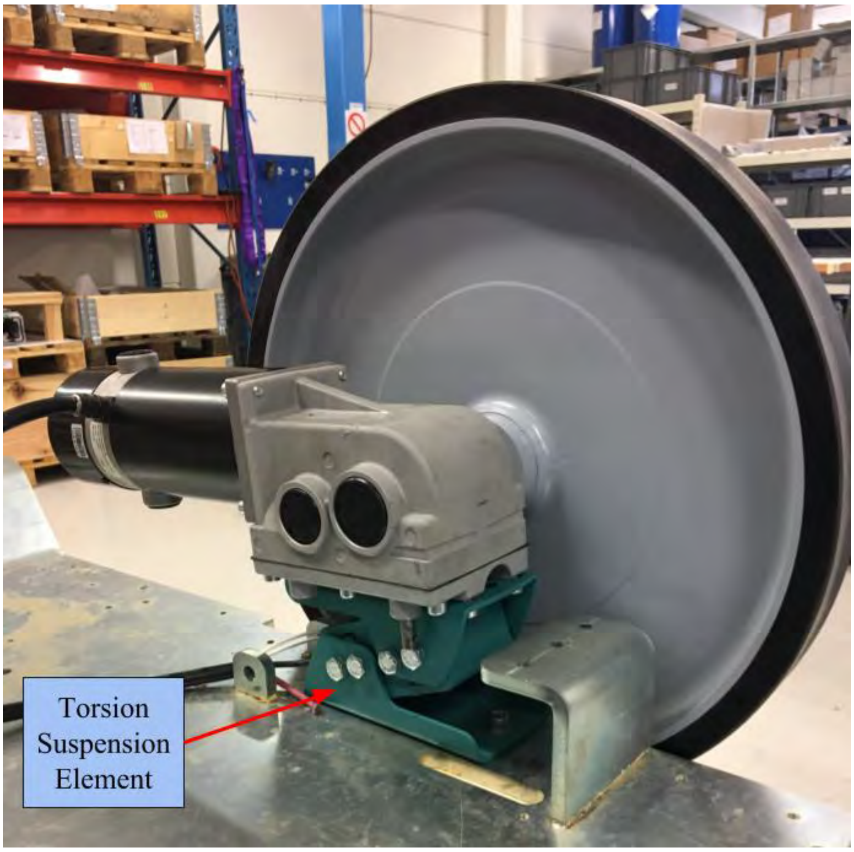


Figure 6.9: Torsion suspension element mounted on the bottom plate

Even though the installation of this suspension was simple, the system did not behave as intended. During testing, a couple of issues surfaced regarding the concept. While driving across uneven surfaces, the suspension element provides good vibration absorption. However, it did barely provide any wheel articulation which is an important aspect for a device meant to be driven on uneven surfaces. Another issue was found when a load was applied to the bottom plate. Because of this load, the wheels began to lean inwards, creating large camber angles. This phenomena is illustrated in Figure 6.10 and led to a less stable device. It is important to bear in mind that the weight causing the increased camber angles in Figure 6.10 is approximately 85 kg. The total weight of a complete device is 300 kg, which means that the camber angles would be significantly larger.

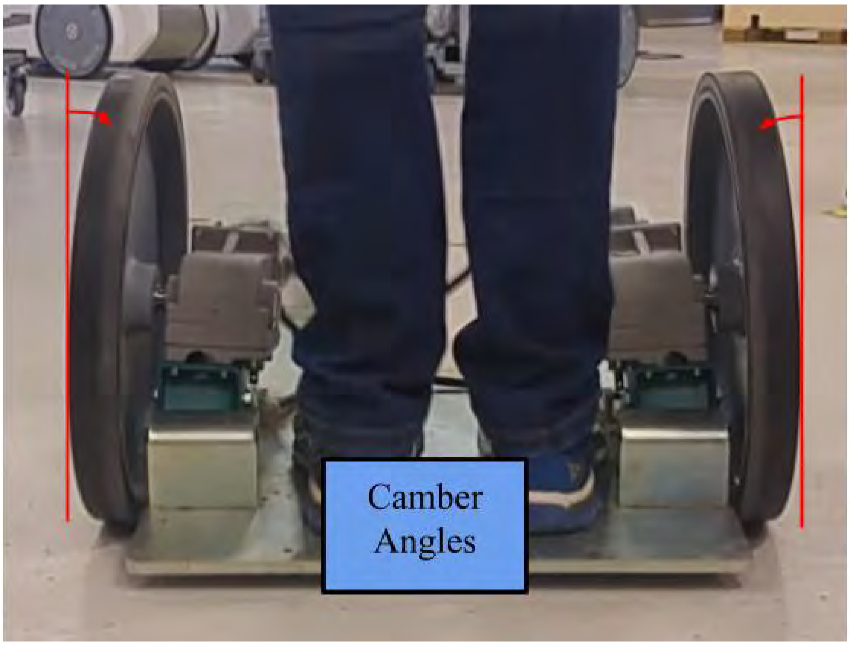


Figure 6.10: Increased camber angles due to applied load

In addition to the increased camber angles, Figure 6.10 shows that the ground clearance of the device is significantly reduced. This means that the bottom plate would require further modification to achieve a satisfying ground clearance with this suspension element. The suspension elements themselves are designed to withstand the loads of this device, however for this application and placement they did not behave satisfyingly.

6.2.2.3 Front

The front suspension was tested both with a new set of wheels and with a softer suspension. In the initial testing, Chapter 3.4, the current wheels vibrated around the fastening axis and created a high noise while driving on rough surfaces. These wheels had difficulties driving through grass, where they often sank, causing dirt to enter the wheel and reducing its performance. To solve these problems, new wheels with a larger diameter were tested. The new wheels also had a rubber tire which are softer than the tires of the current machine. It lead to a more quiet driving experience. The larger diameter led to a better handling while driving on grass and did not collect as much dirt. The new wheels tested are seen in Figure 6.11 in a comparison with the current front wheels.

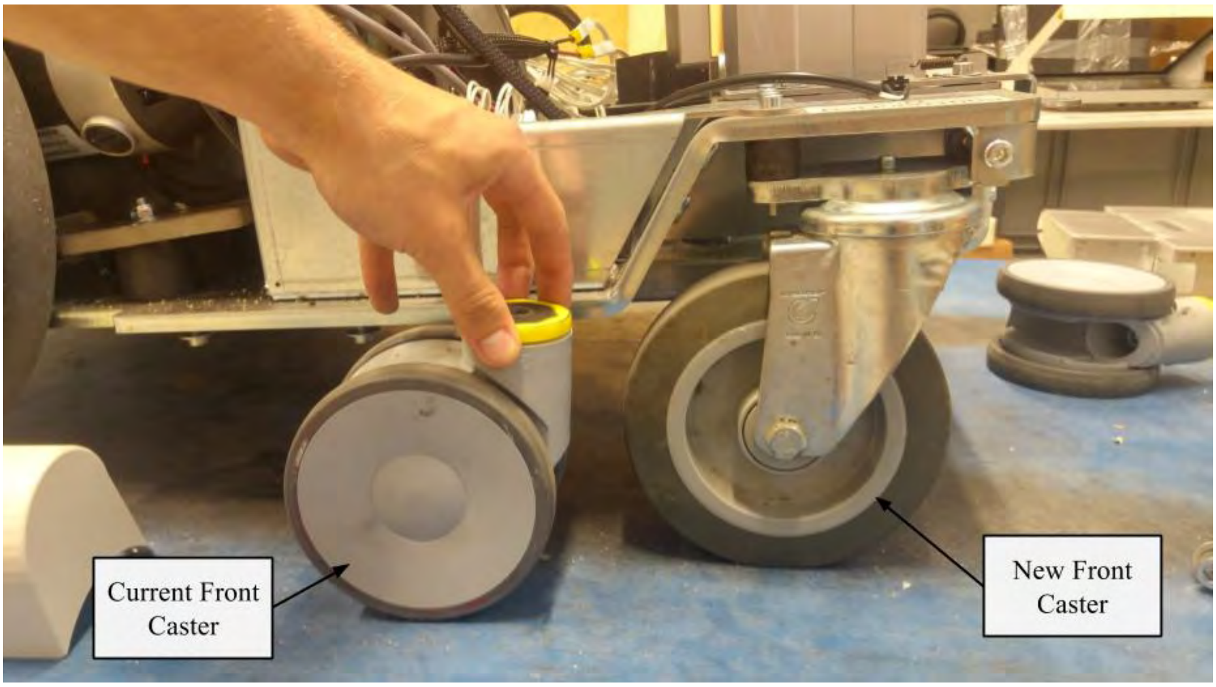


Figure 6.11: Comparison of the size of the front wheels

The tests performed with a softer dampening illustrated that the articulation in the front dampening should be limited. Otherwise, the stability of the device, when in examination mode, would decrease significantly. This caused a trade of between the off road capabilities and the tipping risk of the device. If the device tips over, it could potentially harm the operator making this aspect more important to consider. The caster angle of the front wheel will also play an important role in the machines stability, see Figure 6.12. When the front wheels are positioned in their worst position the tipping risk increases when the examination arm is extended towards that position.

Figure 6.12: The front wheels place in an disadvantageous position

6.3 Final Selection

The tests provided more information of the concepts' behavior. To select the final concept, a second Kesslering matrix was used to evaluate how well each concept performs regarding the different criteria. The Kesselring matrix cover the most important aspects of the machine. The second Kesselring matrix was performed in a similar way as the first seen in Section 5.3. A number of criteria were established for the evaluation, those chosen are described and motivated below.

- **Shock absorption:** The same criterion as used in the first iteration, it holds the same importance, receiving a weight of 3. However this time, there were more understanding regarding the shock absorbing properties of the concepts.
- **Vibration Absorption:** Also the same criterion as previously used, having the same weight of 4 since it has the same importance. Similar to Shock absorption, more information regarding the behaviour has been gathered.
- **Robustness:** This criterion deals with how well the rest of the device copes with the installation of the concept. Primarily this is with regard to structural stability. It is very important since the device is required to stay stable during examination and driving, therefore receiving a weight of 5.
- **Implementation:** Evaluates how simple the new concept is to implement into the device and how much changes that are required on the components and other sub

system to install it. It also covers how well known the long term behaviours of the concept are. This is an important aspect as it is desirable minimize changes to the rest of the device, giving this criterion a weight of 4.

- **Complexity:** The evaluation of this criterion is not only with regards to the amount of different components. How difficult it would be to install is also taken into consideration. Moreover, it covers if it requires a lot of instructions to install or if it is completely intuitive. It is important that the solution is not difficult to install, however a learning curve is always present, giving it a lower weight of 3.

The scales used when evaluating the different concepts in this iteration of the Kesselring matrix are seen in Table 6.1.

Table 6.1: Scales for the second Kesselring matrix

	1	2	3	4	5	Scenario/ Explanation
Shock absorption	Falls over if exposed to a shock	Hard impact (no dampening)	Minor absorption, still transfers most of the impact to the components inside the machine	Good absorption, will handle shocks and reduce the impact on the rest of the machine	Excellent, barley any impact to the rest of the machine	The machines ability to handle shocks, from e.g. thresholds
Vibration absorption	No dampening of vibrations	Long settling time from vibrations	Good, Vibrations are present but not distruptive to the work	Very good, handles most of the vibrations and they are barley noticable on the machine	Excellent, no vibrations transferred into the device	The machines ability to handle vibrations during driving across rough surfaces
Robustness	Falls over in the different modes	Components inside the machine behaves in an undesirable way	Good, some fluctuations in behavior, minor interference of the functionallity	Only minor fluctiation in behavior is seen but does not interfere with the functionallity	Excellent, everything behaves as intended over time	The stability of the construction, both while driving and while in examination mode
Implementaion	Many changes needs to be made and long tests needs to be performed to evaluate it	Many changes needs to be done but the components are tested in similar enviroments	A few surrounding components needs to be redesigned	Minor adjustments required to the surrounding components to mount	No modifications are required - plug and play	How much changes needs to be done to implement it into the machine.
Complexity	Many components included and a none intuitive design	Longer learning curve and many included components	Simple instructions required for installation	Intuitive design	Very intuitive design, very few components	How many parts does the concept contain, how are they mounted and how do they work together. How difficult is the assembly

Using the presented scales, the evaluation of the concepts could be done to establish a final concept. The Kesselring matrix created for this evaluation can be seen in Table 6.2. The reasoning behind the given scores for the three concepts are presented below.

Table 6.2: Second iteration of the Kesselring matrix

Chalmers		**Kesselring Matrix**							
Created by: Ola Delfin Marcus Sandberg		Created: 2017-07-07 Modified: 2017-07-07							
		Ideal		**Concepts**					
Criteria				**Torsion**		**Sulastic**		**Leafy**	
	w	v	t	v	t	v	t	v	t
Shock absorption	3	5	15	2	6	4	12	3	9
Vibration absorption	4	5	20	4	16	4	16	2	8
Robustness	5	5	25	2	10	5	25	3	15
Implementaion	4	5	20	4	16	5	20	1	4
Complexity	3	5	15	5	15	4	12	2	6
Total		25	95	17	63	22	85	11	42
Relative total		1,00	1,00	0,68	0,66	0,88	0,89	0,44	0,44
Ranking			**IDEAL**						

- **Shock Absorption** Since the *Torsion* concept did not absorb any impacts in the vertical direction as mentioned in Section 6.2.2.2, the shock absorption was limited. The *Sulastic* concept on the other hand provided a good shock absorption which also was easy to adjust by moving the dampeners closer to the pivoting axis. Due to the high stresses that the leaf springs are being exposed to it was necessary to limit the articulation in this concept leading to a less satisfying behavior.

- **Vibration Absorption** Even though the *Torsion* concept did not get a high grade in the previous category, it proved to absorb vibrations effectively. This is what the component is designed for, and the rubber inside the component dampens these vibrations well. Also the *Sulastic* concept get a high grade in this area due to its rubber dampeners absorbing vibrations effectively. The *Leafy* concept received a lower grade since the metallic leaf springs takes long time to settle and could create an amplification of the vibrations, since there are no dampening element present. For the Torsion and Sulastic concept, the rubber dampeners acts as both spring and dampening element.

- **Robustness** The *Torsion* concept gets a low grade in this area, as seen in Section 6.2.2.2, since it flexes while it is exposed to a load. This flex will make the wheels hit the body of the machine and therefore lower the machines life span. The *Sulastic* concept is very similar to SFT's current solution and is therefore well tested in this application. The tests also indicated that it behaved in a stable and controlled way. Even though the *Leafy* concept behaved well during the simulations, the stresses are very high within the springs which leaves some uncertainties regarding its behavior over time.

- **Implementation** The *Torsion* concept is easy to implement, only a few holes will need to be drilled to fit it onto the machine. However, the base plate would require adjustments since the suspension elements are very tall. Without this adjustment, the device would have low ground clearance, by introducing the modification, complexity is added to the base plate. The *Sulastic* concept is already proven in this area and will need no adjustments to the surrounding components since it was able to utilize existing mounting points. The *Leafy* concept receives the lowest score here since it is a leaf spring developed only for this application with no significant tests made. Even though the simulations provides a good understanding of what could be expected from the suspension, it will require long and costly testing to prove that it works as intended and to find the desired characteristics. Moreover, several adjustments needs to be made to the surrounding parts to install it.

- **Complexity** The complexity of the *Torsion* concept is low since it only require one component to be assembled together with the machine, and the functionality is intuitive. The *Sulastic* concept still has a low complexity even though its functionality is less intuitive. It also contains more components than the *Torsion* concept. The low grade of the *Leafy* concept is mainly due to the number of parts. This leads to a more difficult system to assemble. The different components included would be required to be assembled together using specific torques for the various fasteners in order to prevent the assembly from falling apart during the device's life span.

6.3.1 Conclusive Remarks Final Selection

The Kesselring matrix reveals that the concept to further develop into the final prototype is concept 2 - *Sulastic*. This concept has a simple design with a high potential of adjusting the suspension characteristics to a desirable level. The modifications required and cost to implement it to the existing design are neglectable compared to the performance increase.

6.4 Final Design

The final design of the undercarriage has been divided into a number of different categories, similar to the concept generation. The different categories used are *Rear Design*, which treats the rear wheels together with the suspension used for the rear wheels, *Motor Choice* describing the choice of suitable motors for the device, *Front Design* treating the front suspension as well as choice of front wheels. Finally, it treats the *Bottom Plate* and how it had to be changed to suit the new design of the device.

6.4.1 Rear Design

It was desired to have the same dimensions of the rear wheels as today, enabling the use of the wheels from the current model of the machine. The final concept consists of a wider tire with a threaded surface. However, these aspects were not tested in the prototype and during the tests as the current rear wheel worked sufficiently in rough terrain.

The rear dampening uses a similar dampening principle as the current model of the machine. Only small adjustments are required to implement the new concept but there are still big improvements compared to the current model. By placing the rubber dampener closer to the rotational axis, a larger articulation of the rear wheel was accomplished. Further tests was performed to evaluate at what distance the rubber dampeners should be placed and which dimension the rubber dampeners should have. The tests were performed by placing a weight m_w, representing the weight of the machine, on a lever that was pressing down on the rubber dampener, seen in Figure 6.13. The weight was placed at a distance L_w which provides the same moment around the axis as the weight of the device would cause. Therefore, it was possible to change the distance between the dampener and rotational point L_D to determine a preferable behaviour. By placing the dampener closer to the pivoting point, the load F_D it is exposed to increases, and therefore compresses the dampener more, giving the suspension more articulation.

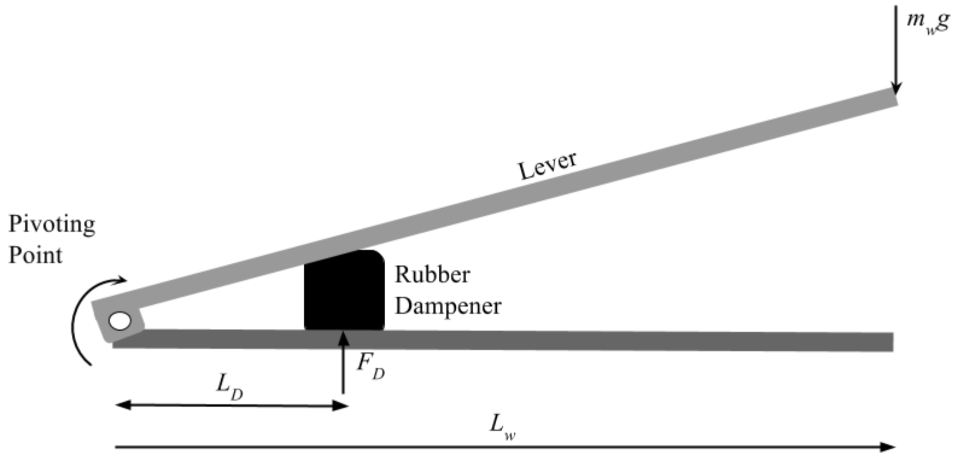


Figure 6.13: Test rig used for determining preferred characteristics of the rear suspension

The outcome of these tests showed that it was possible to get approximately 20 mm of articulation when using a rubber dampener with a diameter of 40 mm and a height of 40 mm, placed 90 mm away from the rotational axis. The dampeners chosen are purchased from Eugen Wiberger AB (Eugen Wiberger AB, 2017) with the article number GN351-40-40-M8-ES-55. With this setup the dampener behaved satisfyingly without being pressed together to much by a load larger than they could handle. The reasoning behind using rubber dampeners with a larger diameter was that they could be place closer to the pivot point and still handle the extra load. This placement allowed for a smaller design of the motor bracket. Therefore, the final design of the rear suspension consists of a new motor bracket, this bracket utilizes two rubber dampeners with a diameter of 40 mm and height of 40 mm, similar to the tests performed. The new setup with bracket and dampeners can be seen in Figure 6.14. A detailed drawing of the new motor mounting bracket can be seen in Appendix C. It is designed to be manufactured using bent steel plate with a thickness of 8 mm. The reason for this is that the current motor brackets are manufactured with this material, therefore it is assumed that the new brackets can be manufactured at a similar cost.

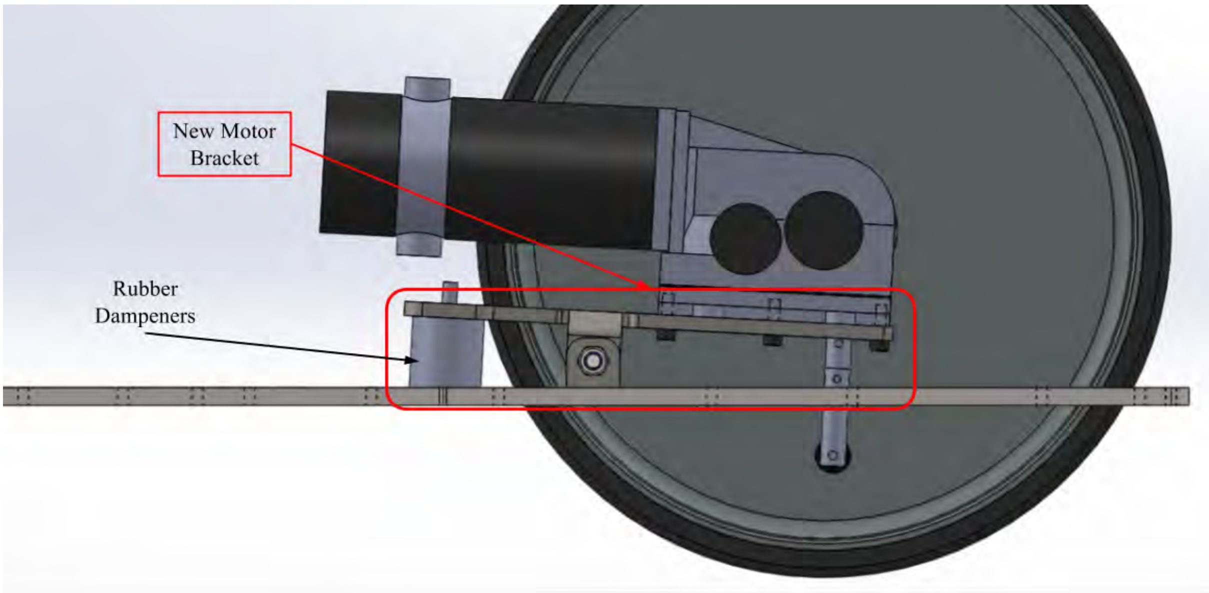


Figure 6.14: The new layout of the motor bracket and rear suspension

As mentioned in Section 3.1.1.2, the ground clearance is important to consider to ensure that the device will be able to cross various obstacles. A way of evaluating it is to estimate the required ground clearance needed to ascend a ramp, using equation 3.2. Inputs used are the angle of the ramp α, which according to the Specification of Requirements is 14.5° and the wheel base w_b, which by measuring the CAD-model, seen in Figure 5.1, is estimated to be 580 mm. Inserting these values into the equation gives a minimum ground clearance c_g of 37 mm. The current model already have a larger ground clearance of 50 mm, and since the new design will slightly increase the ground clearance, it means that this aspect will not be an issue.

6.4.2 Motor Choice

The motors are decided to be geared electrical motors similar to the motors used in the current device. However, since these did not provide sufficient torque to drive up the desired inclinations, or a threshold, a new pair of motors were required. Due to the decision to use the same diameter on the rear wheels as today, the required torque output of the motors had to be determined for a rear wheel diameter of 400 mm. The Specification of Requirements, in Appendix A, states two different scenarios which the device is desired to handle, and where the motors are directly responsible.

The first scenario, where the device is supposed to drive up a sharp threshold from stand still. According to the Specification of Requirements, the preferred height of the threshold which the device should overcome is 25 mm. For this purpose, equation 3.6 from Section 3.2.3.1 is used. Inputs used for this equation are a rear radius r_R of 200 mm, a threshold height h of 25 mm, and a mass m of 180 kg. The reason for using this mass is that the weight distribution of the device is estimated to be approximately 60 % of the weight at the rear and 40 % at the front, with a total weight of 300 kg. The motors are supposed to lift $m = 0.6 \cdot 300kg = 180kg$ across the threshold. Inserting these values into the equation gives a required motor torque of 85.5 Nm.

The second scenario is where the device is required to drive up a ramp, for example into a transport vehicle or into a building with a wheelchair ramp. According to the Specification of Requirements, it is beneficial for the device to drive up a slope with an angle of 14.5°. Using equation 3.12 in Section 3.2.3.2, gives the required torque output of the motors. Inputs used are the total mass m of 300 kg, a rear wheel radius r_R of 200 mm and a slope angle of 14.5°. This results in a required torque output of 74 Nm.

Out of the two scenarios, the torque of crossing the threshold is the highest, which means that this scenario will be the determining factor when choosing motors. These calculations are made for desires in the Specification of Requirements, which means that they do not have to be fulfilled but it is beneficial for the product. There are other requirements that needs to be fulfilled, in the Specification of Requirements, but they require less torque from the motors. Therefore, these two scenarios have been used when choosing the specifications for the motors. The obstacles in these two scenarios are calculated to be handled from a stand still position. Therefore, the torque of 85.5 Nm is not required when the motors are driven at full speed, but rather as a starting moment. The device is intended to travel at speeds of 5.5 km/h on flat surfaces, with a wheel radius of 200 mm. This requires a motor which is able to provide a rotational speed of approximately 95 rpm. Since the torque of 85.5 Nm is not required during regular driving, the high torque will not be needed at the same time as the top speed. As a result of this, the load on the electrical system will not be as high.

The final choice of electrical motor is a geared motor with a peak torque of 100 Nm at lower rotational speeds. The 100 Nm was chosen with the intention to have a safety margin due to the assumptions made regarding for example the weight distribution, and whether there could be larger unexpected obstacles to overcome while driving the device. The motor chosen has model number MP26-W(R/L)-029V24-420 and is supplied by Electrocraft (ElectroCraft, Inc., 2017).

6.4.3 Front Design

The tests showed that it was sufficient to keep the front suspension the same as on the current model. The primary reason for this was that the extra layer of rubber on the new front casters provided enough dampening to the device. Another discovery from the tests was that the front suspension needs to be stiffer than first anticipated, otherwise there is a risk that the device becomes unstable when the arm of the device is extended and turned to the side, as seen in Figure 1.1. Therefore, the decision was made to keep the suspension layout and introduce a new set of front casters with a rubber tires.

Similar to the choice of motors for the device, the required size of the front casters are determined by the obstacles which the device have to overcome. The scenario of driving across a threshold of 25 mm is used to determine the minimum allowed wheel diameter. To calculate the dimension of the casters, equation 3.3 and 3.8 in Section 3.2.3.1 are used. Inserting the motor torque M of 100 Nm, rear wheel radius r_R of 200 mm, mass m of 120 kg and threshold height h of 25 mm, the minimum allowed front wheel radius have been estimated through iterations to be 60 mm, or 120 mm in diameter. The mass of 120 kg is due to the weight distribution mentioned above, with 40 % to be distributed on the front wheels.

The weight distribution is an approximation, and to keep a safety margin to the minimum allowed diameter, a front caster with a diameter of 150 mm has been chosen. The particular caster has a solid rubber tier which provides the additional dampening. The width of the wheel's and the contact surface with the ground is 40 mm. This is wider than on the casters currently used, providing a larger footprint and it is therefore less likely to dig down when driving on soft surfaces. The wheel is supplied by Tellus AB with the model number 31431 (Tellus Hjul & Trade AB, 2017). The new layout of the front design for the device is seen in Figure 6.15.

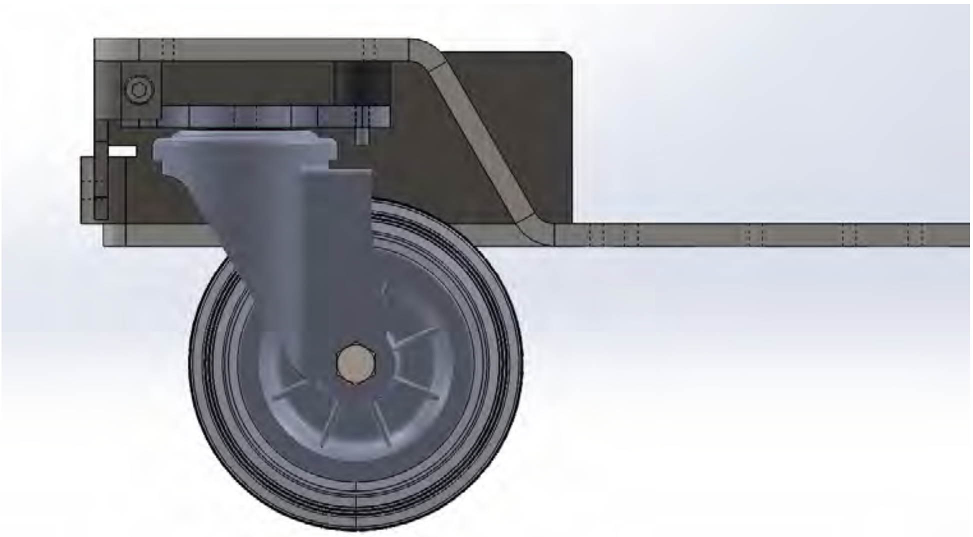


Figure 6.15: The new design of the front suspension

6.4.4 Bottom Plate

Even though the chosen concepts does not require the bottom plate to be modified to test them, modification would be needed to optimize its performance. To get the bottom plate parallel to the ground it will be needed to modify the front due to the larger front wheels. If the bend holding the front suspension in Figure 6.15 is raised, it will be sufficient to keep the machine parallel to the ground.

Considering the rear section of the bottom plate, only small modifications will be needed.

The old rubber dampener holder seen in Figure 6.16, can be removed since the rubber dampeners of the new design are placed in front of the motor. To connect the new rubber dampeners to the bottom plate, a new set of holes will need to be drilled into the bottom plate.

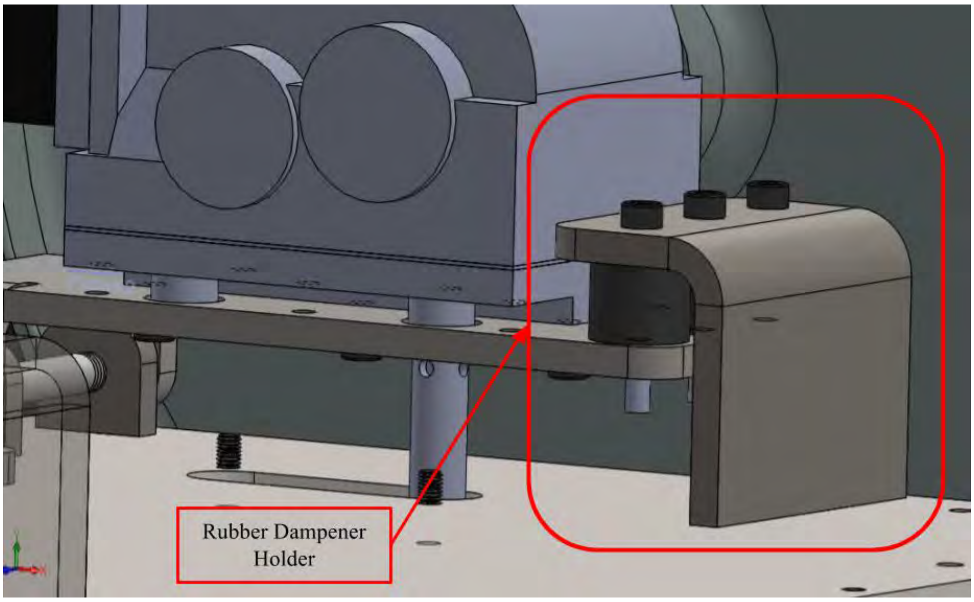


Figure 6.16: The old component holding the rubber dampeners

6.4.5 Cost Analysis

The cost analysis includes all the visible parts in Figure 5.1. These are the parts that have been covered by the new design, and therefore they are the components of interest to compare. Most of the parts are similar to the current configuration of the device and only minor changes have been made to the sheet metal parts. The most significant differences are the change of the motors and the front wheels. However, the new motors costs approximately the same as the old motors used even though they have a better performance. All costs for the components of SFT's current model have been provided by SFT.

The front wheels are selected for the prototype and will therefore be slightly less expensive than the current wheels. These front wheels are mostly used to test the concept with a front wheel with a greater diameter and a rubber tire. However, the visual design of these wheels are not as attractive and a more expensive wheel might be more suitable to improve the design. All components and their prices are included in Table 6.3, these costs are based on the components in the Bill of Materials in Appendix D. Components purchased have been indicated with their respective supplier and article number. Components which have SFT as source are components which have not been changed, with the exception for the new mounting bracket drive unit. This component is assumed to cost the same as the current mounting bracket due to similar dimensions and material choice.

Table 6.3: Cost analysis of the included components in the undercarriage

Current Model	Part	Quantity	Price/Unit [SEK]	Total Price [SEK]
Front	Front Wheel	2	248,50	497,00
	Rubber Buffer	6	6,63	39,78
	Left Front Wheel Bracket	1	76,60	76,60
	Right Front Wheel Bracket	1	74,30	74,30
Rear	Cast Drive wheel	2	2275,95	4551,90
	Left Drive Motor	1	2018,30	2018,30
	Right Drive Motor	1	2018,30	2018,30
	Wheel Coupling	2	290,30	580,60
	Mounting Bracket Drive Unit	2	57,95	115,90
	Motor Clutch Axle	2	93,15	186,30
	Rubber Buffer	6	6,63	39,78
Bottom Plate	Base Plate	1	1418,00	1418,00
Total				11616,76

New Model	Part	Quantity	Price/Unit [SEK]	Total Price [SEK]
Front	Front Wheel	2	130,00	260,00
	Rubber Buffer	6	6,63	39,78
	Left Front Wheel Bracket	1	76,60	76,60
	Right Front Wheel Bracket	1	74,30	74,30
Rear	Cast Drive wheel	2	2275,95	4551,90
	Left Drive Motor	1	2400,00	2400,00
	Right Drive Motor	1	2400,00	2400,00
	Wheel Coupling	2	290,30	580,60
	Mounting Bracket Drive Unit	2	57,95	115,90
	Motor Clutch Axle	2	93,15	186,30
	Rubber Buffer	4	23,40	93,60
Bottom Plate	Base Plate	1	1418,00	1418,00
Total				12196,98

	Current	New	Difference
Price Rear	9511,1	10328,3	8,6%
Price Front	687,68	450,68	-34,5%
Total	10199	10779	5,7%

To summarize the analysis, the cost of the new model will be approximately the same for SFT. However, a machine with these specifications will be possible to sell at a much higher price due to the increased performance, giving SFT a higher profit on each sale. To give the machine a more premium feel it is recommended to change the front wheels to wheels with a better visual design, however accommodating the same properties as the tested casters.

6.4.6 Risk Assessment

It is important to ensure that the changes made to the device does not stand responsible for any failures in the future use of the device. Therefore a Failure Modes and Effects Analysis has been performed. The analysis treats a number of different functions of the device where failure is assumed possible. The created analysis can be seen in Table 6.4, in the analysis, the failure mode for the different functions are described together with an assumed reason and consequence of the failure. Each of the failure modes possesses a Risk Priority Number, (RPN) which indicates which of the failure modes that are most important to resolve, a higher number represents a failure mode with higher priority. The RPN is estimated based on the product of the three factors, seen below. The factors are rated from 1 to 10 based on how prominent they are in the analysis.

- **Probability of occurrence (P_o):** How likely is the occurrence of the failure. A higher probability will result in a higher score.
- **Severity (S):** How severe would the consequences of the failure be to the device. A failure being more severe will receive a high score.
- **Probability of detection (P_d):** How easy is a failure such as this to find before it

causes any harm to the system, or how likely it is to prevent such a failure to occur. The score of this aspect depends on how easy a failure is to detect, a failure that is hard to detect receives higher score.

Each of the three aspects considered are graded based on different scales, seen as tables in Appendix B. The values inside the tables are defined in the same way as the FMEA Scales by Carlson (2012).

Table 6.4: Failure Modes and Effects Analysis

FMEA - Failure Modes and Effects Analysis											
Main System			Part Name								
SFT Model 2			Undercarriage								
Function				Issued by						Status - Hardware	
Enable the x-ray to travel accross rough surfaces				Ola Delfin & Marcus Sandberg							
Part		Characteristics of Failure				Rating				Action - Status	
No.	Function	Failure Mode	Causes of Failure	Effects of Failure on System	Testing	Po	S	Pd	RPN	Recommendations	Decisions or Actions taken
1	Rear dampening	Rubber dampener breaks	Overload	Wheel hits the covers, undrivable	Physical testing	2	7	3	42	Perform tests until failure of the dampeners	Use of heavy duty dampeners
2	Wheel Coupling	Wheel coupling loosen up	Not mounted with the right torque	Wheel could slide on the axis, reduced driving performance	Physical testing	6	7	6	252	Evaluate if service intervals are required or choose new means of fastening the wheels	Fasten coupling according to torque specifications
3	Dampening	Too much compression in dampeners	Excessive wear	Wheel slides against covers	Endurance tests	5	4	3	60	Find out at which load dampeners are too compressed	Use of heavy duty dampeners
4	Motors	Machine stops, due to high load	Overload	Can not drive further	Physical testing & Calculations	3	2	3	18	Implement rating on what driving conditions the device can handle	-
5	Fastening of dampeners	Incorrect mounting	Assembly	Components loosens up, unstable device	Physical testing	2	4	3	24	Implement assembly instruction for correct assembly	-
6	Examinations in slopes	Machine falls over	To high center of gravity, front wheels in bad position	Damaged device and components	Physical testing	5	9	4	180	Purchase front wheels with smaller caster angles	-
7	Driving over rough surfaces	Dampening too stiff	Vibrations spreading througout device	Internal components loosens up	Physical testing	3	7	3	63	Perform endurance tests on the configuration for long term effects	-
8	Driving into houses	Dirt gets stuck on wheels and undercarriage while driving outdoors	Components hard to clean	Brings dirt indoors	Physical testing	6	2	3	36	Clean the device before entering the buildings	Use design which prevents dirt build up or enables cleaning

The different failure modes have received different scores leading up to their final Risk Priority Number, a motivation behind the scores received is presented below for each failure mode. The motivations are using the same enumeration as in Table 6.4

1. The rear dampeners used on the new design are of the same type as the ones used today, but with larger dimensions. These have never been recorded to fail and therefore P_o is set to be 2. If the dampeners would break, the device would no longer be able to be driven. However the device would still be able to use the x-ray function. Therefore it looses parts of it primary function as it is still able to perform x-ray examinations but not move into other positions of examination, giving it a value for the severity S of 7. Excessive tests have been made to test the configuration

of dampeners and the dampeners themselves, both in the form of a test rig and in the various prototypes, therefore there is a high likelihood to detect or prevent this failure, P_d is therefore given a value of 3.

2. The coupling used to fasten the wheels to the motors have a history of loosening, resulting in the torque from the motors not transferring to the wheels. The shaft would be sliding inside the couplings. The reason behind this behavior is that a wrong fastening torque has been used. This behavior can occur also on the new design foremost since it has a even greater output torque giving it a P_o 6. If this occur, the primary function will be reduced and the severity value is estimated to be 7. To handle this problem tests will have to be made on the pilot prototype, using the new motors, to ensure that the coupling will be able to handle the torque. The P_d value is estimated to be 6.

3. When exposing the rubber dampeners to a high load over a longer period of time, it can lead to a lower performance of the dampeners since they could loose some of their flexibility. The dampeners will not go back to its original form which can lead to damages to the machine. The P_o value of this happening is estimated to be 5. The severity will not be particularly high since the compression of the dampeners will occur over time and only a slow reduction of the performance will happen. The compression will however after a while make the wheels interfere with the covers of the machine with unwanted noise as a result. The S value is therefore set to be 4. The behaviour can be prevented by performing endurance tests that evaluates at which load the rubber dampeners will compress to much, giving it a P_d value of 3.

4. The motors used in the new design are chosen to handle the different driving conditions that the machine could be exposed to. According to the calculations, the machine needs a torque per motor of 85 Nm. To give the machine a safety margin, motors with an output torque of 100 Nm have been chosen. However, the motors are at this point untested for this application which gives it a P_o value of 3. If the motors stops while driving up steep slopes, the machine will still be undamaged. The only thing that the operator needs to do is to back it down and take another route, which only leads to annoyance. Therefore it receives an S value of 2. The motors will be tested in all possible driving conditions before the machine is launched, giving it a P_d value of 3 as these issues will be identified.

5. The current layout of the suspension and dampeners are configured to have the dampeners fastened with screws and also to squeeze the dampeners together due to the weight of the device. As a result, there are no failure found today, resulting in a P_o value of 2. If a failure would occur and the dampeners are not secured enough, there might be a noticeable noise coming from the device, causing a significant annoyance but no failure. Giving it a value on S of 4. The suspension is designed for the dampeners to be assembled in a certain way, which makes it difficult to mount them in a way which reduces their performance. If this was to happen, it would be easy to identify and correct if installed incorrectly, giving it a value P_d of 3.

6. Caster wheels purchased for the prototype have big caster angles and larger diameter than current version of the device. The larger diameter and new suspension increases the ground clearance, giving the device a center of gravity further up than the current device. The higher center of gravity together with the casters having a bigger caster angle could make the device more prominent to fall over in a slope or in examination mode. Thus giving this failure mode a P_o of 5. If the device would fall over, there is a risk of substantial damage to the device, affecting the safety of the device, giving it a S of 9. Tests regarding the stability in examination mode have been done excessively, if failure would occur during use and it begins to turn over, it is simple to notice before it falls completely, it is not difficult to stop the fall either. The device will be tested and certified to be used at a certain angle of sloping, giving it a P_d of 4.

7. Since this machine is meant to be driven on rough surfaces, the time that is is used in these conditions will be higher than the current machine. Even though the vibration absorption of the rubber dampeners is good there are some uncertainties regarding the long time behaviour. This gives it a P_o value of 3. The higher level of vibrations could lead to components loosening inside the machine that in turn can reduce the functionality of the device. The S value is therefore estimated to be 7. In order to evaluate this risk endurance tests will have to be performed making sure that this will not happen. The P_d value is therefore set to 3.

8. Components introduced to the new design contains a number of hollow sections where dirt tends to build up, also the rubber sections of the wheels attracts dirt. This results in a high probability of dirt being brought inside after driving outdoors, resulting in a P_o of 6. However, if dirt are brought inside a building, there are not any significant issues since the dirt would primarily be restricted to the floors. The dirt would not cause any noticeable harm to the device. If dirt are brought inside, it can easily be fixed, either by cleaning the floor or cleaning the device before entering, giving it a value on S of 2. It is simple to determine whether dirt might get attached to the various components, and if dirt gets attached, it is simple to detect and remove, giving it a P_d value of 3.

The outcome of the Failure Modes and Effects Analysis indicates that most of the failures identified could be prevented before launching the device on the market. However, a number of failures are more important to investigate, as indicated by the Risk Priority Number in Table 6.4. The two highest risks are the coupling connecting the wheels to the motors loosening and the risk of the device falling over. The wheel coupling would require further investigation before launch and if necessary, a coupling rated for higher torque transfer would be required to purchase. The risk of the device falling will also require future investigation. The assumed solution is to change the caster angle, placing the wheels in a more favourable position even when the casters are in their most disadvantageous position as seen in Figure 6.12.

With a final design chosen and included components selected, a final prototype for verification of fulfillment of the requirements could be created.

7

Prototyping and Verification of Final Design

To evaluate if the final concept could fulfill the established wishes and requirements in the Specification of Requirements, they needed to be verified through different tests. The tests was performed on a prototype containing the solutions for the different areas of the device. This chapter covers both the activity of manufacturing the prototyping and also the verification phase, testing the components of the final concept.

7.1 Manufacturing

Due to difficulties of contracting manufacturing of the new motor brackets, the initial prototype used for testing the Sulastic dampening was repurposed and used for the final prototype. Only a few modifications were required to be able to fit the larger dampeners chosen for the final concept.

The new motors have a maximum torque of 100 Nm, and a different layout of the mounting points. However, the desirable motors were not in stock at the supplier, and lead times for these motors were too long for allowing the tests within the time span of this thesis. Instead, a pair of less powerful motors were available, with a maximum torque of 84.7 Nm. These motors have the article number 868-013-0(17/18)-01 (ElectroCraft, Inc., 2017). The torque output of these are close to the minimum required torque to be able to traverse thresholds, calculated in Section 6.4.2 to be 85 Nm. It was determined that these less powerful motors would have to suffice for the testing of the prototype since they still provide a significant increase in torque. In addition, the motors acquired uses the same layout for the mounting points as the current motors used on the device. This meant that the same mounting brackets could be used, minimizing the need for modifying the components. The assembled rear suspension and motor can be seen in Figure 7.1, which further highlights the limited amount of space within the device. The whole assembly is mounted both by the rotational axis and the rubber dampeners together with the base plate.

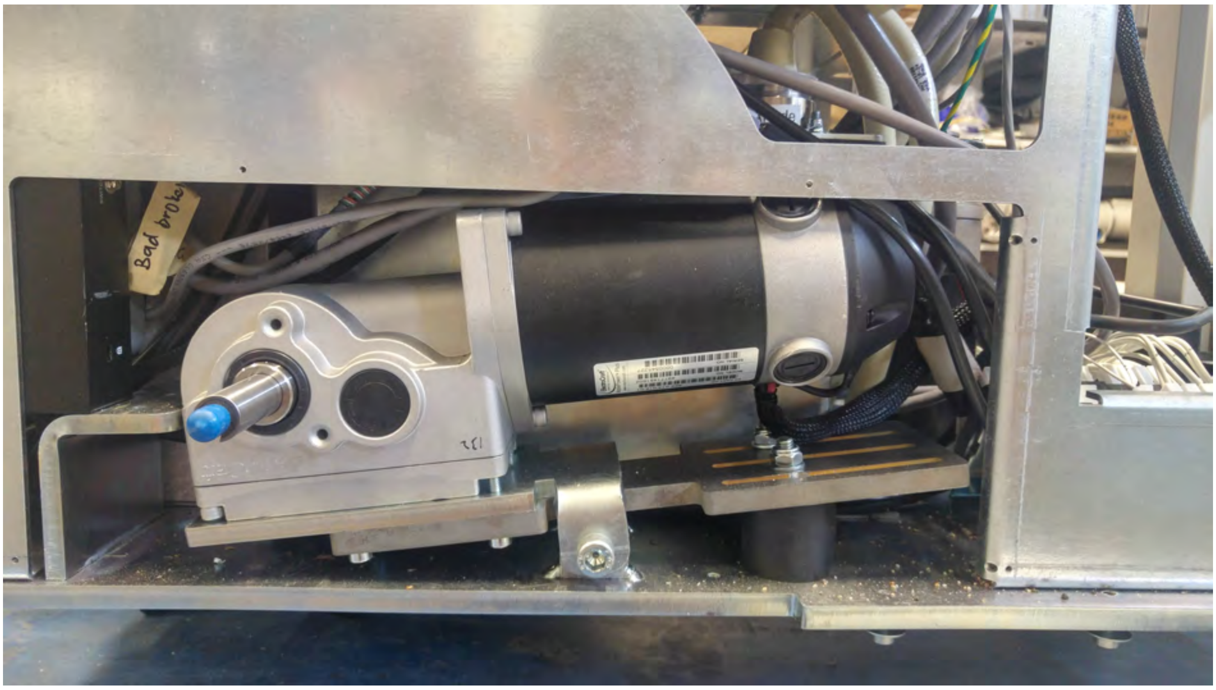


Figure 7.1: Rear suspension assembled

There was also an issue with the delivery of the chosen front wheels with a diameter of 150 mm. Instead, a pair of similar wheels with a diameter of 160 mm, which were in stock at SFT were used. These were assumed to behave similarly. Because of the larger diameter, they caused the device to tilt backwards slightly. It is desirable to keep the device leveled during use, however this did not impact the driving capabilities. The front wheels utilized the same mounting bracket as the current device, allowing for a simple assembly, visualized in Figure 7.2.

Figure 7.2: Front suspension and wheel assembled

The assembly of the final prototype did not require any significant modifications to the current device. It means that the new version of the product can easily be based on the old platform, allowing for a greatly improved product for a low cost. Figure 7.3 illustrates the final prototype used for further testing.

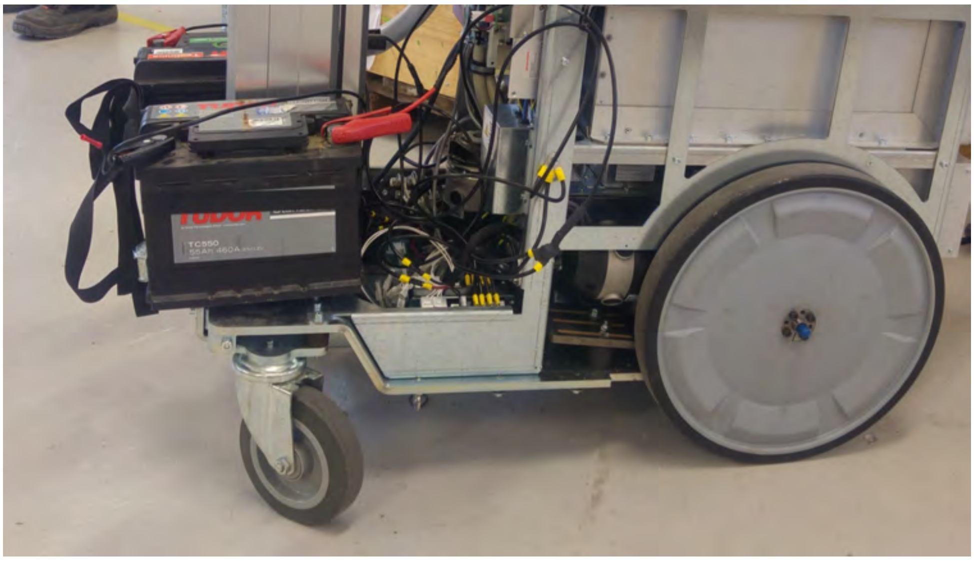


Figure 7.3: Final prototype assembled

7.2 Final Testing

The final testing was performed to evaluate whether the machine fulfills the requirements and wishes established for the machine. During these tests the most prominent aspects of driving the machine outside of the hospitals were evaluated. The machine was first tested with the new setup consisting of new motors, suspension and front wheels. The motors in this setup gave a slightly higher torque output compared to the old motors, allowing the machine to drive up steeper inclinations. However, it was not possible to get as high torque from the motors as specified by the manufacturer. The reason behind this was that the motors did not receive enough current from the power supply, which limited the maximum torque output. This behaviour was also encountered in the earlier testing phase, seen in Figure 3.12a, where the voltage to the drive units dropped when the current increased. To test the performance of the new motors and see if there were any enhancements in the performance of the machine, two car batteries were used to power the drive units and motors. The car batteries have the potential of giving a much higher current than the original electrical layout, therefore allowing a higher output torque from the motors. The car batteries were connected in series to provide the 24 V needed to power the drive units.

7.2.1 Driving in Slopes

One of the requirements concerning driving the machine, was that the machine should be able to drive up ramps angled in 14.5°. For testing this requirement a lift unit, normally used as a platform for assembly, was used to adjust the angle of the ramp, see Figure 7.4. The lift was first positioned in its lowest position, 10°, and was thereafter incrementally elevated upwards until the machine failed to drive up the ramp. During these tests, the car batteries used to increase the supply of current, were positioned beside the machine to not add the extra weight that two car batteries causes.

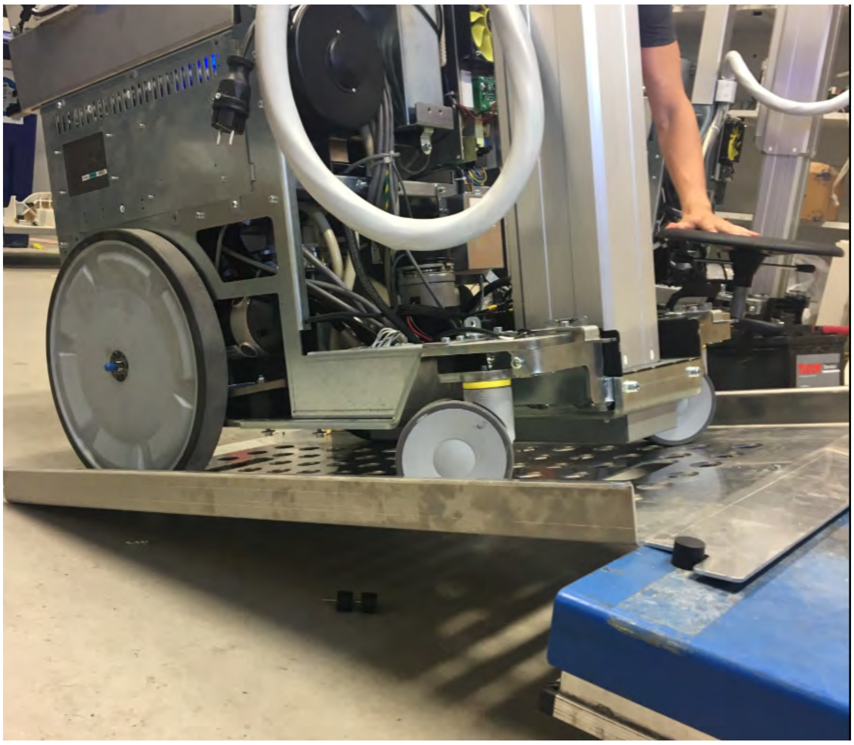


Figure 7.4: Test of driving in a 16° slope

As stated above, the requirement that the machine needed to fulfill was to drive up 14.5° ramps. The tests showed that the machine would be able to handle that angle with no problems and that it could take on angles up to 16°. Above 16° the machine failed to go up the ramp and either stopped, or the wheels started to slip on the steel surface of the ramp. The slipping of the wheels was also seen when driving in grass slopes. Although it was no problem for the current requirements of the machine, further development of the tires could improve the capabilities of the machine even more. Moreover, the machine was tested on a ramp leading up to a retirement home, see Figure 7.5, to verify that the machine would be able to handle the rougher surface this ramp possessed. The ramp had a small threshold before the inclination started, which caused the machine to struggle if the rear wheels were placed right at the start of the ramp at a stand still. However, if the machine had a slight speed before the threshold, it managed both the threshold and the ramp without any issues.

Figure 7.5: Test of driving on an outdoor ramp

A test measuring the current that the batteries was providing to the motors was performed. The maximum current the motors got when driving on a steep inclination was approximately 90 A, seen in Figure 7.6. In this figure the time is shown on the horizontal axis and the voltage on the vertical axis. The current was measured with a current meter that transforms 1 A to 10 mV, and each step in the figure is equal to 200 mV. Since the curve rises approximately 4.5 steps up, the current required for the machine is around 90 A. Therefore the machine would need a power supply that can supply these high currents for the device to have the same performance as in the tests. Moreover, the motors have a maximum rated current of 80 A, which means that these tests pushed them to their maximum and it would not be possible to get a higher torque output from these motors.

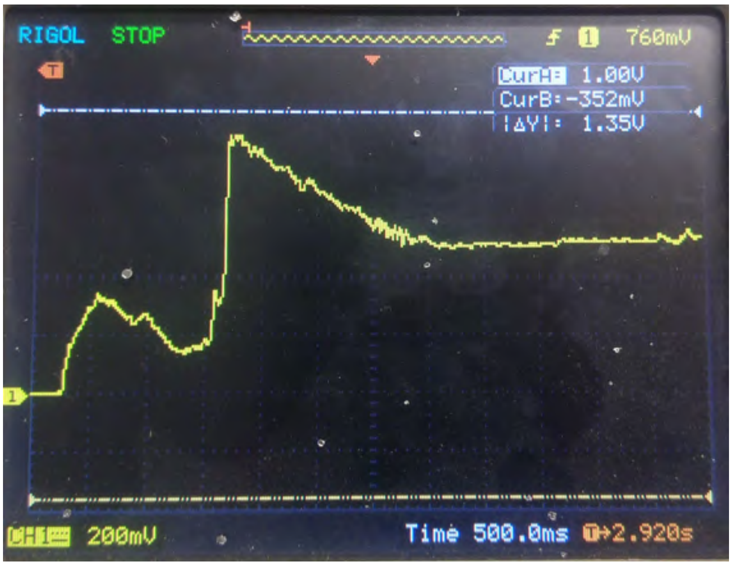
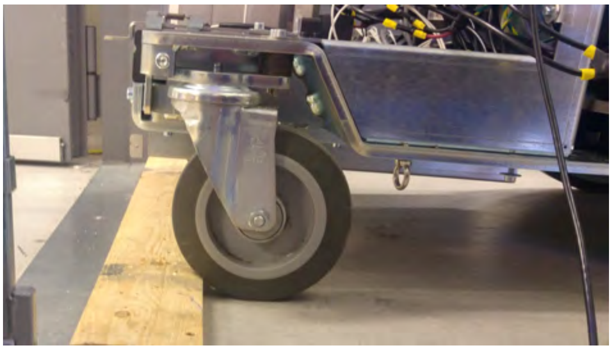


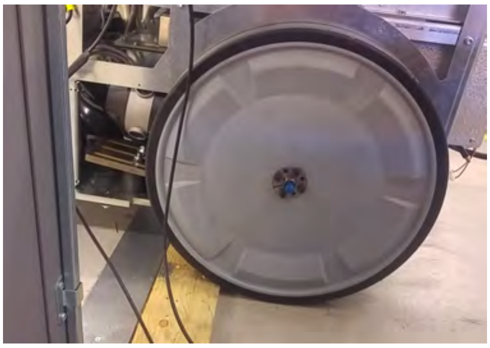
Figure 7.6: Current provided to the motors

7.2.2 Thresholds

Another requirement was that the machine should be able to drive past 25 mm high thresholds, and it was desired to managed it from standing still. This requirement was tested by placing a threshold in front of, first, the front wheels and then the rear wheels, see Figure 7.7a and 7.7b. Thereafter the machine should be able to overcome the threshold without any initial speed. The threshold used during the test was 22 mm high and with the motors that was used for the prototype the rear wheels barely managed to overcome this threshold from standing still. However, with only a small initial speed the machine would have no problem to pass over 25 mm high thresholds.



(a) Front wheels



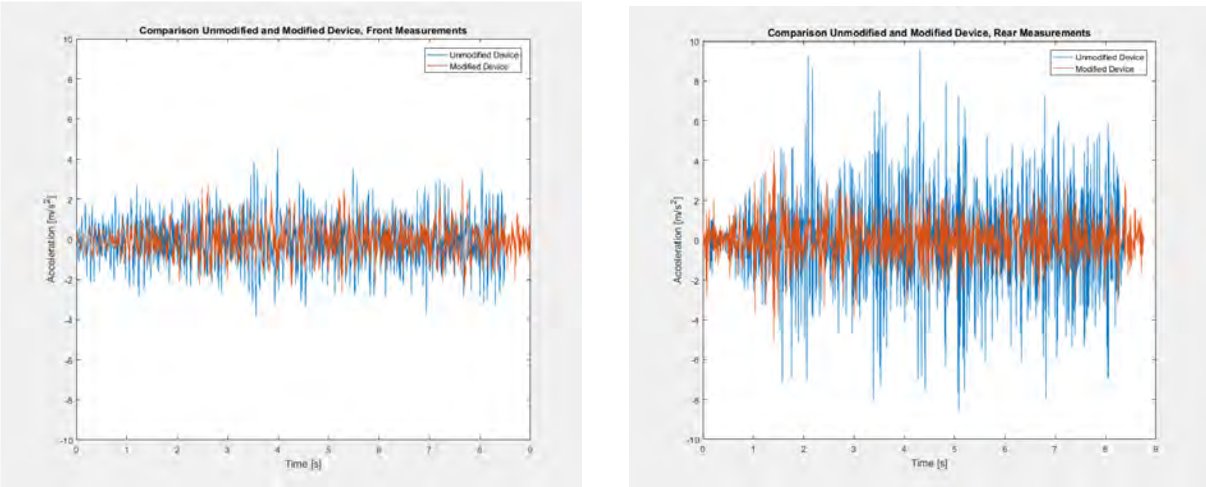
(b) Rear wheels

Figure 7.7: Threshold test of front and rear wheels over a 22 mm threshold

The situation of driving the machine over a threshold from standing still is the most troublesome for the machine, and its the situation that requires most power from the motors. However, if the machine has some movement before the threshold, it will significantly lower the needed power to overcome the obstacle. The tests also indicated that the front wheels struggled less with crossing the threshold than the rear wheels. The reason behind this behaviour could depend both on the weight distribution of the machine but also on the drive units being placed on the rear wheels.

7.2.3 Vibrations

To evaluate the performance of the new suspension compared to the suspension used in SFT's current machine, a couple of vibration tests were performed. These tests were made by driving the machine on a predetermined course, and measuring the vibrations with two accelerometers. The surface of the course was asphalt and the machine was driven in a straight line in order to standardize the test, and minimize the involvement of the driver. The accelerometers were placed in the front and rear of the machine, which allowed for measuring the different behaviour between the front and rear suspension.



(a) Front measurements

(b) Rear measurements

Figure 7.8: Vibration test, measurements comparing prototype to the current model over asphalt

As seen in Figure 7.8, there is a big difference between the two devices. The front suspension does not give as much difference in dampening since only the front wheels have been changed. Still, this small change of front suspension provided an observable and measurable performance increase. The rear suspension have a greater difference which is shown in Figure 7.8 and is also noticeable when driving the unit. Another way of comparing the measurements is to calculate their root-mean-square value (RMS-value). The RMS-value is calculated as in formula 7.1 and is the square root of the mean square (Atkins & Escudier, 2013).

$$X_{RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}|X_n|^2} \tag{7.1}$$

The obtained RMS-value for the unmodified front suspension was 1.1410 m/s^2 while the RMS-value for the modified front suspension was 0.7867 m/s^2. It means that the measured difference between the two suspensions is a 31.05 % reduction in vibration amplitude. Continuing to the RMS-values of the rear suspension, the unmodified rear suspension got a value of 2.5254 m/s^2 while the RMS-value for the modified rear suspension was 1.1889 m/s^2. This indicates a reduction in the RMS-value for the rear suspension by 52.92 %. These large differences occurred when driving on asphalt, which means that the vibration reduction is assumed to be even more significant across rougher surfaces.

7.2.4 Off-Road Driving

Since the machine should be able to handle some off-road conditions, several test were performed on different surfaces to evaluate the handling and the capabilities of the machine. Surfaces tested were for example grass, gravel, asphalt and small tracks in the forest, as Figure 7.9 illustrates. These tests were primarily performed to see if there were any problems with the design, and to get a feeling of the handling of the machine while driving in rough terrain.

Figure 7.9: Driving in the forest

The overall handling in these conditions was good and the result was satisfactory. The only time that the machine had some problems was when the slopes were to steep or when a larger stone or curb came in front of the wheels.

7.2.5 Concluding Remarks on Final Testing

There were many positive results from the final testing, where the device managed most of the obstacles it encountered. It also performed better than expected when driving in ramps, even though the test was performed with a motor with lower torque output than the motor intended to be used. However, these results were only possible if an extra power supply was connected to the drive units of the motors. Therefore an important step would be to increase the amount of current that the power supply of the machine can deliver.

Regarding vibrations, a clear difference could be felt between the prototype an SFT's current model. Both that the machine was easier to handle in rough terrain but also that the noise level on these surfaces was noticeable lower. As stated in the previous test, the articulation in the suspension has a great impact on the stability of the machine while in examination mode. Therefore, there is a trade off between the ability to take up shocks while driving and the stability of the machine while in examination mode. The tests showed that the prototype, even though it have a limited amount of shock absorption, greatly improved the behaviour of the machine without sacrificing stability during examinations.

8

Results and Fulfillment of Requirements

To evaluate whether the prototype is successful, the requirements established in the Specification of Requirements were compared to the results of the various tests. If tests were not possible with regard to a certain requirement, its assumed performance is discussed. The different sections in the specification in Appendix A are treated in separate subsections.

8.1 Maneuverability

Even though the weight of the device is approximately 300 kg, by unlocking the built in gear release on the motors, the wheels are allowed to spin freely, enabling the device to be pushed without support from the motors. The force required is below 200N, which fulfills the requirement.

The motors used in the device allows for rear wheel steering, meaning that by letting one wheel turn slower than the other, the device will turn in that direction. This provides a high level of maneuverability with a small turn radius. The system allows the device to drive around sharp corners and in precise movements, thus fulfilling these requirements. The steering system implemented in the device remains the same as in the current model, this allows for one hand driving if required, fulfilling this requirement.

Due to the new suspension of the device, the vibrations caused while driving which is seen in Section 7.2, are significantly reduced compared to the current device. This also applies to bumpy roads, making the drive more controlled which results in these parts of the requirements being fulfilled. However, it was not possible to properly test the driving capabilities on slippery surfaces. Therefore further testing could be considered. Since the final concept includes threaded rear wheels that provides better traction, it is assumed that this requirement will be fulfilled since the current wheels have a high level of traction already.

During testing, the device could traverse a threshold of 22 mm from stand still, it did not have enough power to drive across a 25 mm threshold without initial speed. It is assumed that this issue is due to the motors available not having the desired torque of 100 Nm. If the tests would have been performed with the more powerful motors, it is estimated to handle the threshold from stand still. If the thresholds were approached with a slight amount of speed however, the device could cross these without effort. It also applies to curbs, meaning that the requirements regarding traversing obstacles with an initial speed are fulfilled.

Driving across 40 mm of snow or mud could not be tested due to the weather conditions during the testing phase. However, since the device has sufficient ground clearance and a high amount of torque, it has the potential of handling these conditions but further tests are preferable.

The motors chosen for the prototype are provided with built in brakes which are applied when the user is not interacting with the device. Therefore, the requirement of braking the system while not using it will be fulfilled. The tests of the brakes was also performed while testing the driving capabilities across an incline. The requirements are with regards to small amounts of movements at an inclination of 10° and 5° respectively. However the prototype was able to be braked at an inclination of 16° without movement, meaning that these requirements are fulfilled. With the brakes engaged, the device is very difficult to push, requiring significantly more force than 150N to move, this requirement is therefore also fulfilled.

Tests performed while driving on slopes in Section 7.2.1 revealed that the motors used for the prototype were able to drive the device across a slope of 16°, with the even more powerful motors that was intended for the final concept, the device would be able to cross even higher inclinations. Therefore the requirement regarding the device being able to handle a slope of 14.5° is fulfilled.

8.2 Ergonomics

The intention is to drive the device into a transport vehicle using the built in ramp, therefore there are no need to bring additional supporting equipment. This also applies to the off road capabilities, this requirement has thereby been fulfilled.

8.3 Durability - Undercarriage

The bottom plate covers the lower parts of the device entirely, the surface is treated to handle outdoor environments such as water and road salt. Ideally, when the device has been used outdoors, it will be cleaned, removing any harmful substances. Therefore these requirements are considered fulfilled.

Since the prototype required the additional power supply, provided by two car batteries, it was not possible to mount the exterior protective covers of the device. Therefore the various collision tests included in the Specification of Requirements were not possible to perform. However, the final design does not introduce any exterior changes to the device, allowing for the original covers to be used in the next model of the device. The current device have been successfully tested with regards to the collision requirements included. Therefore it is assumed that also this new model will be able to fulfill these requirements, future tests will be required for certification when the final device is complete.

Since the suspension has been greatly improved to withstand vibrations and shocks from various obstacles, the interior components are now better protected and therefore unlikely to be damaged in the long run. Future durability tests would be preferable but based on performed tests, these requirements are considered fulfilled.

8.4 Maintenance

Maintaining the prototype only requires removal of the rear wheel together with a covering metal plate. With these removed, the user has full access to the motor and rear suspension for disassemble and repairs. To remove the motor bracket however, the rubber dampeners are required to be tightened down externally as the weight of the device does not press them down with the wheels removed. This adds some level of activity to maintenance. For the final design however, the motor bracket as seen in Figure 6.14 eliminates the extra element to disassemble. Therefore this requirement is considered fulfilled. The design of the prototype allowed for the new suspension to replace the old suspension without any modifications, making it a modular addition to the device. The same applies to the front wheels which were simply mounted the same way as the old front wheels, fulfilling this requirement.

8.5 Miscellaneous

Strapping the device into a transport vehicle is done today through a number of metal rings mounted underneath the bottom plate, the same rings are mounted on the prototype, allowing for the device to be strapped down properly. The requirement is therefore fulfilled, it is however preferable to use another type of strap down method in the future model in order for the rings to not interfere with the ground clearance when driving off-road.

8.6 Assembly

The final design of the undercarriage follows approximately the same mounting procedure as SFT's current model. This procedure is rater intuitive and will allow the person assembling to mount the components in a short time. The exact time that it will take to assemble the units will need to be further investigated, since the design of the prototype is not exactly the same as the final design.

8.7 Cost

In the cost analysis 6.3, it is shown that the cost of the undercarriage has been increased by 5.7 %. It means that the wish to have a maximum cost increase of 5 % was not fulfilled. However, the small difference could be further decreased by future negotiation regarding the costs of the components through large annual orders. This would reduce the unit cost of the components, for example the motors.

8.8 Sanitation

The requirements in this section are with regards to how much dirt the device picks up and brings inside buildings after being driven outside, as well as the ease of cleaning the device for indoor use. After excessive use outside, the dirt buildup on the device was not significant. Due to the majority of the prototype being the same as the current model, it is considered easy to clean and disinfect. The current model is designed for this, these wishes can therefore be considered fulfilled.

8.9 Durability - System

The system has not been tested with regards to falling rain or snow, however it is assumed that the device will only be exposed to short periods of time in these conditions when it is driven between the transport vehicle and a building. Due to having protective covers covering the entirety of the device, it is assumed to be able to withstand small amounts of rain or snow without any significant issues.

The collision test in this section regards to whether the internal components and assemblies will withstand such an impact. However, since there have been no changes to the internal components, except for the suspension and drive units, it is assumed that the internal components will be able to handle the impact like they do on the current model.

8.10 Dimensions

The current model is well within the largest allowed dimensions, and since the prototype does not require any exterior modifications to the device. Therefore, the same covers can be used and the dimensions of the device will neither increase nor decrease. As a result, the requirement to remain within the established dimensions have been fulfilled.

9

Further Development

Even though the prototype is considered to successfully fulfill the established requirements and wishes, there is still a number of elements which needs further considerations before the prototype can be turned into the final product. These aspects are either with respect to modifications required to the existing components, adjustments in the device's system or the design of new parts. These areas are mentioned and described below.

- **Base plate:** The base plate would require minor modifications to be suitable for the new model. As Figure 6.14 illustrates, the new motor brackets will use two rubber dampeners which are in direct contact with the bottom plate, these would preferably be tightened down with screws in the base plate. Therefore, new holes would need to be introduced. Another modification is related to the mounting of the front wheels. Since these are larger in diameter than the old front wheels, the device will not be completely horizontal. Therefore it is preferable to look into the mounting point for the front wheels as seen in Figure 6.15. A recommendation is to raise this point further up, which in turn would lower the front part of the device. Finally, the holder for the old suspension's rubber dampeners, seen in Figure 6.16, is recommended to be removed as it is not used with the new suspension and it obstructs the assembly of it.

- **Front wheels:** The front wheels intended for the product are 150 mm diameter caster wheels with an approximate width of 40 mm, having rubber tires. The wheels chosen for the prototype fulfills these specifications. However, the design does not fit the rest of the device. Therefore, it is recommended to use a new type of front caster with similar specifications, better matching the design of the device. Either if it can be found at a supplier, or designed by SFT. The casters used has a rather large caster angle, resulting in the horizontal axis being far away from the vertical axis of the caster. This could result in issues with the stability when the examination arm of the device is extended and rotated to the side, seen as the examination mode in Figure 1.1.

- **Threaded rear wheels:** The concept which was selected as the final concept also included wider, threaded rear wheels for increased traction. This part of the concept was not possible to test due to the limited time span of the thesis. The current wheels with a flat surface was used and they proved to have sufficient traction in most of the scenarios. However, during a few tests the wheels lost traction across the surface. To increase the device's capabilities it is recommended to further look into some level of threading of the wheels. Important to note is that depending on the type of threading, dirt will get stuck to the wheels and brought indoors, the type of threading will also determine how difficult it is to clean the wheels.

- **Power supply for the new motors:** During the test phase, it became apparent that the current layout of the system was not able to provide enough current into the motors to enable their full potential. For the prototype this problem was resolved by adding a pair of car batteries. For the finished model, having two car batteries attached to the device would not be optimal. Instead, it is recommended to investigate the electrical layout and redesign it. The actual battery of the device has enough performance, it is the power supply and how it feeds the current which creates the issues. By redesigning this system, the motors could receive the right amount of current without the need for external batteries.

- **Column stability:** The tests showed that there are some issues with the rigidity of the elevating column and arm of the device when driving across uneven surfaces. Due to the rough handling, these tended to sway to some extent. Even though this does not influence the performance of the driving capabilities, it can be an annoyance for the operator. By investigating this issue and make a more rigid design, the device would be regarded as more robust and perceived to have a higher quality.

With these modifications, it is recommended to expose the device to real life tests by using it as it is intended. It would reveal if there are any issues which have been missed through the thesis or if the device is behaving in a satisfying way. These tests would also be a good method of marketing, since demonstrating the capabilities of an off-road capable x-ray device will get more people interested in the product.

10
Conclusion

During the course of the thesis, a large number of alternatives and solutions have been generated, tested and evaluated. The final concept selected is considered to fulfill most of the established requirements and wishes in the Specification of Requirements. On top of that, the driving capabilities have increased significantly, primarily the ability to handle various terrains, as well as crossing different obstacles. These improvements have been introduced to the device at a similar cost as the solutions used in the current model. The amount of modifications to surrounding components are minimal, which means that the solution could either be used to create a completely new type of product, or be offered as an upgrade to current models already used by customers.

There were a lot of other concepts which potentially would have been able to provide better characteristics of the suspension for instance. However, most of these would introduce either higher costs or require more modifications, resulting in the need to redesign other parts in the device. Moreover, if higher articulation would have been introduced, it would lead to a more unstable device where the risk of tipping during an examination would increase.

It was discovered early that the device would require a new set of electrical motors able to provide the additional torque required to drive across various obstacles. The process of obtaining these motors have been difficult during the thesis. Several suppliers were contacted, but only a few had motors available with suitable specifications. It was at a late stage in the project the motors were obtained and tested. The higher force generated through more powerful motors could have been achieved through other means than new motors. For instance, the concept with a belt drive could be able to solve this issue with additional gear ratios introduced. However, as the concept selection revealed, such a solution would require too much space inside the device, among other issues. Therefore, obtaining new motors was considered the best alternative as they did not cause any significant need for modifications of the device.

The purpose of this master thesis was to *increase the ability to transport SFT's current mobile x-ray machine to environments outside of hospitals. Therefore, the x-ray machine will need to overcome the varying terrain conditions that may occur when it is driven from the transportation vehicle to the location of the x-ray examination.* With testing of the the final design and prototype of the new undercarriage, this purpose have been considered to be fulfilled. Even with the purpose fulfilled, there are always aspects to consider for further improvements to make the x-ray device a highly competitive product on the market. The main aspects have been covered in the further development section, however, other areas might occur during future development which requires consideration.

Moreover, the purpose was accomplished by using components with approximately the same cost as the components in the current model. Since it does not exist any other products on the market with the same performance as this prototype. The new model would therefore be considered unique and would allow SFT to obtain a high profit of the product.

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A

Specification of Requirements

Table A.1: Specification of Requirements (Weidenmark, 2016), (International Electrotechnical Commisson, 2012).

		Customer needs / Observations	Criteria	D/W	Verification method	Reference
Undercarriage Requirements	Manuverability		*Maximum propulsion required on a hard flat horizontal surface of 200N*	D	*Engineering test*	*Industrial Standard IEC 60601-1 §9.4.2.4.2*
		General good attribute for customer satisfaction. Patient rooms can be small and hard to access.	*The system shall have a high level of manuverability*	W	*Engineering test*	*User study/ interview Lunds sjukhus*
		The system may be operated by less strong persons who cannot use a big force to move the system	*The system shall be easy to manuver with low force applied*	W	*Engineering test*	*User study/Interview Akershus sykehus*
		Patients room is small and sometimes hard to get into because of bad planned architecture or furnitures in the room.	*The system shall be able to drive around sharp corners*	W	*Engineering test Cad assessment*	*User study/ interview Lunds sjukhus*
		Recommendations from Boverket to secure access to public buildings for a electric wheel chair type B; used for in and outdoor use.	*The system shall have a turn circle of maximum 1.5m*	D	*CAD assessment*	*Building regulations; Boverket*
		When carrying equipment or holding doors open the system has to be driven by one hand.	*The system shall be able to be driven with one hand*	W	*Engineering test*	*User study/ interview Lunds sjukhus*
		The ground can be of gravel, packed snow or icy.	*The system shall be able to drive controlled on bumpy and slippery ground*	W	*Engineering test*	*User study/ interview Lunds sjukhus*
		The ground can be of packed snow or icy.	*The system shall be able to drive on slippery surfaces*	W	*Engineering test*	
			The suspension minimizes vibrations during transport	W	*Engineering test*	
		When driving outdoors on a parking lot one may have to drive up and down curbs, approximately 30mm with rounded edges.	*The system shall be able to drive up 30mm high curbs*	D	*Engineering test*	*User study/ interview Lunds sjukhus*
			The system shall be able to pass over a 10mm hight threshold at a speed of 6 km/h	D	*Engineering test*	*Industrial Standard IEC 60601-1 §9.4.2.4.3*
		Based on regulations set by the swedish authority Boverket.	*The system shall be able to drive up 25mm high sharp thresholds*	D	*Engineering test*	*Research building regulations;*
		The machine gets stuck while trying to overcome various types of thresholds, primarily with regards to ramps	*The system shall be able to drive up 25mm high sharp thresholds from standing still*	W	*Engineering test*	*Video recordings*
		The ground can be muddy or slushy with snow	*The system shall be able to drive in 40mm slushy snow or mud.*	W	*Engineering test*	*User study/Interview Akershus sykehus*
			The brakes shall be designed so that they are normally activated and can only be released by continuous actuation of a control	D	*CAD assessment*	*Industrial Standard IEC 60601-1 §9.4.3.1a*
		If the operator has to leave the system standing on uneven road it should not roll away.	*The system shall be standing still and braked when not in operation*	D	*Engineering test*	*User study/ interview Lunds sjukhus*
			The brakes shall be effectively holding the system still at angles of at least 10° in transport position, with a maximum movement of 50mm	D	*Engineering test*	*Industrial Standard IEC 60601-1 §9.4.3.1c*
			The brakes shall be effectively holding the system still at angles of at least 5° in any position excluding transportation, with a maximum movement of 50mm	D	*Engineering test*	*Industrial Standard IEC 60601-1 §9.4.3.2a*
			The brakes shall effectively hold the system still when exposed for a lateral load of 150N applied in any direction, with maximum movement of 50mm	D	*Engineering test*	*Industrial Standard IEC 60601-1 §9.4.3.2b*
			The system shall not risk tipping during examination	D	*Enginering test*	
		The ramp to the vehicle depends on ramp length and vehicle rear height. The angle is calculated from these parameters.	*The system shall be able to drive up and down, forwards and reverse, from a ramp with a slope of 14.5 degrees*	W	*Engineering test*	*Vehicle specifications*

		Customer needs / Observations	Criteria	D/W	Verification method	Reference
Undercarriage Requirements	Ergonomics	General requirement contributing to high level of working comfort.	*The need for the operator to carry equiment in connection with movement shall be minimized*	W		
	Durability	Water may reach the bottom plate and wheels when driving in snow or rain	*The undercarriage's uncovered parts shall sustain some water and snow*	W	*CAD assessment*	*Use simulation*
		Salt may reach uncovered parts when driving on salted roads	*The undercarriage's uncovered parts shall sustain some road salt*	W	*CAD assessment*	*User study/ interview Lunds sjukhus*
		The system do sometimes scratch along the wall or door openings. Scratches should be avoided to maintain good appearence.	*The undercarriage shall be protected from scratches caused by doors and collision*	W	*CAD assessment*	*User simulation*
			The system shall handle shocks three times from driving at max speed down from a 40mm step without causing risk of injury	D	*Engineering test*	*Industrial Standard IEC 60601-1 §15.3.5b*
		The system may be exposed to single hard shocks when driving down curbs and thresholds	*The system shall sustain shocks from driving down 25mm thresholds*	W	*Engineering test*	*Use simulation*
			The system shall handle shocks three times from driving at max speed into a 40mm solid hardwood plane obstruction attached to the floor without causing risk of injury	D	*Engineering test*	*Industrial Standard IEC 60601-1 §15.3.5a*
		Vibrations will affect the system when driving on rough asphalt and gravel	*The vibrations on the system shall be minimized while driving on rough asphalt and gravel*	W	*Engineering test*	*User simulation*
	Maintenance	Generally low need for maintenance contributes to high customer value since time and money is saved. The requirement depends on business case, who pays for maintenance.	*The need for maintaining the undercarriage shall be minimized*	W	*Engineering test*	*User study/ Lunds sjukhus & Akershus sykehus*
		Bad communication service takes time, money and effort from the user. Also wating for service to be carried out is waste of time for the users.	*Modular design of undercarriage to simplify maintenance*	D	*CAD assessment*	*User study/Interview Akershus sykehus*
	Miscellanious		*The system shall be able to be strapped into the transport vehicle using the same standard methods as wheelchairs*	D	*CAD assessment*	
System Requirements	Sanitation	The system will be driven outdoors and into the building for x-ray investigation. The wheels tend to bring dirt.	*The risk of bringing dirt inhouse shall be reduced*	W	*Engineering test*	*User study/ interview Lunds sjukhus*
		After visiting patients with a contagious decease the whole machine has to be cleaned, even the wheels.	*The system shall enable easy disinfection*	W	*CAD assessment*	*User study/Interview Akershus sykehus*
	Durability	The system will be exposed to weather when transferring between vehicle and location for x-ray investigation.	*The system shall sustain rain, snow and weather*	W	*Engineering test*	*User study/ interview Lunds sjukhus*
			The system shall handle shocks three times from driving at max speed into a solid hardwood obstruction with a width and thichness of 40mm while being taller than the machine, without causing risk of injury	D	*Engineering test*	*Industrial Standard IEC 60601-1 §15.3.5c*
	Dimensions	Recommendations from Boverket to secure access to public buildings for a electric wheel chair type B; used for in- and outdoor use.	*Maximum dimensions of system: Length 1.3m, Width 0.7m*	D	*CAD assessment*	*Building regulations; Boverket*
		The patient rooms is usually small and it is hard to get in between bed and furnitures.	*The system shall be of small size; length width and height*	W	*CAD assessment*	*User study/Interview Akershus sykehus*

B

Tables Failure Modes and Effects Analysis

Table B.1: Probability of Occurrence

Likelihood of Failure	Criteria: Occurrence of Cause (Design Life/Reliability of Item/ Vehicle)	Rank
Very High	New technology/new design with no history.	10
High	Failure is inevitable with new design, new application, or change in duty cycle/ operating conditions.	9
	Failure is likely with new design, new application, or change in duty cycle/ operating conditions.	8
	Failure is uncertain with new design, new application, or change in duty cycle/ operating conditions.	7
Moderate	Frequent failures associated with similar designs or in design simulation and testing.	6
	Occasional failures associated with similar designs or in design simulation and testing.	5
	Isolated failures associated with similar design or in design simulation and testing.	4
Low	Only isolated failures associated with almost identical design or in design simulation and testing.	3
	No observed failures associated with almost identical design or in design simulation and testing.	2
Very Low	Failure is eliminated through preventive control.	1

Table B.2: Severity of Failure

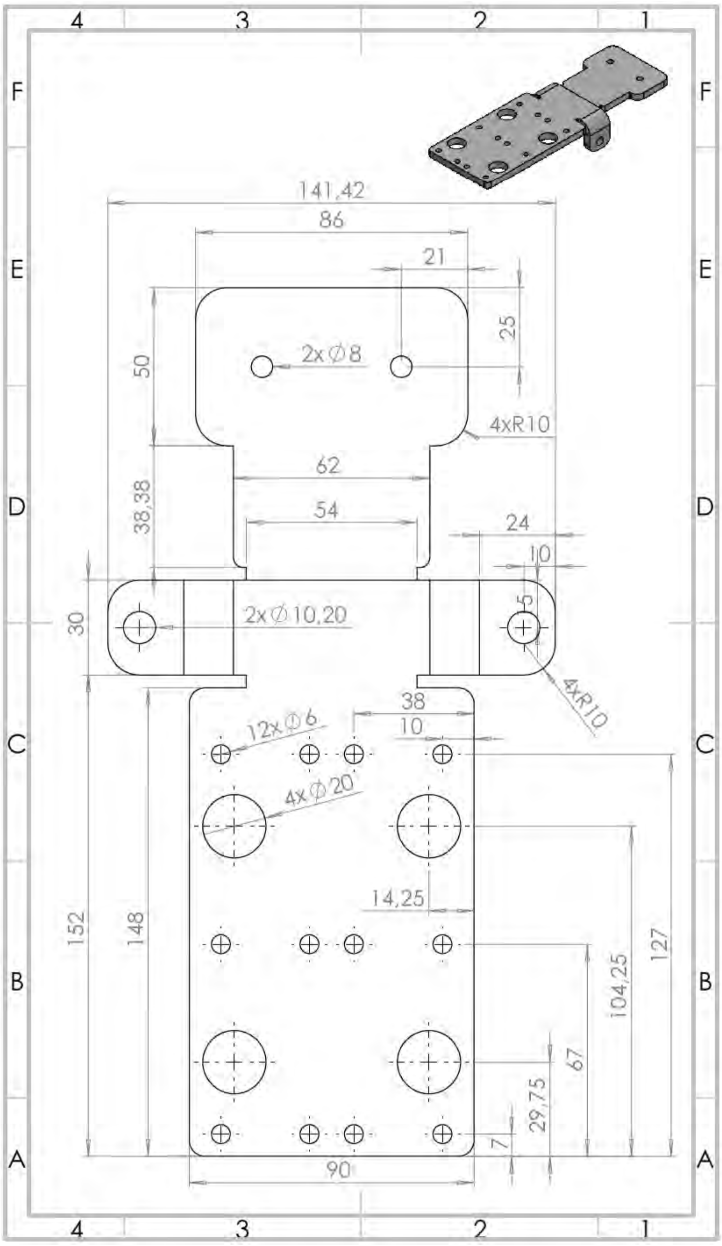
Effect	Criteria: Severity of Effect on Product (Customer Effect)	Rank
Failure to Meet Safety and/or Regulatory Requirements	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning.	**10**
	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning.	**9**
Loss or Degradation of Primary Function	Loss of primary function (vehicle inoperable, does not affect safe vehicle operation).	**8**
	Degradation of primary function (vehicle operable, but at reduced level of performance).	**7**
Loss or Degradation of Secondary Function	Loss of secondary function (vehicle operable, but comfort/convenience functions inoperable).	**6**
	Degradation of secondary function (vehicle operable, but comfort/ convenience functions at reduced level of performance).	**5**
Annoyance	Appearance or audible noise, vehicle operable, item does not conform and noticed by most customers (>75%).	**4**
	Appearance or audible noise, vehicle operable, item does not conform and noticed by many customers (50%).	**3**
	Appearance or audible noise, vehicle operable, item does not conform and noticed by discriminating customers (<25%).	**2**
No Effect	No discernible effect.	**1**

Table B.3: Probability of Detection

Opportunity for Detection	Criteria: Likelihood of Detection by Design Control	Rank	Likelihood of Detection
No Detection Opportunity	No current design control; cannot detect or is not analyzed.	**10**	**Almost Impossible**
Not Likely to Detect at any Stage	Design analysis/detection controls have a weak detection capability; virtual analysis (e.g., CAE, FEA, etc.) is not correlated to expected actual operating conditions.	**9**	**Very Remote**
Postdesign Freeze and Prior to Launch	Product verification/validation after design freeze and prior to launch with pass/fail testing (subsystem or system testing with acceptance criteria such as ride and handling, shipping evaluation, etc.)	**8**	**Remote**
	Product verification/validation after design freeze and prior to launch with test to failure testing (subsystem or system testing until failure occurs, testing of system interactions, etc.)	**7**	**Very Low**
	Product verification/validation after design freeze and prior to launch with degradation testing (subsystem or system testing after durability test, e.g., function check).	**6**	**Low**
Prior to Design Freeze	Product validation (reliability testing, development or validation tests) prior to design freeze using pass/fail testing (e.g., acceptance criteria for performance, function checks, etc.)	**5**	**Moderate**
	Product validation (reliability testing, development or validation tests) prior to design freeze using test to failure(e.g., until leaks, yields, cracks, etc.).	**4**	**Moderately High**
	Product validation (reliability testing, development or validation tests) prior to design freeze using degradation testing (e.g., data trends, before/after values, etc.)	**3**	**High**
Virtual Analysis—Correlated	Design analysis/detection controls have strong detection capability. Virtual analysis (e.g., CAE, FEA, etc.) is highly correlated withactual and/or expected operating conditions prior to design freeze.	**2**	**Very High**
Detection Not Applicable; Failure Prevention	Failure cause or failure mode cannot occur because it is fully prevented through design solutions (e.g. proven design standard, best practice or common material, etc.)	**1**	**Almost Certain**

C

Drawing New Motor Bracket



D

Bill of Materials

Part. No.	Name	Quantity	Supplier/Source	Article No.
1	Front Wheel	2	Tellus Hjul & Trade AB	31431
2	Rubber Buffer Front	6	Eugen Wiberger AB	GN351-25-20-M6-ES-55
3	Left Front wheel Bracket	1	SFT	-
4	Right Front Wheel Bracket	1	SFT	-
5	Cast Drive Wheel	2	SFT	-
6	Left Drive Motor	1	ElectroCraft, Inc.	MP26-WL-029V24-420
7	Right Drive Motor	1	ElectroCraft, Inc.	MP26-WR-029V24-420
8	Wheel Coupling	2	SFT	-
9	Mounting Bracket Drive Unit	2	SFT	-
10	Rubber Buffer Rear	4	Eugen Wiberger AB	GN351-40-40-M8-ES-55
11	Base Plate	1	SFT	-