Maintaining and training walking ability with the Wheels-On

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Abbreviations

Abbreviation	Description
N/A	Not Applicable
N/S	Not Specified
CN	Customer Need
FR	Functional Requirement
CON	Contraint
DP	Design Parameter
CSD	Collective System Design
PCB	Printed Circuitboard
PWM	Pulse Width Modulation
UWB	Ultra-Wideband

Symbols

Symbol	Description	Unit
C	Target cost	ISK
P	End user price	ISK
M	Profit margin	%

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Abstract

Walking can have a positive effect on everyone's health. It can, however, be challenging for people with limited lower extremity function to walk since they may need to rest suddenly. Currently, no product completely solves this problem, causing people to rely more on their wheelchairs. The product being developed aims to enhance or maintain the walking ability of those users. The product, Wheels-On, is an add-on power kit that turns a standard wheelchair into a semi-autonomous following wheelchair, providing security for users and offering more opportunities to walk. The project showed promising results and provided a good foundation for further work on the product.

Acknowledgments

This project was provided and funded by Reykjavík University. Our shepherd, Þórður Helgason, and both of the stakeholders, Kári Halldórsson and Jón Stefánsson, provided essential information and advice regarding the project. The stakeholder, Jón, provided two wheelchairs from Hjálpartækjaleiga Sjálfsbjargar that are allocated for modification.

Chapter 1

Introduction

People with limited lower extremity function can significantly benefit from walking short distances. For example, some benefits are preventing muscle loss, strengthening the bones, and maintaining healthy blood flow [1]. That is why it is important for people who use a wheelchair with some walking ability, also known as ambulatory wheelchair users, to maintain or increase their walking ability and train when circumstances allow [2]. It can be challenging to leave the wheelchair behind when the need for rest arises, which may cause users to skip out on the opportunity to train their walking ability and rely more on their wheelchair. That is why the product being developed is the Wheels-On which is an add-on power kit that turns a standard wheelchair into a semi-autonomous following wheelchair. The Wheels-On makes it possible for the wheelchair to follow its user at a short distance, providing security while walking.

The product can also benefit rehabilitation centers that would use it to help their customers during physiotherapy sessions. Now there is an employee whose job is to push the wheelchair behind the client during sessions, so the product could allow the employees to allocate their time to other tasks. Even though the users can be of all ages, this project focuses on users who use a standard wheelchair size for adults.

Information regarding the product was gathered from an interview with our stakeholders, Kári Halldórsson and Jón Stefánsson. The project can be split into four main parts; hardware, design, sensing, and software. During the course, the focus is on the first three parts: finding suitable components, designing the modification for the wheelchair, and getting the sensors to output the required data.

Chapter 2

Background

2.1 Prior Art

Currently, no product completely fulfills the needs of our customers, ambulatory wheelchair users. However, several products relate to the project and can inspire the development of the add-on power kit. The following chapters cover the main features of these similar products that can be useful for the project.

2.1.1 Light Drive Power Assist

The light drive power assist is a kit attached to a standard wheelchair turning it into an electric wheelchair, which can be seen in figure 2.1.

Figure 2.1: Light Drive Power Assist [3].

It only takes about 20 seconds to attach the kit to a wheelchair, and with the lever, the user can change the modes of the wheelchair; manual and electric. The kit uses two 130W motors with brakes to power the chair, and with the attachable joystick, the user can control the chair. The weight of Light Drive is 8.8 kg for a maximum user weight of 120 kg. The Light Drive uses a 12 Ah lithium-ion battery weighing 3.85 kg, providing a range of 12 to 16 km and a maximum speed of 10 km/h [3, 4].

2.1.2 Permobil Smartdrive MX2+ Power Add-On Kit

The Permobil Smartdrive MX2+ Power Add-On Kit is attached to wheelchairs, providing power assistance for the user. It uses a 250W brushless dc motor to power the chair, giving it a maximum speed of 8.8 km/h and weighing only 5.7 kg for a user weight ranging from 14 to 150 kg. Figure 2.2 shows the Permobil attached to a wheelchair. The user uses as wristband, PushTracker E2, to turn on the power assist and change the speed settings.

Figure 2.2: Permobil Smartdrive MX2+ Power Add-On Kit [5].

Permobil comes with a Switch Control that can be adjusted to the user, which can provide a momentary burst of power or consistent power over extended distances[5].

2.1.3 Airwheel SR5

The Airwheel SR5 is a smart following suitcase. It uses UWB high-accuracy location technology to track the smart band the user has on, recognizing the distance between the user and the suitcase.

It has two modes; auto-follow mode and normal tow mode. If the suitcase is in normal tow mode, it will use a 20W motor to draw up the motors, protecting them and making it easy for the user to tow the luggage. The SR5 has Bluetooth 4.0, so it can be connected to the user's smartphone, making it easy for the user to change settings like changing speed and driving the suitcase manually. It uses an ultrasonic sensor to detect obstacles and plans dynamically to avoid them. It can reach up to 6 km/h with two 50W motors, rated at a speed of 500 rpm. The SR5 is powered by a lithium-ion battery which weighs 340g and has a battery capacity of 62.6Wh. The total weight of the suitcase is 6kg [6]. The Airwheel SR5 can be seen in figure 2.3 along with the smart band.

Figure 2.3: Airwheel SR5 along with the Smart Band [6].

2.1.4 Robotic Wheelchair with Omni-directional vision

The robotic wheelchair with omni-directional vision was a project done at Saitama University. Figure 2.4 shows an overview of the chair. The robotic wheelchair was developed to move alongside the user's companion by observing their behavior, such as body position and orientation.

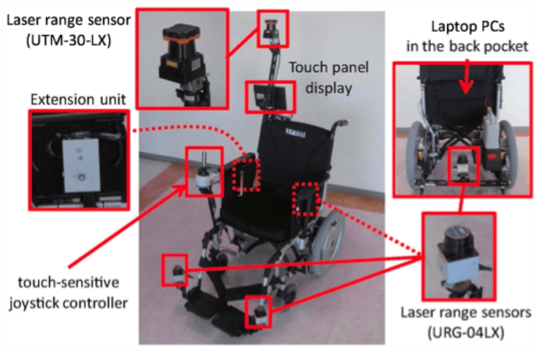


Figure 2.4: Robotic Wheelchair with Omni-directional vision [7].

The companion sets the initial position by tapping the facial image provided by the omni-directional camera. The wheelchair has a laser range sensor, UTM-30LX by Hokuyo Electric Machinery, attached to a pole affixed to the wheelchair to observe the upper body of the companion. It has three additional laser range sensors, URG-04LX, to observe the environment around it. The wheelchair has an extension unit attached to the joystick controller to override the output signal generated by the software. The wheelchair has three modes; side-following mode, where the wheelchair is by the side of the companion, which is its desired mode; back-following mode, where the wheelchair is behind the companion; and insensitive mode, where the wheelchair stops because the companion has stopped [7].

2.2 Performance Metrics

Customer needs were developed from interviewing the stakeholders, and the previous study, made by the stakeholder Jón Stefánsson [8]. The customer needs were organized by grouping similar needs, then organized into a hierarchy, shown in table 2.1, where latent needs were also identified, denoted by !.

Table 2.1: Customer needs and their importance. Importance ratings are indicated by the number of *'s, with *** denoting critically important needs. Latent needs are denoted by !.

No.	Customer Needs	Importance
1	**The wheelchair can move remotely**	***
1.1	The wheelchair can accelerate	***
1.2	The wheelchair can turn	**
2	**The wheelchair is safe**	***
2.1	The wheelchair senses accurately / is reliable	***
2.2	The wheelchair can be aware of its surrounding	**
2.3	The wheelchair doesnt bump into the user	***
2.4	The wheelchair can handle obstacles	**
2.5	The wheelchair can follow the user through doors	*
2.6	The wheelchair can know where the user is	***
3	**The wheelchair is practical**	***
3.1	The wheelchair cannot be heavy	***
3.2	The wheelchair hardware can be easily affixed	**
3.3	Can work as a standard wheelchair when feature is not on	***
3.4	The wheelchair is not loud	**!**
4	**The wheelchair is durable**	**
4.1	The wheelchair can handle an hour session at a time	**
5	**The wheelchair provides feedback**	**
5.1	The wheelchair lets the user know if something is wrong, , i.e., far behind/stuck	***
5.2	The wheelchair can communicate with the user	**
5.3	The wheelchair can let the user know the distance he walked	**!**

A list of metrics was prepared, and competitive benchmarking information was collected for similar products and projects. The information for other creations was gathered from reports and manufacturers' websites; see chapter 2.1. The competitive benchmarking chart can be seen in table 2.3. Since no other product or project currently exists that implements this project's desired features, the units for many metrics in the benchmarking chart are binary. This was done to see if similar products possess a specific essential feature.

An overview of the necessary features to implement for the product, along with information about whether similar products possess the feature, can be seen in table 2.2.

Table 2.2: The necessary features to implement for the product and information about whether similar products possess the feature.

No.	**Feature**	**Light Drive**	**Permobil Smartdrive MX2**	**Airwheel SR5**	**Robotic Wheelchair**
1	Works as a standard wheelchair	Yes	Yes	No	No
2	Can follow a person	No	No	Yes	Yes
3	Can move remotely	No	No	Yes	Yes
4	Has obstacle avoidance	No	No	Yes	Yes
5	Provides feedback	Yes	Yes	Yes	No
6	Rechargeable power supply	Yes	Yes	Yes	Yes

The competitive benchmarking chart was then converted to table 2.4, which considers perceived satisfaction of needs. The rating was done by rating the importance of each need and then assessing how well each need is met by the existing products on a scale from 1 to 5, denoted by stars.

Table 2.3: Competitive benchmarking chart based on metrics. * denotes an educated guess based on information provided by the source of the product/project.

No.	Need No.	Metric	Imp	Unit	Light Drive	Permobil Smartdrive MX2	Airwheel SR5	Robotic Wheelchair
1	1, 2.3	Distance from user	5	m	N/A	N/A	N/S	N/S
2	1.1	Speed	5	km/h	10	8.8	6	N/S
3	1.2	Rotation	5	deg	360*	N/A	360*	360*
4	2	Medical device certificate	4	binary	Pass*	Pass	N/A	Fail*
5	2.1	Sensors have small margin of error	4	%	Low*	N/S	Low*	Low*
6	2.2	Reacts to environment	4	s	N/A	N/A	1*	3*
7	2.4	Minimum distance from obstacles	4	m	N/A	N/A	N/S	N/S
8	2.5	Door test	1	binary	Pass	Pass	Pass	Pass
9	2.6	Coordinates comparing user and wheelchair	5	deg	N/A	N/A	N/S	N/A
10	3	How likely is the user to use the product	4	subj.	1*	1*	1*	1*
11	3.1	Total mass of kit	4	kg	14.5	5.7	6	N/S
12	3.2	Time to assemble for the first time	2	s	360*	60*	0*	0*
13	3.2	80% of user can assemble without assistance	1	binary	N/S	N/S	Pass*	Pass*
14	3.3	Manual propelling available	5	binary	Pass	Pass	Pass	Fail
15	3.4	Maximum noise	2	dB	N/S	N/S	Mute	N/S
16	4	Durability longer than 3 years	3	years	N/S	2+	N/S	N/S
17	4.1	Minimum duration	3	km	15	19.8	5	N/S
18	5	Conveys messages to user	4	binary	Pass	Pass	Pass	Fail
19	5.1, 5.2, 5.3	Sound message	3	binary	N/S	N/S	N/S	N/S
20	5.1	Vibration message	1	binary	N/S	N/S	Pass	N/A
21	5.3	Keep track of distance	1	binary	N/S	Pass	170-240*	N/S
22	5.3	Screen message	1	binary	Pass	Pass	Pass	Fail

Table 2.4: Competitive benchmarking chart based on perceived satisfaction of needs. Having more stars corresponds to greater perceived satisfaction of the need.

No.	Need	Imp	Light Drive	Permobil Smartdrive MX2	Airwheel SR5	Robotic Wheelchair
1	**Can move remotely**	5	*	*	*****	*****
1.1	Can move	5	*****	******	*****	*****
1.2	Can turn	4	*****	***	*****	*****
2	**Is safe**	5	****	**	*****	****
2.1	Senses accurately /is reliable	4	*	*	*****	*****
2.2	Is aware of its surroundings	3	*	*	*****	*****
2.3	Doesnt bump into the user	5	*	*	*****	*****
2.4	Can handle obstacles	4	*	*	*****	*****
2.5	Can follow the user through doors	2	*	*	*****	*****
2.6	Can know where the user is	5	*	*	*****	*****
3	**Is practical**	4	*****	****	****	***
3.1	Can not be heavy	5	****	*****	****	*
3.2	Hardware can be easily affixed	3	****	****	****	***
3.3	Can work as a standard wheelchair when feature is not on	5	*****	*****	*	*
3.4	Is not loud	2	***	***	***	****
4	**Is durable**	2	*****	*****	**	*****
4.1	Can handle an hour session at a time	3	*****	*****	****	*****
5	**Provides feedback**	4	***	***	*****	***
5.1	Lets the user know if something is wrong, i.e. far behind/stuck	4	*	*	*****	*
5.2	Can communicate with the user	4	**	**	*****	***
5.3	Can let the user know the distance he walked	1	*	*****	*	*

Chapter 3

Design

Several steps were followed to decide on a final concept based on the guidance of the book Product Design and Development [9]. Concepts were generated and analyzed to select the best concept as the final one. The final concept was then analyzed, and the ISO standards the product should aim to meet were introduced.

3.1 Design methods

Two common product design methods are the axiomatic design and the Collective System Design, or CSD, decomposition process. The axiomatic design uses matrix methods to develop functional requirements, design parameters, and process variables from customer needs [10]. The two axioms of the method are maintaining the independence of the functional elements and minimizing the information content [11]. To maintain independence, axiom one focuses on developing a design solution that avoids unwanted coupling, but coupling refers to functions that cannot be changed without affecting other functions. Coupling can take place when one design parameter is used to satisfy two functional requirements. Axiom two takes place after axiom one has been performed to minimize the information content. It is done by selecting between promising solutions, considering which one can successfully fulfill the functional requirements [11]. This method has been widely used in product design, mainly because it reduces the number of possible initial designs to one while consuming almost no resources [12]. CSD is an engineering method used to describe a system design. It is done by defining the functional requirements before selecting physical solutions for the product. The physical solutions are presented as a hypothesis to meet the functional requirements [13, 14].

3.2 Concept Development

Concepts were generated by following the step-by-step guidance from chapter 7 in Product Design & Development[15]. Those steps are:

1. Clarify the problem
2. Search externally
3. Search internally
4. Explore systematically
5. Reflect on the solutions and the process

In step one, the problem was defined, as can be seen in chapter 1, which resulted in the solution of creating an add-on power kit. Since the problem is extensive, it was divided into sub-problems, also known as functional requirements. The FRs can be seen below, along with their metric. But they must be met for the project to be successful.

FR0: Can follow its user

Metric: The wheelchair can follow a user at a short distance

FR1: Has obstacle avoidance

Metric: Needs to sense environment to avoid crashing into user/obstacles

FR2: Works as a standard wheelchair

Metric: Needs to keep standard function of wheelchair when feature is not on

FR3: Can move remotely

Metric: Needs to be able to move around when user is at a short distance from wheelchair

FR4: Has rechargeable power supply

Metric: Needs to be able to drive without being plugged in

FR5: Provides feedback

Metric: Needs to be able to deliver messages to the user

CON1: Is not too heavy

Metric: Cannot be heavier than 7kg

CON2: Lasts for a rehabilitation session

Metric: Needs to be able to work for an hour during a rehabilitation session

Step two is an information-gathering process. It went into searching for similar existing solutions for the sub-problems. Those products or prjoects, that can be seen in chapter 2.1, do not have to be a perfect solution for the problem but must include some features that may be helpful for it.

Step three utilizes personal and team knowledge in a brainstorming session to generate solutions for the sub-problems. The result of the brainstorming session can be seen in table 3.1, where each sub-problem can be seen with a viable solution and an argument for each solution.

In step four, the solutions generated by the team were organized, and a concept combination table was created, as can be seen in figure 3.1. The chosen options were based on the brainstorming session and the information-gathering process.

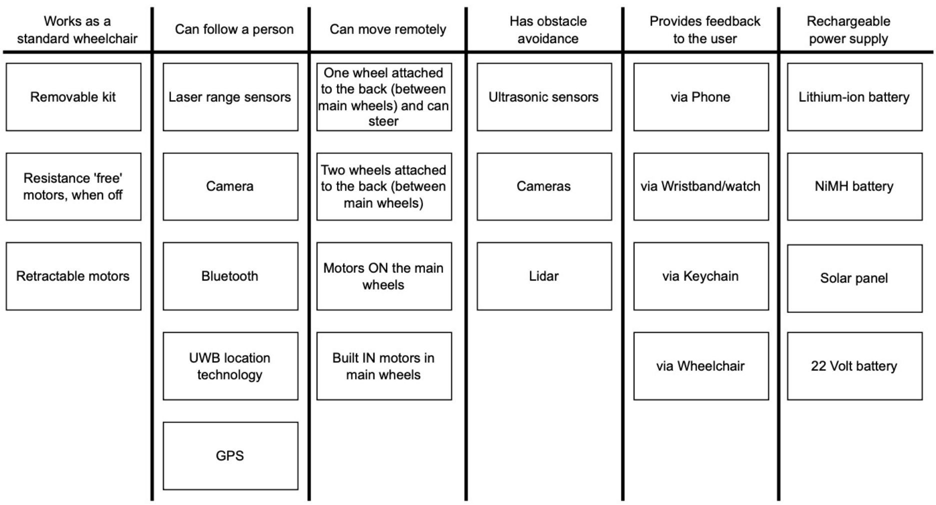


Figure 3.1: Concept combination table with viable options.

From there, solution concepts were created by pairing solutions for the sub-problems, creating a feasible concept for the main problem. The group then voted on the best four solutions by considering the pros and cons of each option, seen in table 3.1, resulting in the concepts seen in chapters 3.2.1 - 3.2.4.

Step five consists of reflections made during steps 1-4, which involves ensuring that all possibilities have been explored and if alternative solutions to the problem are more suitable [15].

Table 3.1: Solution generated for each sub-problem with pros and cons for the solution.

Solution	Pros	Cons
Works as a standard wheelchair		
Removable Kit	User is able to take the product off the wheelchair	Can be time consuming attaching it
Restistance "free" motors, when off	Stay on the main wheels of the wheelchair with minimal user involvement	Could affect how the wheelchair works as a standard wheelchair
Retractable motors	Easy to move on and off the main wheels of the wheelchair	Can be time consuming retracting it
Can follow a person		
Laser range sensors	Is accurate [7]	Expensive [7]
Camera	Is accurate [16]	The user needs to have a tag or wear a certain color [16]
Bluetooth	Does not use a lot of battery power [17]	Low-data-rate applications [17]
UWB location technology	Precise location-tracking capabilities [17]	Newer wireless communication technology [17]
GPS	Unlimited range to navigate [17]	Satellite-based navigation system[17]
Can move remotly		
One wheel attached to the back (between main wheels) and can steer	Does not disturb the user	The mechanism to make it steer the wheelchair is complicated
Two wheels attached to the back (between main wheels)	Does not disturb the user	The mechanism to make it steer the wheelchair is complicated
Motors ON the main wheels	Easy to control the motion of the wheelchair	Can affect the function of the standard wheelchair
Built IN motors in main wheels	Easy to control the motion of the wheelchair	Can affect the function of the standard wheelchair
Has obstacle avoidance		
Ultrasonic Sensors	Easy to operate and low power consumption [18]	Has limited range to would require many sensors to be mounted onto the wheelchair [18]
Camera	Great efficiency in detecting obstacles [19]	Are expensive [20]
Lidar	Fast, accurate, reliable and could be used for mapping [21]	Gives data in 2D or expensive and energy-intensive [22]
Provides feedback to the user		
via Phone	Can provide feedback in the form of messages, light and vibration	Can be difficult to hold if the user's hands are preoccupied
via Wristband/Watch	Can provide feedback in the form of messages, light and vibration	Can irritate the skin
via Keychain	Can provide feedback in the form of light and vibration	Limited in what form the feedback can be in
via Wheelchair	Can provide feedback in the form of messages, light and vibration.	Hard to see when turning your back to the wheelchair
Rechargeable power supply		
Lithium-ion battery	Rechargeable [23]	Heats up when charging [23]
NiMH battery	Rechargeable [24]	Limited amounts of recharges [24]
Solar panel	Rechargeable [25]	Cannot be used indoors [25]
22 Volt battery	Rechargeable and long lasting [26]	Heavy [26]

3.2.1 Concept A

The combination for the solution concept can be seen in figure 3.2.

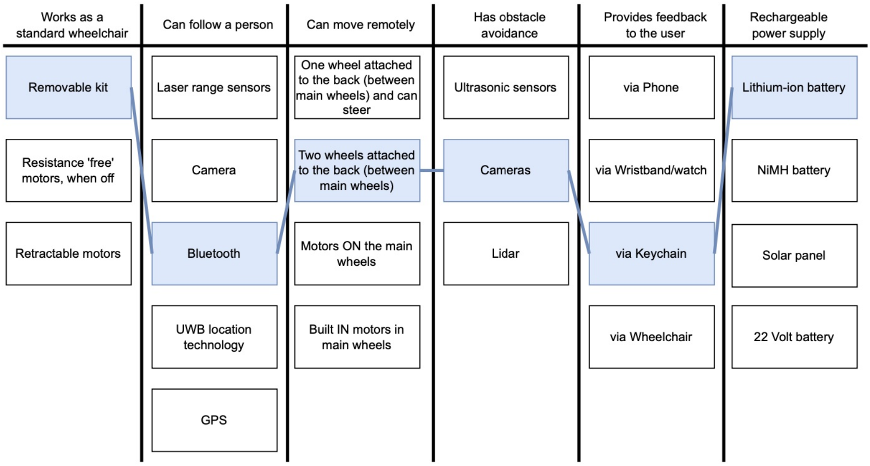


Figure 3.2: Concept combination table for solution concept A.

Concept A consists of a removable kit with a Bluetooth module that communicates to the user via Keychain to know its location. The motors would power two wheels that are attached to the back of the wheelchair in order for it to move. The design of the wheel attachments is inspired by figure 2.2. The camera, used for sensing and avoiding obstacles, would be mounted to the front of the wheelchair.

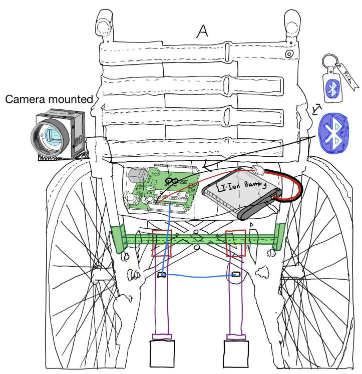


Figure 3.3: A sketch of the solution concept A derived from figure 3.2.

The chair should be powered with a powerful lithium-ion battery to power the motor and all the hardware. The sketch for concept A can be seen in figure 3.3 and the CSD decomposition for the concept can be seen in figure 3.4.

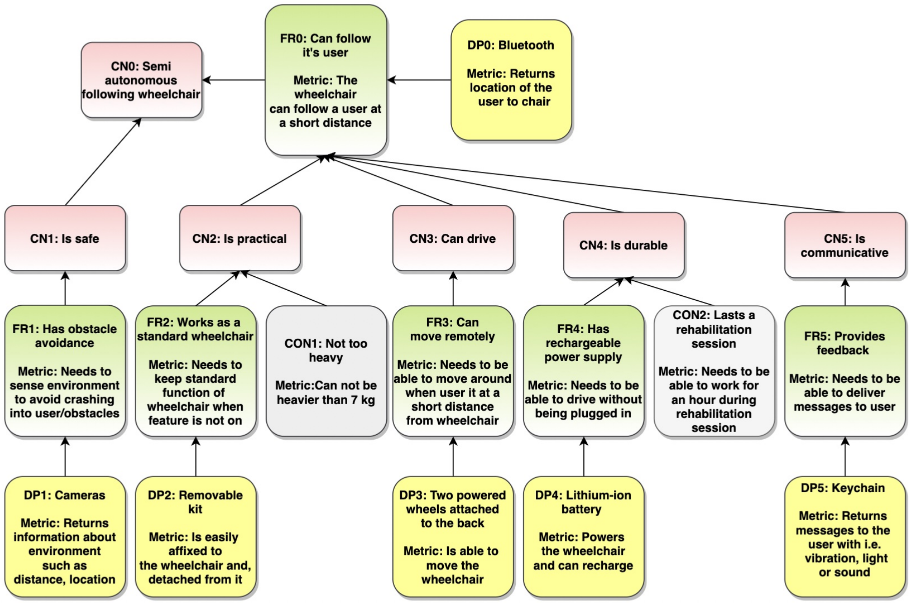


Figure 3.4: Collective System Design Decomposition based on concept A.

When analyzing the design decomposition according to axiom one, the design decomposition is uncoupled since the ordering has all of the coupling lines pointing straight up. When considering how promising each part of the solution is, with axiom two in mind, it can be assessed that the removable kit could be inconvenient for the user since it needs to be removed when not in use. Bluetooth is not the best option compared to the other solutions since others can be more precise. The cameras are expensive compared to the other options, so they might not be the best option financially. Finally, the user might want more information than the keychain can provide.

3.2.2 Concept B

The combination for the solution concept can be seen in figure 3.5.

Works as a standard wheelchair	Can follow a person	Can move remotely	Has obstacle avoidance	Provides feedback to the user	Rechargeable power supply
Removable kit	Laser range sensors	One wheel attached to the back (between main wheels) and can steer	Ultrasonic sensors	via Phone	Lithium-ion battery
Resistance 'free' motors, when off	Camera	Two wheels attached to the back (between main wheels)	Cameras	via Wristband/watch	NiMH battery
Retractable motors	Bluetooth	Motors ON the main wheels	Lidar	via Keychain	Solar panel
	UWB location technology	Built IN motors in main wheels		via Wheelchair	22 Volt battery
	GPS				

Figure 3.5: Concept combination table for solution concept B.

Concept B consists of retractable motors mounted directly onto the tires of the wheelchair. To follow the user, the wristband on the user will include a UWB tag. The wheelchair shall have two anchors with a known distance between them to triangulate the user's location. An ultrasonic scanner will be required for obstacle avoidance, and lithium-ion batteries shall power the chair. The sketch for concept B can be seen in figure 3.6.

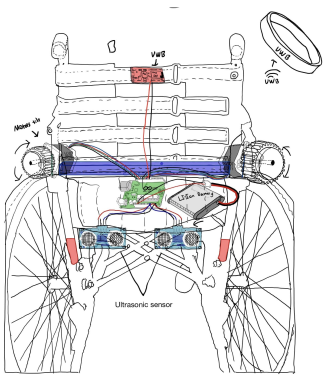


Figure 3.6: A sketch of the solution concept B derived from figure 3.5.

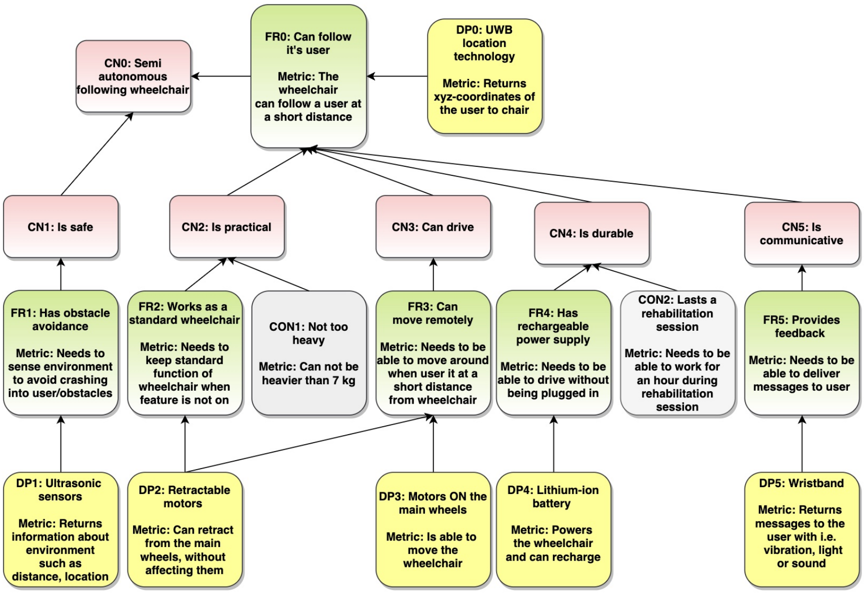


Figure 3.7: Collective System Design Decomposition based on concept B.

The CSD decomposition for concept B can be seen in figure 3.7. According to axiom one, the design decomposition is decoupled since it is not possible to get rid of the coupling lines that do not point straight up. However, the ordering has all of the arrows either pointing to the right or straight up, which makes the decomposition path-dependant, from left to right. When considering how promising each part of the solution is, with axiom two in mind, it can be assessed that the product's durability would not be as good as desired with retractable motors on the main wheels. Other than that, the solution concept looks promising.

3.2.3 Concept C

The combination for the solution concept can be seen in figure 3.8. Concept C consists of resistance-free motors mounted directly onto the wheels of the wheelchair. When the motors are switched off, they should not negatively impact the movement of the chair, for example, by causing friction on the wheels. The wheelchair will use GPS to locate and follow the user and lidar for obstacle avoidance. The chair will communicate with the user and the GPS via smartphone. A 22 V battery will be used to power the motors and the hardware on the chair.

Works as a standard wheelchair	Can follow a person	Can move remotely	Has obstacle avoidance	Provides feedback to the user	Rechargeable power supply
Removable kit	Laser range sensors	One wheel attached to the back (between main wheels) and can steer	Ultrasonic sensors	via Phone	Lithium-ion battery
Resistance 'free' motors, when off	Camera	Two wheels attached to the back (between main wheels)	Cameras	via Wristband/watch	NiMH battery
Retractable motors	Bluetooth	Motors ON the main wheels	Lidar	via Keychain	Solar panel
	UWB location technology	Built IN motors in main wheels		via Wheelchair	22 Volt battery
	GPS				

Figure 3.8: Concept combination table for solution concept C.

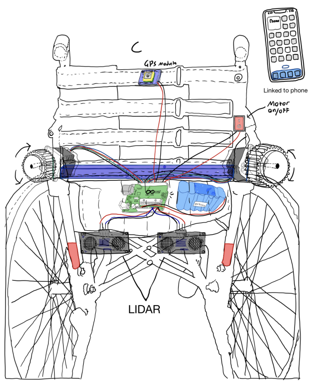


Figure 3.9: A sketch of the solution concept C derived from figure 3.8.

The sketch for concept C can be seen in figure 3.9, and the CSD decomposition can be seen in figure 3.10.

According to axiom one, the design decomposition is decoupled since it is not possible to eliminate the coupling lines that do not point straight up. However, the ordering has all of the arrows either pointing to the right or straight up, which makes the decomposition path-dependant, from left to right.

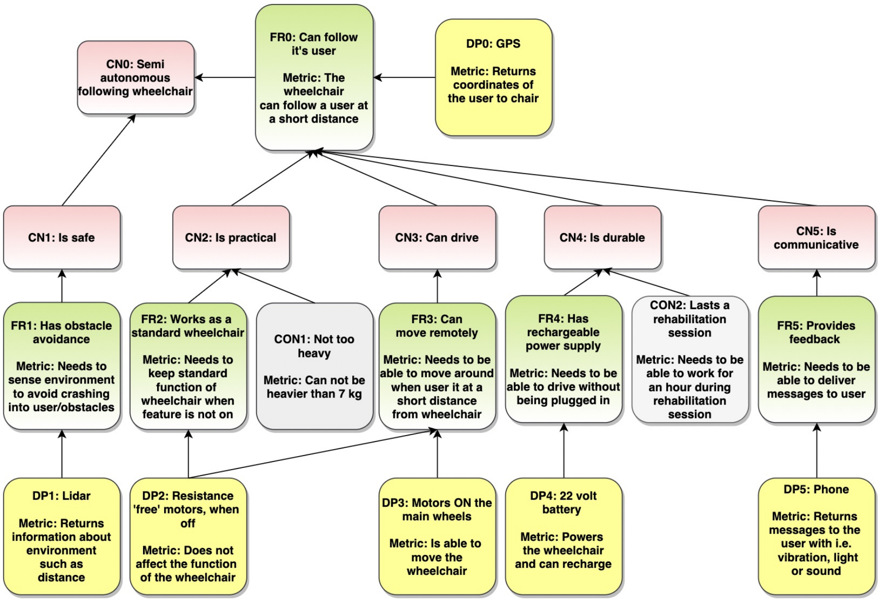


Figure 3.10: Collective System Design Decomposition based on concept C.

Considering how promising each part of the solution is, with axiom two in mind, it can be assessed that the resistance "free" motors on the main wheels could be hard to find and, therefore, would be out expensive. Also, the motors would probably have some resistance, affecting how easy it would be for the user to maneuver the wheelchair. The lidars are precise, but they can be rather expensive compared to the other options, so they might not be the best option financially since more than one would be required. Concerning the feedback aspect, the phone would be a great fit. However, other options could be safer since the user could drop the phone, whereas the wristband would be attached to the user's arm.

3.2.4 Concept D

The combination for the solution concept can be seen in figure 3.11. Concept D consists of a removable kit where the motors would power one wheel attached to the back of the wheelchair. Figure 2.2 inspires the wheel attachment's design and position. A UWB tag will be used to follow the user, and a phone will be used to provide feedback to the user. The wheelchair shall have two anchors with a known distance between them to triangulate the user's location. A lidar will be used for obstacle avoidance, and NiMH batteries will power the wheelchair.

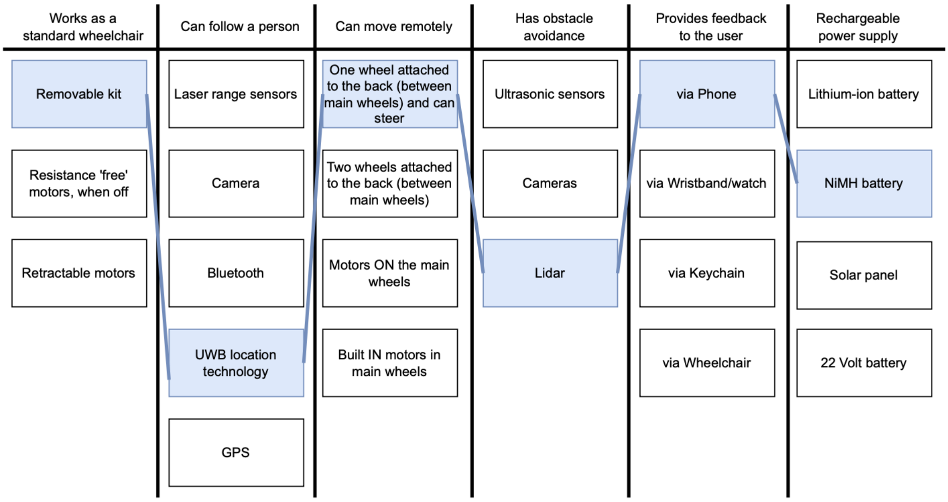


Figure 3.11: Concept combination table for solution concept D.

The sketch for concept D can be seen in figure 3.12, and the CSD decomposition can be seen in figure 3.13.

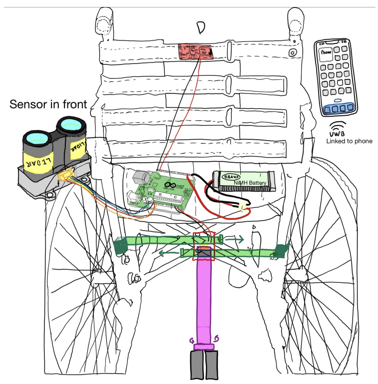


Figure 3.12: A sketch of the solution concept D derived from figure 3.11.

According to axiom one, the design decomposition is uncoupled since the ordering has all the coupling lines pointing straight up. When considering how promising each part of the solution is, with axiom two in mind, it can be assessed that the removable kit could be inconvenient for the user since it needs to be removed when not in use. The lidars are precise, but they can be rather expensive compared to the other options, so they might not be the best option financially since more than one would be required. Finally, the NiMH batteries have limited rechargeability of approximately 500 charges, which could be inconvenient for prolonged use.

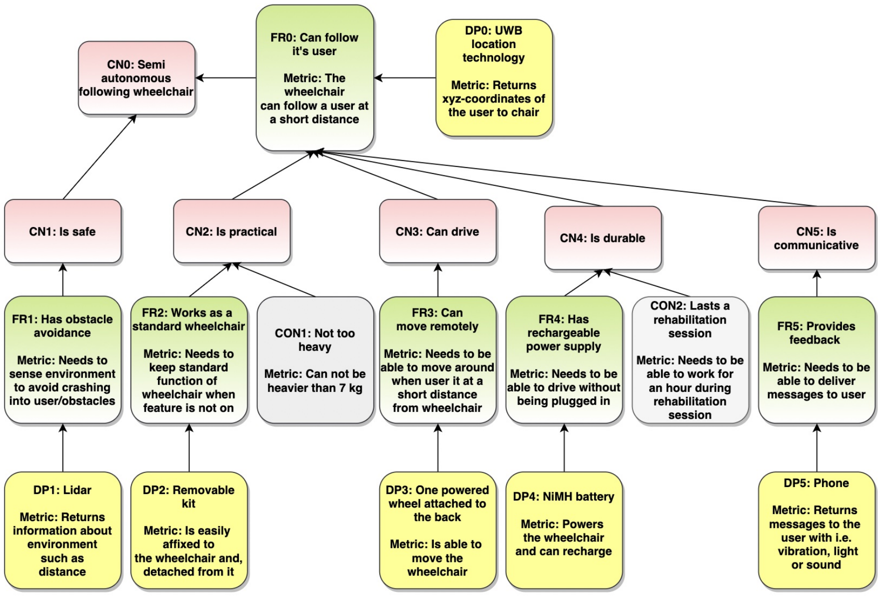


Figure 3.13: Collective System Design Decomposition based on concept D.

3.3 Concept Selection

The concept screening method was used to narrow the number of concepts and improve them to find the most viable final concept. The method consists of six steps. First, the selection matrix was prepared, entering the concepts and criteria into the matrix. Based on customer needs, the team's chosen criteria can be seen below, along with an explanation of each criterion [9].

Ease of handling: How well the wheelchair functions as a standard wheelchair.

Ease of use: How easy it is for the user to use the product.

Sensor accuracy: How accurate the sensors are.

Durability: How long the product lasts.

Portability: How easy it is to travel around with the wheelchair.

Feedback efficiency: How easy it is for the user to receive feedback and the quality of it.

Safety: How safe the product is, and how much you can rely on it.

Next, the team rated the concepts in a complete concept-screening matrix which can be seen in table 3.2.

Table 3.2: Concept-screening matrix.

	Concepts			
Selection Criteria	**A**	**B (Reference)**	**C**	**D**
Ease of handling	-	0	-	-
Ease of use	-	0	0	-
Sensor accuracy	-	0	-	0
Durability	+	0	0	+
Portability	+	0	0	+
Feedback efficiency	-	0	+	+
Safety	-	0	-	0
Sum of +s	2	0	1	3
Sum of 0s	0	7	3	2
Sum of s	5	0	3	2
Net score	-3	0	-2	1
Rank	4	2	3	1
Continue?	Revise	Combine	Revise	Combine

In the concept-screening matrix, the (+) denotes better than, (-) is worse than, and (0) is the same as the reference concept for each selection criteria. The concepts were then ranked by summing up the appropriate score from the ratings.

Then the concepts were combined and improved to ensure the best possible solutions. The next step was to decide which concepts would be selected for further assessment and reflect on the result and process. Then the team moved on to concept scoring as the next step, where concept scoring is used on the remaining concepts to better differentiate between them, using more detailed comparisons [9]. The scale for the rating was made and can be seen in table 3.3.

Table 3.3: Rating score for relative performance.

Relative Performance	Rating
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

The concepts selected for further refinement and analysis were the revised concepts A and C and the new concept BD, which is a combination of concepts B and D. The complete concept-scoring matrix can be seen in table 3.4.

Table 3.4: The concept-scoring matrix.

		Concepts					
		A+		**BD**		**C+ (Reference)**	
Selection Criteria	**Weight**	**Rating**	**Weighted score**	**Rating**	**Weighted score**	**Rating**	**Weighted score**
Ease of handling	20%	4	0,8	4	0,8	**3**	0,6
Ease of use	20%	2	0,4	4	0,8	**3**	0,6
Sensor accuracy	20%	3	0,6	3	0,6	**3**	0,6
Durability	5%	3	0,15	2	0,1	**3**	0,15
Portability	15%	4	0,6	5	0,75	**3**	0,45
Quality of feedback	5%	1	0,05	3	0,15	**3**	0,15
Safety	15%	2	0,3	4	0,6	**3**	0,45
	Total score		2,9		3,8		3
	Rank		3		1		2
	Continue?		No		Develop		No

3.4 Final concept

The collective system design decomposition was made for each concept, and they can be seen in figures 3.4, 3.7, 3.10 and 3.13. After analyzing the design decomposition, with regards to axiom one, it can be seen that concepts A and D are uncoupled while concepts B and C are decoupled and path-dependent from left to right.

From the results shown in table 3.2, it was decided to combine concepts B and D because they ended with the highest score. Table 3.4 shows the concept-scoring matrix for the new concepts, and according to the results, the combination of concepts B and D should be developed.

Each part of the concept solutions was considered with how promising they were, which provided vital information. That resulted in selecting the most viable solution with the greatest possibility of fulfilling the requirements and satisfying the customer's needs.

With respect to the information that CSD decomposition, axiomatic design, concept-screening matrix, and the concept-scoring matrix provided, it was decided that the final concept would be based on concepts B and D, with some modifications. The concept combination table for the final concept can be seen in figure 3.14.

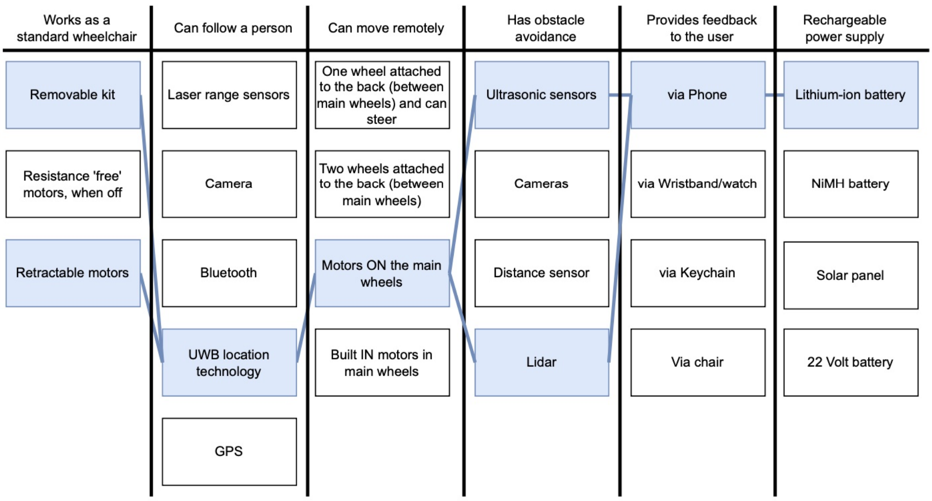
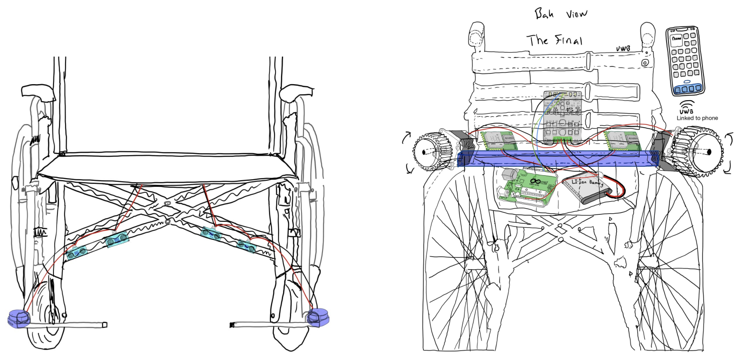


Figure 3.14: Concept combination table for the final solution concept.

A sketch for the final concept can be seen in figure 3.15. The concept consists of a removable kit and retractable motors. By combining the two solutions, the retractable motors no longer depend on the physical solution to the functional requirement that the wheelchair can move remotely. The wheelchair will use UWB location technology to locate and follow the user and both ultrasonic sensors and laser range sensors for obstacle avoidance. The chair will communicate with the user via phone because that is what the stakeholders want, and a lithium-ion battery will power the motors and the hardware on the chair.



(a) The Front View (b) The Back View

Figure 3.15: A sketch of the final solution concept derived from figure 3.14.

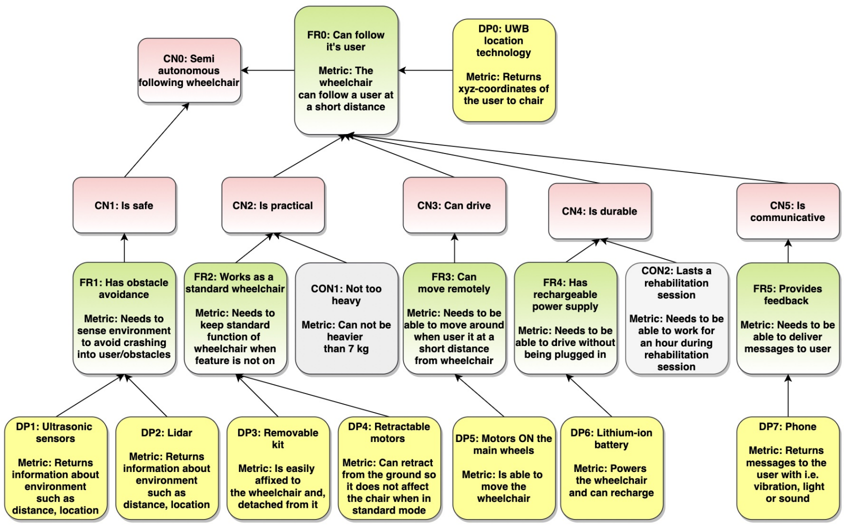


Figure 3.16: Collective System Design Decomposition based on the final concept.

The CSD decomposition for the final concept can be seen in figure 3.16. According to axiom one, the design decomposition is uncoupled since the ordering has all the coupling lines pointing straight up. When considering how promising the final solution is with axiom two in mind, it was deduced that this solution would provide the greatest possibility of success since the products are affordable and reliable.

3.5 Integration

A schematic representing how the add-on power kit communicates and its elements were made to establish the product architecture. The schematic can be seen in figure 3.17, where each element represents a design parameter. Most elements have connections, representing a flow [27].

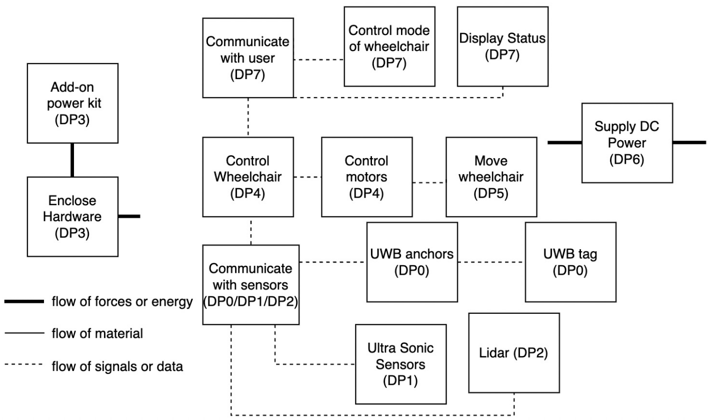


Figure 3.17: Schematic of the Wheels-On, an add-on power kit.

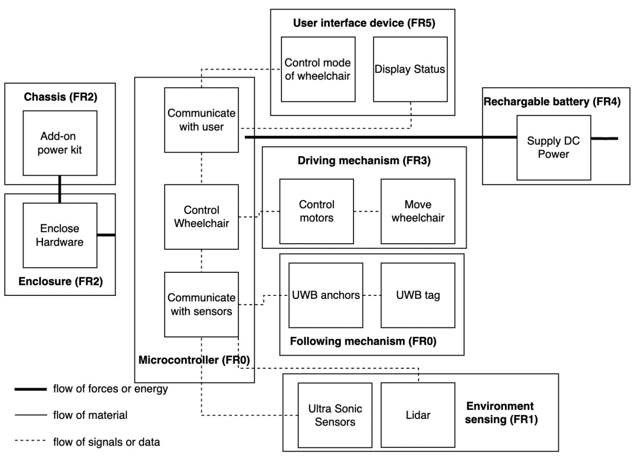


Figure 3.18: Elements clustered into chunks.

Then elements were clustered into chunks, each representing a functional requirement, as shown in figure 3.18. More than one chunk was needed for some functional requirements to represent the requirement fully [27]. An incidental interaction graph was created to map challenges in product development. The interactions between the chunks represent challenges in the development which need to be considered when designing each element. The graph can guide structuring and managing the project [27].

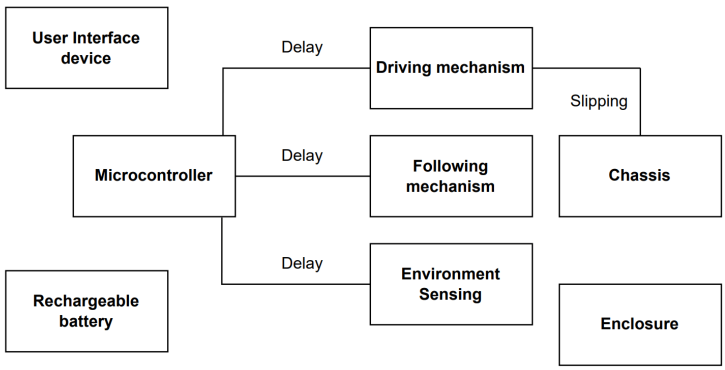


Figure 3.19: Incidental interaction graph.

The delay between elements can be prevented with a powerful microcontroller. To prevent slipping between the driving mechanism and the chassis, the design of rollers that go on the main wheels needs to have high friction on the outside.

3.6 End user price

Estimating the end-user price, the bill of materials, and the target cost needed to be considered. The bill of materials considers the cost of all the parts required for the semi-autonomous following wheelchair, which is approximately 82.000 ISK; see more details in appendix A. Of course, this does not consider costs other than the parts, so looking at the target cost based on competitors' products is important. The end user price based solely upon the target cost is 1.562.500 ISK. More details on the process for the target cost can be seen in appendix B.

Even though these are all hypothetical numbers based on educated guesses, a reasonable estimation of the final end-user price is 1.250.000 ISK. To acquire the precise cost of the wheelchair, information about labor costs, shipping, packaging, and research and development, would be needed.

3.7 User Interface

The importance was classified along two dimensions, user experience, and aesthetics, to determine the important industrial design for the product. The assessment can be seen in figure 3.20. User experience covers how a product meets the users' emotional and functional needs, which relates to the user interface [28]. The aesthetic part refers to the appreciation of the look of the design and its emotional importance. Industrial design improves both the user experience and the aesthetics of the product. The usability is increased with the easily attached kit, which also contributes to the pride of ownership because of the simple and elegant design. The safety is also increased by adding an E-stop button and concealing the wires in the kit. By designing a simple app for the product, the user can easily interact with the product, and therefore the complexity of user interaction is decreased. The storyboard for the usage of the product can be seen in figures 3.21 - 3.28, along with explanations.

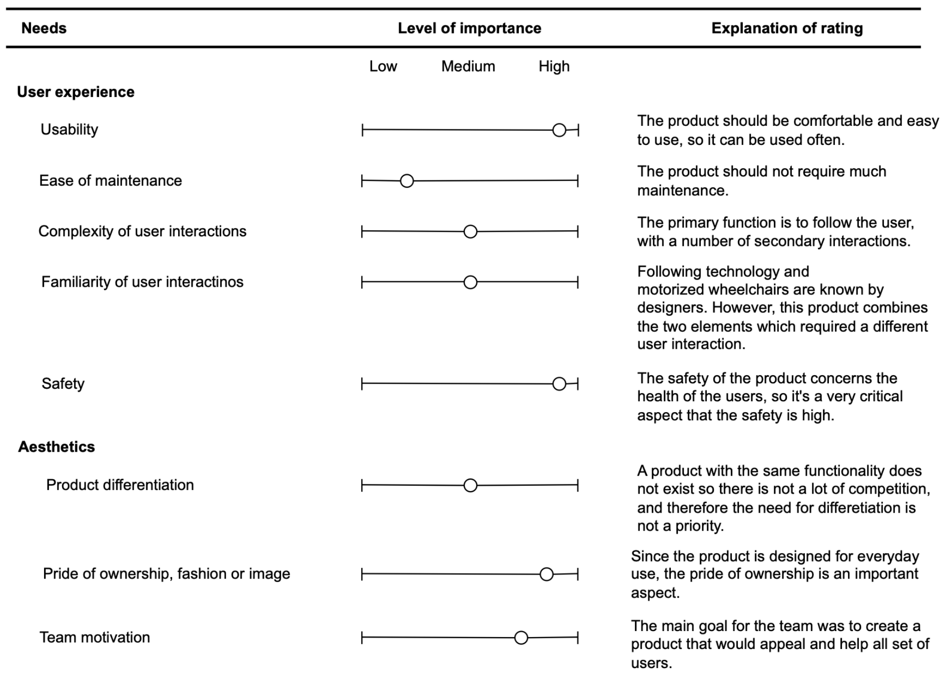


Figure 3.20: Assessment of the importance of industrial design.

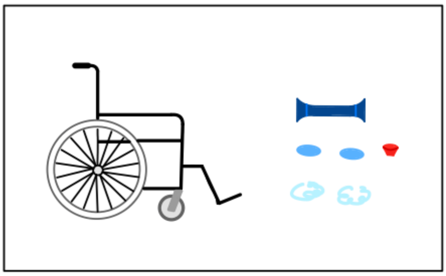


Figure 3.21: When the product is bought, the user gets a kit that must be assembled onto the wheelchair.

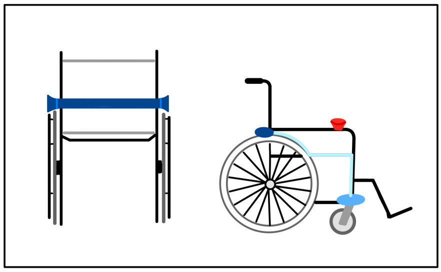


Figure 3.22: When the user assembles the kit to the wheelchair, the kit is attached to the back and the sensors above the front wheels.

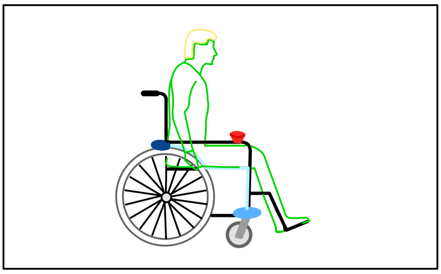


Figure 3.23: The wheelchair can be used as a standard wheelchair with the attached kit.

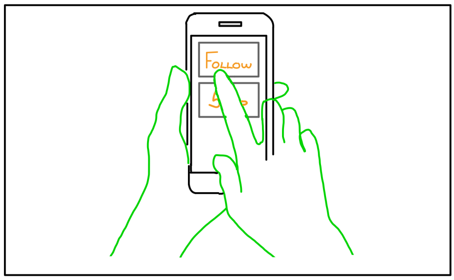


Figure 3.24: To activate the kit, the user must open the app and select "Follow" which will make the kit go into follow mode.

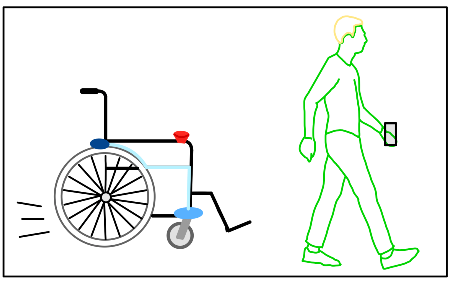


Figure 3.25: When the user walks, the motors depend on the data gathered from the UWB technology and the sensors that ensures that the chair follows its user at a 1-2 m distance behind him.

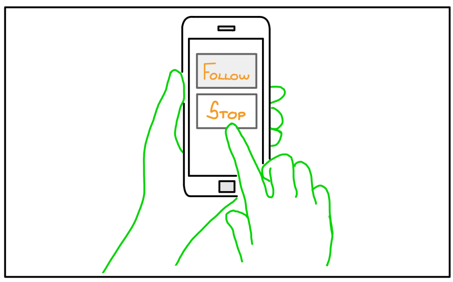


Figure 3.26: To deactivate the following mode, the user uses the app and presses the stop button.

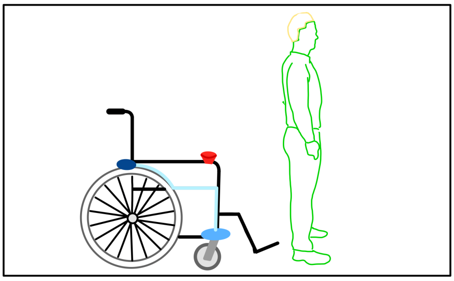


Figure 3.27: The wheelchair moves and stops at a comfortable distance from the user so that the user can sit down.

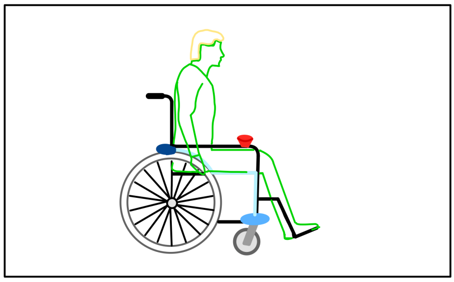


Figure 3.28: The user sits in the wheelchair and can use it again with its standard function.

3.8 ISO standards

The ISO 7176 series of standards specifies requirements and test methods for wheelchairs, including manual wheelchairs, electric wheelchairs, and scooters. The following are the ISO standards that would be ideal for the product, Wheels-On, to obtain as a starting point in the journey of being registered as a medical device [29].

- **ISO 7176-1:2014:** Specifies requirements and test methods for static stability of both manual and electric wheelchairs [30].
- **ISO 7176-8:2014:** Specifies requirements and test methods for electrically powered wheelchairs and scooters, including dimensions, performance, and safety requirements [31].
- **ISO 7176-11:2012:** Specifies requirements and test methods for the power and control systems of electric wheelchairs, including electrical safety and electromagnetic compatibility [32].

Chapter 4

Analysis

Prototypes were developed for learning purposes, integrational purposes, and milestone purposes to answer the questions "Will it work?", "How well does it meet the functional requirements?" and "Do the functions work together as expected?". Most of the prototypes were focused and physical since they only implemented one or a few aspects of the product. The final prototype, however, is comprehensive since it implements most of the product's attributes. Another purpose for the prototypes was to show the stakeholders and instructors to start discussions and get opinions. The purpose of each prototype was stated, along with the level of approximation to define the degree to which the final product is to be approximated. Then the experimental plan and schedule, shown in the following chapters, were created to ensure maximum value extraction from the prototyping effort and to help the group achieve the prototype goals with increased efficiency [33]. Finally, each prototype test result was analyzed and related to appropriate design parameters and functional requirements.

4.1 Physical Design

A necessary part of the project was to design a prototype enclosing all the components.

4.1.1 Preliminary prototype testing

The plan for the preliminary design prototype can be seen in table 4.1, and the prototypes can be seen in figures 4.1 and 4.2.

The main difference is that one prototype is rectangular-shaped, while the other is cylinder-shaped. It relates to DP3: Removable kit and DP5: Motors on the main wheels. These prototypes test FR2: Works as a standard wheelchair, and FR3: Can move remotely, by testing how the motors would be attached to the wheelchair.

Table 4.1: Plan for the design prototype.

Name of prototype	**Design**
Purpose(s)	•Made for learning purposes. •To get an idea of the physical look of the kit. •Select the shape of the kit. •Select the location of the kit. •Select how the kit will be attached to the chair.
Level of Approximation	A focused physical prototype. The shape of the kit and correct location.
Experimental plan	•Build two different design prototypes. •Build a mounting mechanism. •Conduct a mounting test.
Schedule	8 March - Build the two prototypes 8 March - Build the mounting mechanism 8 March - Mounting test started 9 March - Testing completed 17 March - Analysis of test results completed

Figure 4.1: Cylinder-shaped design prototype of the kit.

Figure 4.2: Rectangular-shaped design prototype of the kit.

4.1.1.1 Preliminary Prototype Results

After making the prototypes out of cardboard, it was decided that the shape of the kit would be rectangular and attached to the back of the wheelchair, above the main wheels. It will be attached to a mounting system that will be permanently fastened on the rear support bars of the wheelchair.

4.1.2 CAD design

To implement the removable feature of the product it was decided to create a backplate to which the motor kit would then be attached. The design of the backplate can be seen in figure 4.3. At the rear side of the backplate are two holes, which are used to slide the backplate onto two steel poles that are permanently mounted on the modified wheelchair. At both sides of the plate are knobs that make it possible to fasten the backplate in place, making it retractable. Figure 4.4 shows the backplate attached to the two poles, with their mounting bracket attached to the wheelchair.

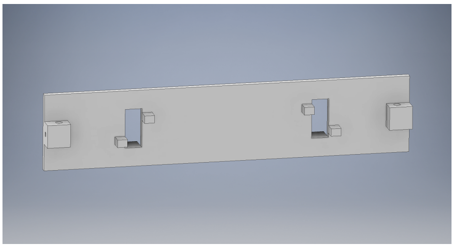


Figure 4.3: The design of the backplate, sketched in Inventor.

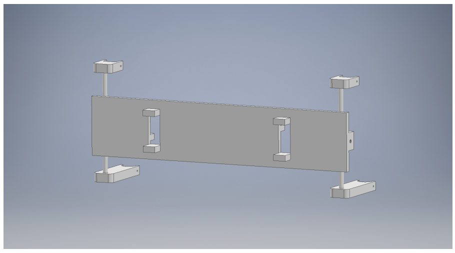


Figure 4.4: The backplate attached to the poles, sketched in Inventor.

The design of the motor kit can be seen in figure 4.5. On the motor kit are two handles on the front that lock it onto the backplate. Once the back pins have reached through the gaps of the backplate, the handles are rotated outwards to secure the motor kit to the backplate. At both ends of the motor kit are internal brackets for the motors, and after the motors have been inserted and secured, using bolts, rollers are attached to the outputs shaft of the motors. A lid for the motor kit was also designed to secure the components while having easy access to them in the development process. The complete design can be seen in figure 4.6.

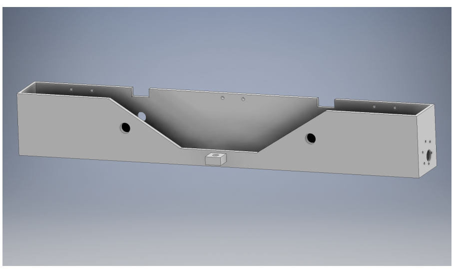


Figure 4.5: The design of the motor kit, sketched in Inventor.

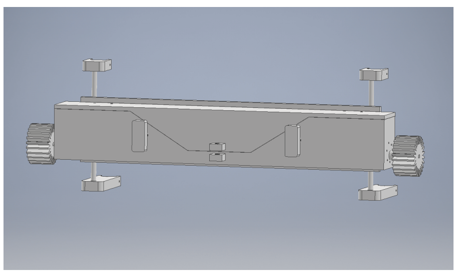


Figure 4.6: The complete design of the kit, sketched in Inventor.

All of the designed components were 3D printed. The parts, along with their dimensions, can be seen in Appendix D.

4.1.3 Prototype Testing

The plan for the retractable mechanism prototype can be seen in table 4.2, and the feature of the prototype can be seen in figures 4.7 and 4.8.

Table 4.2: Plan for the retractable prototype.

Name of prototype	**Retractable mechanism**
Purpose(s)	•Made for learning purposes. •To confirm that the mechanism can retract. •Select the location of the mounting system. •Select the handles used to fasten in place.
Level of Approximation	A focused physical prototype. Confirm that the function works.
Experimental plan	•Sketch in Inventor. •3D print the parts. •Select the location of the mounting system. •Attach the mounting system to the wheelchair. •Conduct a retractable test.
Schedule	24 April - Start sketching. 26 April - Finish the sketches. 26 April - 3D print. 27 April - Select location and attach mounting system. 27 April - Conduct the retractable test 29 April - Analysis of test results completed

Figure 4.7: The backplate attached to the mounting system.

Figure 4.8: The backplate retracted and secured at the top of the mounting system.

The plan for the removable mechanism prototype can be seen in table 4.3, and the prototype feature can be seen in figure 4.9.

Table 4.3: Plan for the removable prototype.

Name of prototype	**Removable mechanism**
Purpose(s)	•Made for learning and integrational purposes. •To confirm that the kit can be attached to and removed from the backplate.
Level of Approximation	A focused physical prototype. Confirm that the function works.
Experimental plan	•Sketch in Inventor. •3D print the parts. •Conduct a removable test.
Schedule	25 April - Start sketching. 26 April - Finish the sketches. 26 April - 3D print. 27 April - Conduct a removable test. 29 April - Analysis of test results completed.

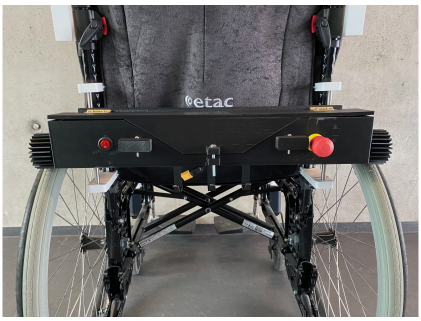


Figure 4.9: The removable motor kit attached to the backplate.

4.1.3.1 Prototype Results

Figures 4.7 and 4.8 confirm the success of the retractable mechanism, since the backplate can slide up and down the mounting system, making it able to retract from the main wheels of the wheelchair. This test relates to the DP4: Retractable motors. Figures 4.7 and 4.9 confirm the success of the removable mechanism, since the motor kit can be easily attached and removed from the backplate. This test relates to the DP3: Removable kit. These tests combined confirm that the design can fulfill the FR2: Works as a standard wheelchair.

4.2 Ultra-Wideband

Ultra-Wideband, UWB, is a short-range, wireless communication protocol that operates at a high frequency. A UWB transmitter operates by sending pulses across the broad spectrum frequency, and a corresponding receiver then translates the pulses into data. The UWB can achieve real-time accuracy by sending the pulses every two nanoseconds [34]. To perform distance and location measurements, the UWB uses anchors and tags. An anchor is generally a fixed UWB device whose location is known, and a tag is a UWB device that moves around. Having multiple anchors makes it possible to determine the tag's location [35].

4.2.1 Preliminary prototype testing

The plan for the user location test can be seen in table 4.4. The prototype is testing a part of the metric: The wheelchair can follow its user at a short distance, which relates to the functional requirement FR0: Can follow its user. The prototype focuses on the metric's locating feature, where the UWB device's functionality was tested.

Table 4.4: Plan for the user location test prototype.

Name of prototype	**User location test**
Purpose(s)	•Made for learning purposes. •Confirm that the signal can be translated into the users position, relative to the wheelchair. •Select how many UWB devices are going to be needed.
Level of Approximation	A focused physical prototype with UWB devices.
Experimental plan	•Two tests, one with two devices and the other with four devices
Schedule	8 March - Set up a UWB server 8 March - Location test started 16 March - Testing completed 17 March - Analysis of test results completed

4.2.1.1 Preliminary prototype results

The location of the user tag, relative to the UWB anchors, can be seen in figure 4.10, where the blue triangle is the tag and the red triangles are the anchors.
Using the DRTLS application on a Samsung Galaxy A7, three anchors, and one tag, it was possible to map out the tag's location [36]. The test confirms that these components work therefore, DP0: UWB location technology is satisfactory to fulfill FR0: Can follow its user.

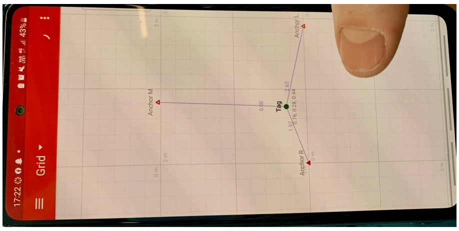


Figure 4.10: User location test.

4.2.2 UWB location

To meet the criteria of following the user, DWM1001c was chosen since the results from the prototype in chapter 4.2.1 showed that it provides adequate accuracy of data containing coordinates. The gathered data needs to provide information on how the wheelchair should react according to it. To make that possible, the UWB that act as anchors on the wheelchair will need to have a fixed location on the wheelchair to form a frame of reference with a known placement of the origin. The origin was decided to be in the middle of the wheelchair and at the edge of the seat. Brackets were 3D printed to mount the UWB anchors onto the wheelchair securing their location. Figure D.8 in Appendix D.3 shows a drawing of the brackets with dimensions. The frame of reference can be seen in figure 4.11 among the axis's direction and the origin's location. The coordinates of the UWB anchors in the frame of reference can be seen in table 4.5.

Figure 4.11: The frame of the reference provided from the UWB anchors, the origin is the purple dot.

Table 4.5: Shows the coordinates of the anchors in the frame of reference.

Anchor	x coordinate [m]	y coordinate [m]	z coordinate [m]
Upper right side	0.24	-0.52	0.37
Lower right side	0.26	0.03	-0.07
Upper left side	-0.24	-0.53	0.37
Lower left side	-0.26	0.02	-0.07

For the wheelchair to move as desired, the ESP32 microcontroller located in the motor kit needs to receive information from the UWB about the tag's location. To make it possible for the ESP32 to receive the necessary data, a gateway was set up based on DWM1001 Gateway Quick Deployment Guide[37]. The UWB tag sends the data onto a bridge node mounted on a Raspberry Pi, and that combination will transfer the data via Wi-Fi to an MQTT Server provided by the Raspberry Pi. The ESP32 on the wheelchair will be connected to the same server as the Raspberry Pi via Wi-Fi and subscribes to a "topic" containing the data. The ESP32 processes that data and will determine the speed and direction the wheelchair needs to move to follow the user.

4.2.3 Prototype testing

The plan for the prototype of testing the direction the wheelchair needs to follow according to the data can be seen in table 4.6. The direction is determined by only using the x coordinate from the data. The setup for the prototype test can be seen in figure 4.12.

Table 4.6: Plan for prototype testing on the direction.

Name of prototype	**Direction test**
Purpose(s)	•Made for learning purposes. •Confirm that the x coordinate can provide the direction the wheelchair needs to follow.
Level of Approximation	A focused physical prototype with UWB devices.
Experimental plan	•Mount UWB anchors to wheelchairs •One test, with four UWB anchors & a UWB tag is moved around and checked if corresponding led lights turn on based on what direction the wheelchair should follow.
Schedule	27 April - Mount anchors on the wheelchair. 27 April - Direction test started. 27 April - Testing completed. 27 April - Analysis of test results completed.

The plan for the prototype testing of the speed the wheelchair needs to move according to the data can be seen in table 4.7. The speed is determined using the Pythagorean theorem to find the distance between the user and the wheelchair, for which the x and y coordinates are used. The setup for the prototype test can be seen in figure 4.13.

Table 4.7: Plan for prototype testing on speed.

Name of prototype	**Speed test**
Purpose(s)	Made for learning purposes. •Confirm that the distance can be used to determine the speed the wheelchair needs to move.
Level of Approximation	A focused physical prototype with UWB devices.
Experimental plan	•One test, with four UWB anchors & a UWB tag is moved around and checked if corresponding led lights turn on based on what speed the wheelchair should move.
Schedule	27 April - Speed test started 27 April - Testing completed 27 April - Analysis of test results completed

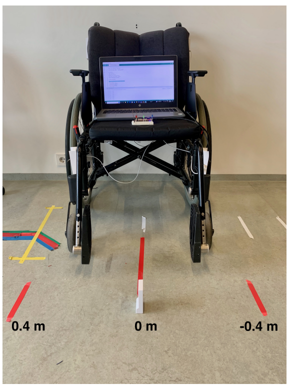


Figure 4.12: Setup for direction test.

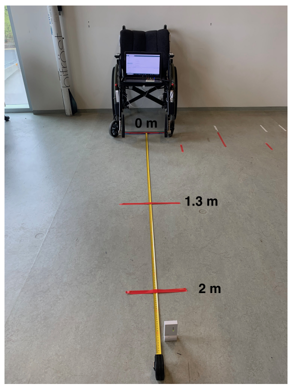


Figure 4.13: Setup for speed test.

Led lights were used for both prototypes to represent what action the wheelchair should take according to the data. The action the led lights represent can be seen in table 4.8.

Table 4.8: The action the led lights represent for both prototypes.

Led light color	Action in direction test	Action in speed test
Red	Turn left	Stop
Yellow	Go Forward	Slow speed
Blue	Turn right	Full speed

4.2.3.1 Prototype Results

The prototype testing of which direction the wheelchair should follow was successful and can be seen in figures 4.14-4.19. The prototype testing of at which speed the wheelchair should go was successful and can be seen in figures 4.20-4.25.

Figure 4.14: Testing having the tag to the left.

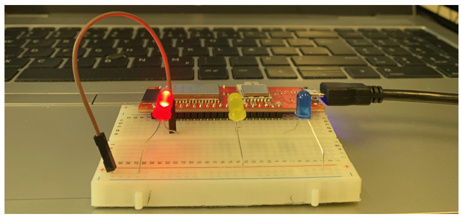


Figure 4.15: Red light on indicating that the wheelchair should turn to the left.

Figure 4.16: Testing having the tag in the middle.

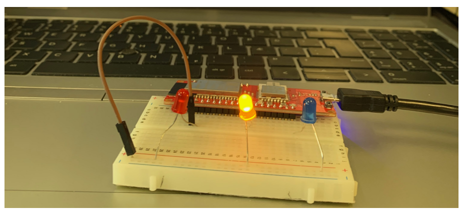


Figure 4.17: Yellow light on indicating that the wheelchair should go straight forward.

Figure 4.18: Testing having the tag to the right.

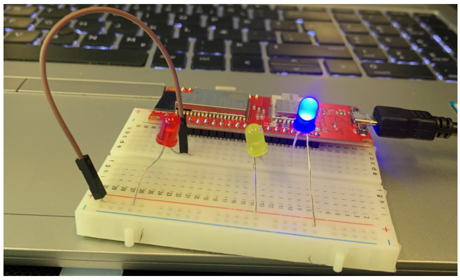


Figure 4.19: Blue light on indicating that the wheelchair should turn to the right.

Figure 4.20: Testing having the tag between 0-1.3 meter.

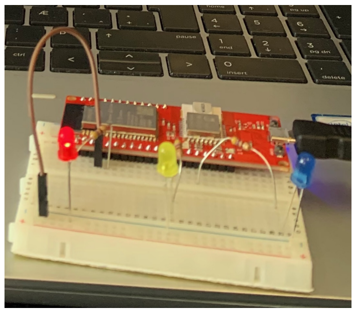


Figure 4.21: Red light on indicating that the wheelchair should turn to the left.

Figure 4.22: Testing having the tag between 1.3-2 meters.

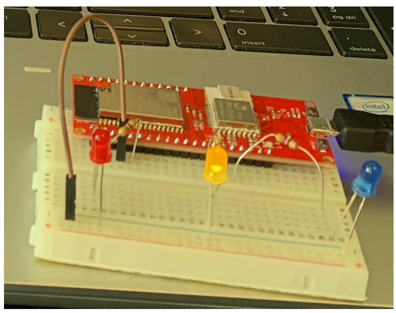


Figure 4.23: Yellow light on indicating that the wheelchair should go straight forward.

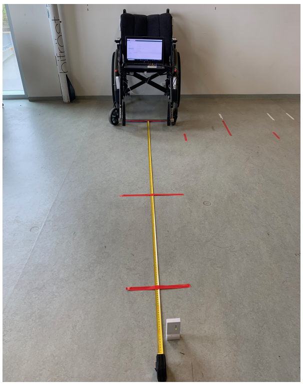


Figure 4.24: Testing having the tag at a distance greater than 2 meters.

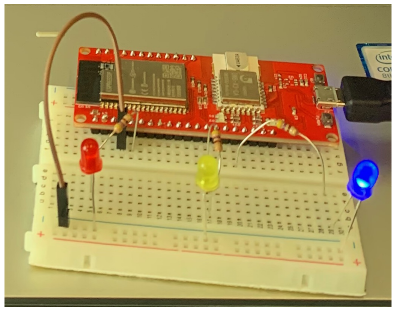


Figure 4.25: Blue light on indicating that the wheelchair should turn to the right.

Both prototypes show that the data provided by the UWB can be used as a design parameter for FR0: Can follow its user, by providing x, y, and z coordinates. By combining the functions from the prototypes, the motor kit will be able to control the direction and speed the wheelchair will move in.

4.3 Motors

To know the desired motor speed and torque, the required force needed to move the wheelchair when empty needed to be measured with a Newton meter. The required force, F, was 4.8 N on an even surface, and the main wheels' radius, r, is 30 cm. Therefore the required torque, T, can be calculated with equation 4.1, where g is the force of gravity.

$$T = \frac{Fr}{g} = \frac{(4.8N)(30cm)}{9.8m/s^2} = 14.69kg.cm \tag{4.1}$$

The torque required is 14.69 kg.cm for an even surface. The needed torque would be greater if measurements were made on a slope. These measurements were not taken since they were unnecessary for this prototype, but they will be important for the product's future development. Therefore, the chosen motors were a pair of 12V Metal DC Geared Motors with Encoders, rated at 122RPM 38Kg.cm [38]. The motors are suitable because they are light and durable, which conduces CON1: Not too heavy. An MDD10A dual motor driver is suitable for the power requirements of the motors, so it was chosen.

4.3.1 Prototype Testing

The plan for the mobility prototype can be seen in table 4.9, and the prototype can be seen in figure 4.26, where the rollers are pressed firmly against the main wheels of the wheelchair.

Table 4.9: Plan for the mobility prototype.

Name of prototype	**Mobility**
Purpose(s)	•Made for learning and integrational purposes. •To confirm that the motors can move the wheelchair.
Level of Approximation	A focused physical prototype. Confirming that the wheelchair can move.
Experimental plan	•Insert the motors into the motor kit. •Connect and program the motors. •Attach rollers to the output shafts. •Conduct a mobility test.
Schedule	28 April - Insert the motors. 29 April - Connect and program. 29 April - Attach rollers. 29 April - Conduct mobility test. 30 April - Analysis of test results completed.

Figure 4.26: Mobility prototype testing.

4.3.1.1 Prototype Results

The motors can move the wheelchair while located in the motor kit. The calculated gear ratio between the rollers and the main wheels of the wheelchair turned out to be 10:1, which resulted in a top speed of 1.3 km/h. This prototype test relates to the DP5: motors on the main wheels. It confirms that the wheelchair can move remotely, which is FR3.

4.4 Feedback

An important feature of the product is that the user needs to be able to receive feedback from the product.

4.4.1 Prototype Testing

The plan for the feedback prototype can be seen in table 4.10, and the prototype can be seen in figures 4.27 and 4.28.

Table 4.10: Plan for the feedback prototype.

Name of prototype	**Feedback**
Purpose(s)	•Made for learning and integrational purposes. •To confirm that the product can provide feedback to the user with a phone.
Level of Approximation	A focused physical prototype. Confirming that the product can provide feedback.
Experimental plan	•Research the Blynk application. •Set up the application. •Program and integrate the functions connected to the buttons.
Schedule	28 April - Research 29 April - Set up the application 29 April - Program 29 April - Conduct feedback test. 30 April - Analysis of test results completed.

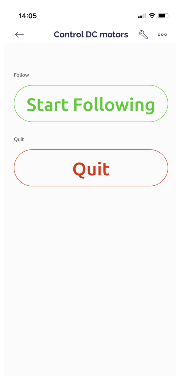


Figure 4.27: Unpressed buttons in the Blynk application.

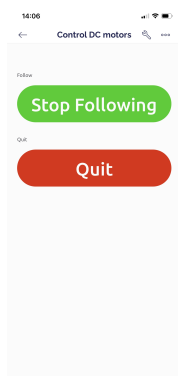


Figure 4.28: Pressed buttons in the Blynk application.

4.4.1.1 Prototype Results

The user can receive feedback from the system with a smartphone. Figure 4.27 shows the user interface when the buttons are unpressed. Then the product, the Wheels-On, is not in the following mode. As soon as the buttons are pressed, they change color, providing feedback to the user. The pressed buttons can be seen in figure 4.28. This prototype relates to DP7: Phone, and the prototype test confirms that a phone can provide feedback to the user, which is FR5.

4.5 Power Control

To power the Wheels-On, a 14.8V Gens Ace Li-Po battery is used, which provides 4000 mAh [39]. The battery is placed in a battery bracket that is attached to the backplate, using hooks that are permanently fastened to the back plate. The drawing for the bracket with dimensions can be seen in figure D.9 in Appendix D.3, and a drawing of the hooks can be seen in figure D.3 in Appendix D.1. For safety, a 3A fuse was added before connecting the battery to a 3A buck converter, which regulates the voltage to 12V for the motors. An Estop button is also used for safety, which breaks the circuit when pressed. To easily power on the Wheels-On, a power switch is used. The ESP32 mentioned in chapter 4.2 requires 5V and the UWB anchors, so a 5V regulator was added to the circuit. So the ESP32 and the UWB anchors would be provided with stable power, and a 1500 μF capacitor was added. The wire schematic for the circuit can be seen in figure 4.29. An enlarged schematic can also be seen in figure E.3 in Appendix E.2.

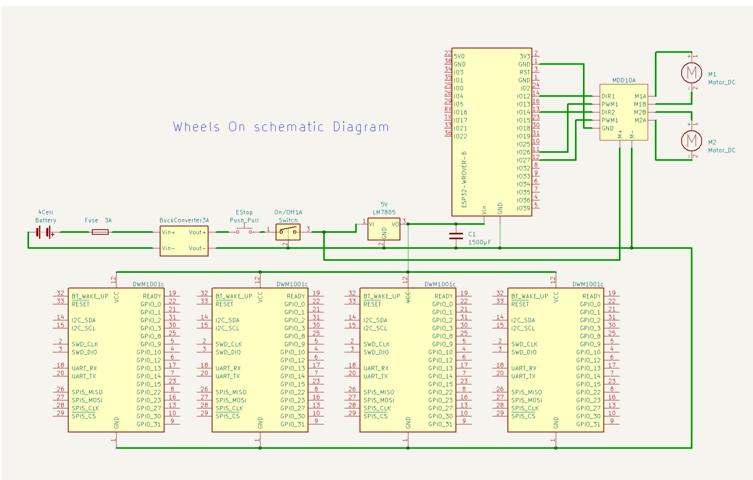


Figure 4.29: A wiring schematic for Wheels-On.

4.5.1 Prototype Testing

The plan for the durability prototype can be seen in table 4.11.

Table 4.11: Plan for the durability prototype.

Name of prototype	**Durability**
Purpose(s)	•Made for learning and integrational purposes. •To confirm that the product has a rechargeable power supply. •To confirm that the product can last a rehabilitation session.
Level of Approximation	A focused physical prototype. Confirming that the product is durable.
Experimental plan	•Connect the battery to the circuit. •Measure the current drawn from the circuit when in use. •Perform calculations. •Recharge the battery.
Schedule	9 May - Connect battery. 9 May - Conduct durability test. 9 May - Recharge the battery. 10 May - Analyse of test results completed.

4.5.1.1 Prototype Results

The measured current drawn from the circuit reached a maximum of 956 milliamperes. Since the battery provides 4000mAh, it can be assumed that the battery can last up to four hours while in use on one charge. The test fulfills CON2: Last a rehabilitation session, and FR4: Has rechargeable power supply. This test relates to DP8: Lithium-ion battery.

4.6 Functionality of the Wheels-On

To create a semi-autonomous following wheelchair, the functions tested separately in chapters 4.1 - 4.5 needed to be combined. Once the test results from each function had proven to be satisfactory, all of the functions were connected to create the final prototype, the Wheels-On add-on power kit. The complete design of the Wheels-On, attached to a wheelchair, can be seen in figure 4.30. Once assembled, the total weight of the product is 3.0kg. The total weight relates to CON1: Not too heavy, where the metric is that it cannot be heavier than 7.0kg. The durability of the main components can be seen in Appendix C.

The ESP32 located in the motor kit receives data from the server created by the Raspberry Pi and the DWM1001c gateway module. A schematic for the gateway connection to the Raspberry Pi can be seen in figure E.2 in Appendix E.2. When the

Figure 4.30: The complete design of the Wheels-On.

motor kit gets activated, the code on the ESP32 starts executing. Figure 4.31 shows a state diagram for the code.

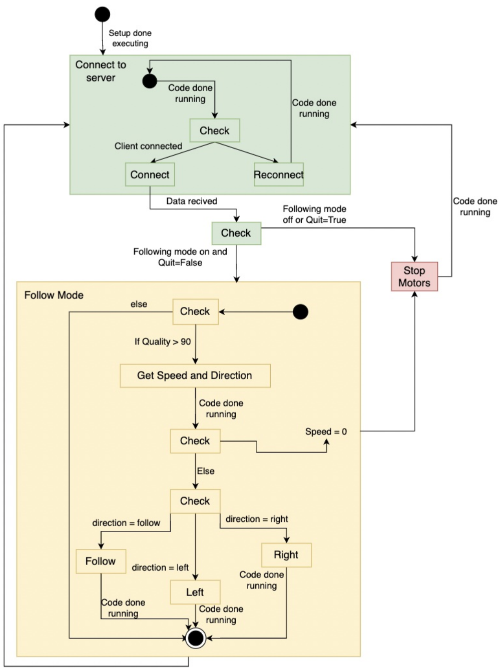


Figure 4.31: A state diagram for the code running on the ESP32.

Figure 4.32 shows what direction the wheelchair should follow, based on the x coordinate of the user's location, and figure 4.33 shows what PWM value is sent to the motor driver based on the distance between the user and the wheelchair. The figures cover the function "Get Speed and Direction" shown in figure 4.31.

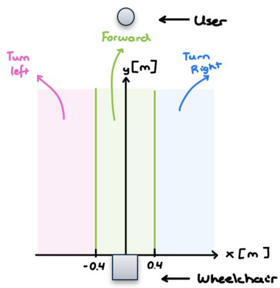


Figure 4.32: Direction the wheelchair should follow.

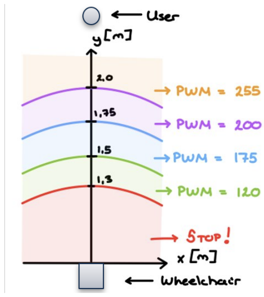


Figure 4.33: PWM value is sent to the motor driver.

4.6.1 Prototype Testing

The plan for the final prototype can be seen in table 4.12, where the purpose and the level of approximation are stated.

Table 4.12: Plan for the final prototype.

Name of prototype	**Functionality of the Wheels-On**
Purpose(s)	•Made for integrational and milestone purposes. •To confirm that all of the functions work together. •To confirm that the product has achieved the semi-autonomous following wheelchair functionality.
Level of Approximation	A comprehensive physical prototype. Confirming that the functions work together and that it can follow the user.
Experimental plan	•Connect all hardware. •Program and integrate functions. •A semi-autonomous following test.
Schedule	3 May - Connect hardware. 5 May - Program. 8 May - Start conducting a semi-autonomous following test. 10 May - Analysis of test results completed.

Figure 4.34 shows the semi-autonomous following test being conducted.

Figure 4.34: Conducting the semi-autonomous following test.

4.6.1.1 Prototype Results

The prototype shows that the Wheels-On can transform a standard wheelchair into a semi-autonomous following wheelchair. The results of testing, if the Wheels-On can react to collected data and move the wheelchair accordingly, can be seen in table 4.13.

Table 4.13: Results of testing the functionality of the Wheels-On.

Test	Pass/Fail
Straight forward	Pass
Left turn	Pass
Right turn	Pass
Stop	Pass
Speed changes	Pass

The test confirms that the wheelchair can follow its user at a short distance of 1-2 meters, which is FR0.

4.7 Obstacle Avoidance

Obstacle avoidance is a desired feature of the product. It ensures that the wheelchair does not crash into objects or any other obstacles. For FR1: Has obstacle avoidance, are two design parameters, DP1: Ultrasonic sensors, and DP2: Lidar. It is essential to determine whether these sensors provide acceptable results to fulfill these design parameters. Ultrasonic sensors measure the distance to an object using sound waves, and the measurement is based on how long it takes the soundwave to return[40]. Lidar detects the distance from an object by sending out pulses in all directions and timing how long it takes for the pulses to return after striking a target[40]. This is, however, not a critical feature of the Wheels-On at this stage in the development since it is not required for the wheelchair to follow its user. Due to a limited amount of time and because the feature is not of high priority, it was scaled down and implemented as two prototypes. One prototype uses an ultrasonic sensor, and the other uses lidar and is implemented on a digital twin in the form of a miniature robot car.

4.7.1 Prototype Testing

The plan for the ultrasonic sensor prototype can be seen in table 4.14, and the setup can be seen in figure 4.35.

Table 4.14: Plan for the ultrasonic prototype.

Name of prototype	**Ultrasonic obstacle avoidance test**
Purpose(s)	•Made for learning purposes. •Confirm that the ultrasonic sensors are precise enough.
Level of Approximation	A focused physical prototype with ultrasonic sensors.
Experimental plan	•Conduct a test, using one sensor, to test out the accuracy of the distance sensing.
Schedule	14 March - connect sensors 14 March - conduct distance tests 17 March - testing completed 17 March - analysis of test results completed

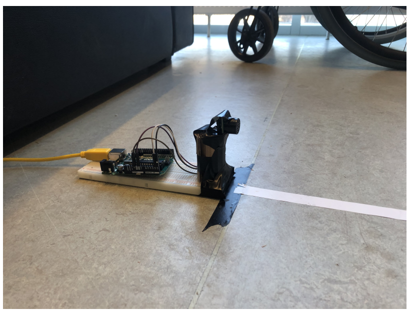


Figure 4.35: Obstacle avoidance test.

The plan for the obstacle avoidance test using a lidar can be seen in table 4.15, and the setup of the miniature robot car can be seen in figure 4.36. By combining a TF mini

Plus Lidar [41] and an SM-S2309S Servo motor [42], a rotating lidar can be created. Appendix E.1 shows a wiring schematic for the miniature robot car. The lidar scans ahead to detect objects nearby, and if an object is nearby, the lidar is supposed to start sweeping 180 degrees from left to right and calculate the most optimal path. It should then rotate its body in that direction and continue on its path.

Table 4.15: Plan for the lidar prototype.

Name of prototype	**Lidar obstacle avoidance test**
Purpose(s)	•To confirm that the miniature robot car can avoid obstacles. •To confirm a lidar can be used.
Level of Approximation	A focused physical prototype. Obstacle detection and avoidance with lidar and motors
Experimental plan	•Connect motors to the motor driver. •Mount a lidar on a servo •Connect the motor driver, servo, and lidar to Arduino Mega •Run code and conduct obstacle avoidance test.
Schedule	05 May - Connect components. 06 May - Attach wires between components. 06 May - Run code. 06 May - Conduct Obstacle avoidance test. 07 May - Analysis of test results completed.

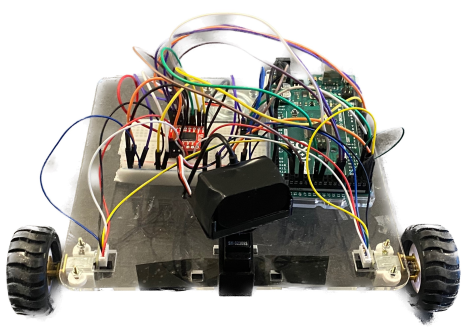


Figure 4.36: Miniature robot car in the form of a digital twin.

4.7.1.1 Prototype Results

The measurements from the ultrasonic obstacle avoidance test can be seen in 4.16. The measurements were performed by placing obstacles straight ahead of the sensor. The data provided from the distance sensor did not have any decimals, which was limiting, but the sensor's accuracy proved acceptable for the desired purposes.

Table 4.16: The data given by the distance sensor when targeting different distances.

Trial number	50 cm	80 cm	100 cm	120 cm	140 cm
1	49	81	100	119	140
2	50	81	100	119	139
3	50	80	100	119	140

The miniature robot car with the lidar could detect objects at a distance of choosing, in this case, 40 cm, and make a 180-degree sweep from left to right and calculate the most optimal path. The results from the prototype test can be seen in table 4.17.

Table 4.17: Results of testing the miniature robot car.

Test	Expected behavior	Pass/Fail
Obstacle in front	Goes to the optimal direction	Pass
Obstacle in front and at the left side	Goes to the right	Pass
Obstacle in front and at the right side	Goes to the left	Pass
Obstacle in front and at both sides	Turns around	Pass

Both the prototypes confirm that both design parameters, DP1: Ultrasonic sensors and DP2: lidar, can be used to fulfill FR1: Has obstacle avoidance. Combined, they would act as the obstacle avoidance mechanism of Wheels-On. However, this was not implemented as a part of the Wheels-On due to a limited amount of time, so the functional requirement was not fulfilled.

If implemented on the Wheels-On add-on power kit, the lidar could be replaced with two RPLidar S2 from Slamtech [43]. They are more powerful and can be used to map the path ahead. Additionally, they spin 360 degrees, which would make the servo unnecessary. When the wheelchair has gotten past the obstacle, it would start searching for the location of the tag, rotate its body in the direction of the tag, and start following the user again.

Chapter 5

Results & Discussions

5.1 Results

The prototype showed promising results and provided proof of concept by following its user at a short distance. It fulfilled its two constraints and all of the functional requirements except one, as seen in table 5.1. The functional requirement that was not met was that it has obstacle avoidance. Even though it was not implemented on the wheelchair, it was implemented on a digital twin and showed promising results.

Table 5.1: Summary of the result of the functional requirements and constraints.

Nr.	Functional Requirement	Result	Argument
0	Can follow its user	Pass	Uses UWB technology
1	Has obstacle avoidance	Fail	Not implemented
2	Works as a standard wheelchair	Pass	Is removable and retractable
3	Can move remotely	Pass	Has motors on the wheel that react to data
4	Has rechargeable power supply	Pass	Has rechargeable Li-Po battery pack
5	Provides feedback	Pass	Displays information via Blynk application
Nr.	**Constraints**		
1	Not too heavy	Pass	Total weight is 3.0 kg
2	Lasts a rehabilitation session	Pass	Battery lasts 4 hours based on the maximum current drawn from Wheels-On's circuit

5.2 Discussions

It is apparent that this project's development is necessary to address the need for a semi-autonomous following wheelchair, which provides security for ambulatory wheelchair users when walking.

As stated above, in chapter 5.1, the prototype fulfills five of its six functional requirements. Nevertheless, it can serve its purpose, which is to follow its user at a short distance.

The impressive results of the final prototype are ideal for building future work, and since this is only the first generation prototype, it offers much room for improvement. Future improvements would include, but are not limited to:

- Implementing the functional requirement for obstacle avoidance, previously implemented on the digital twin, by scaling it up and using a lidar scanner for obstacle detection.
- Improving the user device, so the user would be able to switch between modes, change settings, and have more control of the behavior of the wheelchair.
- Replacing the Blynk application with an application with more informative feedback for the user.
- Implementing more features in the software, such as the wheelchair moving closer to the user, once the Stop following button in the Blynk application is pressed.
- Implementing the ISO standards, stated in chapter 3.8, to register Wheels-On as a medical device.
- Moving away from and replacing the Raspberry Pi 3B with a better microcontroller that could both function as a server and the brain of the Wheels-On.
- Upgrading the retractable mechanism to enhance the ease of use.

All these changes would affect the kit's design, which would also require updates. The improvements would consequently affect the price of Wheels-On, the add-on power kit.

Chapter 6

Conclusion

6.1 Motivation

Everyone can benefit from a short walk; some advantages include preventing muscular atrophy, strengthening the bones, and keeping healthy blood flow [1]. Hence, it is beneficial for wheelchair users with some walking capacity, commonly called ambulatory wheelchair users, to walk. It can be challenging to leave the wheelchair behind, leading users to forego the chance to walk and instead rely more on their wheelchairs. Therefore, the product, Wheels-On, turns a standard wheelchair into a semi-autonomous following wheelchair, which provides ambulatory wheelchair users the confidence to walk a short distance, knowing that the wheelchair will be behind them if they feel the need to rest.

6.2 Process

The design process started with researching similar products that could inspire the design and give an idea of the components needed. Concept development was performed to determine the final concept: a removable and retractable kit with motors on the main wheels. It uses UWB location technology to locate its user and ultrasonic and laser range sensors to avoid obstacles. It communicates to its user via phone, and a lithium-ion battery powers all the components.

After determining the final concept, parts and components were ordered accordingly. Each component was tested by making multiple prototypes until the results were satisfactory. Previous prototypes were combined to create a final prototype of the Wheels-On, an add-on power kit for a standard wheelchair. The prototype was attached to the back of a wheelchair, and the functionality was tested.

6.3 Evaluation of Results

The result from the final prototype is that the wheelchair can follow its user at a distance of 1-2 meters. It uses data from a UWB tag which is located on the user that locates him relative to the wheelchair with the four UWB DWM1000c anchors positioned on the wheelchair, which relates to FR0: Can follow its user. The kit weighs 3.0 kg, consistent with CON1: Not too heavy, and is attached easily to the back of the wheelchair. It has knobs that are used to fasten and retract the motor rollers on the wheels making the wheelchair able to move remotely. When the motors are retracted, the wheelchair can work as a standard. That relates to FR2: It works as a standard wheelchair, and FR3: can move remotely. The kit uses a 14.8V Li-Ion rechargeable battery, which fulfills FR4: It has a rechargeable power supply that lasts up to four hours to power its components, consistent with CON2: It lasts a rehabilitation session. The Wheels-On communicates with the user using an application on a smartphone with a "Quit" button to suddenly shut off the system if needed. That relates to the final functional requirement, FR5: Provides feedback. The Wheels-On is not able to detect and avoid obstacles, which contradicts FR1: Has obstacle avoidance. Prototype testing of the feature with an ultrasonic sensor and a lidar showed promising results and could later be implemented onto the Wheels-On add-on power kit.

6.4 The Future

The next steps in the development of Wheels-On are to build on the promising results. This would include implementing the functional requirement for obstacle avoidance onto Wheels-On by adding ultrasonic sensors and lidars. There is much room for improvement in the software aspect of Wheels-on since the focus during this project was to find appropriate hardware for Wheels-On. An application needs to be developed to allow more feedback to be provided to the user, along with improving the software that controls Wheels-On. The retractable mechanism would need to be upgraded to improve the ease of use. All of the improvements would enhance the user's experience, making it more beneficial for ambulatory wheelchair users when training or maintaining their walking ability.

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Appendix A

Bill of material

A bill of materials was created and can be seen in table A.1. The bill of materials shows the total price of all the components for one prototype kit.

Table A.1: Bill of Materials.

Part	Currency	Price	Qty	Total Price	Cost ISK
Raspberry Pi Model 3B [44]	USD	41.25	1	41.25	5700
Metal DC Geared Motor w/Encoder - 12V 122RPM 38Kg.cm* [38]	USD	29	2	58	8013
Buck Converter 3 A 3V - 40V[45]	USD	0.71	1	0.71	98
5V Voltage Regulator LM7085[46]	USD	2.1	1	2.1	290
MDD10A Motor Driver [47]	USD	23.5	1	23.5	3247
1500ţF Capacitor[48]	USD	3	1	3	415
Wires[49]	USD	1	x	1	138
ESP32 Wrover-B UWB3000[50]	USD	45.80	1	45.80	6328
Quorvo DWM1001c[36]	USD	40.2	5	201	27770
Ad North PLA[51]	USD	34.67	1.8kg	62.4	8621
Fuse 3A	USD	0.1	1	0.1	14
Gens Ace Li-Po Battery[39]	USD	30	1	30	4145
Printed PCB[52]	USD	2.4	1	2.4	332
Bolts and nuts	USD	3	x	3	415
Small Button	USD	0.99	1	0.99	137
Emergency Stop[53]	USD	43.9	1	43.9	6065
Sandström USB to USB Micro[54]	ISK	2.495	4	10.091	10.091
Total					**81.820 ISK**

Currently, the rough material cost for Wheels-On's components is 82.000 ISK.

Appendix B

Target Cost

The product is in the early stages of product design, so the cost analysis is only based on assumptions formed by using information from table 2.2 regarding essential features and comparing the cost of similar creations. Similar products to our own can be seen in table B.1 along with the product's price.

Name	Cost [ISK]
LightDrive Power Assist	1.614.113 [3]
Permobil Smartdrive	878.180 [55]
Airwheel SR5	123.445 [6, 56, 57]
Robotic Wheelchair	1.225.989* [58, 59, 60]

Table B.1: The price of similar products. * denotes an assumption based on the information provided.

The price range of similar products is from 123.445 to 1.614.113 ISK. Based on this information, the cost of the devices or parts needed to implement the product's features can be assumed. The target price for the semi-autonomous following wheelchair, based on the competitor's products, is approximately 1.250.000 ISK. Using equation B.1, the end user price can be calculated using a 20% profit margin, which comes down to 1.562.500 ISK. That is based on the assumption that the product is sold directly by a manufacturer to end users of the product.

$$P = \frac{C}{1 - M} \tag{B.1}$$

Appendix C

Durability of main components

The durability of the main components can be seen in table C.1.

Table C.1: Durability of Wheels-On's main components.

Main Components	**Durability**
Raspberry Pi Model 3B	7- 10 years [61]
Metal DC Geared Motor w/Encoder - 12V 122RPM 38Kg.cm*	20.000 - 100.000 [62]
MDD10A Motor Driver	N/S
ESP32 Wrover-B UWB3000	About 12 years [63]
Quorvo DWM1001c	N/S
SRF02 Ultrasonic Sensor	Approx 15-20 years [64]
TF Mini Plus Lidar	close to 10 years [65]
Gens Ace Li-Po Battery	2 to 3 years [66]

Appendix D

CAD drawings - dimensions

The figures below show the CAD drawings for Wheels-Ons components, with dimensions, all in mm.

D.1 Backplate components

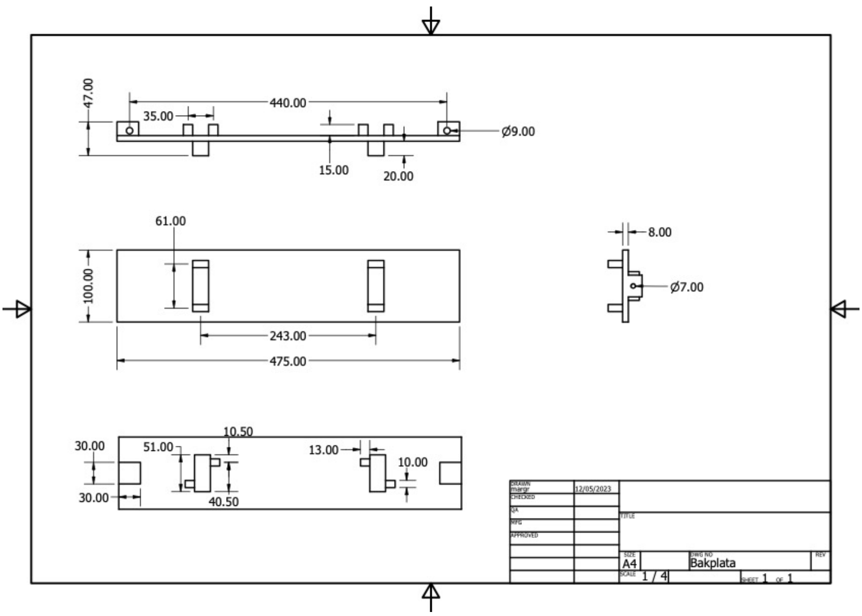

Figure D.1: CAD drawing of the backplate.

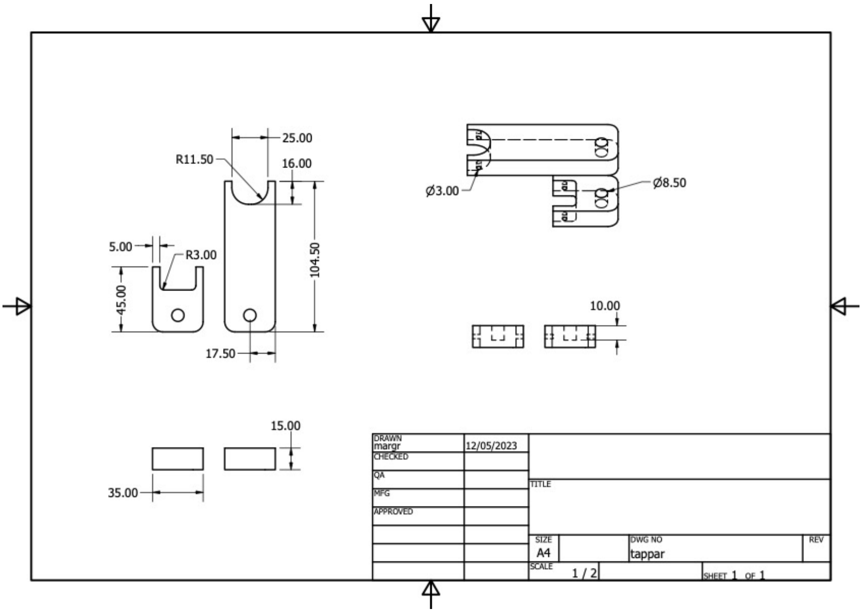

Figure D.2: CAD drawing of the upper and lower mounting brackets.

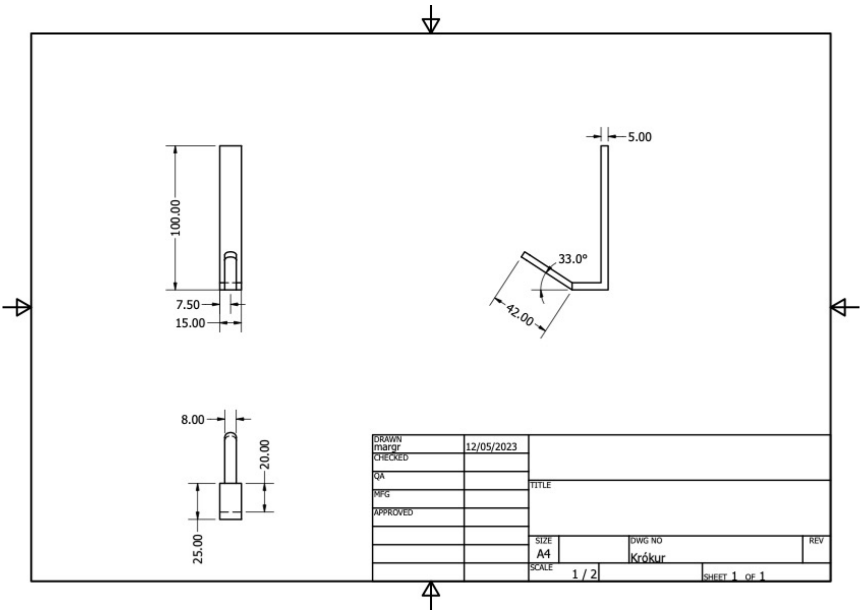

Figure D.3: CAD drawing of the hook.

D.2 Motor-kit components

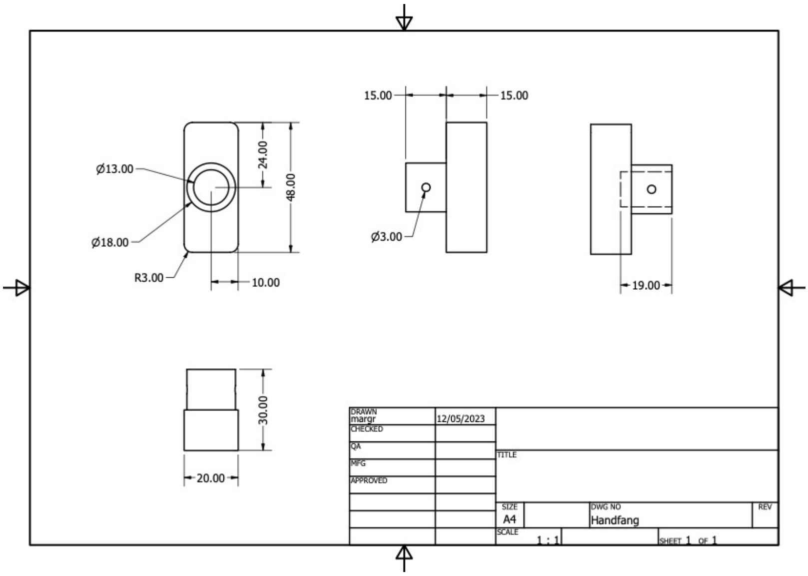

Figure D.4: CAD drawing of the handle.

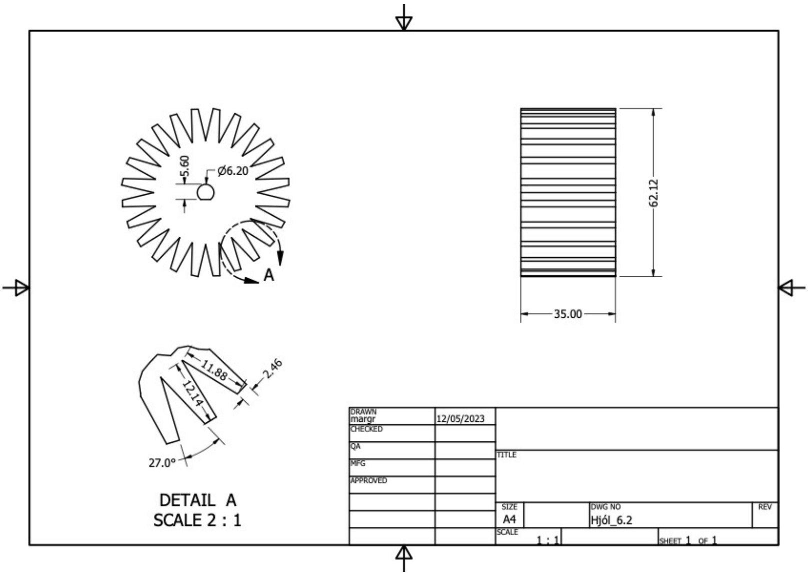

Figure D.5: CAD drawing of the roller.

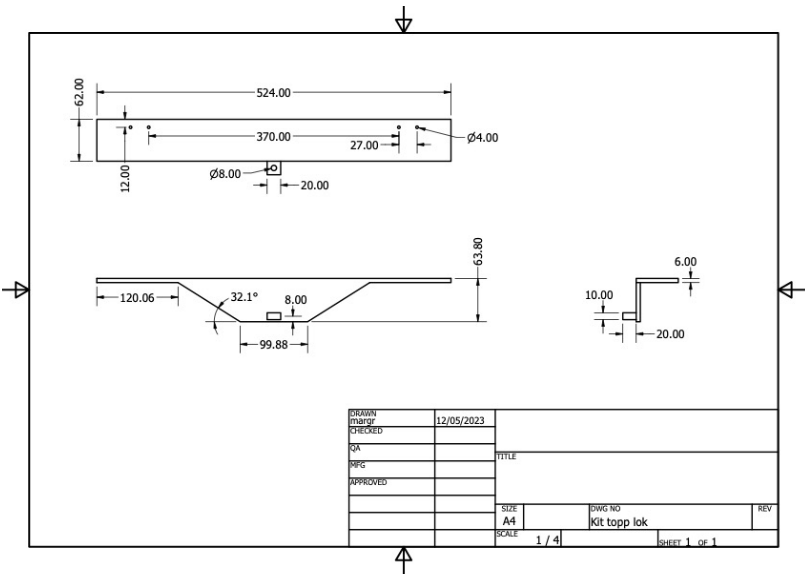

Figure D.6: CAD drawing of the lid of the motor kit.

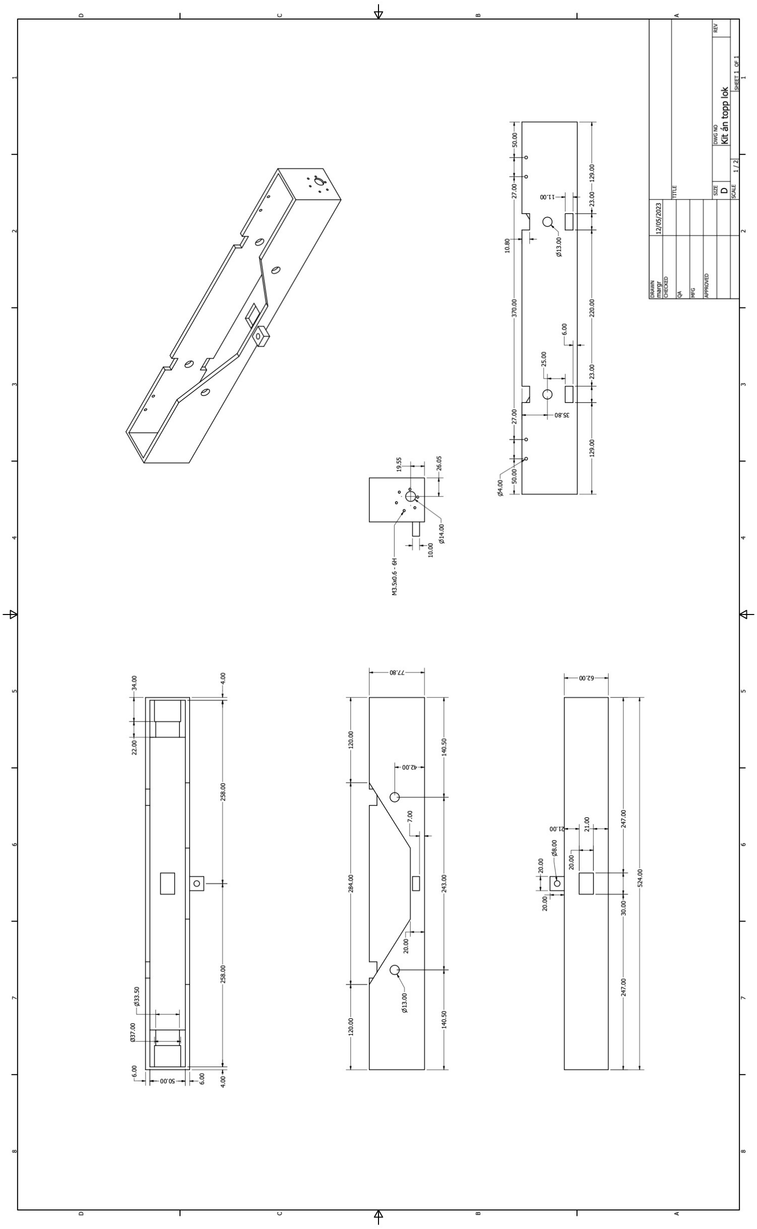

Figure D.7: CAD drawing of the motor-kit.

D.3 Brackets

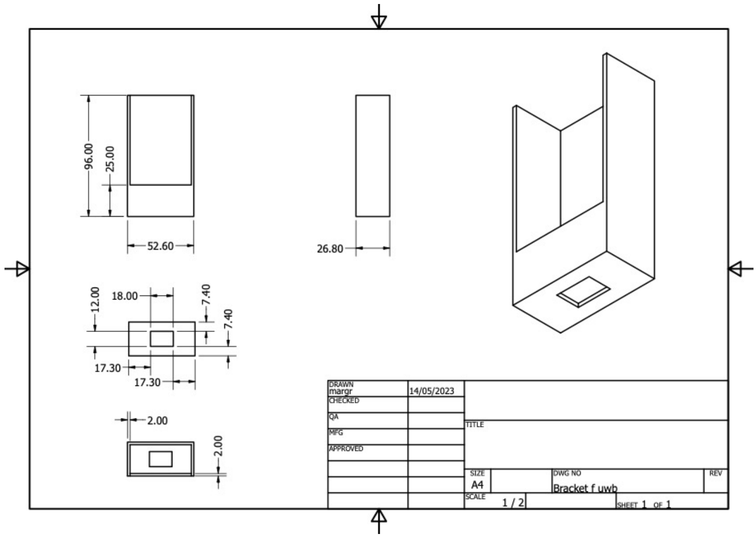

Figure D.8: CAD drawing of the UWB anchor bracket.

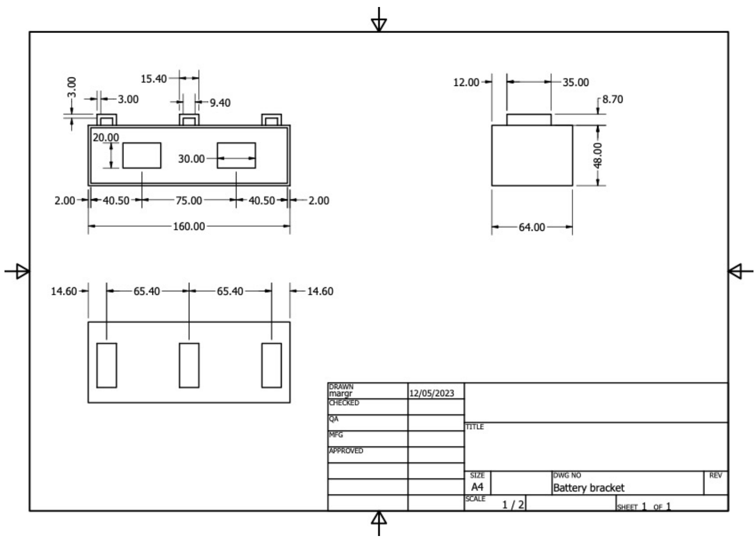

Figure D.9: CAD drawing of the battery bracket.

Appendix E

Wire schematic

Below is the wiring schematic for the robot that serves as a digital twin for the implementation of the obstacle avoidance feature.

E.1 Schematic for Digital Twin

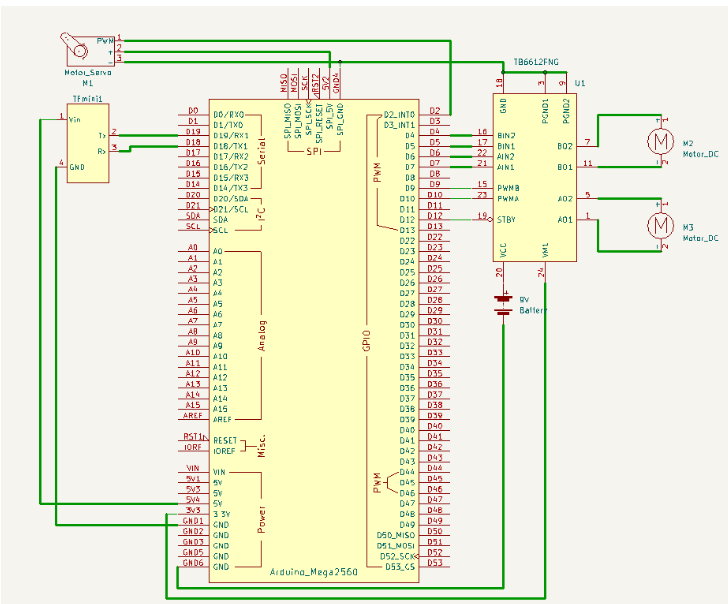

Figure E.1: The schematic diagram for the miniature robot car.

E.2 Schematic for Wheels-On

Figures below show the wiring schematic for the Raspberry Pi 3B and for Wheels-On.

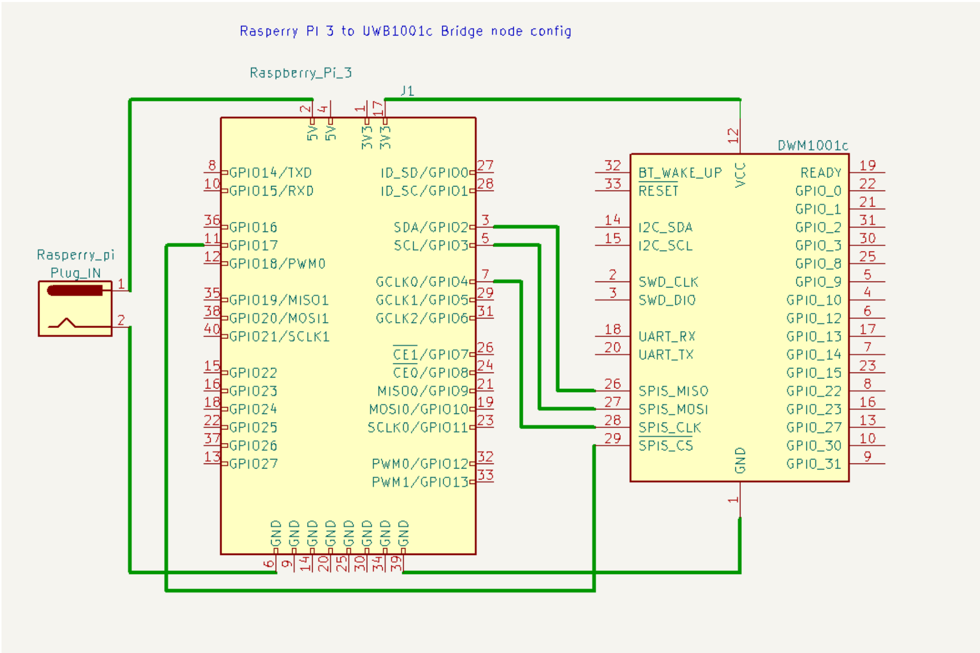

Figure E.2: A wiring schematic for the Raspberry Pi 3B.

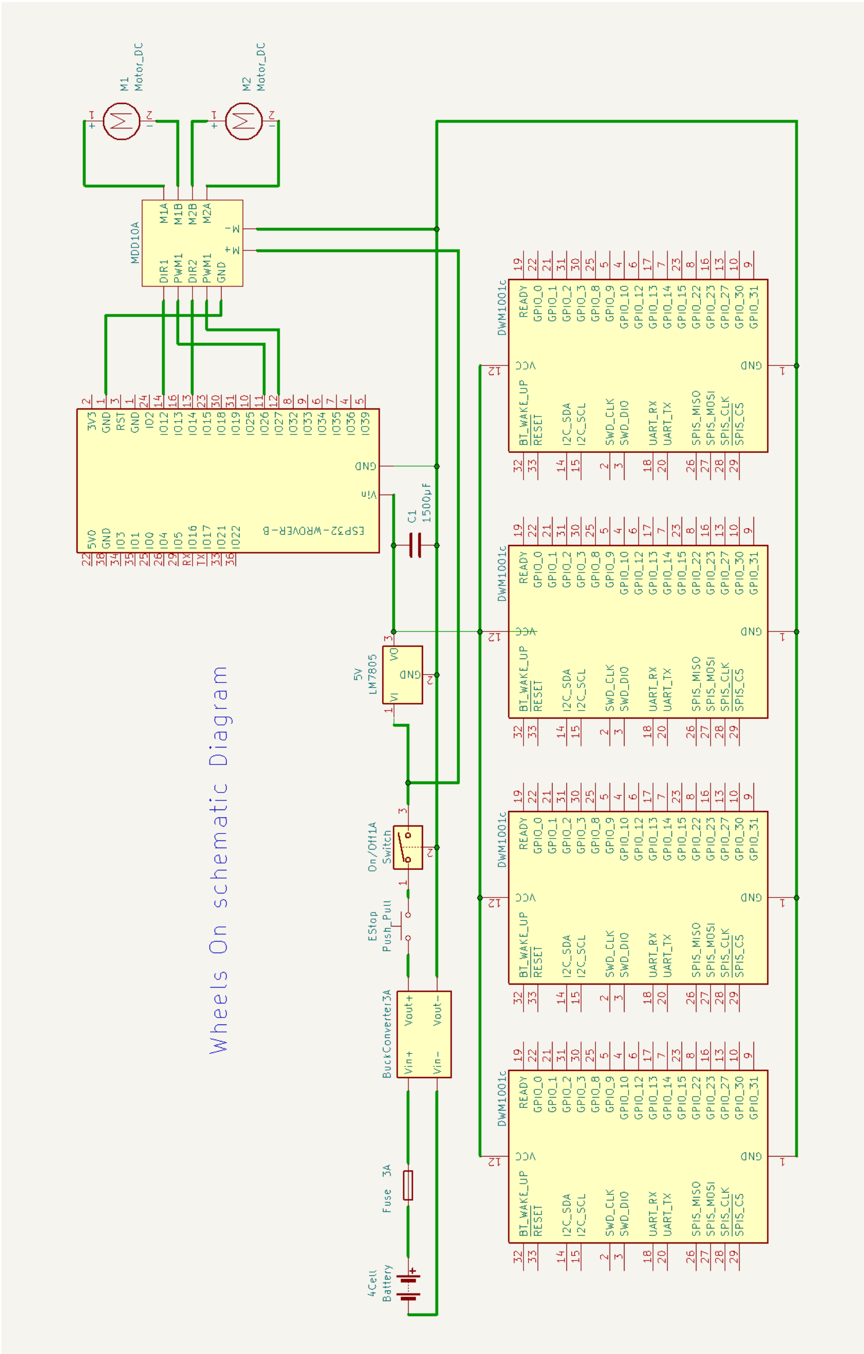

Figure E.3: A wiring schematic for Wheels-On.