LAFAYETTE COLLEGE

Department of Mechanical Engineering

[*Image: Wheelchair accessibility in tough terrain at Hawk Mountain, PA]*

Wheelchair Team Design Report

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1. Team Mission Statement

Through the application of our mechanical engineering knowledge, our mission is to make areas that are difficult to navigate more accessible for people with limited mobility by creating a device designed to assist manual wheelchair users in ascending and descending inclines and declines. The focus of this project is to assist people who use wheelchairs or are considering using a wheelchair and allow accessibility to a greater number of locations. Additionally, we believe that people should not be limited in their accessibility based on their ability, or socio-economic status.

2. Report Objective and Organization

A prototype for a manual wheelchair add-on that is intended to aid users in ascending and descending inclines has been developed. The purpose of this report is to describe how this project was developed, the current prototype and an assessment of the success of the project. This includes the following sections: design pathway and process, engineering specifications, current state of the project, further testing and design modifications, final budget, team self examination, and recommendations for future work. The design pathway and process describes the motivation, stakeholder engagement, project organization and puts the current effort into a technological and societal context. The following section is the engineering specifications which describes the specifications that were developed for the project in general as well as the specifications developed for the various subteams. The current state of the project describes the current prototype for the different subteams as well as the testing that has been completed for the prototype. Following the current prototype description, additional testing and modifications to the prototype is described. The overall budget of this project is also broken down in this report. Additionally a team evaluation was conducted for the entire team as well as for the subteams. With all the work that has been done for this project the team has developed and noted recommendations for future work of what would have improved the overall project, and what advice the team would give to future capstone projects. A lot of work has been done to create the wheelchair add-on device and this report reflects the project development, prototyping, and further improvements that have been made throughout the entire project timeline.

3. Design Pathway and Process

The design process and pathway was highly collaborative throughout the entire project timeline. Every team member included their input and helped narrow down and develop the project. At the start of the project, the entire team had an interest in 3D-printing and medical devices and was eventually narrowed down into the current device which aids manual wheelchair users. The following sections describe the motivation, stakeholder engagement, context, and project organization that has been developed to achieve the current device prototype.

3.1. Motivation and Summary of Project Selection Process

As of 2015, there were 2.7 million wheelchair users in the US [1], and according to the CDC, 13.7% of US adults have some form of disability relating to their mobility [2]. Assistive mobility technology is a very large market, and many people stand to benefit from improvements in this field. The aim of this project is to make a quality of life change for people with mobility issues by allowing current wheelchair users to have more independence and perhaps even opening the door to the mobility-impaired to feel more comfortable with the idea of transitioning to a wheelchair.

Improvements to wheelchairs is a broad category, but reaching a wide audience was a priority. To reach a wide audience, the project would benefit from being designed as a device that could be acquired and installed at a relatively low cost, weight, and could be attached to an existing wheelchair. Wheelchair users face a variety of issues, but this project must have a more specific focus. Table A.1 (Appendix A) is from a study conducted to measure the usability of assistive technology from a multi-contextual perspective. This table demonstrates some of the major identified challenges wheelchair users tend to face. Notably, users' experience issues are mainly within their community and outdoor environments, rather than at their homes or workplaces. Among challenges posed by outdoor environments include driving through streets, access to sidewalks, and climatic influences [3]. Ramps specifically have been identified as an issue for some wheelchair users within their communities. Stairs were also a specific issue identified for wheelchair users [4]. These challenges and issues are intended to be mitigated by the design of the wheelchair add-on design. Simultaneously, accessibility issues created by the add-on itself must be minimized and taken into consideration [5]. For example, Table A.1 (Appendix A) emphasizes the accessibility issues associated with restrooms or narrow aisles [3] and ultimately any add-ons for this project should not worsen the accessibility of a manual wheelchair. With the research presented above, there were two main interests: steep inclines and declines and stair climbing. The focus was centered on inclines and declines in part because of safety concerns for stair climbing as well as the difficulty involved with creating a stair climber that could also be an attachment for an existing wheelchair. With the focus solidified, a strong understanding of the audience was still required.

While wheelchairs do allow those who cannot walk or have limited mobility to travel on their own, manually operated wheelchairs can put a serious strain on a person's body, especially their upper body. Injuries are not uncommon; between 42% and 66% of manual wheelchair users experience shoulder pain from frequent use of the wheelchair [6]. These issues can be concerning for both wheelchair users and those considering using wheelchairs. The goal of this project is to create a device that can be added to an existing manual wheelchair that is relatively low cost and low weight that will assist the user if they become tired or sore, but does not completely take away the feeling of autonomy. This device will help lower the amount of fatigue experienced by manual wheelchair users and lower the barrier to entry for those considering a modestly priced wheelchair who fear being unable to independently push it. Such a device would also be useful to someone who is transitioning from a powered chair into a manual one. Overall, the success of this project means the ability to safely implement an accessory allowing many current or new wheelchair users to experience more independence and ease of mobility even when trying to ascend and descend steep slopes.

Assuming the project is successful, this new system still needs to be made available to the public. An attempt could be made to file a patent and sell production rights, which if possible could be beneficial for the team, but may limit the market of consumers. The work could also be made open source, which would give opportunities to others to build off what was done in this project or produce similar products cheaply. Plans for this last stage of the project have not yet been discussed. Ultimately, the motivation of this project is to use engineering knowledge to make a positive difference in the lives of millions of people by improving the wheelchair user experience.

3.2. Stakeholder Engagement

As with any human centered project, the primary stakeholders are the individuals the project intended to support. In this case, the primary stakeholders are wheelchair users, specifically those who are primarily independent or are striving to be primarily independent. In addition to these stakeholders, external partnerships were formed with a variety of individuals with mechanical or medical knowledge that is beyond the current expertise of the team.

The team has consulted a combination of individuals with technical backgrounds and individuals who have experience working with or using wheelchairs. The team completed an IRB application and received approval. The team has gathered information from a variety of healthcare professionals and wheelchair users by conducting the surveys and interviews that were approved by the IRB committee. The surveys were found to be relatively ineffective as there were too many steps required for the volunteer to take the survey. However, the team was able conduct three interviews of wheelchair users who expressed their excitement for the new technology and their appreciation for being included in the project. All three interviewees were friends of team members.

Some of the feedback from the interview process includes an emphasis on keeping the device lightweight and some concerns about placing hands near the moving spokes of the wheels. It was pointed out that the battery being used to power the motors is too large to be taken into an airport as a carry-on which would decrease the device's portability. It was also brought up that it is virtually impossible to avoid going over bumps in a wheelchair making that a crucial function of the design. Interviewees also helped the team understand the various types of wheelchairs available for wheelchair users. The wheelchairs vary significantly in size and weight making the adjustability of the team's design crucial. Finally, the interviewees helped identify a more specific target audience of wheelchair users who were previously dependent on another person or an automatic wheelchair but would like to be more independent. Since our device allows wheelchair users to gradually adjust from fully automatic to fully manual, it makes sense for it to be used by a transitioning group.

For the surveys, the team hoped to survey and interview more people with the help of the connections of team members as well as the individuals who were interviewed using the survey questions found in Appendix D. The current survey results are inconclusive due to a low number of initial responses. If the team was able to go through the process again, there would be an emphasis on making the processes of completing the survey easier with the hopes of obtaining more responses. One way the survey could be improved in the future is to include the consent form as part of a single survey link. Currently, the survey requires participants to print out a consent form, physically sign it, and then send it back to the team before completing the survey. By allowing for an e-signature on the survey the process could be quicker and easier. Since none of the team members use a wheelchair or interact directly with a wheelchair user, it is difficult to design a product focused on wheelchairs without the additional feedback gathered from the surveys and interviews.

3.3. Current Effort in Context

3.3.1. Societal and Technological Context of Design

A successful design effort will have implications in the larger societal and technological context. First, the design will impact the health, welfare, and safety of manual wheelchair users. Safety is a top priority for the device. This device will provide a safe alternative to manual and motorized wheelchair usage and is a major factor in design considerations. Also, in terms of the overall welfare of users, the device will provide increased accessibility and maneuverability for wheelchair users allowing them to overcome barriers created by inaccessibility or challenges when ascending or descending inclines in a wheelchair. The health of stakeholders and wheelchair users is also impacted by the increased ability for people who use wheelchairs to participate and engage in activities requiring ascending or descending inclines or declines, respectively. This medical device positively impacts the health of users because it allows for users to engage their bodies physically depending on the effort setting they have requested from the device. Similarly, increased accessibility and ability to engage as a person who uses wheelchairs has positive social implications for users. Eliminating or mitigating challenges associated with traversing inclines and declines for a person who uses wheelchairs helps remove social barriers created by accessibility challenges. Lastly, economically this device will provide an affordable alternative to current wheelchair add-ons. This will provide an opportunity for greater access to the product and the assistance it provides.

3.3.2. Description of Current State of the Art

There are several different options on the market for wheelchair users to either have motorized wheelchairs or to add assistive technology to their wheelchairs to aid with mobility. Motorized wheelchairs constrain a wheelchair design in terms of cost and accessibility related to bulk and weight of the wheelchair. Therefore, wheelchair attachments try to mitigate the major drawbacks associated with motorized wheelchairs. Wheelchair attachments, often referred to as mobility add-ons, are defined as “relatively small and lightweight accessories for manual wheelchairs that increase the chair’s mobility capabilities, which can be easily removed when not in use” [5]. There are significant gaps and opportunities for growth within this market to provide better opportunities and experiences for wheelchair users. Even with all the innovations occurring in wheelchair design, many users still experience difficulty associated with current wheelchair technology for daily usage [7]. Research was conducted to examine current wheelchair add-ons on the market and where improvements could be made. This research provided motivation for the team to provide a lightweight, low cost, accessible, safe, and easily transportable add-on device for a wheelchair to assist a person to ascend inclines and descend declines and help to improve their quality of life. The assistive technology or add-ons currently available for wheelchair users traversing slopes fall into three main categories: push rim-activated power-assist wheels (Figure 1), wheelchair power drives (Figure 2), and mechanical advantage devices (Figure 3) [8].

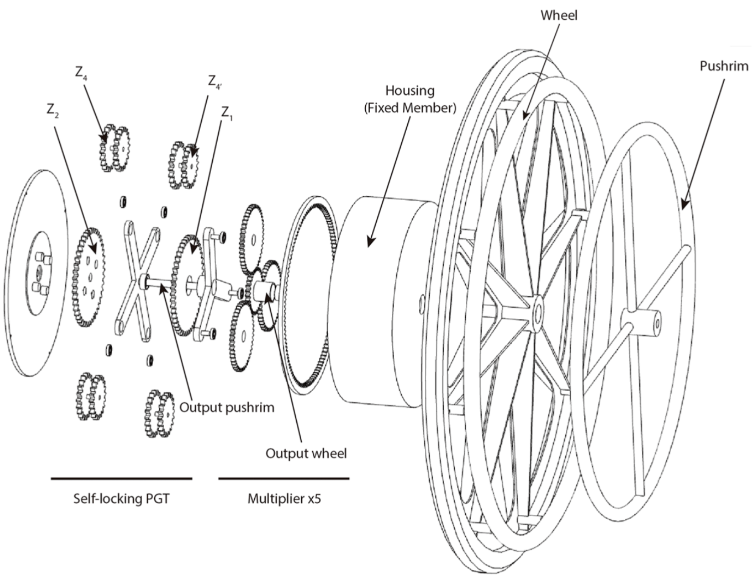


Figure 1 Pushrim-activated Power Assist Wheels (PAWAW) [9]

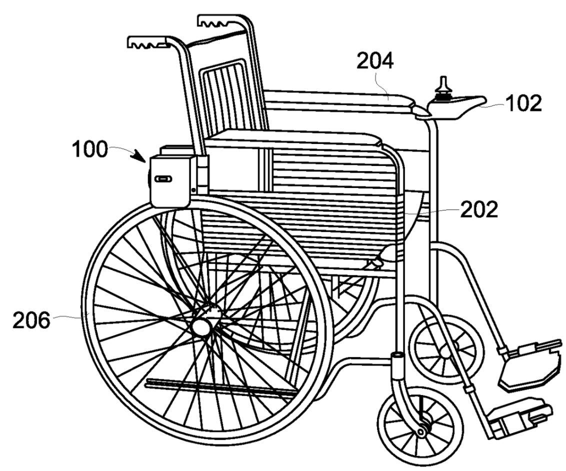


Figure 2 Wheelchair Power Drives [10]

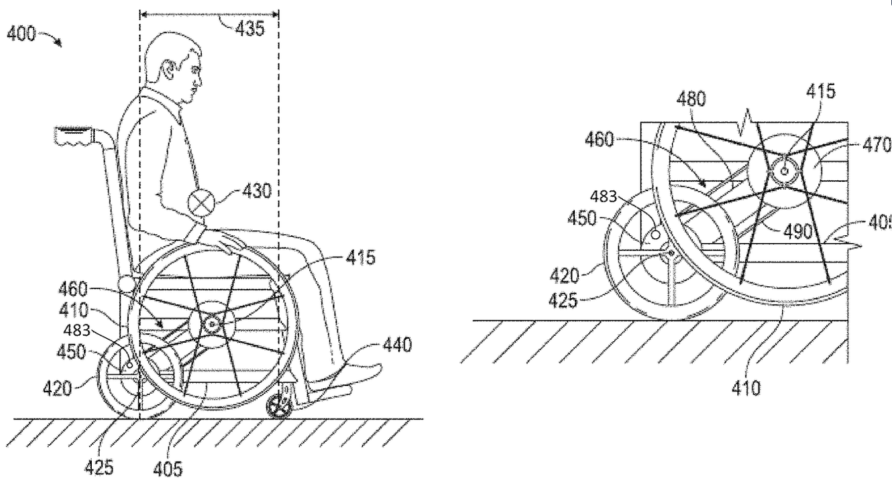


Figure 3 Mechanical Advantage Add-on [11]

Pushrim-activated power-assist wheels (PAWAW) is a manual wheelchair to which motorized wheels are added to provide power and aid with mobility [12]. Essentially, a person uses their hands to propel the wheelchair and the motors in the hubs of the wheels respond to the torque created by the user. This allows for the user to have the ability to propel themselves further forwards or backward with a single push compared to a generic manual wheelchair. One of the issues associated with the use of PAWAWs is that the overall width of the wheelchair is increased due to the addition of the small motors in the hubs of the wheels. Added width contributes to accessibility issues for the user. Lastly, the transportability of the add-on is often challenging and requires the add-on to be lifted if removed, which is sometimes not possible [12].

Wheelchair power drives consist of three main components: a control unit, battery pack, and a drive unit. Wheelchair power drives include two main types of controls: user-controlled and attendant controlled. User-controlled means operated by the user and attendant controlled means operated by an attendant or helper to the user in the wheelchair. The biggest disadvantage of wheelchair power drives is the weight the add-on contributes to the overall weight of the wheelchair mainly due to the battery [8].

Finally, there are simple mechanical advantage devices. The main advantage of this type of device is it is lightweight due to the absence of a battery and motors. This propulsion device uses levers to propel a user forward and backward. It reduces the overall effort of the user, but could potentially create muscular strain for the user from operation [8].

There has been a patent granted for a device that falls under the category of a user-controlled power drive that converts a manual wheelchair into an electric wheelchair [10]. The device includes the following components: a joystick, a communication unit, a motor, a retractable friction roller, and an engagement unit and power source. This device mitigates issues seen with electric wheelchairs including cost, portability, weight, and structural bulk [10]. Identified issues of the device include installation with the user needing to be in or out of the chair as the add-on is being installed or removed from the wheelchair.

Taking a look into the current motor assist devices on the market the below table (Table 1) shows four products currently easily available. The four devices, the SmartDrive MX2 Power Assist [21], Firefly 2.5 [19], E-Motion [20] and SMOOV One [22] are broken down into their prices, added weight, maximum supported weight, range on full battery, and maximum speed.

The Smart Drive MX2 Power Assist attaches to the back of the wheelchair and has a single wheel to propel the wheelchair [21]. Similarly, the SMOOV One attaches to the back of the wheelchair with a single wheel and motor in a slightly different configuration [22]. Conversely, Firefly 2.5 attaches to the front of the manual wheelchair and has a similar steering to an electric scooter or motorbike [19]. The E-Motion replaces the wheels of a manual wheelchair and uses hub motors and other technologies to assist in propulsion. These different values heavily influenced the metrics and constraints of the device, as shown below in the associated section (Section 5.1), consequently affecting design choices and considerations.

Table 1: Pricing, Weights, Range and Speeds of Different Wheelchair Add-On Devices currently on the market

	SmartDrive MX2 Power Assist [21]	**Firefly 2.5 [19]**	**E-Motion [20]**	**SMOOV One [22]**
Price (USD)	$6,317.90	$2,595.00	$2,595.00	$6,895+
Added Weight (lbs)	13.5	35 (shipping weight)	22	16
Maximum Supported Weight (lbs)	331	~	286	310
Range on full battery (miles)	12	15	15.53	12
Maximum Speed (mph)	5.5 (flat ground) 5.3 (6% degree incline)	12	3.73	6

Many of the conceptual drawings and designs were inspired by prior art from other technologies. The hub motor, Figure A.1 and A.2 (Appendix A) used in E-Bikes inspired a few designs, which can be found in Appendix B (See Figures B.4, B.5, & B.6). This allows E-bikes to be pedaled while the motor is running [13]. The intent in the conceptual designs is that the hub motor would allow the wheel to spin while also being pushed by the user. Other designs have been influenced by technologies outside of current motorized wheelchair prior art in addition to the prior art as seen in Appendix B (See Figures B.1-B.3, B.7-B.11, B.13).

Ultimately, manual wheelchairs are a very inefficient form of transportation [8]. Just to traverse inclines or declines requires a significant amount of upper body strength and endurance [8]. Especially over a longer period of time, using a wheelchair can contribute to upper-body injuries including chronic shoulder pain [8]. The identified needs of wheelchair users coupled with analysis of current technology highlight the need for assistive technology that help wheelchair users navigate slopes. The major areas identified for potential improvements in the current technologies are cost, weight, accessibility, safety, and transportability while preventing the user from getting their hands dirty while operating the wheelchair. Wheelchair add-ons tend to be heavy, restrict accessibility, and costly, so the goal of the wheelchair add-on design is to combat these factors while creating an affordable and easily transportable product [8].

3.4. Project Organization

The team structure was organized in various categories: team leader, assistant team leader, subteam leader/individual roles, copy editor, budget team, scribe team, sprint/schedule manager, and technical shop liaison. Outside of these roles, the team was split up into 3 groups: the propulsion team, the electrical mechanical integration team, and the effort sensing team. Each member of the wheelchair team held a position in their subteam as well as in the main group. Our team charter, which can be found in Appendix C, states that there was a team leader who led the team in weekly meetings, created and followed the agenda for the upcoming meeting, and made sure that the team was on schedule. The assistant leader ran the meeting if the team leader could not or if the group was getting off task. The subteam leaders were in charge of their respective group since there was a subteam leader for each category during the project. They were responsible for making sure their team reached their deadlines on time. The budget leader interacted with Colt Houser who was in charge of purchasing and maintaining a spreadsheet that tracks purchases. They also made sure that we had a budget and we would follow the budget we created. The scribe team was in charge of recording minutes for each meeting. The technical shop liaison was in charge of revising engineering drawings and bringing materials to and from the shop. The copy editor would compile/assemble reports, finalize them, and then submit the reports. There was also an IRB team that was in charge of submitting and finalizing the survey/interview documents. These documents were distributed to participants in the form of surveys and interviews, along with consent and debriefing forms. The individual roles within the subteams were described as secondary roles to their roles with the team.

For the duration of the whole class, the team leader was Charlotte Sullivan. She took over this role after Professor Utter led the team for about two weeks. The scribe team was composed of Katie Rice, Charlotte Sullivan, and Nicole Stanec. There were multiple people interested in this position, so a team was created to prevent team members from becoming overworked. The budget team was Carolyn Pye, Katie Rice, and Emily Eng. Nicole Stanec was the technical shop liaison, and the copy editors rotated with each report. Emily Eng and Carolyn Pye were a part of the IRB team and were working with Professor Nees and Professor Vinchur. The first copy editors were Charlotte and Nicole, Emily and Drew were the next pair, and Carolyn and Katie were the most recent copy editors. Check-ins also occurred frequently to ensure that people had a balanced workload and no one felt overworked or like they were not contributing enough to the team.

Within the subteams, each member of the class had a position. The effort sensing team was composed of Nick Moosic and Drew Freeland. They were in charge of creating the effort sensor for the wheelchair. The propulsion team had Charlotte Sullivan, Nicole Stanec, Katie Rice, and Geoffrey Toth. This team was working on the propulsion aspect for the wheelchair as seen in Figure 5 of Section 5.2.1. The Electro-mechanical team was Emily Eng, Carolyn Pye, and Matt Urban. This team was responsible for steering and electrical integration for the entire system. Within the electro-mechanical integration team, Carolyn was the subteam leader, Emily was the circuit manager, and Matt was the CAD manager. For the effort sensing group, Nick was in charge of the 9 Degrees of Freedom sensor and Drew dealt with the strain gauges. In the propulsion group, Nicole was the subteam leader and each member had aspects in which they focused. Charlotte was in charge of the ISO information, wheel, hitch, torque transmitter, spring attachment, and braking. Katie was responsible for the motors, attachment, lifting mechanism and the subteam budget. Geoffrey was in charge of the batteries. Nicole was in charge of the transmission, and transmission housing. All of these teams were integrated with one another, so although everyone had a designated team, there was frequent collaboration on all aspects of the project. There was frequent communication among the team to ensure that all aspects of the project were covered. Table 2 shows all the positions held by each member of the team.

Table 2: Positions Held by Each Team Member

Name of Team Member	Positions Held	Subteam
Emily	Part of budget team, subteam code manager, IRB team	Electro-Mechanical
Nicole	Technical shop liaison, part of scribe team, subteam leader	Propulsion
Charlotte	Team leader, part of scribe team	Propulsion
Carolyn	Part of budget team, subteam leader, subteam circuit manager, IRB team	Electro-Mechanical
Matt	Subteam CAD manager, Subteam arduino manager	Electro-Mechanical
Nick	Subteam member	Effort Sensing
Drew	Subteam member	Effort Sensing
Geoffrey	Subteam member	Propulsion
Katie	Part of budget team, member of scribe team, motor manager	Propulsion

Members of the team were expected to maintain a level of professionalism and respect. The benefit of the doubt was given to everyone and set up the team's success. Each person was held accountable and held each other accountable. Communication was the key to success. In order to have open communication, all members were expected to be at meetings and let everyone know if they would not be attending. Members were conscious of the way they interacted with one another and remembered to be open and respectful. This team cannot have performed its best work without everyone in the team working their hardest. Since everyone gave it their all, the team succeeded.

4. Engineering Specifications

The purpose of the Engineering Specification section is to describe the different specifications and functions for the entire wheelchair team and each subsystem team. The general specifications cover the specifications that overlap among subsystems and testing methods for the full wheelchair device assembly. In addition to general specifications, the subteam sections cover specifications that are specific to the functionality of the subsystem. The specifications identified in this report are derived from the design objectives, which have been informed by research on the largest areas of improvement for wheelchair users. Initially, general specifications, functions, and constraints were developed, but as subteam work developed, subteam specific metrics emerged. Some measurable quantities identified are velocity, acceleration, weight of the device components, weight the device and wheelchair can support, cost, and maximum incline grade the wheelchair is designed to climb. These complement design objectives that have developed through rigorous discussion.

The following four sections are organized into: the general specifications, propulsion team specifications, electro-mechanical integration team specifications, and effort sensing team specifications. Each section discusses functionality, including the general functionality and the subteam specific functionality. Following the brief overview of function, each section includes a specification table and an explanation of the specifications below.

4.1. General Specifications

The general specifications include cost, weight, waterproofing, width, and International Organization for Standardization (ISO) specifications and testing procedures. Many are based on the ISO, the source that will be used to ensure the entire device is safe and accessible for users. The general specifications incorporate aspects of the design and testing that overlap among subteams. These overlapping specifications can be seen in the table below (Table 3).

The following tables have a distinction between target minimum value, target maximum value and constrained maximum/minimum value. This is to distinguish between the target values that the device is trying to achieve (target maximum and minimum value) and the constrained minimum or maximum that would cause the device to violate a critical function or ISO standard. The target values were intended to be met, but if they were not met a redesign may not be required. However, if a constrained value was not met, a redesign should be considered and discussed because the device was not meeting a critical constraint required for target goals to be met. In addition to numerical values, constrained values require answers such as "yes" and "no" to show if the specification must be met. The maximize/minimize/target/constraint column found in the table shows whether the target values should be maximized, minimized, meet a target value, or if the specification is constrained and must meet a value, standard, or function. Modifications that would be made if this project continued due to failure to meet specifications is discussed in Section 6.

Table 3: General Design Specifications and Metrics

#	Metric/Specification	Target Minimum Value	Target Maximum Value	Unit	Maximize /Minimize/ Target/Constraint	Constrained Max/Min or Yes/No
G1	Total cost of device	0	$2,500	USD	Minimize	
G2	Total added weight of the device	0	25	lbs.	Minimize	
G3	Water Resistance				Constraint	Yes
G4	Maximum added width	0	4	in.	Minimize	
G5	Static stability ISO 7176-1				Costraint	Yes
G6	Dynamic stability ISO 7176-2				Constraint	Yes
G7	Brake effectiveness ISO 7176-3				Constraint	Yes
G8	Obstacle climbing ability ISO 7176-10				Constraint	Yes
G9	Power and control systems ISO 7176-14				Constraint	Yes
G10	Batteries and charges ISO 7176-25				Constraint	Yes

G1. Specification G1 involves the maximum total cost of the device. The device cost shoul not have exceeded $2500 to stay within competitive pricing of prior art (Table 1). This puts the device in the same price range as the Firefly 2.5 [5] and E-Motion [1] and significantly below the SmartDrive MX2 Power Assist [11], and the SMOOV One [9], all of which are existing motor assist devices on the market (Table 1). Cost of manufacturing, and cost of parts were considered in determining the design of the device to ensure this specification was met.

G2. Specification G2 sets the total weight of the add-on device to a target maximum of 25 lbs. Specifically, the total weight of all the parts being added to the wheelchair should not have exceeded 25 lbs. Setting the total added weight to 25 lbs allows the user to push the wheelchair when the device is not in use, but attached to the device to the wheelchair with minimal added strain [2]. Similarly to Specification G1, Specification G2 was determined by putting the maximum added weight of the device components within the range of other motor assist devices currently on the market. As seen in Table 1 (Section 3), the range of added weight of the four prior art is 13.5 lbs - 35 lbs. 25 lbs is the specified added weight as it is in the middle of the prior art range. To try to achieve this specification, lightweight materials were used where applicable such as aluminum while also balancing Specification G1 to keep costs low.

G3. The device should be able to withstand different weather phenomena such as snow and rain to allow the greatest accessibility and utility of the device. ISO 7176-9 specifies the requirements and test methods to determine the effects of different climatic events for electric wheelchairs [12]. Standard ISO 7176-9 would test the device and assess the device's ability to withstand different weather changes. To aid in weatherproofing, the device's electrical components were waterproofed. Stainless steel and aluminum were the main materials used to deter corrosion and allow the device to operate in most outdoor environments.

G4. The added width of the device is defined as the width the device extends outward from the current width of the wheelchair. It should not have exceeded the specified value of 4 inches to allow the device and wheelchair to pass through an ADA regulated doorway [12]. Specification G4 is derived from the width of the standard manual wheelchair (26 inches) and the standard width of a doorway (36 inches) [12]. Adding a width of 4 inches at maximum would make the width of the wheelchair and device 30 inches, which would still allow a wheelchair user enough space to pass through a standard doorway. Any added width limits the accessibility of the device. To reduce added width of the design components of the propulsion system have been sized and positioned to fit within the original footprint of the wheelchair. The control interface is the only component that extends past the original footprint of the wheelchair and was tested to see if it meets this specification the result of which is discussed below.

G5. Specification G5 is defined as the static stability testing method for the wheelchair with the device attached. Specification G5 ensures the device passes the static stability testing for wheelchairs set by ISO 7176-1 [12]. Both Specification G5 and G6 ensure that the device will not make the wheelchair unsafe while it is and is not moving. This testing was carried out when the device prototype was fully assembled. Results of this test are discussed below.

G6. ISO 7176-2 sets the standards for determining dynamic stability of the wheelchair and is intended to be followed [12]. Testing using ISO 7176-2 would require a full assembly prototype of the device attached to a wheelchair. This specification was not tested because of time constraints and complexity of ISO 7176-2 procedures.

G7. Specification G7 focuses on safety and is derived from ISO 7176-3, which specifies the test methods and effectiveness of brakes for manual and electric wheelchairs [12]. The current design allows for some electrical braking of the wheelchair from the add-on device. This specification test was planned but not performed.

G8. Specification G8 constrains the device to the standards and testing method of ISO 7176-10 which determines the obstacle-climbing ability of electrically powered wheelchairs [12]. It specifies the test methods for determining the ability of the device and wheelchair to climb and descend obstacles [12]. This standard covers the intended goal of the device. The testing as defined by ISO 7176-10 was planned but not performed during the project duration.

G9. Specification G9 determines the requirements and testing method as set by ISO 7176-14 for the power and control system of electric wheelchairs. It also states the maximum speed of the wheelchair, 9.32 mph [12]. This constraint would be used to confirm that the device's control and power system meet the requirements of the standard. The maximum speed would have been handled by the precision of the speed being controlled by the Electro-Mechanical Integration Team. This also overlaps with Specification P4 below for the propulsion team which ensures the propulsion system does not violate ISO 7176-6 which will limit the maximum speed of an electric wheelchair. This testing of this specification was not planned because of the complexity of testing procedures.

G10. The wheelchair design must not violate the ISO 7176-25 requirements for batteries and chargers [12]. This requirement defines that for lead acid batteries and chargers, the rated input voltage should be no greater than 250 Vac and the nominal output voltage should be no greater than 36V. Specification G10 ensures that the device's batteries meet the requirements of this standard. This was taken into account when choosing the battery. We have currently chosen a 48V lithium ion battery. While this goes over the nominal voltage, this is not a lead acid battery, which is the one specified in this ISO requirement. This standard also defines the testing method for batteries and battery chargers intended for use with electrically powered wheelchairs [12]. This specification test was not completed during the project duration.

4.2. <u>Propulsion Team Specifications</u>

The purpose of the propulsive subsystem are the following functions: to be able to propel, slow down, turn, and stop a user in a wheelchair on level ground, inclines, and declines. Below is a list of metrics and specifications used by the Propulsion Team when designing the device. These are based on both knowledge of prior art, and research of speeds of wheelchair users and people who do not regularly use wheelchairs. Note that all speeds in the table below are being calculated based on the average weight of an American man, 198 lbs [9]. This was a conservative design choice because the weight of an average American man is greater than the average weight of an American person.

Table 4: Propulsion Team Specifications and Metrics

#	Metric/Specification	Target Minimum Value	Target Maximum Value	Unit	Maximize /Minimize /Target/ Constraint	Constrained Max/Min or Yes/No
P1	Range of device on full battery with no user effort	1.5	∞	Miles	Maximize	
P2	Range of device on full battery with 50% user effort	12	∞	Miles	Maximize	
P3	Safely Tranversible grade of incline/decline	8.3		% grade	Maximize	
P4	Maximum possible speed on level ground, incline and decline			mph	Constraint	9.32
P5	Unassisted speed on level ground	3	9.32	mph	Maximize	
P6	Unassisted speed on a incline	2.25	9.32	mph	Maximize	
P7	Unassisted speed on a decline	3	9.32	mph	Maximize	
P8	Curb height device can overcome	6	∞	in	Maximize	
P9	Grade incline or decline on which the device can stop without user intervention	5		% grade	Maximize	
P10	Ability to go backwards				Constraint	Yes
P11	Ability to steer				Constraint	Yes

P1. The range of the device on a full battery with no user effort is the allowable distance the user can travel in the device with 0% effort input from the user before the battery runs out of charge. The value of 1.5 miles was chosen based on the average distance an American walks in a day, which was determined to be around 1.5 to 2 miles per day [8]. This distance was used when determining the necessary amp hours of the battery, and it was used to determine the distance the battery of the device should be able to accomplish with no user effort (Specification P3).

P2. The range of the device on a full battery with 50% effort from the user is the allowable distance the user can travel in the device with effort input from the user 50% of the time, until the battery runs out of charge. This range of 12 miles was chosen because it is comparable and competitive to other prior art (Table 1). To ensure that the device is competitive with other motor assist devices on the market, the range of the battery should also be able to achieve a range of 12-15 miles at 50% user effort. The 50% user effort is defined as the motor running at half the speed, thus the user has to put in effort equivalent to 50% of the full speed motor. This value was used when determining the necessary amp hours of the battery.

P3. Specification P3 defines the grade of the incline or decline our device should be able to safely traverse. It was created based on the maximum grade of “hand-propelled wheelchair ramps,” which is 8.3%. The maximum grade for an electric wheelchair is 12.5%. At minimum, the device needs to be able to allow the user to navigate the maximum ramp built for a manual wheelchair. However, the grade at which the device can operate was maximized to help the user navigate steeper inclines and declines [13]. The maximum grade was used to determine the necessary motor horsepower.

P4. The maximum possible speed of the device on level ground, an incline or a decline, is the maximum speed of the user when the device is in use, which includes any input from the user. Specification P4 is based on the International Organization for Standardization (ISO) Standard 7176-6, which states that the maximum speed for electric wheelchairs is 9.32 mph (15 km/hr) [12]. This has not been used in any of our current calculations; however, in accordance with the ISO standard, when testing and using the prototype, it will not push the wheelchair at a speed exceeding 9.32 mph.

P5. The unassisted achievable speed is defined as the speed the motor is able to propel the user without any user assistance. It is the lower bound of the maximum speed achievable by the device and controller with no user input for acceleration or deceleration. On flat ground, the user should be able to travel 3.0 mph without any user input [9]. This value was chosen because it is the average walking speed of an adult [3]. This is used to ensure the user is at a safe speed, but not too slow to keep pace with additional foot traffic. This specification was taken into consideration when choosing the motor horsepower.

P6. The unassisted achievable speed on an incline is defined as the speed the motor is able to propel the user without any user assistance on an 8.3-12.5% grade, as defined in Specification P5. It is the lower bound of the maximum speed achievable by the device and controller with no user input for acceleration or deceleration. The unassisted achievable speed of the user on an 8.3%-12.5% grade incline should be 2.25 mph. This is the speed of the user without any user input. The value was chosen based on the average speed of a person who uses a manual wheelchair [6]. While this is slower than the unassisted achievable speed for the flat ground and a decline, this is an achievable speed that would allow a wheelchair user to safely navigate an incline. This specification was taken into consideration when choosing the motor horsepower.

P7. The unassisted achievable speed on a decline is defined as the speed the motor is able to propel the user without any user assistance on an 8.3-12.5% grade, as defined in Specification P5. This is the speed of the user without any user input. This value was determined by using the average walking speed of an adult [3]. This is used to ensure the user is at a safe speed, but not too slow to keep pace with additional foot traffic. This unassisted achievable speed was used for the maximum grade decline (Specification P3) to keep the user within the same safe operating level but this speed can be increased or decreased based on the user's comfort. As with Specification P6 and P7, this value was used when calculating the motor horsepower. Specification P6 was more important when calculating the motor horsepower because gravity can assist in the speed of the user, while on flat ground it is solely dependent on the motor in the device.

P8. The curb height the device can overcome is the maximum curb the device will be able to go over while going up and down the curb. The device should be able to overcome a 6 inch curb or bump up or down in the road. The device should be able to overcome inconsistencies in the road to allow for greater accessibility and use on different surfaces and roads. A 6 in curb is the standard curb height, so the device should be able to allow the device and wheelchair to overcome this without overextending the spring or putting too much added strain on the user [7]. This maximum curb height was used when determining what spring we should use. Our spring is able to extend the correct amount to allow the device to overcome a 6 in curb.

P9. The device should be able to stop the wheelchair and the user on at least a 5% grade decline or incline. The maximum grade of most pedestrian facilities and public access routes is limited to a 5% grade at maximum[7]. No user intervention means that the person using the wheelchair would not have to aid in stopping by gripping the wheels or using the wheelchairs built in braking mechanism. An extension spring mechanism is the current mechanism in place to allow the device to break using the motors of the add-on device. The spring ensures a normal force at the point of contact going forwards and backwards. Static analysis was done to design a spring that would allow the device to stop on a grade between 5% and 8.3% further testing would need to be done to further specify the braking capabilities.

P10. The device is able to go backwards on level ground, which means the user will be able to propel the wheelchair backwards without the use of their hands on the wheels of the wheelchair. The ability to go backwards was chosen due to safety concerns regarding the user's hands on the wheels while also being propelled by the device, and because it increases the accessibility of the wheelchair and device. Using static calculations on an inclined plane the device is able to come to a complete stop without user input so with the addition of the spring the device should be able to go backwards on level ground as well. Going backwards on an incline or decline may also be possible but may add additional safety concerns so should be addressed further at a later point in time.

P11. The device is capable of steering on level ground, inclines and declines, which means the user should not have to use their hands on wheels of the wheelchair to complete a turn. The ability to steer was chosen due to concern regarding the safety of the user's hands on the wheel of the wheelchair while being propelled by our device. To achieve this, the propulsion system includes two identical housings and motors that can operate independently at different speeds and control steering of the user to some extent. The extent of the turning radius and other specifications relating to steering have not yet been determined.

4.3. Electro-Mechanical Integration Team Specifications

The goal of this subsystem is to have a user-friendly interface that allows the wheelchair user to control the system. This includes control over whether the system is automatic, semi-automatic, or manual as well as altering the speed and direction of the wheelchair in automatic mode and the assistance level in semi-automatic mode. There will also be an LCD screen that allows the user to check the battery level, speed, effort level, and which mode their wheelchair is in.

Table 5: Electro-Mechanical Integration Team Specification and Metrics

#	Metric/Specification	Minimum Value	Maximum Value	Unit	Maximize /Minimize/ Target/ Constraint	Constrained Max/Min
E1	Resolution of controllable speed in automatic mode	0	0.2	mph	Minimize	0.5
E2	Resolution of propulsive force of the user relative to the device in semi-automatic mode	0	2	%	Minimize	
E3	System should not overheat		104	°F	Minimize	302
E4	Ability to quickly disable electronics and motors					Necessary

E1. If the wheelchair is in automatic mode, the user should be able to accurately adjust the speed of the wheelchair. The accuracy of the desired speed read from the potentiometer should be ± 0.2 mph. The user must feel comfortable in the wheelchair and the way in which it is performing. If the wheelchair is going faster than the requested speed by a noticeable amount the user may feel unsafe and if the wheelchair is going slower than the requested speed the user may be worried about the functionality of the device. A difference in speed of ± 0.2 mph is the beginning of what is noticeable and less than 10% of the average walking speed.

E2. The user will change the amount of assistance desired in semi-automatic mode by a potentiometer on the interface housing. The user should be able to be within ± 2% of the desired effort level in order to ensure the user is comfortable using the wheelchair. The user will operate the chair differently based on the percentages of the propulsion force that they expect the chair to provide. If the device does not provide an accurate and consistent propulsion level, the user could be going faster or slower than they are comfortable with. A force difference of 2% from expected is noticeable.

E3. Fans are being used to remove the heat inside the housing from the electrical components. The system should not overheat and damage any of the internal electrical components. At 104°F , the user may be uncomfortable touching the interface, defeating its purpose, and at 302°F, the interface itself will begin to melt.

E4. An emergency stop button will be on the side of the interface housing for the user to press in the case of an emergency. Pressing this button will stop all electronic components and the running motor. The emergency stop returns the wheelchair to its manual mode.

4.4. Effort Sensing Team Specifications

The goal of the effort sensing subsystem is to take the measurements necessary to determine the effort input by the user. The system must be able to distinguish between user applied forces and system applied forces to ensure the mathematical model has the information to determine the output force that needs to be applied based on those different inputs. This ensures the effort sensing system can provide accurately calculated output to communicate the input to the other subsystems. The specifications below relate to the timeliness and accuracy of these measurements. For all sensor sampling rate constraints, further development is required to determine appropriate sampling rates. The specific metrics for sampling rates are unknown, but these rates should be maximized.

Table 6: Effort Sensing Team Specification and Metrics

#	Metric/Specification	Minimum Value	Maximum Value	Unit	Maximize /Minimize/ Target/Constraint	Constrained Max/Min
ES1	Sampling period of 9DOF measurement system	0	10	ms	Minimize	
ES2	Sampling period of strain gauge measurement system	0	10	ms	Minimize	
ES3	Error in measurement of force needed to overcome gravity on a slope	0	10	N	Minimize	
ES4	Error in strain measurement	0	+/- 0.05	kg	Minimize	

ES1. The sampling rate of the 9 degree of freedom, or 9DOF, measurement system must be fast enough to ensure data is collected quickly enough for the system to provide an output for the angle and orientation of the chair in space. This ensures the 9DOF measurement system can provide timely output to communicate the input to the other subsystems.

ES2. The sampling rate of the strain gauge measurement system must be fast enough to ensure data is collected quickly enough for the system to provide an output for the force of the wheel add-on on the chair. This ensures the strain gauge measurement system can provide timely output to communicate the input to the other subsystems.

ES3. The error in the measurement of the force needed to overcome gravity on a slope should be minimized so that the chair can adapt appropriately to inclines. However, the value doesn't need to be incredibly precise so long as it is reasonably close and the system will still function effectively enough.

ES4. The error in the strain measurement of the wheelchair must be minimized to ensure the strain gauge measurement system's force calculation is accurate and can be used with confidence in determining the horizontal component of the propulsive force. This is a critical measurement for both the mathematical model and to provide information for the propulsive subsystem.

5. Current State of the Project

5.1. Description of Current Prototypes and Proof-of-Concept

An initial prototype was created that eliminates jerk, measures effort to some extent, applies positive torque, applies negative torque, controls directions, allows folding to some extent and interfaces with common wheelchairs. The team decided on the functions of the prototype. To eliminate jerk the device has progressive stopping and accelerations. Additionally the device is able to measure the angle of incline the wheelchair is on and change the settings accordingly to measure the effort of the user based on incline grade. Further functionality is that the two motor systems used for the device enables positive torque, negative torque and control of direction. Folding the wheelchair while the device is limited, but possible. Overall a lot of work has been done to enable the device to move the wheelchair and steer the device safely. The device is currently a ways away from being a finished product that could be sold to the public but makes areas that may have been hard to navigate before easier for users.

5.1.1. Propulsion Team Current Prototype

The propulsion team is faced with the design objectives of providing positive and negative torque, eliminating jerk, allowing folding and interfacing with common wheelchairs. The propulsion team has decided on the placement of the device, the motor type, the battery type, the attaching mechanism, the transmission system, and the braking system. The team has created detailed CAD models and manufactured all the components of the subsystem, which will be described in detail below. The full design can be seen in Figure 5.

Figure 5 Propulsion Team Current Prototype

The propulsion team's main metrics were the cost of the device, added weight of the device, range of the device, waterproofing housing for electric components, overcoming obstacles, and maximum grade. The main constraint considerations for the propulsion system are maximum added width, maximum speed of a manual wheelchair, and the maximum weight. These specifications and constraints at times competed with the desired functions of the device. In deciding the placement of the device, the conceptual designs were narrowed down to designs that included systems attaching to the back of the wheelchair and a system integrated entirely into the wheels of the wheelchair. Adding a device to the existing wheels would add extra width to the wheelchair, which makes it difficult for wheelchair users to go through tight spaces including doorways. The attachment to the back of the wheelchair would still allow the wheelchair to fold to some extent, there would be little to no added width, it would be more likely to interface with different manual wheelchairs, and it would be an attachable and detachable device, thus we decided the add-on will be attached to the back of the wheelchair, and two motors will be used to allow for steering.

Figure 6 shows the CAD model for the current prototype of the transmission and the transmission housing for the propulsion team. This system is made up of many components: base plate, sheet metal housing, back plate, vertical plate, two shaft supporting walls, shaft with e-clips, flats, and a woodruff key slot, ODrive Dual Shaft Motor - D6374, motor plate, encoder holder, two pulleys, and a belt. Because there are two of these to allow for steering, the right side is a mirror image of the left side, but they both contain the exact same components.

The base is made from 0.190" aluminum, and the housing cover is made from 0.032" aluminum sheet metal. Aluminum was chosen because it is both lightweight and weather-resistant (Specification G2, G3). The housing has a hole on the top because the threaded ball joints, which connect the housing to the rod that is attached to the wheelchair, are installed after the housing is secured to the base. This hole allows for these to be installed and tightened. These holes are filled with 3D printed parts and an expandable grommet, which act as a plug, to ensure no debris gets into the housing.

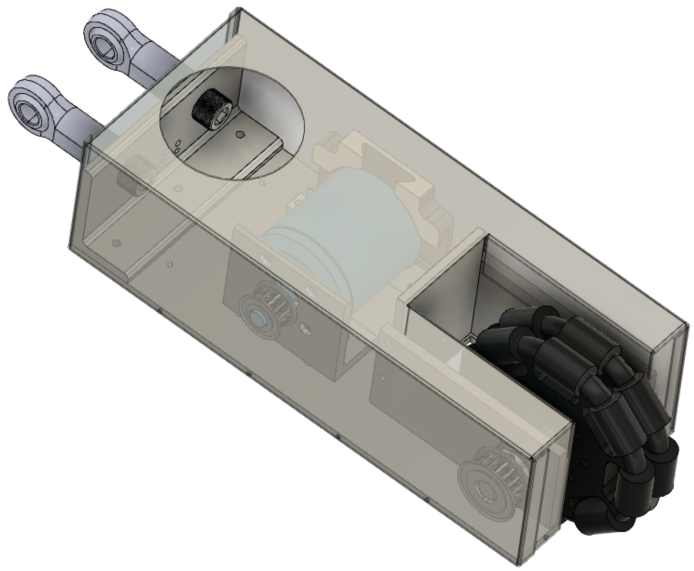


Figure 6 Transmission and Housing

The ODrive Dual Shaft Motor - D6374 has been chosen due to the motor horsepower calculations found in Appendix B. A motor with a minimum of ⅛ horsepower is needed to move the wheelchair at 3 mph on a 12% grade. 3 mph was chosen because it is the average walking speed of an adult, so it provides safety and keeps the motor operating above the minimum velocity [8]. The ODrive Dual Shaft Motor - D6374 exceeds the need for ⅛ horsepower at 3.12 horsepower. The motor was chosen because it achieves the desired horsepower and was the least expensive of other motors in a similar horsepower range commercially available.

To support the motor, a motor plate was manufactured out of an aluminum 90 degree angle, and an encoder holder was 3D printed. The motor plate is used to support the motor and secure it to the base plate. The encoder holder is used to hold the encoder to the rear shaft of the motor, which is used by the EMI team to know the speed of the motor. Previously, the motor was placed in an entire housing whose design was provided by the creators of ODrive. This approach was abandoned because having a plate in the front and a holder in the back means the body of the motor is not enclosed, thus the motor is less likely to overheat. The motor plate has slots for where it is secured to the base plate. This allows for the motor to slightly shift in order for the tightness of the belt to be adjusted.

A belt drive is being used for the transmission. The gear ratio for the belt drive was determined using the gear ratio calculation, which can be found in Appendix B (Figure B.17). From this code, a gear ratio of 1.39 is needed to move a wheelchair with a person of 198 lbs 2.25 mph on a 12.5% grade (Specification P3). To achieve this gear ratio, pulleys with 14 teeth, and 20 teeth were chosen for the shaft of the motor and the shaft that holds the wheel respectively. As a result, the gear ratio is 1.43, which is slightly higher than the calculated gear ratio needed to move the wheelchair 3 mph on a 12% grade. This is okay because the device will be able to move the wheelchair slightly faster than 3 mph on 12% grade, but this small difference will not push it past the allowable speed of 9.32 mph specified by ISO standards.

Using the same material as the motor plate, the back plate was manufactured using an aluminum 90 degree angle. The back plate's purpose is to transfer the force from the wheel to the attachment and to provide stability. On an earlier iteration, there was no back plate, which would have meant the only piece transferring the force from the wheel on the ground to the attachment bar would have been the sheet metal housing. This would have been a high amount of force on a thin piece of metal and would have most likely failed.

A stainless-steel drive shaft has been designed to hold the 20 teeth pulley, the wheel, and the torque transmitter, and CAD model can be seen in Figure 7. The shaft is stainless steel because it needs to be a higher strength metal, while also being able to withstand various weather conditions. The drive shaft is supported by two walls with ball bearings. It has grooves for e-clips to keep the shaft in the correct spot, a woodruff key slot for the pulley, and flats were milled for both the pulley and the wheel. A flat and a woodruff key were chosen for the pulley to ensure the maximum torque produced by the wheel would be able to be transferred from the wheel to the pulley.

Figure 7 Drive Shaft

Rotacaster wheels were chosen and purchased as the wheels for the device shown in Figure 6 and Figure 8. They have rollers on the extremity allowing them to roll in multiple directions. This will decrease drag when the wheelchair is turning. Additionally, a part is needed to be created to transmit torque from the axle to the wheel. The current part is seen in Figure 8. It interfaces with a current hole pattern from the purchased wheels which have been modified to be thru holes instead of partial depth holes. Bolts go through both parts of the wheels and are secured using nuts on the other side. A bushing was press-fit into a natural depression in the wheel to ensure the wheel has a tight enough fit with the shaft. A set screw was used to ensure the wheel is turning with the axle. The torque transmitter and wheel currently fit well based on turning the wheel and motor with no slip between the wheel and driveshaft.

Figure 8 Rotacaster Wheels and Torque Transmitter

The transmission and housing are attached to the wheelchair using the attachment bar shown in Figure 9. The attachment consists of two v-blocks and a threaded rod. The v-blocks are tightened around the bars of the wheelchair with bolts and rubber to secure the attachment, while the threaded rod offers an extension to securely attach the transmission housing and spring housing to the wheelchair. The v-block design was chosen to standardize the attachment, regardless of the diameter of the tubing. The v-blocks are clamped together with bolts and dowel nuts to allow for alignment adjustments. Neoprene rubber is used to further secure the v-block to the frame. This was done because without an intermediate layer the attachment is prone to rotate when pushed. The v-blocks are made of multipurpose 6061 aluminum, which is lightweight, strong, and corrosion-resistant. The larger v-block has a threaded hole to attach to the threaded rod. A stress analysis simulation for the attachment rod assuming that the rod was fixed, weight may be neglected, and the forces on the rod were the normal force (variable) and propulsive force (60.82 N) from the motor housing and a 25 Nm torque from the spring. The forces were applied to the end of the rod to account for the worst case scenario of the motor housing moving to the end of the rod. The stress analysis on the rod is shown in Figure 10. The subteam wanted to have a factor of safety greater than three for the rod to ensure that the part did not fail under loading from the transmission over time. To achieve this factor of safety, the material for the rod needed to have a higher yield strength than that of multipurpose 6061 aluminum without raising the cost and changing the material, which could cause corrosion over time that would damage the part. To fit this criteria, the rod was manufactured out of high-strength 7075 aluminum. The threading is in opposite directions for each rod to ensure that the spring tightens the rod instead of loosening it on both sides of the device.

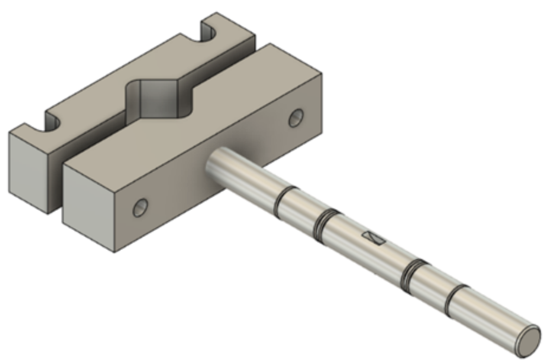


Figure 9 Attachment mechanism that clamps to the frame of the wheelchair

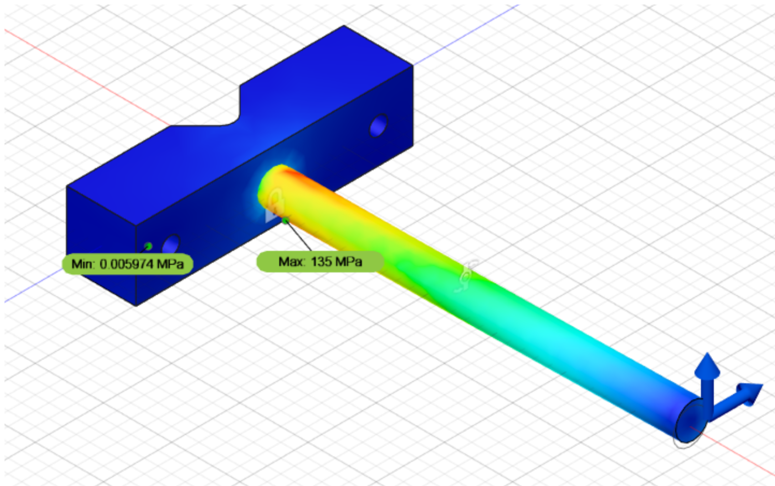


Figure 10 Stress Analysis on the attachment rod

There were several different designs for the connection between the transmission housing and attachment. This part has been referred to as a hitch by the propulsion team to denote the connection it makes. The main goal of this part was to allow rotation about the attachment rod. This goal was developed to make sure that the device would be able to overcome bumps, curbs and other inconsistencies in the road. This functionality was emphasized by some participants in interviews. Many initial designs included shaft collars or different milled aluminum. Shaft collars were used at first because of the ability to detach from the attachment rod. After further discussion, this was determined to not be a vital functionality because of the attachment being removable. Initially, only one connection part was going to be used but two were decided to add stability. The different options of hitches were simplified to the current design which uses two internally threaded ball joint rod ends seen below in Figure 11. This part allows for rotation about the attachment rod because of ball bearings used in the part. Overall, this greatly simplified the design of the hitch and decreased cost and manufacturing time because it is an easily accessible product that performs the needed functions of the connection.

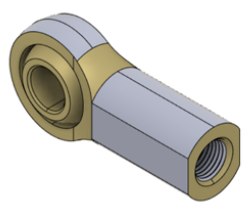


Figure 11 Connection between the transmission and housing and the attachment rod

A large concern that was discovered well into the design process was the need to ensure a normal force on the wheel at all times. A spring was decided to be used to ensure that the device maintained a normal force. Calculations were performed to determine what normal force needed in various configurations and inclines and declines. The contributing forces to the normal force calculations were the weight of the device, the force of friction, the normal force, and the reaction forces about the point of rotation. The force of friction was assumed to be the force needed to maintain an orientation of the wheelchair on an inclined plane with a 198 lbs occupant. 198 lbs was used because it is the average weight of an american male [9]. These calculations determined the torque needed from a spring on different types of surfaces ranging from Rubber on asphalt to rubber on wet pavement to simulate different conditions the device would encounter. The static derivation of the different forces and torques can be seen in Appendix B Figure B.18. This is to show the different free body diagrams and equations used to calculate the spring needed. Calculations were done for 12.5%, 8.3% and 5% grades. These were chosen because 12.5% -8.3% is the normal operating range of electric wheelchairs (Table 6) and a 5% grade which is the maximum grade of most pedestrian pathways [7]. The results of these calculations can be seen below in Appendix B Table B.1-B.3.

Based on the calculations, an extension spring was decided to be used because of the higher spring constants and maximum loads compared to torsional springs. Compression and leaf springs were also considered, but determined to be hard to implement. The main need for the spring comes from trying to maintain a normal force when running the motors backwards. This would enable the device to stop on a decline if the spring force was great enough.

Another desired characteristic of spring design was to self contain it into the profile of the prototype to ease installation as well as keep the device safer. An extension spring snapping would pose serious problems so keeping it within the profile of the device was decided to make the device safer. To achieve this, a spring attachment bar was added to the middle of the attachment rod, which can be seen in Figure 12. It is attached using a key and keyway to keep the rod at the same orientation and it keeps the spring extended. U-bolts were used to attach the spring to the bar and to the transmission housing. The spring attachment bar is made out of solid aluminum stock material of 1.5 in thickness.

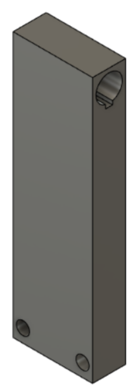


Figure 12 Spring Attachment Bar

Calculations were done to determine the spring needed for the device (Appendix B Figure B.19). The attachment bar was calculated to be parallel with the back of the transmission and housing to simplify calculations. A problem that was encountered in this design was that to enable stopping, the spring adds difficulty in overcoming curbs and other obstacles in the roadway when being used. To understand which function was more important to a successful design, our team asked current wheelchair users which function is more important in a device during our stakeholder interviewers. The consensus was overcoming curbs and bumps is of greater importance than braking. For this reason a smaller spring with a spring constant of 5 lbs/in was implemented. This would allow the spring to add some braking capabilities and maintain a normal force going backwards on some declines, but would still be able to extend over a standard curb height of 6 in [7]. Other larger spring constant springs were ordered and tested and deemed to be very hard to extend and not practical to use in the design.

In implementing the spring into the design, creating a perfectly parallel spring attachment bar was difficult and shims were needed to be used in the attachment rod to align the slots better. This was done initially to align the attachment rods to be parallel to the propulsion system but due to a miscalculation or mismeasurement it was below the expected angle making the spring not extend as much as initially anticipated. To correct this additional shims were added to the attachment rods to extend the spring further. This interfered with the effort sensing strain gages and added an unexpected setback late in the project timeline. The current prototype has a spring extended further than initially calculated for. This means the spring force is larger than expected but does not put the spring at risk of over extending over a standard curb height because of the excess stretch the spring has.

The current spring used should provide a torque of around 19 lbs-in. This would put the stopping capabilities of the device on an incline between 8.3 and 5%. By having this braking range the device satisfies specification P9. Testing is needed Testing is needed to measure the actual braking capabilities.

As mentioned, the spring breaking or pinching the user was a concern for safety. For this reason a spring housing was created to conceal the spring. This was done using aluminum sheet metal that was bent. Two separate housings were riveted together to make the complete housing. Two housings were used to better secure the housings to the baseplate and transmission housing. This also allowed for the housing to overhang outside the profile of the transmission housing adding further protection from the extended spring. The complete assembly of the spring can be seen below in Figure 13, which shows the spring, attachment, and housings.

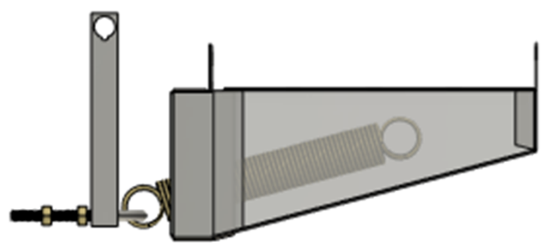


Figure 13 Spring Assembly including the spring, attachment bar and two part aluminum housing

A 48V, 10 amp-hour battery must be used, as this was determined to provide enough energy capacity for this specific motor. To determine the capacity needed, a torque-speed curve was created from the max torque and no load speed of the motor provided by the manufacturer. This linear relationship between torque and speed allows for the torque required to go certain speeds to be determined. Using the torque required to go at a speed of roughly 3 mph, the current that each motor draws per second can be calculated by multiplying this torque by the motor's speed in rad/sec then dividing this by the voltage of the battery. Using this, the distance needed to travel, and the travel speed, the battery capacity needed can be calculated. These calculations are shown in Appendix B (Figure B.16). As determined by our calculations, this battery will allow for the user to use the device at full speed for 6 miles, and at half speed, the device can be used for approximately 13 miles. This is consistent with Specification 3 and 4. Although the total capacity was calculated, these calculations were simplified as they do not take into account any friction and assume that the user is traveling along a flat surface. The estimation, therefore, for the capacity needed is a small underestimate of how much capacity is actually needed and these calculations would not work if the wheelchair was traveling up an incline.

In order to store the battery and to protect it from outside influences such as bumps and weather, a simple battery housing was constructed which can be seen in Figure 14. The housing consists of walls made of 1/16th inch aluminum sheets that are attached to each other using

L-brackets. A simple door is attached to the front of the housing which allows for easy access to the battery in case it needs to be replaced. The battery is attached to the underside of the wheelchair by using two aluminum loop clamps on each side of the frame. The battery is then dropped down an inch before being attached to the loop clamps via a square tube. The housing is placed far enough forward so that it can be easily reached in order to change/remove the battery while being far enough back so that the user does not accidentally damage the battery.

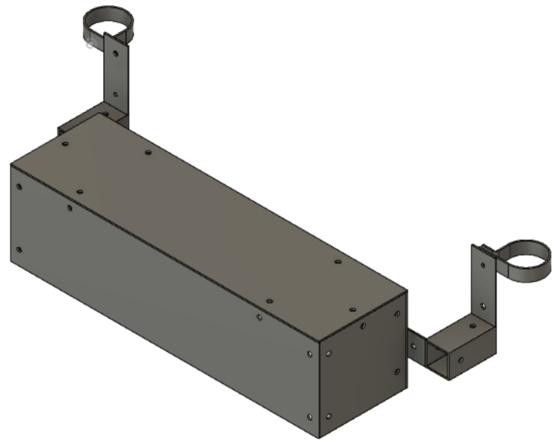


Figure 14 Battery housing

5.1.2. Electro-Mechanical Integration Team Current Prototype

The electro-mechanical integration team's focus was connecting the effort sensing and propulsion subteams to control the chair and create a user interface capable of controlling the system. The electro-mechanical integration subteam was responsible for creating an arduino script to control the logic of the chair, to integrate the propulsion and effort sensing subsystems into the main script in order for all parts to communicate, and to create a controller that could control the direction of motion and the mode of the chair.

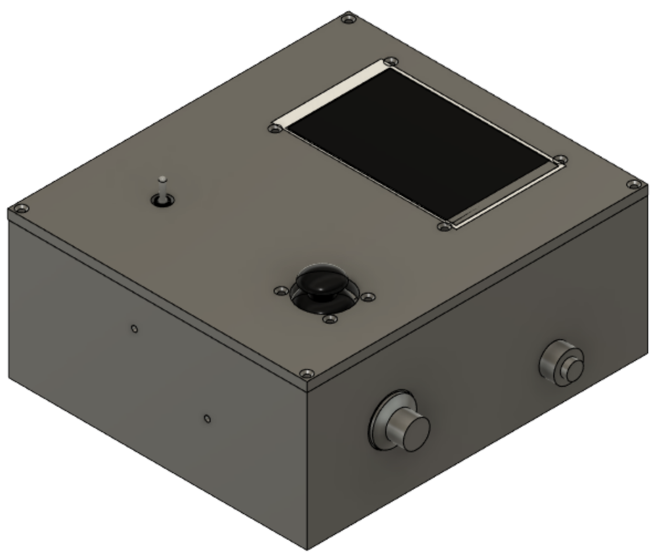


Figure 15 EMI team housing

The controller was created to set the max speed of the chair, to control the direction of the motion of the chair and the speed at which it travels in that direction, to set the mode of the chair to effort-sensing mode, all assistance mode, or waiting mode, to house the emergency stop button, and to output information about the chair such as battery level, speed, and mode on the LCD screen. Additionally, the controller intended to create a beeping sound to notify the user of different circumstances such as low battery, reversing in the chair, etc.

The speed was intended to be set using the potentiometer. The max setting on the potentiometer would be the max speed allowable by safety standards and the user could set the max velocity of the speed of the chair at any given time using the potentiometer's linear scaling. This final version of this concept has one revision from the intended design. Instead of the max setting of the potentiometer being determined by safety standards, the max setting is determined by the max input speed of the motor without causing an error, which was significantly lower than the safety guidelines. During testing, any voltage input to the motor greater than 5V caused an overload to one of the motors, disabling it until the code was reuploaded.

The joystick was intended to act as the way for the user to dynamically control the direction of the chair and the speed in that direction relative to the max speed set by the potentiometer. The farther the joystick was pushed from the center, the faster the chair would move, scaling linearly from motionless to the max speed. The arduino would perform calculations to determine how the chair would respond given how far the joystick was pushed in the horizontal and vertical directions and determine the motion based off of that. In the final design, the joystick acts as a purely directional controller, essentially allowing the chair to travel straight forwards and backwards and rotate clockwise and counter-clockwise. This change was made due to noise found in the reading of the joystick inputs that would spike and create issues with the motors while the joystick was in resting position.

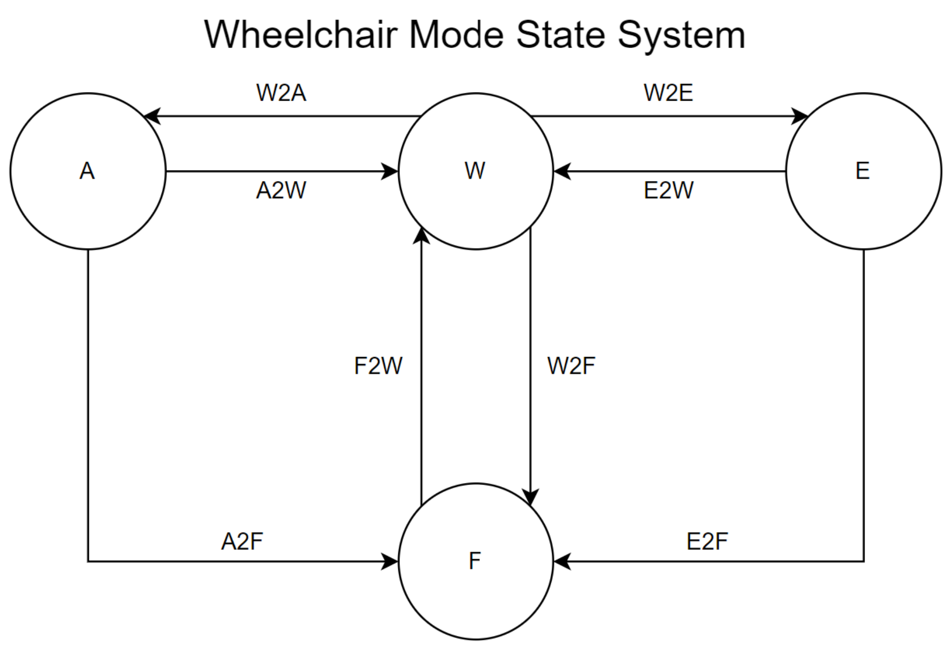


Figure 16 Wheelchair mode state system

The mode switch was the intended method of changing between the chair's modes. The chair was designed to have 4 modes: effort-sensing, full assistance, waiting, and fault. In effort sensing, the chair would make full use of the effort sensing subsystem to calculate the power and torque output by the motors to assist the user as desired. The potentiometer would set the effort level and the joystick would not be active. In the all assistance mode, the potentiometer and joystick would act as described earlier in this section. The waiting mode was intended to be the mode in which the chair would default upon start-up and the mode in which the motors would calibrate. Additionally, waiting mode acted as the intermediate mode during every mode transition. The final mode was fault, which acted as a fail-safe mode. The fault mode would be activated by depressing the emergency stop button and would cause the motors to stop the chair's movement. This mode can only transition to the waiting mode and to do so the switch must be set to waiting and the emergency stop button must be unpressed. The switch is a three-point toggle switch with all assistance, effort-sensing, and waiting modes designated to each position of the switch.

The LCD screen was intended to display information about the chair such as battery level, chair speed, and effort level. Due to time constraints, the LCD board will be inactive. The buzzer will also be inactive within the housing due to the same time constraints. In addition to the components described above, the controller housing also contains the arduino mega board that controls the logic of the chair, the motor driver that acts as a medium through which the arduino communicates with the motors, the custom PCB circuit board used to connect the components to the arduino, fans acting as the system's cooling mechanism, and a voltage regulator for the fans and arduino.

In addition to the electrical components used to control the chair's motion, the electro-mechanical integration team created an adjustable mechanism to attach the controller to the chair. This mechanism is the combination of four concepts: adjustable interlocking hollow beams, a pin system to lock the sliding beams in place, a hinge for accessibility, and clamps to attach the beams to the chair. The sliding beams consisted of one beam in which the other two beams would slide into. These beams would have a spring inside to assist in adjusting the positioning of the beams. The pin system would act as the way to lock the beams into place. The initial design for this mechanism involved a small spring and rods that would compress the spring and allow the beams to slide. Through difficulties 3D printing the small rods, this rod system was replaced in the final design with a simple pin and key system in which a pin would be inserted through the beam holes to lock the beams into place and a smaller rod would be inserted into the pin to lock the pin in place. The hinge would attach to the top of the uppermost beam and would act as the mounting mechanism for the housing and allow the user to angle the screen and controls for comfort. The initial design of the clamps involved circular cups that would perfectly conform to the beams. Inspiration for the final design of the clamp came from the clamp design used in the propulsion team's motor attachment mechanism. The final design includes v groove clamps with wing head screws and barrel nuts to bind the clamps together.

5.1.3. Effort Sensing Current Prototype

The effort sensing subteam was tasked with goals relating to sensor measurement and the usage of those measurements in determining unknown forces. The three main goals included: modeling the linear acceleration and velocity profiles of the chair, determining the angle of the chair to be used in modeling gravitational forces, and measuring the force applied to the chair from the propulsion system.

The first two design goals were planned to be accomplished using a nine degree of freedom, or 9DoF sensor. This type of sensor is capable of sensor fusion of an accelerometer, a gyroscope, and a magnetometer which in combination model the three dimensional orientation of an object. Originally the intention was to place this sensor in the control module for the chair with the rest of the electronics, but this placement was not adequate for several reasons. The control module is designed to move freely which means the relative orientation of the sensor and the chair would not be fixed, and this would be difficult to account for. Additionally, the magnomemeter component of the 9DoF sensor is highly sensitive to changes in magnetic fields and this close proximity to other electronics could skew the data. To solve this problem a separate mount was designed to hold the sensor away from other possible sources of magnetic fields which would also be very stable. This mounting component, shown in figure17, was designed to be something that could be easily 3D printed while maintaining an easily latching cover so that the sensor could easily be accessed in this prototyping phase. Additionally, this component was designed so that it could be attached to the intersection of two pipes in the lower rear of the chair so that it could be clamped down in place, restricting motion in all directions.

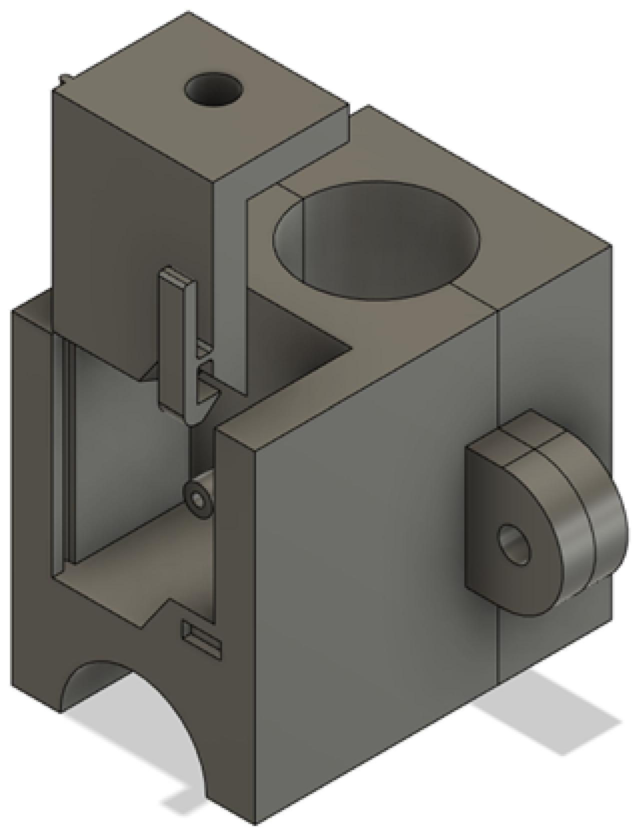


Figure 17 9DoF sensor mounting component.

This sensor seemed ideal for measuring angle as well as linear acceleration, but there were several unforeseen problems. This type of sensor is commonly used to determine orientation in space, and as such worked beautifully to measure the orientation angle of the chair while at rest. However, when any sort of linear motion was introduced the error in the measurement increases. This error was somewhat proportional to the magnitude of linear motion, but all attempts at error mitigation under the current time constraints have proved unsuccessful.

The angle data from the sensor is not completely useless, but it has its limitations within this application. The effects of gravity on the chair can still be modeled and the propulsion system can be called accordingly to make hills feel more flat. The confidence in this system just decreases when any motion occurs which can be accounted for by having the system underestimate the needed force if motion is detected. This will prevent the system from becoming unstable with motion causing more error, causing more motion and so on, but it does mean that this assistance mode will be less effective than anticipated.

While the angle measurement data could still be used, the linear acceleration and derived velocity could not be used. At first glance the data appears to be accurate. When a sudden push was applied to the chair a peak would appear in the acceleration reading which slowly damped out. However, when deriving the velocity, using a high pass filter to eliminate drift, it became much more clear that the data being collected was not accurate. When the chair began to slow down the measured velocity would start to go negative and overshoot back into positive values for several seconds even after the chair had stopped moving. Consisting of only a single energy storing element in the form of its own mass, the chair should be a first order, and visually appeared to be the case, but the 9DoF sensor was producing a plot which looked to be a heavily damped second order system. To make matters worse, if the chair happened to hit even a small bump the data would briefly become unstable and completely unusable. Despite numerous attempts to determine a solution, including increased filtering, a complete rewire, and several different coding approaches, no suitable solutions were found. At this time it has been deemed unreasonable to use a measurement of linear motion to model the interactions of the user with the chair as originally planned. However, in making improvements on this design in the future it would be desirable to further research this system and possible other sensors that could be used.

To complete the third design goal of measuring the applied force from the propulsion system, the effort sensing team decided to design a custom force measurement system using strain gauges. There were two strain gauges per rod aligned in a type II half bridge configuration used to isolate the bending strain in the rod caused by the propulsive force. Flats were milled into the propulsive rods to allow the gauges to attach fully to the bar. Similarly, strain relief was incorporated with zip tie attachments seen in the figure below.

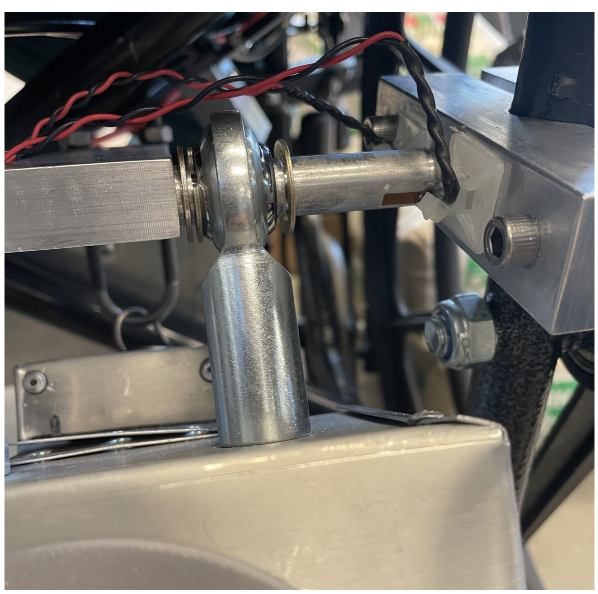


Figure 18 Strain gauge assembly attached to the propulsive rod.

An amplifier board was used to amplify the gain of the readings from the sensor and allow for processing the data. The strain gauges were calibrated using a variety of weights from approximately 0 to 7 kg. The larger threshold was tested because it was slightly larger than the maximum propulsive force of approximately 60 N. Raw readings from the sensors were collected and fitted versus mass in MATLAB to determine if the correlation was linear. Because the correlation was linear and the masses were hung on the rod at a known distance from the fixed end, a moment versus raw readings from the sensor were also calculated from the collected data. This allowed for calculation of the propulsive force. The distance of the force applied by the propulsive add-on was assumed to be approximately the distance from the fixed end to the middle of the rod.

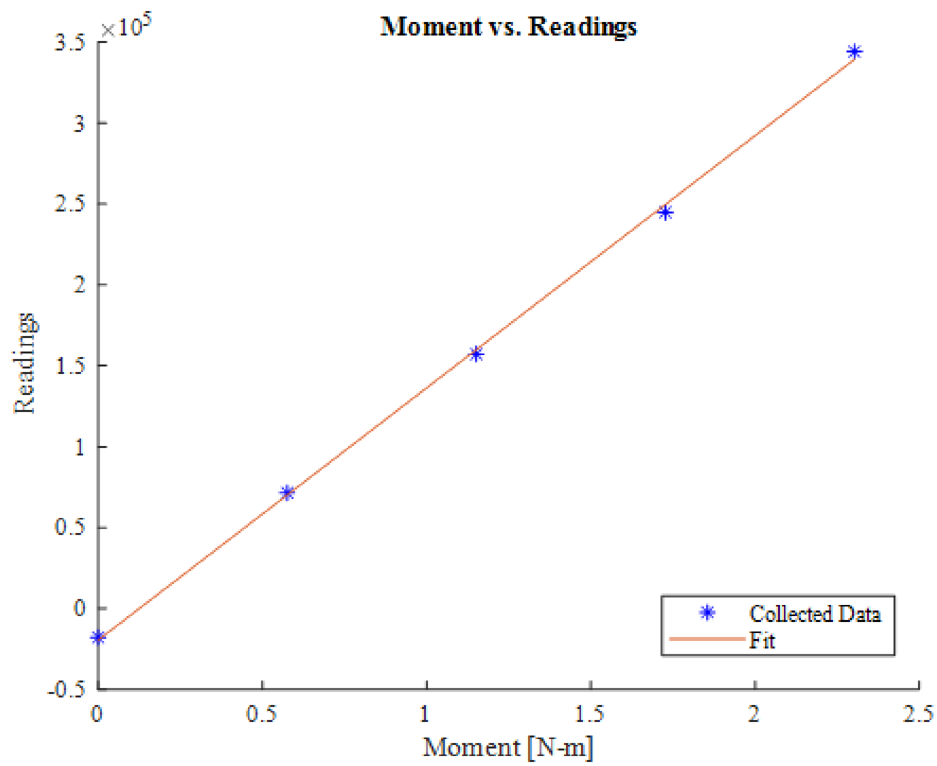


Figure 19 Correlation between moment and readings for the left strain gauge assembly.

Initially, the strain gauges were designed to be attached to the direct top and bottom of the rod; however, this didn't happen due to threading issues and the strain gauges were positioned at an angle of approximately 46 degrees off from the initially desired position. To account for this, the strain gauges were secured at this angle during testing to account for this change in angle. By doing this and experimentally determining that the change in strain gauge measurement was proportional to the angle at which the gauges were configured, both the right and left sides of the strain gauges were properly calibrated to correctly calculate the propulsive force.

In the end, the left side sub assembly had some issues and ended up breaking during integration with the full prototype assembly; however, the assembly works on the right side and theoretically could be used and just multiplied by two assuming the propulsive force on both is the same. Because of the limitations and challenges in integrating and using the 9DOF system, a full effort sensing code was never implemented, but ultimately the propulsive force was isolated.

The goal once the propulsive force and angle had been accurately isolated and calculated was to use each to power the motors as a function of those values. The angle measurement from the 9DoF sensor was used to calculate the force that would be needed to overcome gravity on an incline. Knowing the propulsive force from the strain gauge system, we could use a proportional controller coupled with overcoming gravity to provide a proper response to the user.

5.1.4. Full Assembly Current Prototype

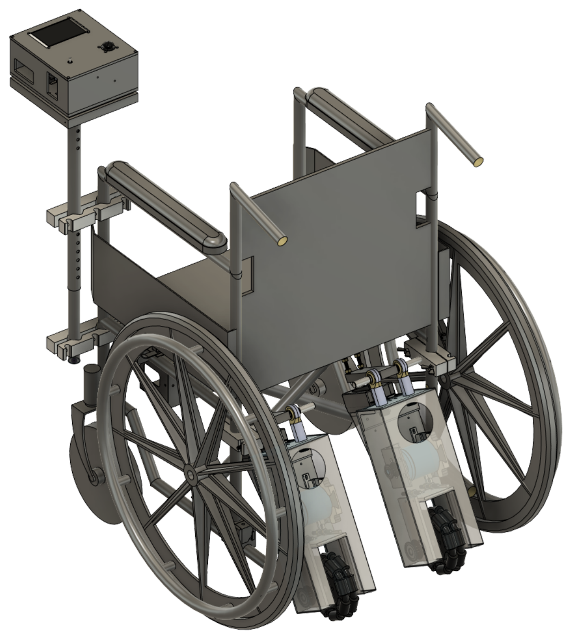


Figure 20 Full Assembly Prototype

Figure 20 shows the current fully assembled prototype where all three subteams have integrated their components to create a device that meets our design goals of allowing for forward motion, backward motion, steering, measuring the effort of the user, eliminates sudden movements, and can interface with many common wheelchairs. With all three systems integrated together, the user can interact with the chair through the controller and effort sensing subsystem to control the motion of the chair. This controller interacts with the drive train through the motor driver which transfers information from the encoders to the arduino and transfers the commands from the arduino to the motors. The system battery connects to the motor driver directly and to the arduino and fans through a voltage regulator. The wires connecting the subsystems are zip tied to the poles on the underside of the chair to prevent contact with the user and the chair's wheels. The two effort sensing sensors allow for the system to measure the effort of the user by measuring the propulsive force, and the angle of the wheelchair. The effort sensing strain gages are attached to the mounting poles of the drivetrain system. The accelerometer and strain gages interact with the arduino through the amplifier board located in the controller housing.

5.2. Completed Testing

The overall device and functionality has been tested using the following tests: static stability, propulsion force measurement accuracy, gravitational force accuracy, added weight, added width, emergency stop functionality, ability to go backwards and forwards, and ability to steer. The procedure, required equipment, safety, and results of the tests are described below. These tests conducted cover many of the different specifications described above. The static stability test is for Specification G5 (ISO 7176-1), and it will also encompass Specification P12. The propulsion force measurement accuracy test is for Specification ES2. Added weight, added width, E-stop, ability to go backwards, and ability to steer tests Specification G2, G4, E4, P10, P11 respectively. Additional information provided below pertains to the different testing apparatus that was built by the team to conduct different tests and general safety considerations.

5.3. Testing Apparatuses

______A test ramp, test dummy, and obstacles were all made over the course of the project for purposes of testing. The test ramp was used in the static stability and gravitational force accuracy tests. Another important testing apparatus was the test dummy created and used in the static stability, gravitational force accuracy, ability to go backwards, and ability to steer tests. Wood for obstacles were cut and designed for the obstacle climbing test. The obstacle climbing test was not completed so the obstacles were not used.

5.3.1. Test Ramp

The test ramp, which can be seen below in Figure 21, was built using lumber and two car jacks. This design enables the ramp's angle to be increased and decreased to desired angles. The maximum angle is around 17.58°. The test ramp was used in the static stability test, and gravitational force accuracy test. This would be useful in other testing as well because of the adjustable angle.

Figure 21 Adjustable test ramp with test dummy and wheelchair on ramp

5.3.2. Test Dummy

An important testing apparatus was a test dummy. The test dummy was made out of about 180 lbs of sand packed into clothing to create a model roughly the size, weight and shape of a person sitting in the wheelchair. It was intended for the test dummy to be 198 lbs to model the average weight of an american male, but the physical construction limited this. The current weight is around 180 lbs which was deemed to be a useful weight for the dummy. The test dummy was used in the static stability, and gravitational force accuracy. Overall the test dummy was very useful in testing and maintaining the safety of everyone by not having to test with a person in the wheelchair.

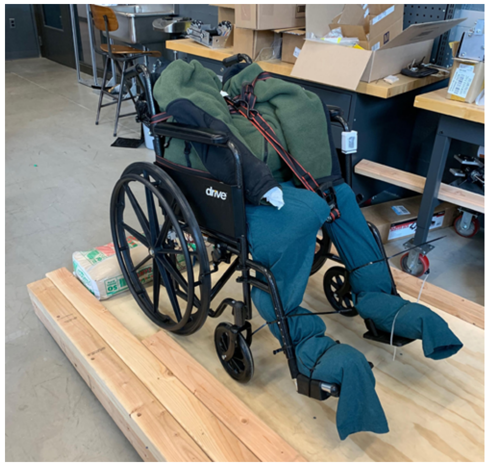


Figure 22 Test dummy sitting in the wheelchair

5.3.3. Obstacles

______An obstacle climbing test was planned to be conducted. This test was in accordance with ISO 7176-10 and would test Specifications G8 and P8. The test procedure called for obstacles the wheelchair and device would approach and attempt to overcome in increasing heights. To achieve this, wood was cut and intended to increase in 0.75 in intervals until reaching 6 in which is the standard height of a curb [7]. Additionally 300 lbs of sand was acquired to secure the obstacles when the wheelchair was approaching the obstacle. While this test was not attempted, the procedure, and materials are ready to be used to test the obstacle climbing capabilities.

5.4. General Safety Considerations

There are general safety precautions and considerations that are consistent throughout the various testing that were performed. They include safety concerns involving the use of the test dummy, the wheelchair, and the use of the ramp and its components.

When using the test dummy, there is a concern that the test dummy will fall out of the wheelchair and possibly impact something or someone. To mitigate concerns, the dummy was properly secured in the wheelchair with zip ties and ratchet straps. This prevented the test dummy from falling out of the wheelchair or moving from the desired position. Additionally, all people running or viewing the test were out of the way of the wheelchair and test dummy when possible.

The wheelchair and the device also posed a safety concern. Concerns included the risk of the device and wheelchair slipping, tipping, or falling and injuring someone or causing damage to the test ramp, or other testing equipment. This was increased anytime that the device was running. For these reasons, it was important to keep the people running the test and people viewing the experiment away from the experiment whenever possible.

The next concern involved potential instability using the car jack to raise and lower the ramp. To avoid these issues, Nicole Stanec and Charlotte Sullivan were provided safety training by Nick Moosic on how to operate the apparatus. Having this training mitigated safety concerns.

Generally, safety checks of the wheelchair, device and ramp were done before testing was conducted. This included safety checks of the electrical components, the test dummy security, and ramp stability. This helped mitigate any mechanical or electrical failures during testing and kept participants, testers, and spectators safe.

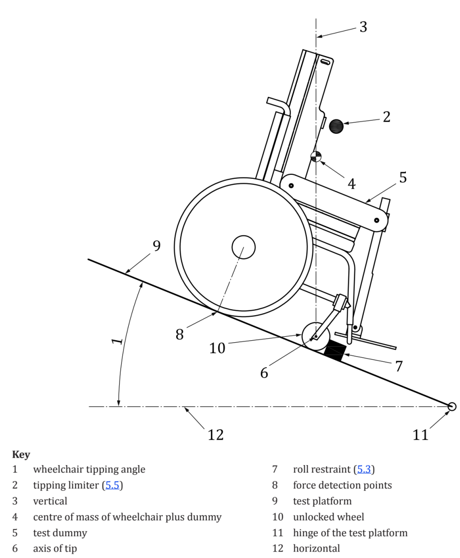
5.5. Static Stability Test

5.5.1. Goal of Test

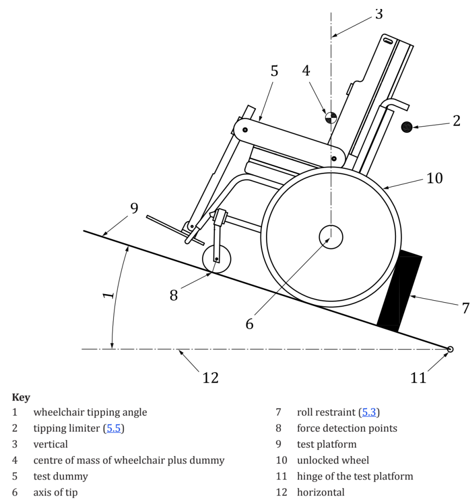
The goal of the static stability test is to ensure stability of the wheelchair with the add-on on a ramp under varying inclination conditions. This test procedure is given by ISO standard 7176-1 referring to Specification P3 [Section 4] [14]. This test will test for Specification G5 and P12 [Section 4].

5.5.2. Procedure

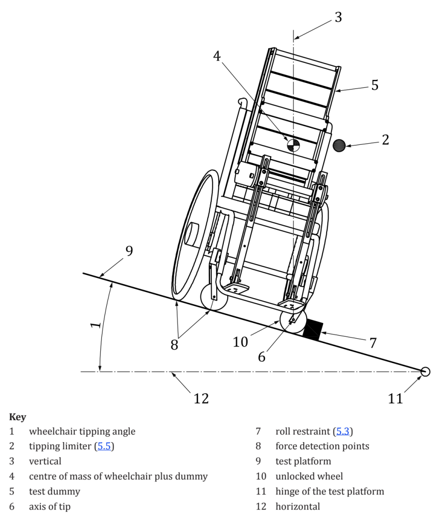
1. Prepare ramp for testing by positioning the ramp to the lowest angle using the car jack.
2. Place the wheelchair on the test ramp. The test should be repeated 3 times for a forward (*Figure 24a*), backward (*Figure 24b*) and lateral orientation (*Figure 24c*). The following diagrams depict the orientation for the three different orientations:



a. Forward



b. Backward



c. Lateral

Figure *24.* ISO diagrams for three different wheelchair positionings [2].

3. Place the roll restraints in front of the wheels located closest to the bottom of the ramp.
4. Position dummy in wheelchair at specified location according to center of mass positioning requirements.
5. Secure the test dummy using ratchet straps to the rail of test ramp to secure wheelchair in case of tipping
6. Increase the angle of the platform by cranking the car jack until wheelchair tips. Record this angle to the nearest degree.
7. Lower the test platform using the crank on the car jack until it is in its lowest position.
8. Repeat steps 2-7 to ensure the wheelchair and add-on are tested with the three different orientations. Reference *Figures 1a, 1b,* and *1c*

5.5.3. <u>Required Equipment</u>

- Adjustable Ramp
  - Car jack and mating attachment for raising and lowering the ramp

    - Ramp
- Test Dummy (eg. a bag of sand)
- Ratchet Straps
- Roll Restraints
    - Roll restraint surfaces that contact a wheel shall be perpendicular to the test plane. The height of the roll restraint shall be sufficiently large to prevent rolling of the wheels during testing
    - For specific orientations, reference *Figures 1a, 1b,* and *1c*.
    - Sandbags were used as roll restraints
- Angle Measurement Device
    - Tape measure and trigonometry was used to determine the angle

5.5.4. <u>Safety</u>

We were concerned with the instability of the roll restraints. However, the sandbags worked well to restrain the wheelchair. Clearing the area surrounding the ramp was important for bystander safety. We wanted to ensure that no one gets injured by the wheelchair or any of the setup. We only had experienced individuals touching the equipment and kept bystanders away during testing. The trained individuals remained at the top of the ramp before and during the test.

5.5.5. <u>Results</u>

The results of the static stability test showed that the addition of the device did not pose a threat to the static stability of the wheelchair. As shown in Table 7 the angle at which the wheelchair would tip with the device attached is greater than 17.58° for all orientations. This occurred because the wheelchair did not tip in any orientation at the maximum angle the adjustable ramp can achieve. An angle of 17.58° is a very large incline especially for a roadway and is not expected to be found regularly. This can be seen in the figures below of the different orientations of the wheelchair at the maximum angle of the ramp. 17.58° is 31.7% grade which is larger than the safely transferable grade incline of 8.5% specified in Specification P3. This means that the device should not pose an additional risk of tipping in the majority of uses.

Table 7 Results of the Static Stability Test

Orientation	Angle (deg)
Forward	> 17.58
Backward	> 17.58
Lateral	> 17.58

a. b. c.

Figures 25a 25b &25c Static Stability test at maximum angle in the backwards (a), forwards (b) and lateral (c) orientations

5.6. Propulsion Force Measurement Accuracy

5.6.1. Goal of Test

The goal of this test is to determine if the propulsion force measurement using the strain gauge measurement apparatus is within the percent error stated in the specification report. Similarly, this will also ensure the horizontal propulsive force, applied by the propulsion subsystem, is being properly isolated by the measurement system. This test will test for Specification ES2 [Appendix A].

5.6.2. Procedure

1. Attach the strain gauge measurement system attachment to the apparatus shown in figure _ at the specified angle from table 8 (use trig to ensure proper angle). Use bolts to screw it into place or clamps as necessary (depending on the angle).
2. Turn on the strain gauge measurement system by booking up the arduino to the computer.
3. Hang the weighted hanger on the rod. Record the strain gauge reading output by the subsystem.
4. Increase the mass at this angle by adding approximately a 0.5 kg weight to the hanger. Repeat this step for all of the mass requirements listed in the table per angle. The mass should have a minimum of approximately 0.5 kg up to 2kg in increments of 0.5 kg.
5. Repeat steps 3 and 4 for the different angles of the rod specified in the table below

Table 8 Specification angles of the propulsive rod and weights for testing.

Angle of the Rod (θ_1) [degrees]	Minimum Weight Applied [kg] (+/- 0.005 kg)	Increments of Added Weight [kg] (+/- 0.005 kg)	Maximum Weight Applied [kg] (+/- 0.005 kg)
0 (strain gauges parallel with the top of the plate, bottom gauge on top)	0.5	0.5	2
14.50	0.5	0.5	2
26.20	0.5	0.5	2

46.57	0.5	0.5	2
180 (strain gauges parallel with the top of the plate, top gauge on top)	0.5	0.5	2

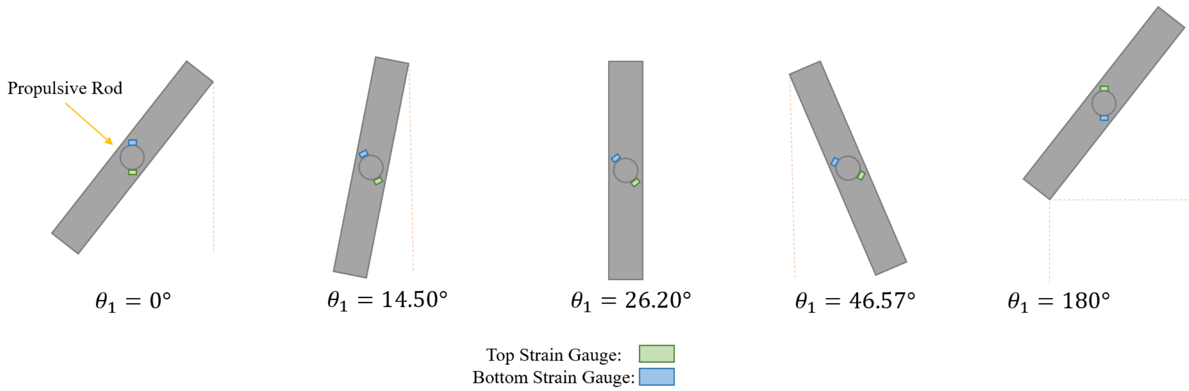


Figure 26 Orientation of the rod corresponding to the specification angles in the testing table.

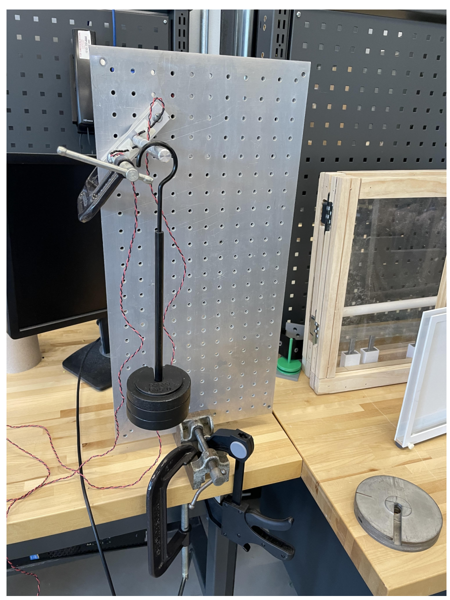


Figure 27 Experimental apparatus and set up used for calibrating and testing strain gauges.

5.6.3. Required Equipment

- Weights and a hanger
- Vice
- Clamps
- Bolts
- Aluminum sheet with holes big enough for bolts to secure the subassembly in place

5.6.4. Safety

Overall, this test does not have extreme safety concerns. The biggest safety concern was the usage of the heavy weights. To further mitigate risk they were handled with care and the applied weight did not exceed 2 kg.

5.6.5. Results

The linear relationship between mass and readings and similarly moment and readings were found using these tests and were linear. This linear relationship was used in the arduino code to calibrate the readings produced by the sensor and properly determine the force. When calibrated, the mass readings were accurate at approximately +/- 0.2 kg which meets the specification goals. Also, it was determined as angle changed, the readings changed proportionally based on the angle as seen in the figure below.

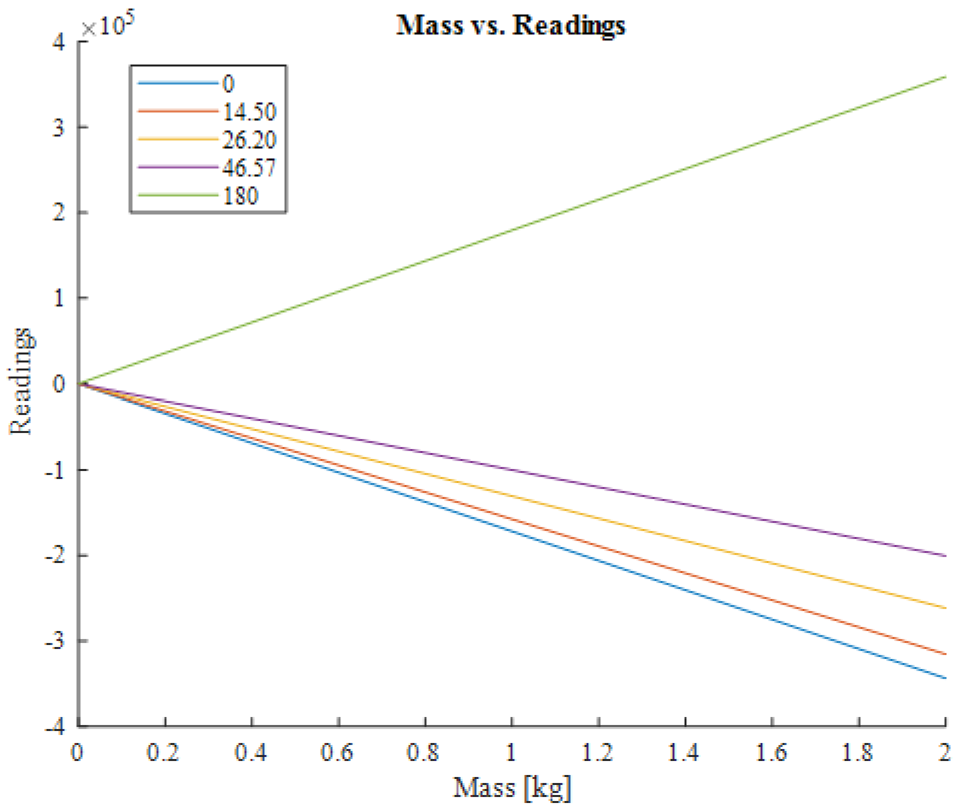


Figure 28 Mass versus readings for the different angles (normalized to all start at 0).

5.7. Gravitational Force Accuracy

The goal of this test was to determine the accuracy of the 9DoF sensor in calculating the applied force needed to counter the effects of gravity while the chair is at an angle. To accomplish this a test code was run with the 9DoF sensor which used the measured angle and the mass of the chair to calculate the force of gravity pulling the chair down the ramp. With this code running, the chair with the test dummy was placed on the test ramp at a set angle. A spring scale was then attached to the front of the chair and used to hold the chair in place thereby measuring the force needed to counter the force of gravity at that angle in newtons. This value was then compared to the value produced by the 9DoF sensor and the test code. This test was repeated for several angles to ensure consistent results. It was found that the test code was capable of calculating the force needed to counter gravity within the goal of 10N of maximum error.

5.8. Weight

The goal of this test is to weigh all of the added material to the wheelchair to see if the added weight of the device exceeds the max value of Specification G2. To accomplish this all components of the device including the propulsion, electro-mechanical, and effort sensing systems were weighed using a scale. The weight of all components is 30.5 lbs. This exceeds the 25 lb limit set by Specification G2. This means that modifications that would cut down on weight should be considered in further prototyping. As shown in Table 9 below, the propulsion system, which includes the transmission and battery assembly together exceed Specification G2. The effort sensing system was not included in testing because the weight of them is insignificant compared to the other components.

Table 9 Added weight of different components in the device

Component	Weight
Transmission Assembly	19 lbs
Battery Assembly	7.8 lbs
User Interface	3.7 lbs

5.9. Added Width

The goal of this test was to measure the overall added width of the device while it is attached to the wheelchair to make sure that the overall added width does not exceed the max value of Specification G4. All parts of the device were attached to the wheelchair and then the outermost protruding part of the device was measured and recorded.The user interface is the only component that exceeds the original profile of the wheelchair. The added width of the user interface is 3 in. This is under the maximum value set by Specification G4 of 4 in.

5.10. E-Stop

______The goal of this test was to ensure that the emergency stop would immediately stop the motors. This was performed during testing when the system was in the all assistance mode. The motors were running at full speed when the emergency stop button was pressed. The motors immediately stopped when the button was pressed and put the system into a Fault mode where nothing could be done until the button was un-pressed, confirming that the E-stop does work how it was intended. When the button was un-pressed, the toggle switch had to be switched back into the waiting state before the user could run the motors again in either all assistance or effort sensing mode.

5.11. Ability to Go Backwards

The goal of this test was to ensure that the wheelchair would be able to go backwards when the motors were in use. This test was conducted by putting the system into all assistance mode and having the motors run at full speed. Once the motors were running, we pulled down on the joystick, which would be towards the user. When we did this and pushed the wheelchair slightly to overcome static friction, the wheels propelled the chair backwards. Both wheels were at the same speed and same direction. When not attached to the wheelchair, there was no push required to overcome static friction. When the test dummy was in the wheelchair and the same test was run attached to the wheelchair, the only way that the wheelchair was able to go backwards was if there was slight assistance. Someone had to push the wheelchair in order to overcome static friction. Once the wheelchair started to move via assistance, the joystick was able to control the motors and have the wheelchair go backwards when the joystick was pulled towards the user. We believe that if the wheelchair had less weight, this would work that same as having a push-start.

5.12. Ability to Steer

The goal of this test was to ensure that the wheelchair would be able to change directions when the motors were in use. This test was conducted by putting the system into all assistance mode and having the motors run at full speed. Once the motors were running, we moved the joystick in four different directions. When moved to the left or right of the center, the wheels went in the opposite direction of one another. When the joystick was pushed to the right, the left motor went forwards and the right motor went backwards. When the joystick was pushed to the left, the opposite happened. Furthermore, when the joystick was pushed forwards indicating forwards, the wheels went in the same direction as when the system went into the all assistance mode. When the joystick was pulled down, indicating the wheelchair was supposed to go backwards, both the right and left wheels changed directions. When the test dummy was put in the wheelchair, this was not the case. The wheelchair was not able to overcome the static friction without assistance, so because of this, the wheelchair does not have the ability to steer. If there was less weight on the wheelchair, this might have solved the issue.

6. Further Testing and Design Modifications

While progress has been made there are design modifications and further testing that would improve the functionality of the entire device. This is described at a subteam level below for what each subteam would like to see improved if there was more time or an additional prototype. Further testing includes tests that were planned to be completed initially but based on timelines and safety considerations were not completed during the project timeline.

6.1. Subteam Design Modifications

6.1.1. Propulsion Team Design Modifications

The propulsion system overall performed well and a considerable amount of thought and design went into creating a successful first prototype. Despite the effort, there are improvements that would have improved the overall design and functionality of the device.

The main issue with the transmission and the transmission housing is that the design is flipped for the left and right housing, which was chosen because the design is not symmetrical. The wheel is not completely centered on the shaft, so to make sure we go straight, it was chosen to have the two different housings as mirrors of each other. This added extra difficulty for the EMI team when coding the motors because the two motors were different orientations. By making the design symmetrical, this would have cut out the extra difficulty added for coding the motors. Another issue with the design of the transmission, is the slots in the motor plate allowed for a tight fit for the belt on one of the transmission assemblies, but not as tight of one for the other. In another iteration, the slots would be designed to be larger to allow for more room to shift the motor forward and backward.

Installing the device is quite difficult for the user, which limits accessibility. To install the device themselves, the user would need to get out of the wheelchair. The attachment rods that link the transmission to the chair require tools to install in order to ensure that the grip is tight enough to fix the transmission housing to the wheelchair and prevent it from rotating around the tubing. Originally, wing nuts that could be tightened by hand were used instead of the bolts to attach the v-blocks to the wheelchair (Figure 29). Though this may have been easier for the user to install, it did not create a tight enough grip on the tubing to cause the transmission to push the wheelchair. A solution that would be easier for the user to install without tools without sacrificing the strength of the attachment grip would need to be developed.

Figure 29 : Wing nuts used in an older design iteration that could be tightened by hand but did not provide enough force to fix the attachment.

Installation is also difficult currently because the spring has to be extended to be installed. This would most likely be difficult for many of the devices intended users as many might have limited mobility or upper body strength. For this reason, a redesign of the spring should be considered especially when considering multiple installations. A device that aids in the extension of the spring may be useful or a weaker spring may mitigate some of the difficulty. Additionally having the spring as an optional piece may be wanted by some users. This might be wanted because of the decrease of difficulty of installation and the ability to overcome obstacles of greater height than 6 inches. The spring allows the device to stop and go backwards on some declines/inclines but does not prevent the device from stopping or going backwards on all inclines. The device should maintain a normal force on level ground when going backwards and up to a 5% grade based on spring calculations. Further testing would show if these calculations were correct. Another solution would be to change the implementation of what creates the normal force. This might include leaf springs or other configurations of extension springs or torsion springs.

Using bent aluminum proved to be difficult to manufacture and make consistently. As shown in the figure below (Figure 30) there are some differences and alignment issues of using aluminum for the spring housing. This occurred because of the complexity of the sheet metal design and the size being quite small. While the aluminum makes the device consistent with the aluminum transmission housing and makes for a fairly weather resistant design, this inconsistency in housings is concerning. To improve this, it may prove to be more effective to 3D print the spring housings as they are a safety addition not a structural addition so they do not need the strength of the aluminum. Waterproofing 3D printed housing would keep the housings consistent and repeatable which would be great for manufacturing.

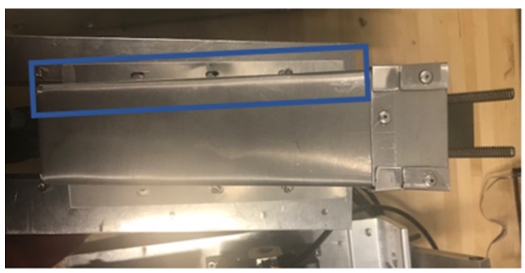


Figure 30: Spring Housing not aligning with tapped holes on base plate due to imperfect bending and complexity of design

The torque transmitter works well but it could be improved. This could happen through better aligning the holes of the transmitter ensuring that they align with the holes of the wheel. The wheel works well but further testing might have shown that the wheel could not withstand the constant loading of the device. If this was shown to happen, manufacturing our own omni-directional wheel out of a stronger material could improve the overall performance.

The battery and the battery housing have complications with the design of the housing, and the chosen battery. The chosen battery is lithium ion, 48V, 10 amp-hour, and 5.2 lb. According to the Federal Aviation Administration, FAA, lithium ion batteries can be carried on a plane if they are under 100 watt hours [17]. Our battery is 480 watt hours, which means the current battery cannot be carried onto an airplane. In order to fix this problem, a method of hot swapping could be used with smaller amp-hour batteries. By using five 48V, 2 amp-hour batteries, the batteries would be allowed on a plane, and still allow for the same desired range, 1.5 miles with no user assistance (Specification P1). There were difficulties with finding a way to clamp the housing to the frame of the wheelchair. Currently, it swings when the wheelchair is moving. If given more time, a new clamping mechanism would have been designed. The current housing also has a side that is not secured to any other side, which means it opens similar to a door. While this does allow for the battery to easily be removed from the housing, it could prove problematic if the battery moves too much. If given more time, a mechanism to secure this, while also allowing for the battery to easily be removed would also be designed.

The weight of the propulsion system is quite heavy. Weighing 26.8 lbs total exceeds Specification G2 putting a limit at 25 lbs of additional weight. To cut down on weight the spring attachment bar may be made out of different lighter material or some of the bar be cut out because it is currently a solid block of aluminum which is quite heavy. The use of different materials may generally cut down on weight and the use of plastic for non structural pieces such as the housings may cut down on some of the weight of the device. Also, by making the adjustment described above about the battery, the weight of the battery can significantly be reduced, which will reduce the overall weight of the propulsion assembly.

6.1.2. Electro-Mechanical Design Modifications

Modifications to the current design would involve waterproofing the electrical components. We were able to waterproof the housing using a clear sealant spray, but the electronic components were not a priority. The wheelchair is ideally going to be in use in various weather conditions, so making sure the components are protected is important. Environmental conditions such as rain or snow can be an example of aspects that we want to protect against. There is a chance for water to seep through the holes where the LCD screen is, where the joystick is, and where the switch is. To prevent damage to these components as well as other electrical components inside of the interface housing box, we would want to get a protective covering for all the components. We have considered using epoxy, silicone, and fluoropolymer as waterproofing options.

There could also be modifications to the housing, including the size and materials used. The interface housing box is about 6.5 inches wide by about 7 inches long, so trying to minimize this would be ideal. A measurement of the current box can be found in Figure 31. We could create shelves for the various electronic components to sit on so the box could be shortened in both length and width. The material can also be switched from 3D printed material to aluminum sheet metal. This may help with reducing the overall weight of the box, although it may increase costs. That is something that needs to be considered when designing and budgeting for the interface.

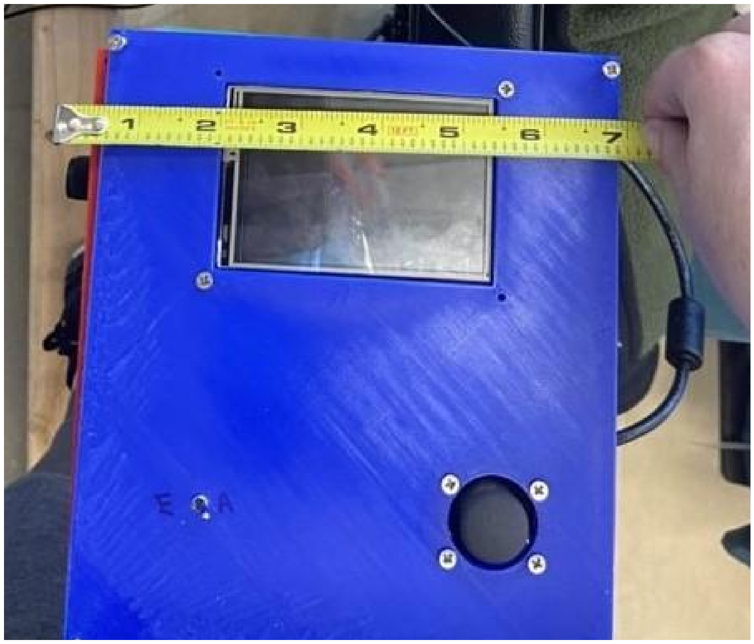


Figure 31. Current interface housing width

Furthermore, the spring rod attachment needs to be modified in the sense that the rods need to be re-drilled. The holes are not aligned directly across from each other, which has caused issues when trying to insert the pins into the system. We used zip-ties to secure the rods to the wheelchair and to the hinge, but this does not allow the spring-rod attachment to be adjustable. An image of this can be seen below in Figure 32. The user cannot raise or lower the interface, which was not ideal. By creating new holes in the rods, we could have the user adjust the height of the interface rather than only having it at one height.

Figure 32. Spring rod attachments connected using zip ties

Another modification would be to the code, allowing the user to have a working LCD screen to see various aspects of the wheelchair add-on features and an indication of if the battery needs to be charged. The LCD would ideally show the user the battery level, the mode the user is in, the speed the user is going, and if the emergency stop button is activated or not. An example of this can be found in Figure 33. Having a working LCD screen will allow the user to to identify important aspects of the wheelchair add-ons and make them aware of important information. The noise to indicate that the battery level is low and needs to be charged is important so the user does not try to use the motors and they do not run. This will prevent frustration and allow the user to plan how they can use their wheelchair and if it will run how they want it to, when they want it to.

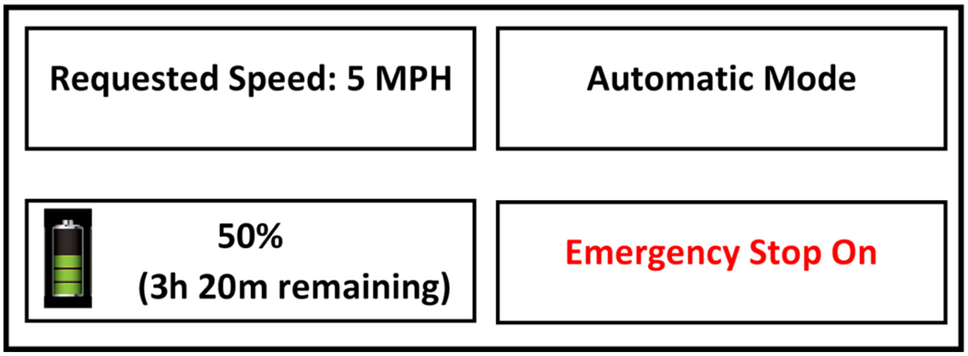


Figure 33. An example of the LCD display that would be located on housing interface

Finally, modification to the circuit board should be made as well. We did not include the voltage regulator on the final version of the customized circuit board, making use of a separate circuit board wrapped in tape for this, shown in Figure 34. For the next prototype development, a voltage regulator should be included to simplify the electrical components and wiring that is inside of the box. Simplifying the amount of wires and electrical components is desired and would be a simple modification in later versions.

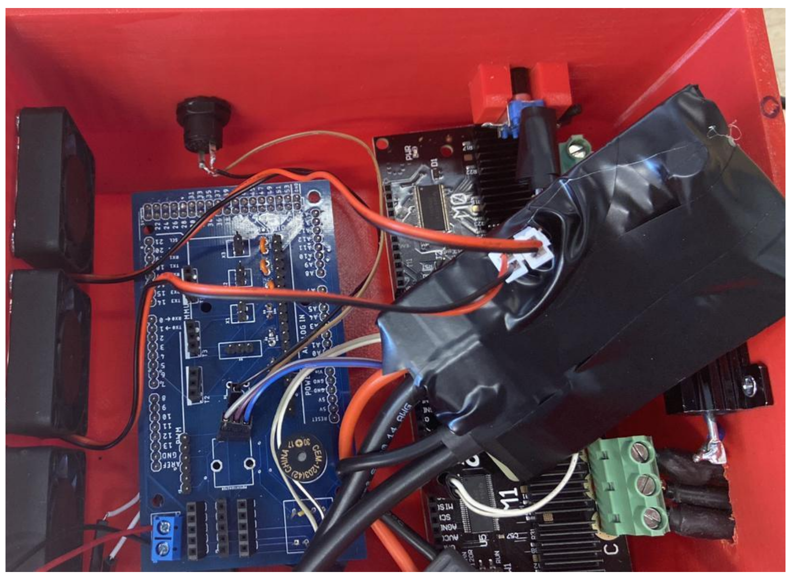


Figure 34. Fans into voltage regulator on separate circuit board

6.1.3. Effort Sensing Design Modifications

In terms of general improvements for both of the measurement systems, in the future ideally the electrical components would be waterproofed. For the strain gauge subassembly, ideally smaller strain gauges would be used to allow for a smaller area to be milled out of the rods for their attachment so a type II full bridge configured could be used to increase accuracy and sensitivity. Lastly, an improved strain relief strategy would be implemented to prevent the strain gauges from breaking easily.

Ideally for the measurement of linear motion a better system could be implemented to allow for the effort sensing functionality as originally planned. This could mean improvements to the code implemented or the use of different sensor options. Additionally, steps should ideally be taken to reduce the error in the angle measurements taken while the chair is in motion. Lastly, in terms of improvements surrounding the 9DoF sensor, a redesign of the mounting system would be beneficial. At the moment the sensor is mounted in a hard to reach location and would be difficult for a user to install. Determining a better placement option is important for future iterations of the chair.

6.2. Further Testing

Testing beyond what is described in Section 5 was planned but not performed. This includes obstacle climbing, brake effectiveness, and user input measurement accuracy. Obstacle climbing and brake effectiveness were not tested because of time constraints as well as the threat of the test causing damage to the current prototype. The user input measurement accuracy test was not tested because of issues with the 9DOF sensor which is described further above. The test plans for the obstacle climbing and brake effectiveness were developed and can be found in Appendix D. The user input measurement accuracy test plan would need to be further developed to be adequately tested.

Obstacle climbing would have tested the ability to overcome curbs and other inconsistencies in the road. Obstacle climbing followed the procedures of ISO 7176-10 [16]. This test would have tested Specification G8 and P8. The test plan included an increase in test obstacle size starting at 0.75 in and ending at 6 in. The results of this may have changed the spring design to a weaker spring if it was deemed too difficult to use over curbs and bumps. Preparations for this test were made including the testing procedure and apparatus being prepared.

An additional test that was planned but not performed was the brake effectiveness test. This test followed ISO 7176-3 requirements [15]. The brake effectiveness test would have determined whether Specifications G7, P3, P4, P5, P6, P7, and P9 were met. The results of this test could have changed a lot about the prototype. Depending on the results the spring, and motor/transmission may have been changed. The spring may have been changed to either increase or decrease the braking capabilities of the device. Balancing the results of the obstacle climbing and braking test to consider utility and users needs may have been difficult. The motor/transmission may have been changed as a result of this test to increase or decrease the speed of the device.

7. Final Budget

The current cost of the prototype is approximately $1,975.22. This was calculated to include the cost of extra material including screws and scrap metal. This satisfies Specification G1 by staying below $2500, but we would still like to continue to work to minimize the cost without sacrificing functionality or safety. The bill of materials for the prototype is shown in Table 10.

Table 10: Prototype Bill of Materials

Subteam	Vendor	Item	Unit Cost	Quantity	Total Cost
Effort	AdaFruit Industries	Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout - BNO055 - STEMMA QT / Qwiic	$19.95	2	$39.90
	SparkFun	SparkFun Load Cell Amplifier - HX711	$9.95	1	$9.95
	SparkFun	Wire Wrap Wire - Blue	$14.95	1	$14.95
	Digikey Electronics	Vishay Dale Through Hole Resistor	$0.59	6	$3.56
EMI	sparkfun	Mini Speaker - PC Mount 12mm 2.048kHz	$1.95	1	$1.95
	sparkfun	Arduino Mega 2560 R3	$38.95	1	$38.95
	sparkfun	Toggle Switch - 125 VAC	$2.95	1	$2.95
	sparkfun	GTE Knob - Small	$0.95	1	$0.95
	sparkfun	Ribbon Cable - 10 wire (15ft)	$4.95	1	$4.95
	sparkfun	Rotary Potentiometer - Linear (10k ohm)	$0.95	1	$0.95
	adafruit	3.5" TFT 320x480 + Touchscreen Breakout Board w/MicroSD Socket - HXD8357D	$39.95	1	$39.95
	Mcmaster	Compression Spring Stock 36" Long, 0.75" OD, 0.59" ID	$4.69	1	$4.69
	Mcmaster	Compression Spring 0.75" Long, 0.24" OD, 0.196" ID	$10.84	1	$10.84
	sparkfun	Screw Terminal	$0.95	1	$0.95
	sparkfun	10K Ohm Resistor	$1.20	1	$1.20
	JLC PCB	Circuit Board	$1.28	1	$1.28
	Amazon	SPST Latching Pushbutton Switch	$7.81	1	$7.81
	Amazon	40mmx40mm mini fans (6 pack)	$10.99	1	$10.99
	Amazon	40mmx40mm mini fan cages (20 cages in a pack)	$10.99	1	$10.99
	McMaster	General Purpose Aluminum Tubing 1" OD, 0.058"	$22.32	1	$22.32
	McMaster	General Purpose Aluminum Tubing 7/8" OD, 0.035"	$12.25	1	$12.25

	McMaster	18-8 Stainless Steel Phillips Flat Head Screw- 5/8" long	$5.17	1	$5.17
	McMaster	Multipurpose Aluminum disk- 4"dia , 1/2"	$8.30	1	$8.30
	Amazon	PLA Spool, blue	$27.93	1	$27.93
	Amazon	PLA Spool, black	$22.99	1	$22.99
	Amazon	Waterproofing Spray	$15.19	1	$15.19
	Amazon	Elegoo EL-CP-004 120pcs Multicolored Dupont Wire 40pin Male to Female, 40pin Male to Male, 40pin Female to Female Breadboard Jumper Wires Ribbon Cables Kit for arduino	$6.98	1	$6.98
	Amazon	Todiys New 12Pcs for P55NF06 P55NF06L STP55NF06 50A 60V to-220 N-Channel Power Mosfet Transistors STP55NF06L	$9.95	1	$9.95
	Amazon	Electrical Wire 10 AWG 10 Gauge Silicone Wire Hook Up Wire Cables 20 Feet	$15.38	1	$15.38
	McMaster	Rubber Slip-on Feet	$6.40	1	$6.40
	McMaster	Stainless Steel Wing-Head Thumb Screw	$10.68	6	$64.08
	McMaster	Dowel Nuts for Wood	$7.86	1	$7.86
	Digikey Electronics	Voltage Regulator IC REG LIN POS ADJ 1.5A TO39-3	$25.68	1	$25.68
	Amazon	Magliner 130502 Rotacaster Double Row Multi-Directional Wheels	$24.99	2	$49.98
Propulsion	ODrive Robotics	Dual Shaft Motor - D6374 150KV	$99.00	2	$198.00
	ODrive Robotics	8192 CPR Encoder with Cable	$39.00	2	$78.00
	ODrive Robotics	ODrive V3.6 56V with connectors	$159.00	1	$159.00
	SDP/SI	Timing Pulley: 20 teeth	$13.31	2	$26.62
	SDP/SI	Timing Pulley: 14 teeth	$10.30	2	$20.60
	SDP/SI	15.8 in Belt	$7.01	2	$14.02
	McMaster	Stainless Steel Ball Bearing	$19.83	4	$79.32

	McMaster	Stainless Steel Rotary Shaft - 1/2" Diameter, 12" long	$27.22	1	$27.22
	McMaster	Domed Head Sealing Blind Rivet with Plastic Seal	$9.75	1	$9.75
	McMaster	Corrosion-Resistant 316 Stainless Steel Socket Head Screw	$7.67	5	$38.35
	McMaster	Multipurpose 6061 Aluminum 90 Degree Angle	$19.35	1	$19.35
	McMaster	18-8 Stainless Steel Socket Head Screw	$6.82	1	$6.82
	McMaster	Corrosion Resistant 3003 Aluminum Sheet (.190" thick)	$52.27	1	$52.27
	McMaster	Easy to Weld 5052 Aluminum Sheet (.032" thick)	$31.95	1	$31.95
	McMaster	Oversized Multipurpose 6061 Aluminum Sheet (0.250" thick)	$26.29	1	$26.29
	McMaster	18-8 Stainless Steel Socket Head Screw M4 x .7, 8mm	$6.78	1	$6.78
	McMaster	18-8 Stainless Steel Socket Head Screw M3 x .5, 8mm	$4.52	1	$4.52
	McMaster	Side-Mount External Retaining Rings	$12.37	1	$12.37
	McMaster	316 Stainless Steel Woodruff Key	$12.65	1	$12.65
	McMaster	Super-Corrosion-Resistant 316 Stainless Steel Socket Head Screw 4-40 Thread Size, 1/2" Long	$6.61	1	$6.61
	McMaster	Super-Corrosion-Resistant 316 Stainless Steel Socket Head Screw 2-56 Thread Size, 1/2" Long	$3.79	2	$7.58
	McMaster	Ball Joint Rod End, 1/2"-20 Thread Shank Trad Direction Right Hand	$7.08	4	$28.32
	McMaster	18-8 Stainless Steel Socket Head Screw 1/2"-20 Thread Size, 1-1/4" Long	$8.71	1	$8.71
	McMaster	316 Stainless Steel Male-Female Threaded Hex Standoff	$3.13	10	$31.30
	McMaster	Passivated 18-8 Stainless Steel Phillips Flat Head Screw - 7/8" long	$5.27	1	$5.27

	McMaster	Passivated 18-8 Stainless Steel Phillips Flat Head Screw - 1" long	$6.33	1	$6.33
	McMaster	Dowel Nuts for Wood, 1/4"-20 Size, 0.472" Long	$6.83	1	$6.83
	McMaster	Domed Head Sealing Blind Rivet with Plastic Seal	$9.75	4	$39.00
	McMaster	10 mm bushing	$16.93	1	$16.93
	McMaster	18-8 Stainless Steel Cup-Point Set Screw 8-32 Thread, 7/8" Long	$6.97	1	$6.97
	McMaster	18-8 Stainless Steel Socket Head Screw 1/4"-20 Thread Size, 3/4" Long	$10.87	1	$10.87
	McMaster	Mortise-Mount Hinge with Holes	$1.57	3	$4.71
	McMaster	Zinc-Plated Steel Corner Bracket , 7/8" x 7/8" x 5/8"	$0.43	16	$6.88
	Amazon	48 V 10 AH lithium ion Battery pack	$199.00	1	$199.00
	McMaster	18-8 Stainless Steel Pan Head Screw - 8/32 - 7/16" Length	$6.06	1	$6.06
	McMaster	Steel U-Bolt 1/4"-20 Thread Size, 1-3/8" ID	$5.60	1	$5.60
	McMaster	Steel U-Bolt 1/4"-20 Thread Size, 7/8" ID	$5.00	1	$5.00
	McMaster	Bronze Sleeve Bearing	$2.77	2	$5.54
	McMaster	18-8 Stainless Steel Hex Nut 1/4"-20 Thread Size	$3.87	1	$3.87
	McMaster	18-8 Stainless Steel Socket Head Screw 1/4"-20 Thread Size, 1-1/2" Long, Partially Threaded	$9.22	1	$9.22
	McMaster	Multipurpose 6061 Aluminum 5/8" Thick x 1-1/2" Wide	$8.89	1	$8.89
	McMaster	Multipurpose 6061 Aluminum 0.063" Thick 4x24"	$11.01	3	$33.03
	McMaster	Zinc-plated steel corner bracket 7/8" x 7/8" x 5/8"	$0.43	4	$1.72
	McMaster	Aluminum loop clamp 1-3/8" ID 2-18/" long	$5.34	1	$5.34

	McMaster	18-8 Stainless Steel Socket Head Screw 10-32 Thread Size, 1-3/4" Long	$10.51	1	$10.51
	McMaster	18-8 Stainless Steel Hex Nut 10-32 Thread Size	$3.49	1	$3.49
	McMaster	316 Stainless Steel Ring Shim 0.02" Thick, 1/4" ID	$4.97	1	$4.97
	McMaster	316 Stainless Steel Ring Shim 0.016" Thick, 1/4" ID	$5.96	1	$5.96
	McMaster	316 Stainless Steel Ring Shim 0.001" Thick, 1/4" ID	$12.61	1	$12.61
	McMaster	Extension Spring with Loop Ends 7" Long, 1" OD, 0.125" Wire Diameter	$9.87	1	$9.87
	McMaster	Passivated 18-8 Stainless Steel Phillips Flat Head Screw	$3.75	1	$3.75
	McMaster	Multipurpose 6061 Aluminum Rectangular Tube 1/16" Wall Thickness 1"High x 1"Wide x 1" Length 1/16" Wall Thickness, 1" High x 1" Wide	$6.11	1	$6.11
	McMaster	Passivated 18-8 Stainless Steel Pan Head Phillips Screw 8-32 Thread, 3/8" long	$6.88	1	$6.88
	McMaster	Passivated 18-8 Stainless Steel Pan Head Phillips Screw 8-32 Thread, 1-1/4" long	$10.47	1	$10.47
	McMaster	Extension Spring with Loop Ends 7" Long, 1" OD, 0.115" Wire Diameter	$8.79	1	$8.79
	McMaster	Multipurpose 6061 Aluminum Bar, 1"x1", 2 ft. long	$14.42	1	$14.42
	McMaster	High-Strength 7075 Aluminum Rod, 1/2" Diameter, 2 ft long	$11.37	1	$11.37
	McMaster	Water and Steam Resistant EPDM O-Ring	$9.49	1	$9.49
	McMaster	Expandable Grommets for 1" Hole Diameter	$10.42	1	$10.42

	McMaster	Extension Spring with Loop Ends 7" Long, 1" OD, 0.105" Wire Diameter	$8.79	1	$8.79
	Home Depot	#8 x 1 in. Zinc Plated Phillips Flat Head Wood Screw (100-Pack)	$5.28	1	$5.28
	McMaster	Aluminum Unthreaded Spacer 1/2" OD, 3/4" Long, for 1/4" Screw Size	$1.71	5	$8.55
	McMaster	18-8 Stainless Steel Socket Head Screw 2-56 Thread Size, 3/16" Long	$6.51	1	$6.51
	McMaster	18-8 Stainless Steel Socket Head Screw 1/4"-20 Thread Size, 2-1/4" Long, Fully Threaded	$15.30	1	$15.30
				Total	$1,975.22

The team has spent an additional $1,268.76 for testing equipment, tools, and extra components for testing or replacement. In total, the team's budget is $3,388.56. This was higher than we anticipated, but we did not spare expenses to ensure that the project's needs were met for the safety of team members and users. Additional expenses that were not included in the prototype bill of materials are shown in Table 11.

Table 11: Bill of materials for testing equipment, tools and extra components

Subteam	**Vendor**	**Item**	**Unit Cost**	**Quantity**	**Total Cost**
all	Amazon	Drive Medical Silver Sport 1 Wheelchair	$109.29	1	$109.29
	Harbor Freight	2.5 Ton Leveling Scissor Jack	$36.99	1	$36.99
	Home Depot	2 in. x 4 in. x 96 in. Prime Whitewood Stud	$6.15	14	$86.10
	Home Depot	#9 x 2-1/2 in. Phillips Bugle Head Coarse Thread Sharp Point Polymer Coated Exterior Screws (1 lb./Pack)	$8.97	1	$8.97
Effort	Home Depot	1-3/4 in. x 48 in. Round Hardwood Dowel	$13.09	1	$13.09
	Home Depot	Cabinet Grade Plywood Panel (Common: 23/32 in. x 4 ft. x 8 ft.; Actual: 0.688 in. x 48 in. x 96 in.)	$45.98	1	$45.98
	Amazon	10 FT USB Extension Cable	$8.99	1	$8.99

	Harbor Freight	2.5 Ton Leveling Scissor Jack	$36.99	1	$36.99
	Home Depot	1 in x 48 in Galvanized Steel Pipe	$24.60	1	$24.60
	digikey electronics	MOD ADXL335 5V READY 3AXIS +-3G	$14.95	1	$14.95
	sparkfun	Arduino Uno R3	$22.95	1	$22.95
	sparkfun	SparkFun 9DoF IMU Breakout	$16.95	2	$33.90
EMI	JLC PCB	Circuit Board	$1.28	4	$5.12
	sparkfun	Break Away Headers - Straight	$1.50	5	$7.50
	sparkfun	Female Headers	$1.50	5	$7.50
	adafruit	16mm Panel Mount Momentary Pushbutton - Red	$0.95	1	$0.95
	adafruit	Solder Wire - 60/40 Rosin Core - 0.5mm/0.02" diameter - 50 grams	$5.95	2	$11.90
	sparkfun	Arcade Joystick	$19.95	1	$19.95
	sparkfun	Mini Speaker - PC Mount 12mm 2.048kHz	$1.95	1	$1.95
	sparkfun	Toggle Switch - 125 VAC	$2.95	1	$2.95
	sparkfun	GTE Knob - Small	$0.95	1	$0.95
	sparkfun	Rotary Potentiometer - Linear (10k ohm)	$0.95	1	$0.95
	sparkfun	Breadboard	$4.95	2	$9.90
	sparkfun	M/F Connector	$1.95	1	$1.95
	sparkfun	F/F Connector	$1.95	1	$1.95
	sparkfun	M/M Connector	$1.95	1	$1.95
	Mcmaster	Compression Spring Stock 36" Long, 0.75" OD, 0.59" ID	$4.69	1	$4.69
	sparkfun	Screw Terminal	$0.95	1	$0.95
	amazon	SPST Latching Pushbutton Switch	$7.81	1	$7.81
	Amazon	Zip Ties	$8.99	1	$8.99
	McMaster	Multipurpose 6061 Aluminum T-Bar	$13.91	1	$13.91
Propulsion	McMaster	Multipurpose 6061 Aluminum Rod, 1/2" Diameter, 2 ft. long	$4.77	1	$4.77

	McMaster	Stainless Steel Wing-Head Thumb Screw - 1/4"-20 Thread Size, 2" Long	$10.68	4	$42.72
	McMaster	Multipurpose 6061 Aluminum Bar, 1"x1", 2 ft. long	$14.42	1	$14.42
	SparkFun	Arduino Mega 2560 R3	$38.95	1	$38.95
	McMaster	High-Speed Steel Round-Shank Reamer	$30.72	1	$30.72
	McMaster	3 mm broach	$61.93	1	$61.93
	McMaster	High-Strength 7075 Aluminum Rod, 1/2" Diameter, 2 ft long	$11.37	1	$11.37
	McMaster	Steel Extension Spring with Loop Ends, 7" Long, 1.5" OD, 0.177" Wire Diameter	$11.29	1	$11.29
	McMaster	Corrosion-Resistant Extension Spring with Loop Ends 302 Stainless Steel, 7" Long, 1.25" OD, 0.148" Wire Diameter	$20.49	1	$20.49
	McMaster	Extension Spring with Loop Ends 7" Long, 1" OD, 0.148" Wire Diameter	$11.77	1	$11.77
	McMaster	Oversized Multipurpose 6061 Aluminum Sheet 5/8" Thick 2"x24"	$36.84	1	$36.84
	McMaster	Multipurpose 6061 Aluminum round tube 0.035" wall thickness 1" OD 1ft Length	$10.28	2	$20.56
	McMaster	Bushing for B Style Keyway Broaches, with Collar 1/2" Diameter	$14.87	1	$14.87
	McMaster	Keyway Broach Uncoated, for 1/8" Keyway Width, B Style	$72.94	1	$72.94
	McMaster	Left-Hand Tap Set, 1/2"-13 Sizes	$50.68	1	$50.68
	McMaster	Carbon Steel Screw Thread Die 1" OD, 1/2"-13 UNC Left-Hand Thread	$15.91	1	$15.91

	MSC	3/8" Diam x 1/8" Face Width, High Speed Steel, 6 Teeth, Shank Connection Woodruff Keyseat Cutter	$37.52	1	$37.52
	Home Depot	1 in. x 8 ft. Lashing Strap (2-Pack)	$6.98	2	$13.96
Testing	Home Depot	Sakrete 50lb Play Sand	$5.25	4	$21.00
	Amazon	Ziploc Storage Bags with New Grip 'n Seal Technology, For Food, Sandwich, Organization and More, Gallon, 75 Count	$8.89	1	$8.89
	Amazon	Hot Glue Gun Sticks 65 Count, Mini Size 4" Length x 0.28" Diameter for Industrial & Crafting, Small Glue Stick for Kids Crafts, No Ordor Good Adhesion Few Bubble,Quickly Melting Meeting DIY Needs	$10.79	1	$10.79
	Amazon	boruizhen Kids & Adult/Youth Knee and Elbow Pads with Wrist Guards 3 in 1 Protective Gear Set for Skateboarding Cycling BMX Bike Scooter Skating Rollerblading Riding (ADULT SIZE)	$19.79	1	$19.79
	Amazon	Hanging Weight Scale | 660 lb Digital Electronic Weighing Scale with Accurate Senesors	$27.99	1	$27.99
	Amazon	Mr. Pen- Packing Tape, 2 Pack, 2 inch Wide, 60 Yards, 1.9mil, No Smell, Shipping Tape, Packaging Tape, Packing Tape Rolls, Clear Packing Tape, Moving Tape, Box Tape, Packing Tape Refill, Mailing Tape	$6.99	1	$6.99
	Home Depot	50 lb. Quikrete Premium Play Sand	$4.20	6	$25.20
	Home Depot	12 ft. x 1 in. Ratchet Tie Down with S-Hook (4-Pack)	$8.97	2	$17.94

	Home Depot	2 in. x 4 in. x 96 in. Prime Whitewood Stud	$7.98	8	$63.84
				Total	$1,268.76

8. Team Self-Examination

The team progressed well with the overall goals of the project. The goal for the end of the year was to accomplish an initial prototype that achieves most of the functionalities determined by the team. Further improvements could be made to improve overall functionality of the device, but the device functions as a motor assist. The team overall has worked well together over the course of the year. The team is generally good at meeting internal deadlines for rough and final drafts. The team is always productive during set class times, especially the lab periods. Despite the challenges associated with online learning, group discussions have been largely engaging and productive. The structure of the team has remained consistent throughout the year once subteams were created and subteam leaders were chosen. As a whole, the team works well together and was productive. This is evident in the finished product of the project.

8.1. Propulsion Team's Self-Examination

Throughout the first semester, interim, and the second semester, the propulsion team was able to keep relatively on track to have a final product and worked well as a team. The responsibilities were well divided between the team members, and even though each member focused on their own part(s) of the sub-system, there was constant communication between members, and all members were willing to help each other with any problem or question that arose. Nicole led the team, and focused on the transmission, and the transmission housing. Charlotte focused on the spring, the spring housing, the torque transmitter, and the joint between the attachment and the transmission. Katie focused on the attachment, and the motor. Geoffrey focused on the battery, and the battery housing. All roles stayed the same since the beginning of the project, but each person picked up a new role as the design evolved, specifically regarding the spring.

In general, when planning the schedule for the semester, some buffer room was always taken into account. In the end, all tasks were completed on time or even early. During the second semester, all of our parts were manufactured and assembled in time for integration with the EMI team. The interim period was also a very productive time for the propulsion team. Working during this period allowed for designs to begin being finalized and is one of the main reasons all components were able to be manufactured and assembled in time to integrate with the rest of the team. One change that would be made is all manufactured parts would be tested as soon as possible. Issues were found with designs later on than wanted, which included problems with the attachment slipping on the frame, and the spring not being at the correct angle. While these issues were eventually resolved, it caused some stress on the team because of the short amount of time left in the semester.

8.2. Electro-Mechanical Integration Team's Self-Examination

The electro-mechanical integration team has worked well together all semester. All subteam members have readily contributed to the project in alignment with their skill sets and the team's needs. The subteam had a strong communication network that allowed members to reach each other whenever they needed help. All initial prototypes were completed on time although further modifications took longer than the team anticipated at points. If given an opportunity to repeat the project, the subteam would try to complete the initial prototypes sooner to account for the additional time needed for testing and modifications. Additionally, the electro-mechanical integration team would begin testing prototypes of manufactured components as soon as possible. The integration of the manufactured components and the 3D printed components did not go as smoothly as planned resulting in some of the flaws that would need to be addressed in future iterations. The electro-mechanical integration team also was the primary team focusing on subteam integration. In hindsight, the subteam integration should have begun earlier. Despite changes that could improve the success of the project, the subteam was overall very successful and worked very well together.

Although the assigned roles stayed largely the same over the course of the semester, each person ended up as the point person for a certain aspect of the project. Matt Urban acted as the point person for making the CAD improvements to the 3D printed components, soldering, and fabrication. Emily Eng had the ambitious job of spearheading the Arduino code and the integration of the three subteams. Carolyn Pye coordinated all of the electrical components of the device such as the circuit board and voltage regulator as well as all of the 3D printing. Despite these specializations, every subteam member worked on all parts of the project. For the electro-mechanical integration team, the project scope did not change over the course of the semester. However, the scope that could be achieved during integration was impacted by the progress of the other subteams. Overall, everyone in the electro-mechanical integration subteam pulled their weight and were able to achieve the majority of the goals set out at the beginning of the semester.

8.3. <u>Effort Sensing Team Self-Examination</u>

Overall, the team structure worked well. Both members had different capabilities and strengths that complimented each other well. The tasks remained distributed well overall. The main division of labor was with the strain gauge measurement system and the 9DOF measurement system which each team member took responsibility for. Ultimately, the building of the ramp was taken care of by this subteam and this took time which could have been used to work more with the 9DOF sensor which was a setback that didn’t allow us to fully reach the goals in terms of isolating the user input force. This timing and planning could have been better to increase productivity.

9. Recommendations for Future Work

9.1. Organizational Changes

Overall, the organization of the team was well thought out before the process of creating the prototype of the device. Although the organization of the team and the project was thought out beforehand, there are still adjustments that could have been made in order to ensure that everything goes as smoothly as possible. One such method is to adjust how sprints were used throughout the entire project. When they were being used near the beginning of the project, all of the information and tasks were bundled together, making it hard to understand which tasks were being done by which subteam as well as when everything was planned on being completed. Another change that could have made the project smoother was to have more inter-subteam cooperation. This would have been especially helpful during the middle and late stages of the project, especially when all the subteams were trying to integrate with each other.

9.2. Timeline Adjustments

A few timeline changes would have made the flow of the project a little smoother and possibly led to great success of the project. The team generally progressed well and made a lot of progress during the entire project duration. At the end of the project there was a large time crunch where a lot of things needed to be done in a short amount of time. It would have been nice to have more buffer room to complete tasks. Things often took longer than anticipated so adding additional time to account for this would be beneficial. Similarly, integrating the different subteams sooner would have helped the overall project. This was difficult to achieve due to setbacks in manufacturing and redesigns. General advice about the timeline is to not be complacent. If it seems that you are ahead of schedule do not get complacent and comfortable because the schedule will catch up to you.

9.3. Advice to Future Capstone Teams

When reflecting on these past two semesters and the interim period, the team has a couple pieces of advice that could be helpful for incoming seniors. One of the major takeaways was based on what we think our team did successfully, which was being on top of deadlines. Our team leader, Charlotte, did a good job of reminding us of when bi-weekly reports were due, when we had an upcoming 5-minute presentation, and when we had to either complete a report, website update, or final presentation. Because we were never writing reports at the last minute, there was never tension in the team to get our assignments done. Our last piece of advice is if you are working on a project that involves an audience that you do not have anything, or not that much in common with, it is a good idea to speak directly with them. One of the major resources for our team during the interim and second semester were our three interviews. The people we interviewed were able to not only answer our questions about what design would best fit their needs, but they were also able to ask us their own questions and bring up topics that we never thought about before. While we could have assumed certain needs/wants of our audience, speaking to them directly made it easier for us when making design choices.

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Acknowledgements

The team has consulted our assigned shop tech, Rob Layng, and the shop supervisor, Marv Snyder, on improvements to designs that would allow parts to be cheaper and easier to manufacture without sacrificing the quality of the part, specifically the use of sheet metal for some of the metal housings. Additionally, the team has elicited the help of Professor Nees from the psychology department to share his expertise on human factors in engineering, especially his experience in how technology impacts those with disabilities. Professor Vinchur in the psychology department has helped the team in completing the IRB process. He responded quickly to all emails regarding the IRB. Other individuals provided smaller levels of support for specific activities. Adam Smith worked with Drew to help with the mounting of the strain gages to ensure they were properly positioned. Professor T. Rossman helped multiple subteams recall and expand on material from his courses. The team would like to thank all of these individuals who helped the team achieve their goal of creating an assistive wheelchair device.

Appendix A: Background Research and Prior Art

Table A.1 Usability Issues Applicable to the Usability Scale for Assistive Technology (from a usability study conducted to measure the usability of assistive technology from a multi-contextual perspective) [3].

Table 3. Usability Issues Applicable to the Usability Scale for Assistive Technology–Wheelchair Mobility Intervention Framework

Subscale	Usability Issues	Reported Problems	Possible Intervention	Stakeholders
Home Usability	• Indoor mobility • Home arrangement • Space • Wheelchair suitability • Exit and entry	• Clutter • Organization • Narrow space in kitchen and bathroom • Narrow entrance • Wheelchair damages the house	• Home modification • Reduce clutter • Widen doorways • Pad wheelchairs to reduce impact	• User • Clinician • Technician • Home owner/family
Workplace/School Usability	• Access to classrooms and workstation	• Wheelchair does not fit with the table • Narrow aisles in classroom • Problems reaching the table	• Provision of adjustable workstations • Ensure ADA compliance • Intervene through Individualized Education Program	• User • Clinician • Employer or school admin
Community Usability	• Shopping	• Narrow aisles • Obstacles • Problems with reach • Restrooms inaccessible • Streets inaccessible	• Ensure ADA compliance • Encourage use of reachers	• Community • Store manager • End users • Architects • Policy advocates
	• Going to restaurants	• Narrow aisles • Restrooms inaccessible • Seating problems	• Ensure ADA compliance	
Outdoor Usability	• Driving through streets • Access to sidewalks	• Sidewalks uneven, cracked, and unsafe	• Inform civic authorities • Improve PWC stability and capability to drive on rough terrain	• Community • Policy advocates
	• Climatic influence	• Wheelchair frame corrosion • Electronic components fail • Terrain slippery • Falls and accidents • Surface barriers	• Improve material resistance • Improve concealment of wheelchair parts • User training	• Manufacturers • Technology developers • Researchers
Usability: Ease of Use	• Limited reach	• Difficulty performing tasks such as picking up objects and accessing work surface	• Postural interventions • Consider use of a reacher	• User • Clinician • Technician
Usability: Seating	• High incidence of pain in lower back, hips, and shoulders • Problems with postural alignment	• Pain when sitting for a long time	• Periodical seating evaluation and intervention	• User • Clinician • Technician
Usability: Safety	• High incidence of falls and accidents	• Environmental hazards • Device safety • User awareness	• User training • Clinician/technician training • Identify and reduce environmental hazards	• User • Clinician • Technician • Researchers

Note. ADA = Americans With Disabilities Act; PWC = power wheelchair.

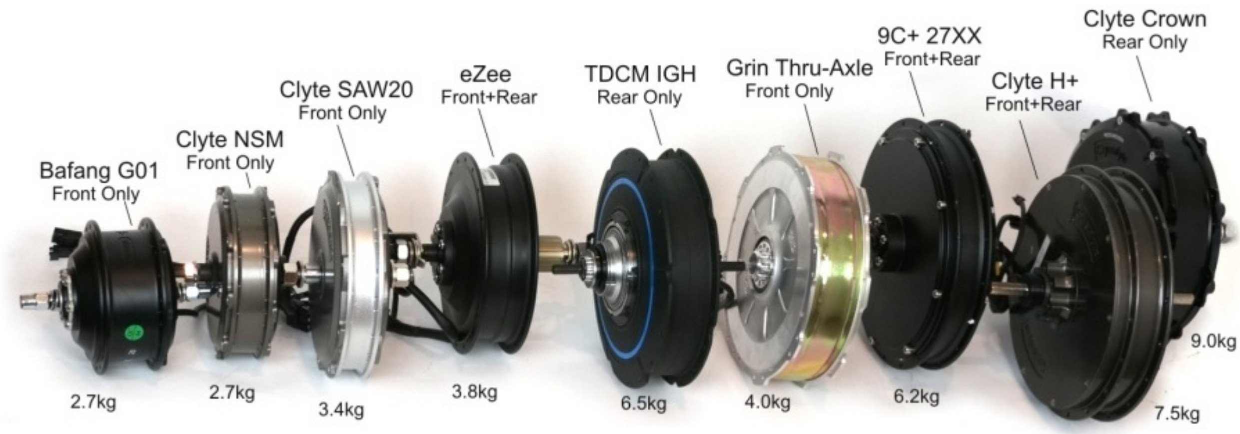


Figure A.1 Hub Motors used in E-Bikes [13]

Figure A.2 Hub Motor in E-Bike Wheel [13]

Appendix B: Conceptual Designs and Calculations for Prototype

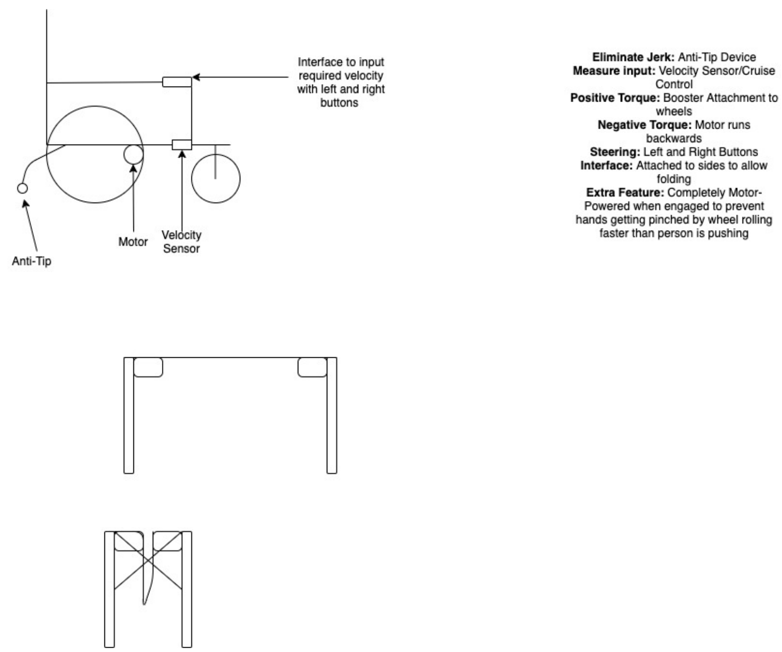


Figure B.1 Wheelchair design with motor-driven wheels

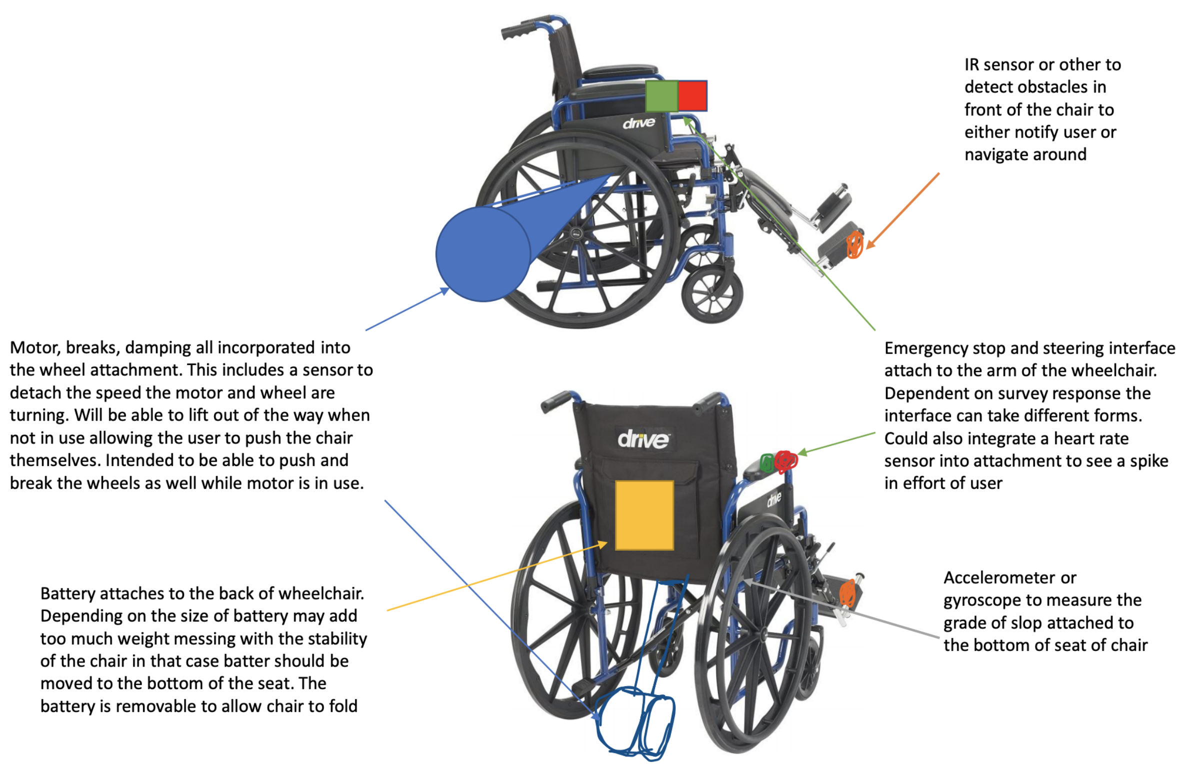


Figure B.2 Attachable wheel to the back of the wheelchair[17, modified]

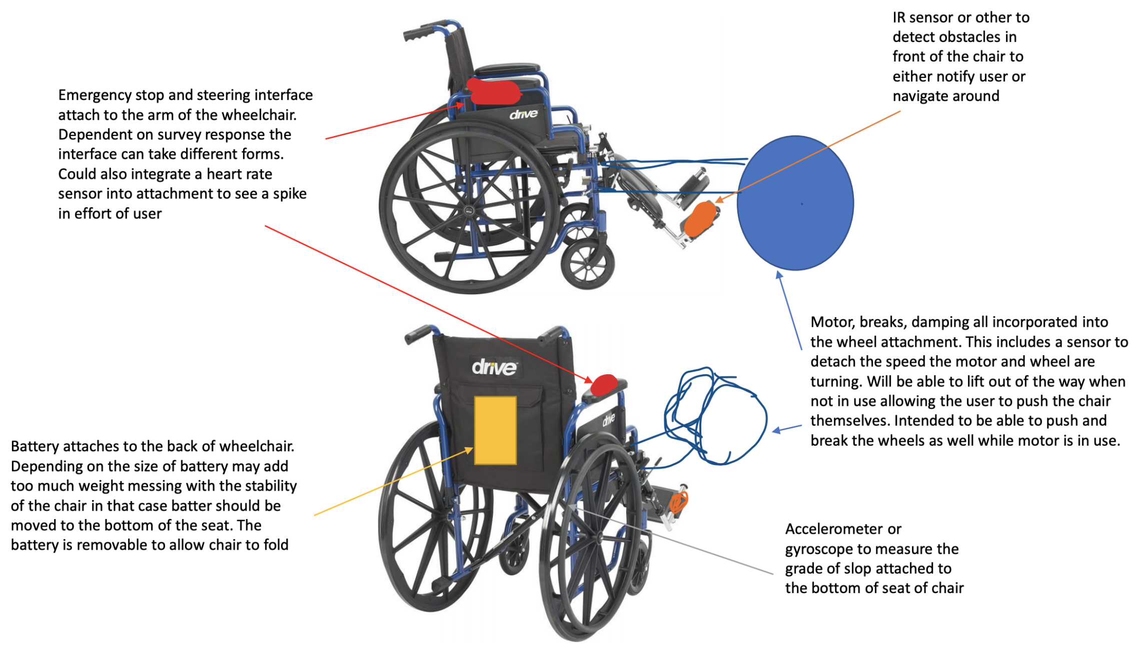


Figure B.3 Attachable wheel to the front of the wheelchair [17, modified]

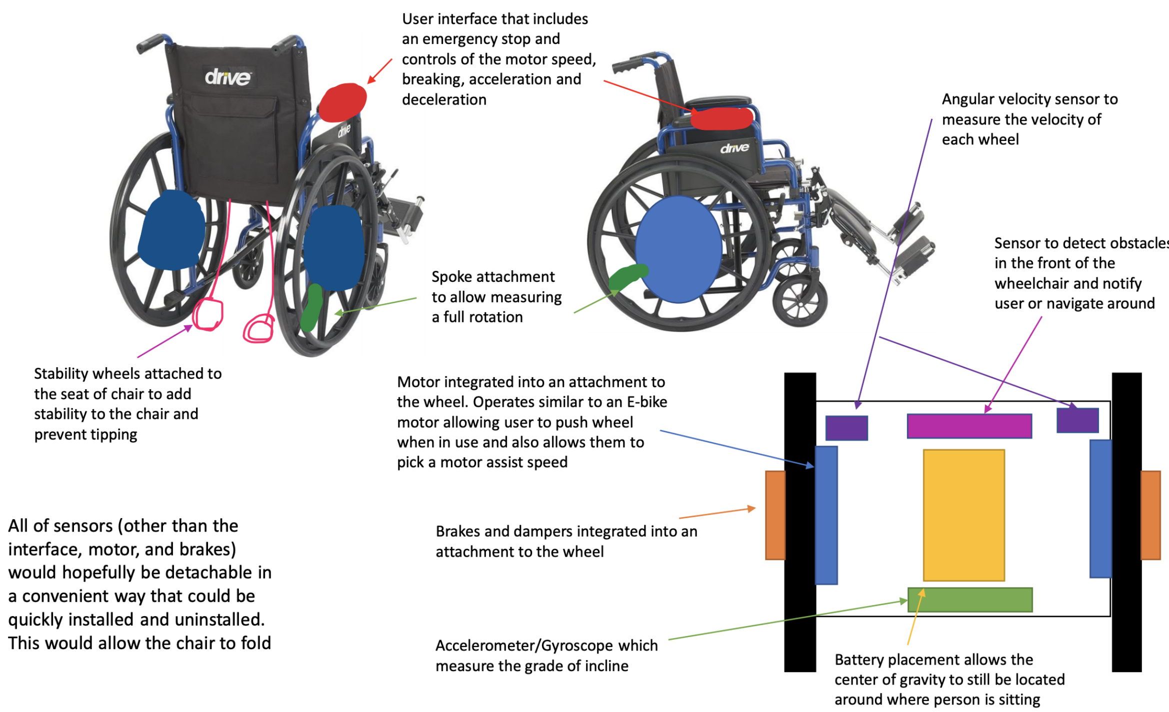


Figure B.4 E-bike mechanism design with layout of various components under the seat [17, modified]

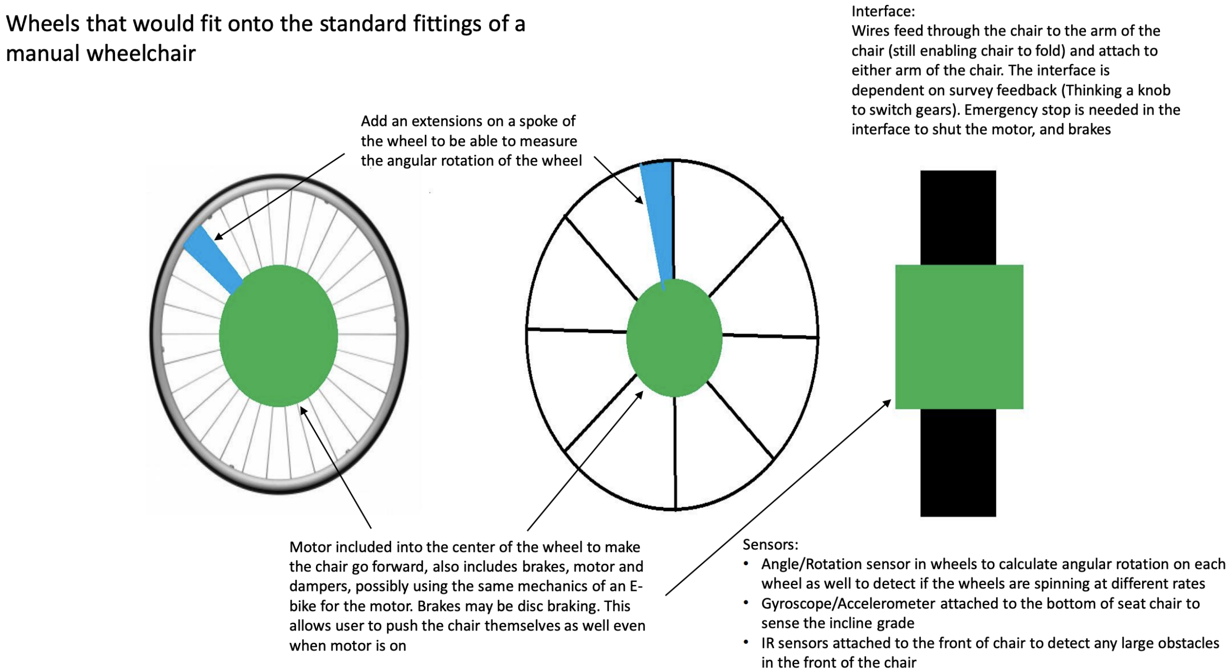


Figure B.5 Detachable wheels powered by motors at the hub

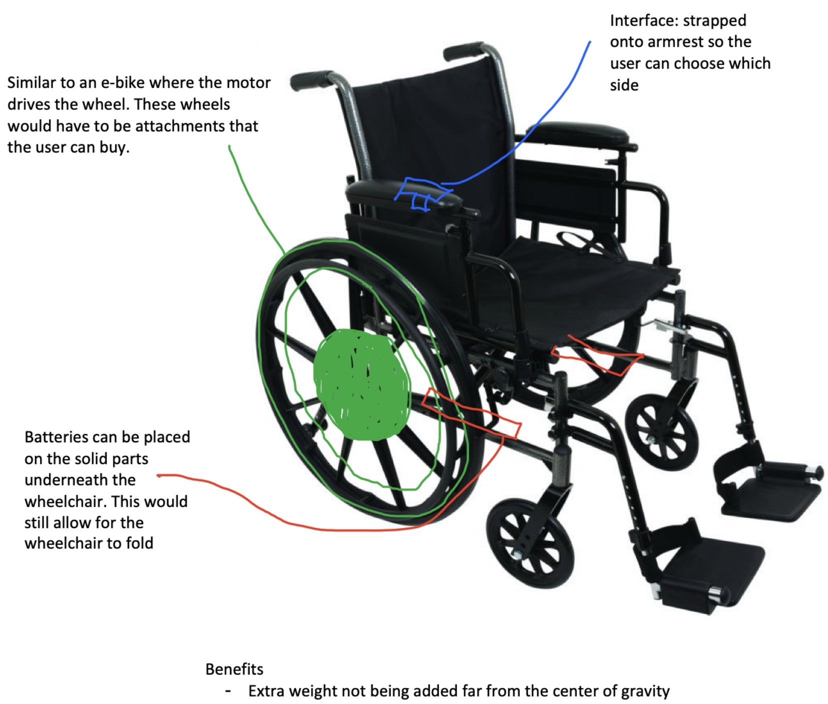
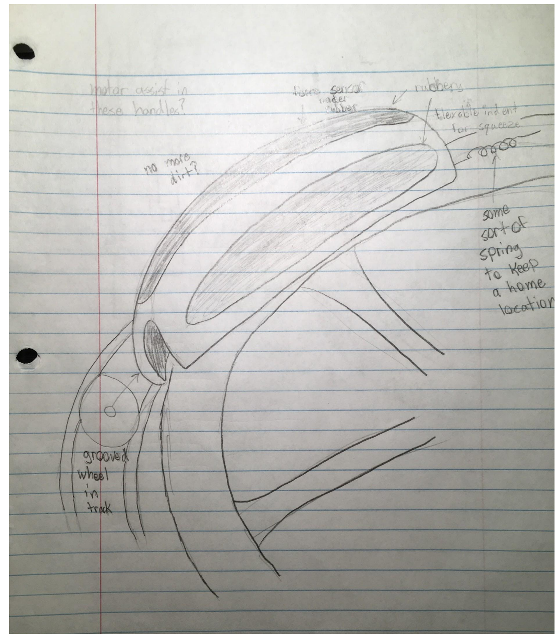


Figure B.6 Wheelchair design with new wheel attachments [29, modified]

(a)

(b)



(c)

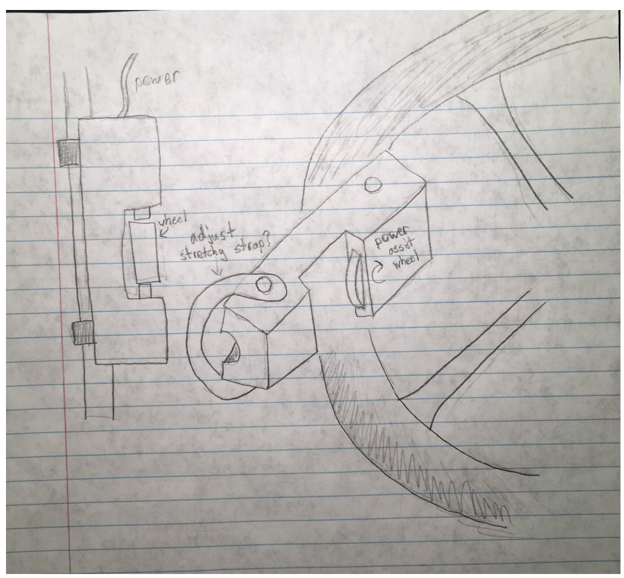


Figure B.7 (a) Overall wheelchair design (b) Force sensor design (c) Motor Attachment

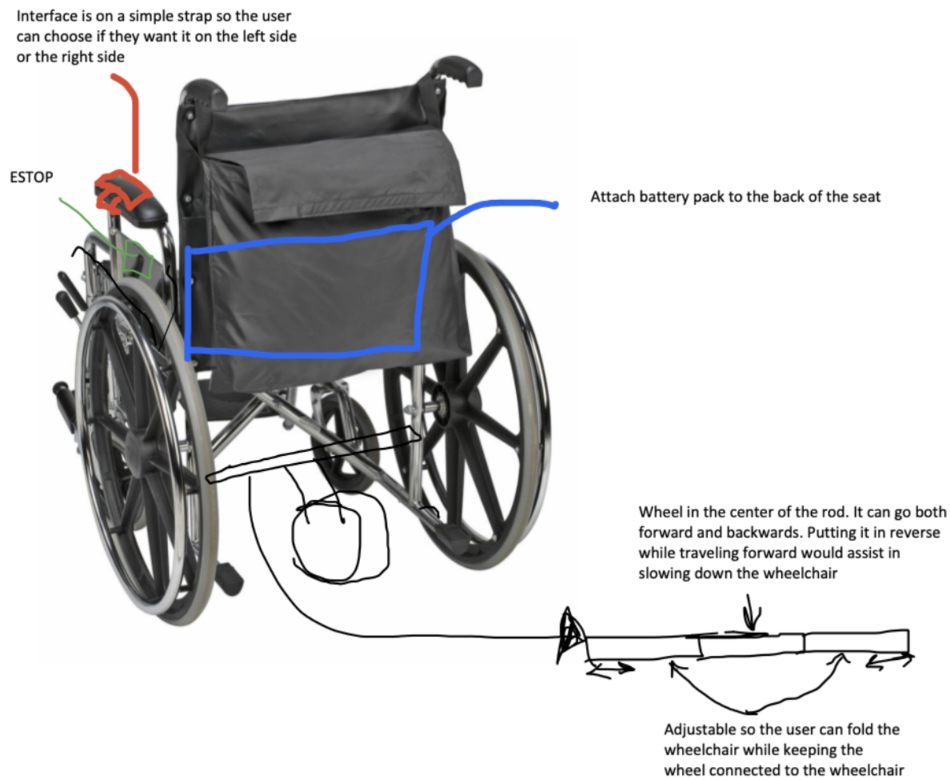


Figure B.8 Rear wheel addition with expandable bar[29, modified]

Figure B.9 Option for where we can place batteries, Estop, user interface and speedometer [5, modified]

(a) **(b)**

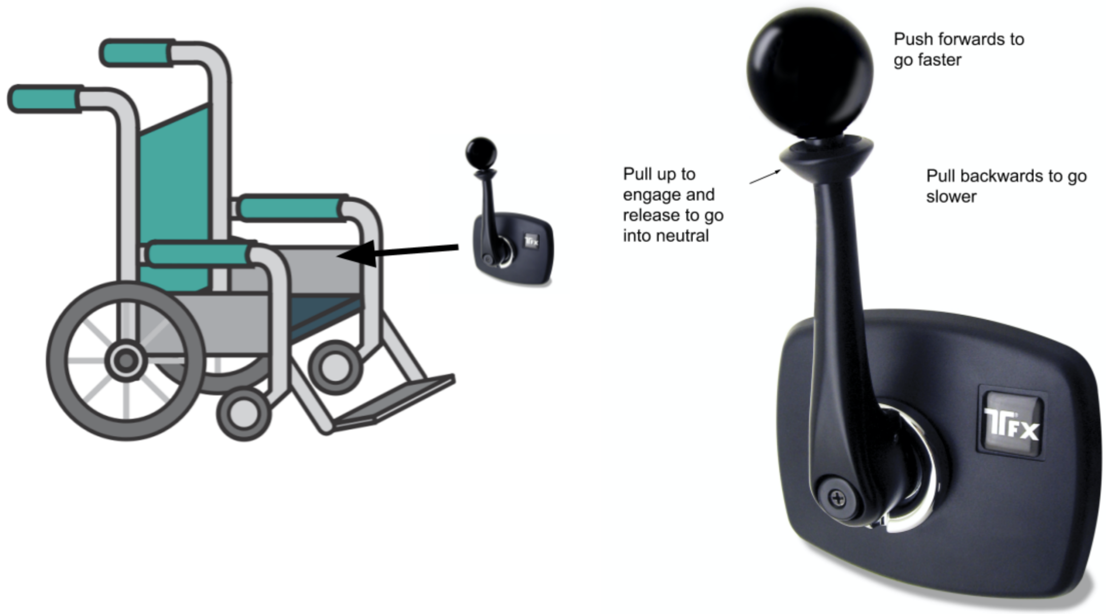


Figure B.10 (a) Placement of throttle (b) Throttle with description of mechanism [30, 31, modified]

Figure B.11 Placement of batteries and sensors [32, modified]

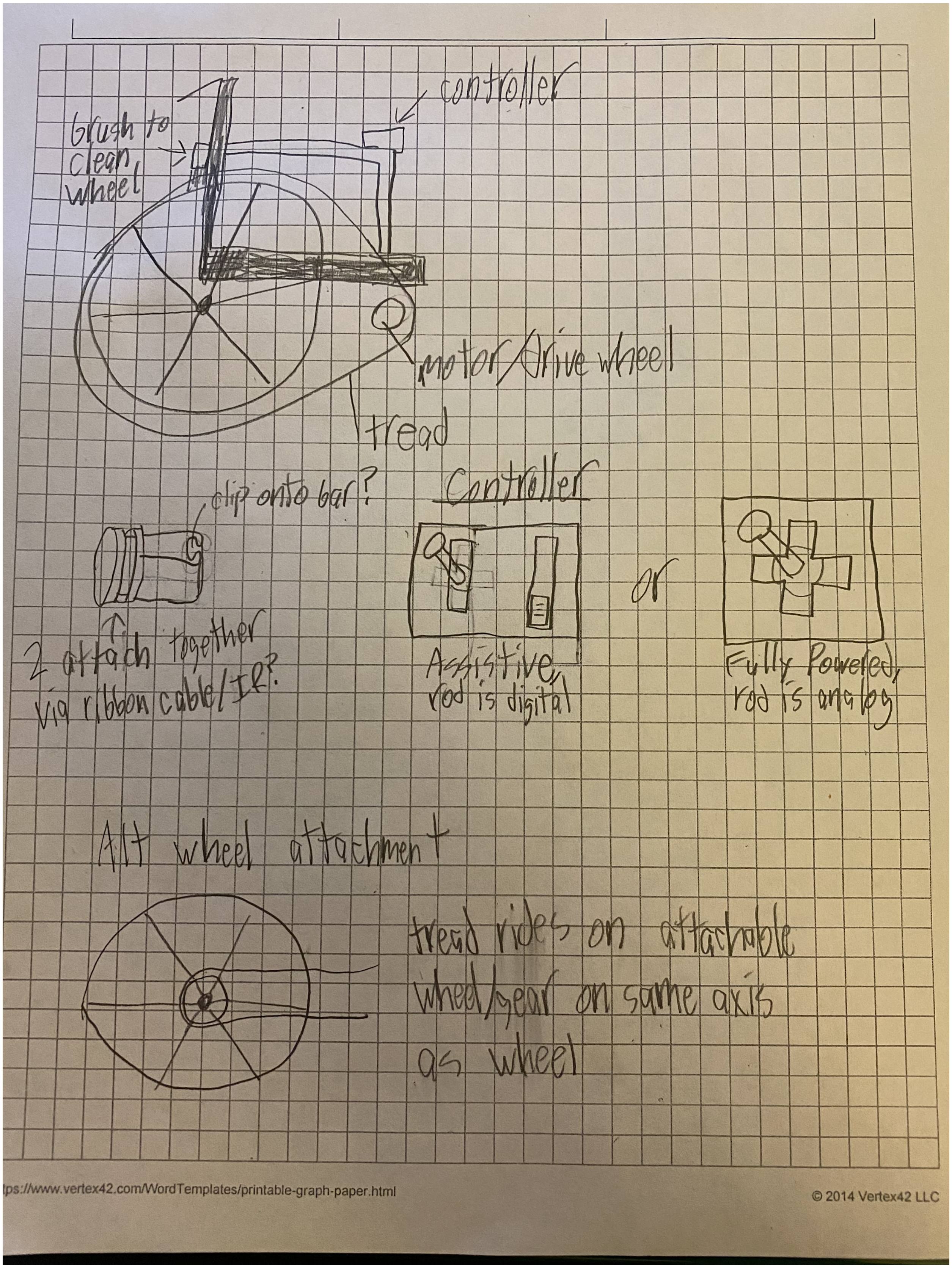


Figure B.12 Motor/drive wheel with a description of a controller

Ideas for Device/Attachment

- ~~One piece attaches to the back axel of the wheel chair – the motor that drives the chair~~
- The "controller" can be attached in multiple places
    - wheelchair user can use or someone assisting someone in a wheelchair
- Something that drives a boat type of thing, can maneuver and turn the wheels
- Some type of hanging attachment on the back of the wheelchair so the device can be stored and used if necessary
    - Easy snap button to be attached or detached
    - Easily folds with the fabric of the rest of the wheelchair
    - Some type of mesh with zippers/pocket system to hold the rest of the device (battery etc.)
        - Also holds a charger cord
    - Charging cable (?) how do we power?

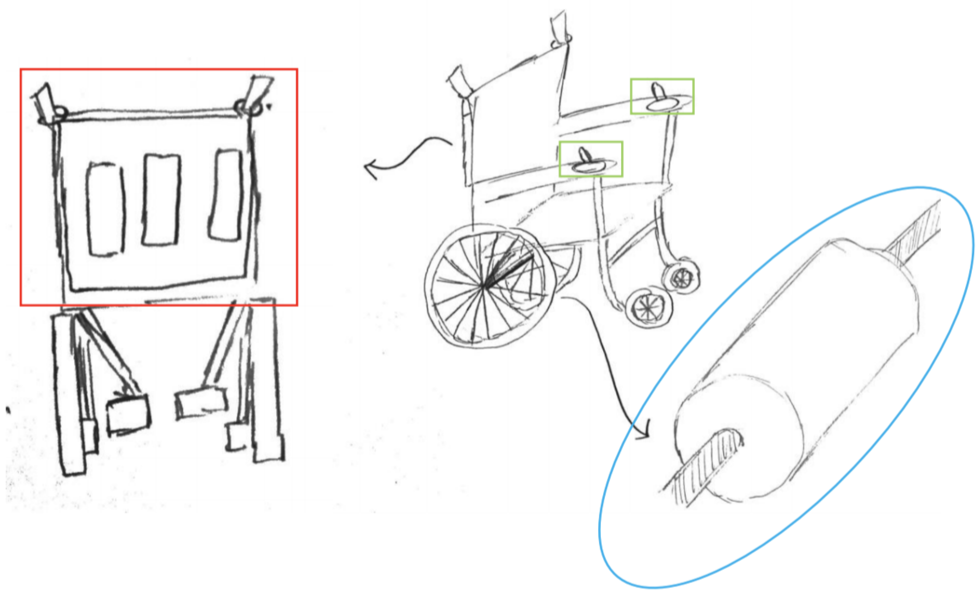


Figure B.13 Wheelchair design with hanging attachment for storage

```
close all
clear all
clc
%Motor Horsepower Calculation
m = (198+25+36.7)/2.205/2; %kg, assuming two wheels in the back
mu = 0.9; %static friction coefficient, rubber on dry asphalt
grade1 = 4.76; %degrees
grade2 = 7.13; %degrees
g = 9.81; %m/s^2
r = [5 7.5 8 8.5 9 12]/2; %in, but will get same hp for any r
r= r./39.37; %m, wheel radius
v = 3.0/2.237; %m/s, translational velocity
omega = v./r; %rad/s, rotational velocity

Fp1 = mu*m*g*cosd(grade1)+m*g*sind(grade1); %N
Fp2 = mu*m*g*cosd(grade2)+m*g*sind(grade2); %N

Fp1 = m*g*sind(grade1); %no friction
Fp2 = m*g*sind(grade2); %no friction

T1 = Fp1.*r; %Nm
T2 = Fp2.*r; %Nm

P1 = T1.*omega/745.7; %hp (1 mechanical hp = 745.7 W)
P2 = T2(1).*omega(1)/745.7 %hp (1 mechanical hp = 745.7 W)
```

```
P2 =

    0.1290
```

Figure B.14 Motor horsepower calculations in MATLAB

```
clear all;
clc;


BV = 48;%Battery Voltage
BC = 10;%Battery capacity in amp-hours
MV = 32;%Motor voltage
MPH = 2;%Speed traveling Mph
wheelRad = 2.5; %in
GearRat = 1.38;
%1.38 for 48 volt
%2.69 for 32
MotorInput = [1,0.5]; %what percentage of torque is generated by motor
CircumWheel = 2*pi*wheelRad; %circumference of wheel
WheelRpm = ((MPH*63360)/60)/CircumWheel;  %converts Mph to RPM for calc
MotorRpm = WheelRpm * GearRat;
MotorRads = (MotorRpm*(2*pi))/60; %converts RPM to Rad/s for motor
MaxTorque = 3.86; %N-M
NoLoadSpd = 5760; %RPM
TScSlope = -(MaxTorque/NoLoadSpd); %slope of Torque speed curve
TorqueM = ((TScSlope * MotorRpm) + MaxTorque)*MotorInput; %motor torque needed to travel

MC = (2*((TorqueM*MotorRads)/BV));%Motor Current amps using 60% efficiency
maxDist = 4; %in miles
runTime = (maxDist/MPH)*3600; %in seconds
Power = ((MotorRpm*(2*pi)/60)*TorqueM)/0.6; %power generated at specific speed, in watts
BatEngC = runTime*Power; %joules of battery needed
AHN = 2*(BatEngC/(3600*BV)); %conversion from jouls to Amp-Hours
%multiplying AHN by 2 because using 2 motors

AmpHours = (MC*(runTime/3600))/0.6
%max weight added is 22 lbs
```

```
AmpHours =

   10.0813    5.0406
```

Figure B.15 Battery ampere hour calculations for chosen motor in MATLAB for running motor at 100% and 50%

distance calculations based on battery capacity

```
BV = 48;%Battery Voltage
BC = 10;%Battery capacity in amp-hours
MV = 32;%Motor voltage
MPH = 2;%Speed traveling Mph
wheelRad = 2.5; %in
GearRat = 1.38;
%1.38 for 48 volt
%2.69 for 32
MotorInput = [1, 0.5]; %what percentage of torque is generated by motor
CircumWheel = 2*pi*wheelRad; %circumference of wheel
WheelRpm = ((MPH*63360)/60)/CircumWheel;  %converts Mph to RPM for calc
MotorRpm = WheelRpm * GearRat;
MotorRads = (MotorRpm*(2*pi))/60; %converts RPM to Rad/s for motor
MaxTorque = 3.86; %N-M
NoLoadSpd = 5760; %RPM
TScSlope = -(MaxTorque/NoLoadSpd); %slope of Torque speed curve
TorqueM = ((TScSlope * MotorRpm) + MaxTorque)*MotorInput; %motor torque needed to travel

MC = (2*((TorqueM*MotorRads)/BV));%Motor Current amps using 60% efficiency
AHPM = MC/MPH; %calculate the amp hours per mile
Dist = BC./AHPM
```

```
Dist =

    6.6129   13.2258
```

Figure B.16 Distance calculations based on battery capacity for chosen motor in MATLAB for running motor at 100% and 50%

```
close all
clear all
clc

%Motor Horsepower Calculation
m = (198+25+36.7)/2.205/2; %kg, assuming two wheels in the back
mu = 0.9; %static friction coefficient, rubber on dry asphalt
grade1 = 4.76; %degrees
grade2 = 7.13; %degrees
g = 9.81; %m/s^2
r = 5/2; %radius of the wheel we purchased
r= r./39.37; %m, wheel radius
v = 2.25/2.237; %m/s, translational velocity
omega = v/r; %rad/s, rotational velocity


Fp2 = m*g*sind(grade2); %no friction


T2 = Fp2*r; %Nm


P2 = T2*omega/745.7; %hp (1 mechanical hp = 745.7 W)

%what we know
Tmotor = 3.86;
eff = 0.85;
Tout = T2;
wout = omega; %rad/s

Geff_T = Tout(1) / Tmotor(1)/ eff(1)
```

```
Geff_T =

    1.3878
```

Figure B.17 Gear ratio calculations in MATLAB

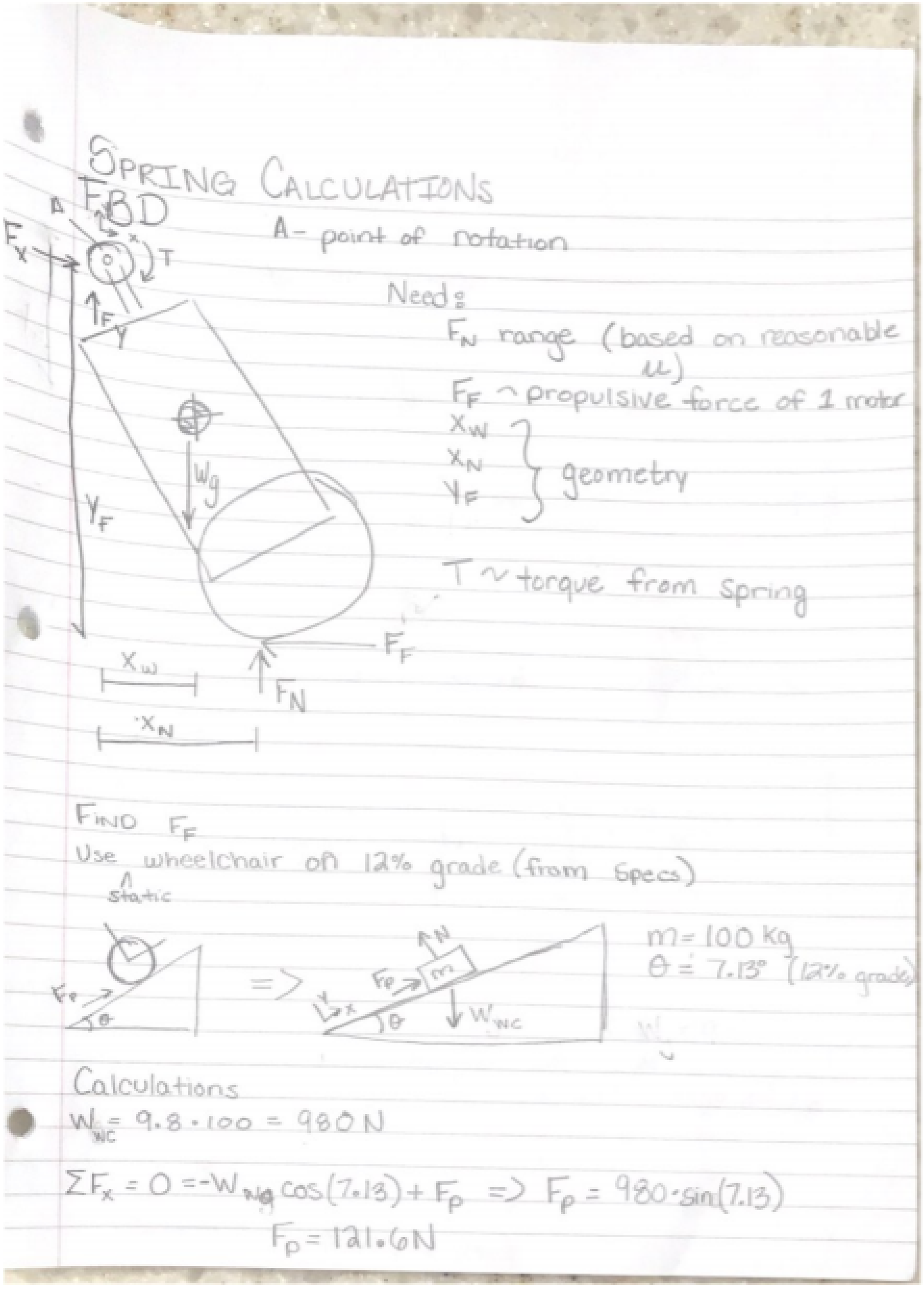


Figure B.18.1 Spring Calculations Derivations using Free Body Diagrams

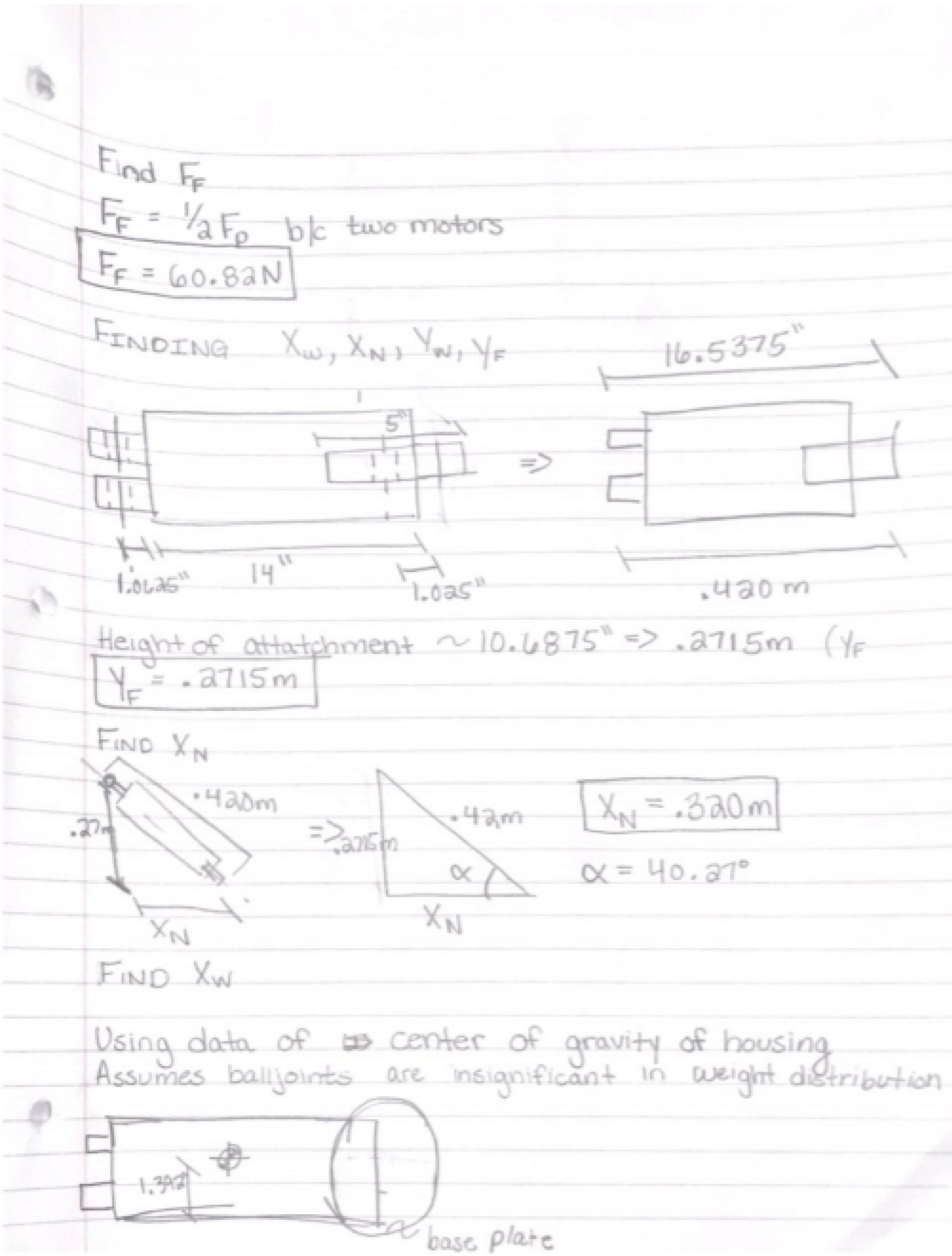


Figure B.18.2 Spring Calculations Derivations using Free Body Diagrams

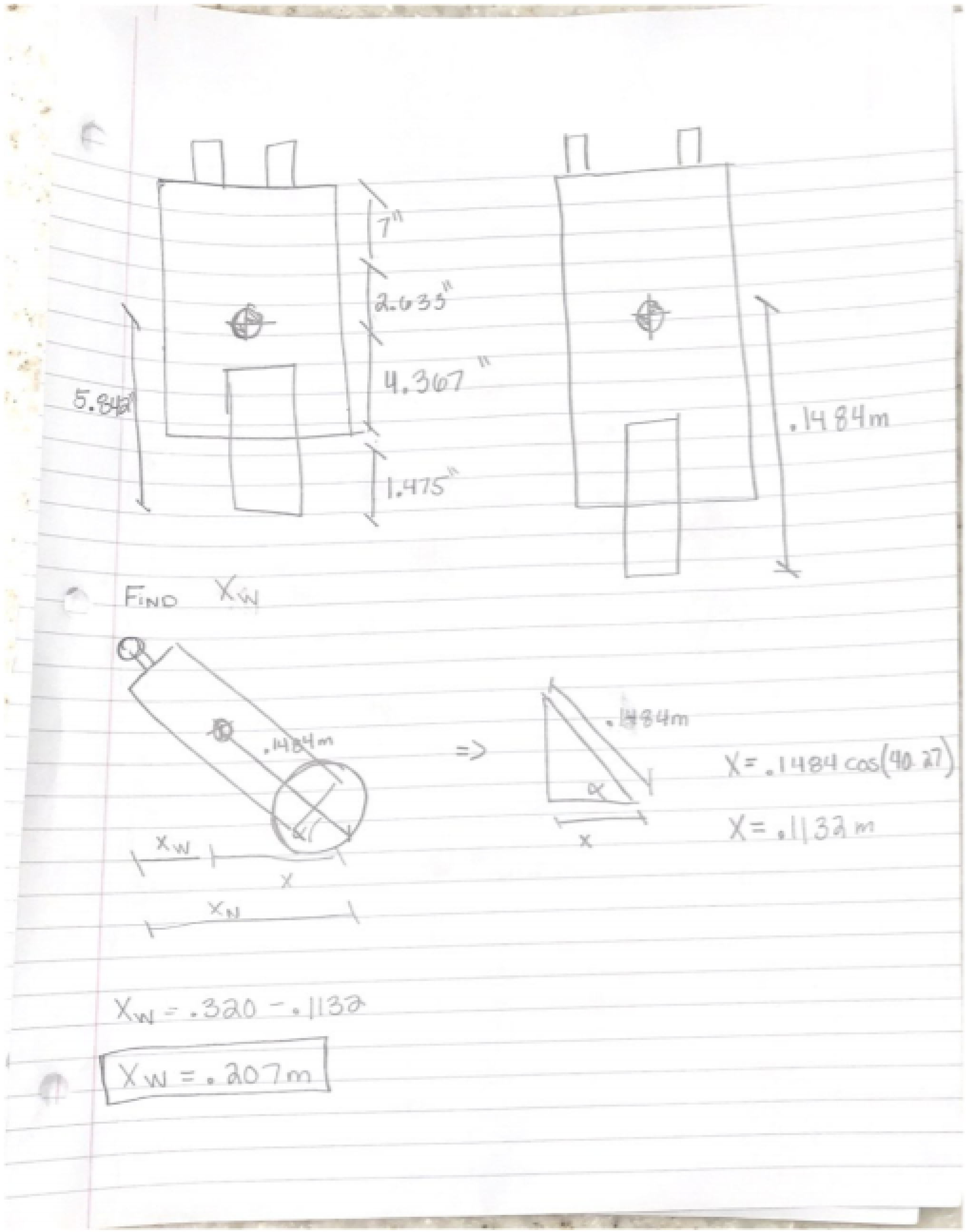
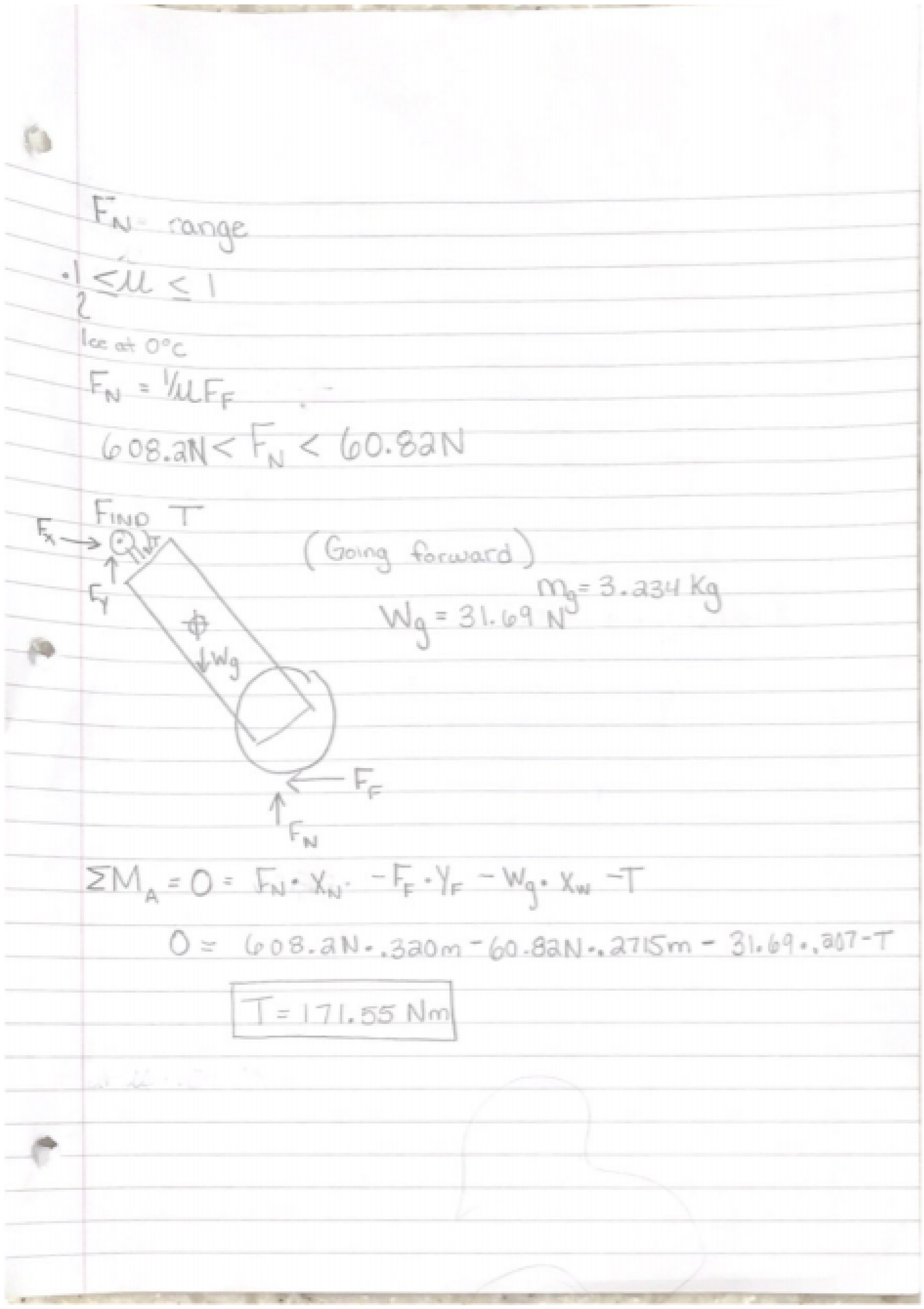


Figure B.18.3 Spring Calculations Derivations using Free Body Diagrams



F_N range

$.1 \leq \mu \leq 1$
2

Ice at 0°C

$F_N = 1/\mu F_F$

$608.2N < F_N < 60.82N$

Find T

(Going forward)

$m_g = 3.234$ Kg

$W_g = 31.69$ N

$\Sigma M_A = 0 = F_N \cdot X_N - F_F \cdot Y_F - W_g \cdot X_w - T$

$0 = 608.2N \cdot .320m - 60.82N \cdot .2715m - 31.69 \cdot .207 - T$

$T = 171.55$ Nm

Figure B.18.4 Spring Calculations Derivations using Free Body Diagrams

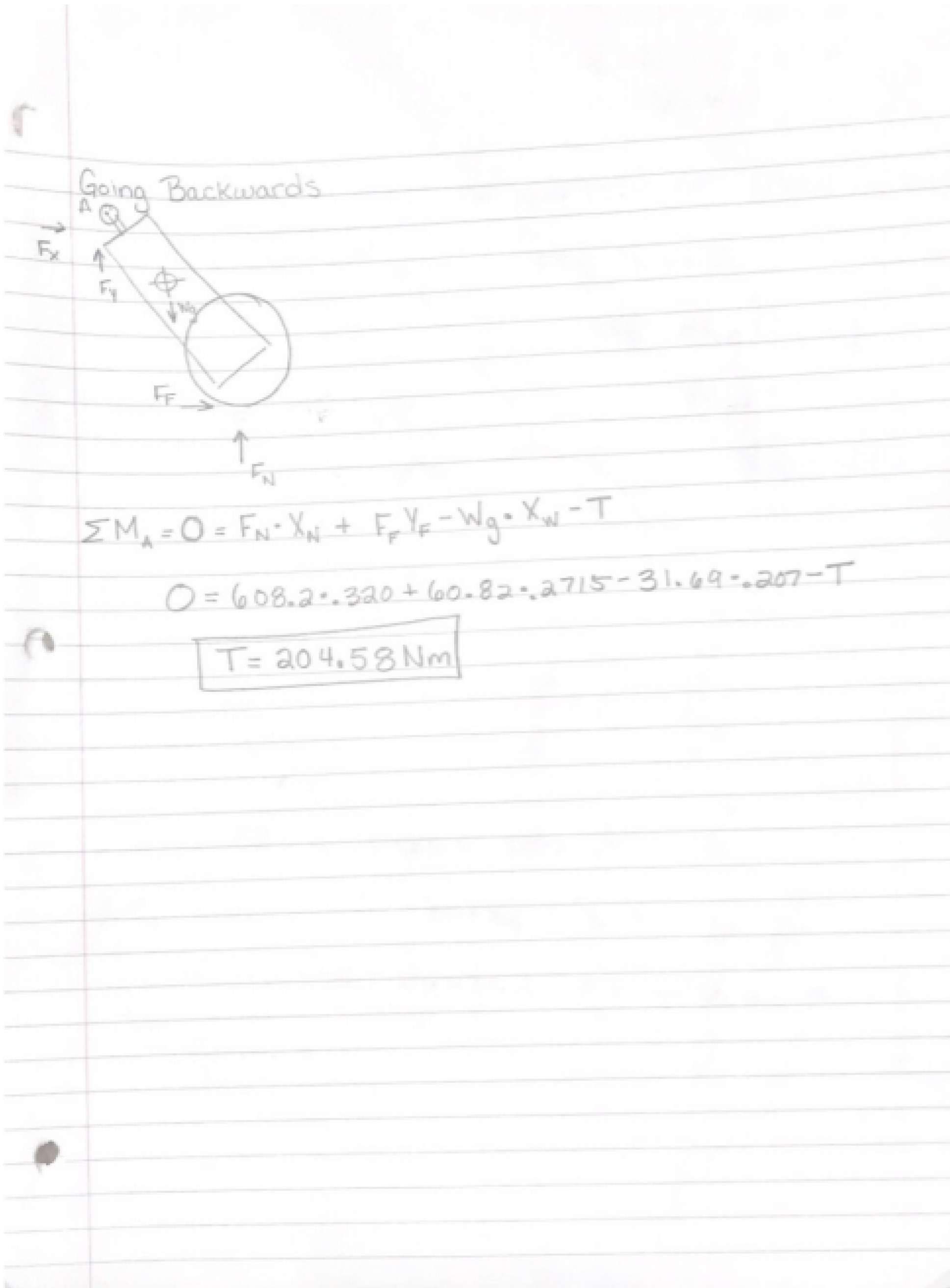


Figure B.18.5 Spring Calculations Derivations using Free Body Diagrams

Table B.1 Spring Calculations showing torque needed going forward and backwards for different surfaces on 12.5% grade

Surface	Coeff of Friction	Torque Forwards (Nm) Ma	Torque Backwards (Nm) Ma	Torque Forward (lb-in)	Torque Backwards (lb-in)	Normal Force On (Fn,on) (N)	Normal Force Off Forwards(Fn,off) (N)	Normal Force Off Backwards (Fn,off) (N)
Rubber on Concrete	0.6	-19.6332714	18.2089326	-173.7690937	161.1626332	101.3666667	-64.09000417	97.60625675
Rubber on Asphalt	0.9	-27.54097451	10.30122949	-243.7581636	91.17356329	67.57777778	-97.87889306	63.81736786
Rubber on Rubber	1.15	-30.9791063	6.863097699	-274.188194	60.74353291	52.88695652	-112.5697143	49.1265466
	1	-29.12251513	8.719688865	-257.7559776	77.17574932	60.82	-104.6366708	57.05959008
Rubber on Wet Pavement	0.5	-14.88864953	22.95355447	-131.7756518	203.1560751	121.64	-43.81667083	117.8795901
hard plastic on dry wood	0.4	-7.771716722	30.07048728	-68.78548888	266.146238	152.05	-13.40667083	148.2895901

Table B.2 Spring Calculations showing torque needed going forward and backwards for different surfaces on 8.3% grade

Surface	Coeff of Friction	Torque Forwards (Nm) Ma	Torque Backwards (Nm) Ma	Torque Forward (lb-in)	Torque Backwards (lb-in)	Normal Force On (Fn,on) (N)	Normal Force Off Forwards(Fn,off) (N)	Normal Force Off Backwards (Fn,off) (N)
Rubber on Concrete	0.6	-21.23835057	3.955032017	-187.9752414	35.00498289	67.48468494	-70.94835999	36.70064913
Rubber on Asphalt	0.9	-26.50289039	-1.309507806	-234.5703449	-11.59012067	44.98978996	-93.44325497	14.20575415
Rubber on Rubber	1.15	-28.79182075	-3.598438163	-254.8290856	-31.84886134	35.20940084	-103.2236441	4.425365024
	1	-27.55579835	-2.36241577	-243.8893656	-20.90914138	40.49081097	-97.94223397	9.70677515
Rubber on Wet Pavement	0.5	-18.07962667	7.113755911	-160.0181792	62.96204502	80.98162193	-57.451423	50.19758612
hard plastic on dry wood	0.4	-13.34154083	11.85184175	-118.082586	104.8976382	101.2270274	-37.20601752	70.4429916

Table B.3 Spring Calculations showing torque needed going forward and backwards for different surfaces on 5% grade

Surface	Coeff of Friction	Torque Forwards (Nm) Ma	Torque Backwards (Nm) Ma	Torque Forward (lb-in)	Torque Backwards (lb-in)	Normal Force On (Fn,on) (N)	Normal Force Off Forwards(Fn,off) (N)	Normal Force Off Backwards (Fn,off) (N)
Rubber on Concrete	0.6	-22.50493102	-7.29283176	-199.185423	-64.54699983	40.74814973	-76.3603419	-11.36043939
Ruber on Asphalt	0.9	-25.68373014	-10.47163088	-227.3201658	-92.68174267	27.16543315	-89.94305848	-24.94315597
Rubber on Rubber	1.15	-27.06581671	-11.85371745	-239.5526627	-104.9142396	21.25990421	-95.84858742	-30.84868491
	1	-26.31948996	-11.1073907	-232.9471144	-98.30869124	24.44888984	-92.65960179	-27.65969928
Rubber on Wet Pavement	0.5	-20.59765155	-5.385552289	-182.3045772	-47.66615413	48.89777968	-68.21071195	-3.210809443
hard plastic on dry wood	0.4	-17.73673234	-2.524633083	-156.9833087	-22.34488557	61.1222246	-55.98626703	9.013635477

```
clear all;
close all;
clc;

% all in
yf = 0.3111; % m % y distance from contact point to attatchment
l = 0.3893; % m % length of the entire attatchment
a = asin(yf/l); % rad % angle between the attatchment and ground
adeg = rad2deg(a);
xn = ((l^2)-(yf^2))^(1/2); % m % x distance from A to the point of contact
s = 0.0254*(5+1.475); %m % distance from point of contact to the spring
se = l-s;
e = 0.0254*2.5; % m extension of the attatchment overhang
x = s*cos(a); %m x distance from the spring to point of contact
y = s*sin(a); % m y distance from the spring to the point of contact
ys = yf - y; % m  y distance from the spring to A
xs = xn - x; % m x distance from the spring to A

o = atan(e/se) ; % angle of the spring with housing
```

```
odeg = rad2deg(o);
t = a-o;
lext = (((se^2)+(e^2))^(1/2)); %extended length of spring
lextin = lext*39.3701;
k = 5 *175.126835; % 65 lb-in
lsp = 7*0.0254; % length of spring given by manufacturor
dx = lext - lsp - (0.625*.0254); % change in length
Fs = k*dx;
Fsx = Fs*cos(t);
Fsy = Fs*sin(t);
Max = Fsy.*xs;
May = Fsx.*ys;
Ma = Max - May
Malb = Ma*8.85074576737892
Ff = 60.82;
Fn = 150;
Wg = 30.18;
Ftot = Ff+Fn+Wg+Fs;
```

Figure B.19 Matlab Script to determine torque created by spring

APPENDIX C: Team Charter

Roles and Responsibilities:

- Leader of team
  - Runs the meeting
- Assistant Leader
  - Runs the meeting if the leader cannot
- Subteam Leaders (upcoming)
- Budget person(s)
  - Interact with Colt Hauser (Purchasing)
  - Maintain a spreadsheet that tracks purchases
- Scribe (one person or rotating, or or or)
- Copy Editor(s) of sort
  - Compile/Assemble Reports
  - Finalizes/Submits
- Sprint/Schedule Manager
- Technical shop liaison
  - Engineering drawing revision
  - Bring materials to/from shop

Internal Team Deadlines:

- Scrum Agile Mindset Upcoming

Expectations for Discussions during Meeting + What we'll strive for:

- Make and follow meeting agendas (Team Leader)
- Maintain a level of professionalism and respect
  - We need to give our peers the benefit of the doubt
    - Don't assume another person isn't doing their part (trust each other)
  - Set each other up for success
    - Personal accountability and holding each other accountable
  - Communicate with the group!

Attendance:

- All members expected to be at meetings, so please let us know if you're not going to be there.

Communication + Conflict Resolution:

- Open and respectful

Appendix D

1. Braking Effectiveness Test

Goal of Test: The goal of the braking effectiveness test is to ensure that the wheelchair is able to stop on flat ground, inclines, and declines with the device running at maximum speed. The brake effectiveness test will determine whether Specifications G7, P3, P4, P5, P6, P7, and P9 are met [Section 4]. The test procedure is given by ISO standard 7176-3 [15].

Procedure:
Braking Test 1: Motor Stopping

1. Secure test dummy to the wheelchair
2. Use the motors to propel the wheelchair on flat ground (tentatively Tennis Courts) at maximum speed
3. Stop the wheelchair by stopping the motors.
4. Measure the distance it takes for the wheelchair to stop without tipping. Repeat steps 1-3 3 times and take the average.
5. Repeat Steps 1-4 going up the wheelchair ramp at Skillman Library
6. Repeat Steps 1-4 going down the wheelchair ramp at Skillman Library forward
7. Repeat Steps 1-4 going down the wheelchair ramp at Skillman Library backward

Braking Test 2: Motor Running Backwards

1. Repeat procedure for Test 1, changing the behavior of the motors from completely stopping to running backward in order to assist in stopping the wheelchair.

Braking Test 3: Manual Braking and Motor Stopping

1. A team member will sit in the chair wearing protective gear. Ensure that the teammate properly seated in the chair and all protective gear is securely fastened.
2. Use the motor to propel the wheelchair on flat ground (tentatively Tennis Courts) at a 25% of maximum speed to ensure that the team member is comfortable.
3. Stop the wheelchair using a combination of the team member stopping the wheels of the wheelchair by hand and stopping the motors.
4. Measure the distance it takes for the wheelchair to stop without tipping. Repeat steps 1-3 3 times and take the average.
5. If the team member is comfortable, repeat Steps 1-4 at 50%, 75%, and 100% of maximum speed.
6. Repeat Steps 1-5 going up the wheelchair ramp at Skillman Library.
7. Repeat Steps 1-5 going down the wheelchair ramp at Skillman Library forward.
8. Repeat Steps 1-5 going down the wheelchair ramp at Skillman Library backward.

Braking Test 4:

1. Repeat procedure for Test 3, changing the behavior of the motors from completely stopping to running backward in order to assist in stopping the wheelchair in combination with the team member stopping the wheels.

Required Equipment:
- Flat test plane: tentatively Tennis Courts
- Inclined test ramp: Skillman Library wheelchair ramp
- Test dummy
- Ratchet straps and zip ties to secure test dummy
- Measurement equipment: braking distance, inclinometer, force measurement
- Safety equipment for team member: helmet, knee pads, elbow pads

Safety:

The main safety concern in these braking tests is during the use of manual breaking, which requires an active participant in the wheelchair. Several measures will be taken to ensure the safety of this participant. Rather than just starting at full speed, Tests 3 and 4 will begin at lower speeds and be incremented until maximum speed is reached so that the participant can become comfortable with the wheelchair and any safety risks that may have been missed can be identified. Additionally, the participant will be wearing protective gear such as a helmet, knee pads, and elbow pads as well as long pants, closed-toed shoes, and a protective jacket to limit injury in case a fall occurs. All tests will be performed with mostly clear and flat surroundings to limit possible injury from impacts or falls.

To ensure that the wheelchair properly initiates braking, the system code will be run while the wheelchair is held off of the ground. The propulsions system will be suspended by a team member holding the transmission housing such that the motorized wheels are not in contact with the ground or the team member. The system will be activated as if it were going to perform a breaking test, and the team will check to make sure that after a set time, the braking system will actually engage. This will prevent any simple coding glitches from causing a runaway wheelchair in the actual test.

2. <u>Obstacle Climbing Test</u>

Goal of Test: The goal of the obstacle climbing test is to ensure that the wheelchair will be able to climb and descend obstacles such as curbs, door thresholds, and other changes in height in compliance with ISO standard 7176-10 [16]. This test will test for Specification G8 and P8 [Section 4].

Procedure:

I. General Test
    1. Prepare the wheelchair: have fully charged battery and test dummy, and place the wheelchair with the dummy on the flat testing plane
    2. Set and secure obstacle on testing plane using clamps
    3. Position wheelchair with the obstacle according to the descriptions listed in Section III
    4. Send 25% speed command to the motors

5. Stop the motor once the wheelchair has gone both on and off of the obstacle
6. Record any part of the wheelchair other than the wheels and the device that came into contact with the obstacle and whether it was going on the obstacle or going off of the obstacle
7. Increase the height of the obstacle (increase in increments of 0.75 inches) and repeat steps 2-5
8. Once the wheelchair can no longer overcome the obstacle, record the maximum height of the obstacle it was able to overcome

II. Other Tests

A. Powered Off
   1. Prepare wheelchair: have a person of the weight of the average American man sit in the wheelchair [1]
   2. Set and secure obstacle on flat testing plane using clamps
   3. Position wheelchair with the obstacle according to the descriptions listed in Section III
   4. Have the person attempt to overcome the obstacle
   5. Record any part of the wheelchair other than the wheels and the device that came into contact with the obstacle
   6. Increase the height of the obstacle by 0.75 inches and repeat steps 2-5
   7. Once the wheelchair can no longer overcome the obstacle, record the maximum height of the obstacle it was able to overcome

B. Varying Power
   1. Repeat the general test, except instead of 25% power command being sent in step 4, increase the power command to the motors
      a. Do trials for 50%, 75%, and 100%. If the speed seems unsafe, do not proceed to a higher speed.

C. Incline
   1. Repeat the general test with positions 1-4, except instead of on a flat testing plane, use a car jack to increase the percent grade to 3, 6 and 10 degrees.
      a. Repeat the general test, but change the speed of the motor. Do trials for 50%, 75%, and 100%. If the speed seems unsafe, do not proceed to a higher speed.
      b. The obstacle should be placed at a higher elevation than the wheelchair

D. Decline
   1. Repeat the general test with positions 1-4, except instead of on a flat testing plane, use a car jack to increase the percent grade to 3, 6 and 10 degrees.
      a. Repeat the general test, but change the speed of the motor. Do trials for 50%, 75%, and 100%. If the speed seems unsafe, do not proceed to a higher speed.
      b. The obstacle should be placed at a lower elevation than the wheelchair

III. Positions

1. Front wheels in contact, wheelchair facing forwards, onto obstacle and off of obstacle
2. Approximately 20 in away, wheelchair facing forwards, onto obstacle and off of obstacle
3. Back wheels in contact, wheelchair facing backward, onto obstacle and off of obstacle
4. Approximately 20 in away, wheelchair facing backward, onto obstacle and off of obstacle

Required Equipment:

- Flat test plane and ramp
  - Car jack and mating attachment for raising and lowering the ramp
  - Ramp
- Test obstacles
  - Obstacles should make a 90° angle with the testing surface
  - Obstacle should be in increments of 0.75 in of height
- Clamps
- Test dummy
- Safety equipment for team member: helmet, knee pads, elbow pads

Safety:

The powered off testing poses serious safety concerns because it uses a human test subject to run the test. Risks include injury due to falling and the possible impact of any part of the device or wheelchair on the test subject. To mitigate these risks, the participant will wear protective gear including a helmet and skate pads. The risks are lessened in this experiment because the device will not be on or providing assistance. The test participant should also practice maneuvering a wheelchair before the test is conducted to familiarize themselves with the equipment.

Another consideration is the clamps that clamp the test obstacles to the test surface or ramp coming undone. This could cause the test obstacle to slip especially when attached to the test ramp which in turn could cause the wheelchair and device to tip or fall and cause damage. To mitigate this, the clamping system should be attached securely to the surface and should be tested to make sure it is rigorously clamping the test obstacle to the surface. This clamp should be resecured, adjusted and tested between each time the wheelchair approaches the obstacle.

The next safety concern is the risk of the wheelchair going over the end of the ramp at full speed. This concern is very high because this could cause extreme damage to the equipment, wheelchair, device, and testing space. To mitigate this the full speed test should only be performed when confidence in the emergency stop is ensured. The test obstacle should also be placed as close to the beginning of the ramp as possible to allow the wheelchair as much time to decelerate as possible. Other safety measures may be added such as netting or railing to decrease this risk. These additions will only be known once some testing has been done to understand the capabilities of the wheelchair and device. As with other testing, people should be as far away from the device as possible.

Apart from the safety concerns of conducting this test, a general safety check of the device and wheelchairs various components should be done beforehand. This will mitigate the risks associated with mechanical and electrical failure of the device. Overall, the testers, test participants, and spectators should all conduct themselves in a safe manner and in accordance with the safety guidelines of the test and of the space the test is being conducted in.