LAFAYETTE COLLEGE

Department of Mechanical Engineering

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

Wheelchair Team Prototype Testing Report

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1. Introduction

The purpose of the report is to explain our planned tests for the specifications in our Specifications Report [Appendix A]. We will have five main large tests: static stability test, braking effectiveness test, obstacle climbing test, user input force measurement accuracy, and a test for the propulsion force measurement accuracy. The static stability test is for Specification G5 (ISO 7176-1), and it will also encompass Specification P12. The braking effectiveness test is for specification G7 (ISO 7176-3), and it will also encompass Specification P3-7, and P9. The obstacle climbing test is for Specification G8 (ISO 7176-10), and it will also encompass Specification P8. The user input force measurement accuracy test is for Specification ES1. The propulsion force measurement accuracy test is for Specification ES2. Some smaller tests will be performed to verify Specification G2, G4, P10, P11, and E4.

When specifying the use of a dummy, we will be purchasing four 50 lb bags of sand and using straps to best distribute the weight of the sand. This will allow us to have a testing dummy of around 200 lbs with a distributed weight close to a human. Additionally when specifying a test ramp, a ramp is being built for testing which uses a car jack to raise and lower the ramp to different inclines.

2. General Safety Considerations

There are general safety precautions and considerations that are consistent throughout the various testing that will be 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 will be properly secured in the wheelchair with zip ties and ratchet straps. This will prevent the test dummy from falling out of the wheelchair or moving from the desired position. Additionally, all people running or viewing the test will be out of the way of the wheelchair and test dummy when possible.

The wheelchair and the device also pose a safety concern. Concerns include 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 is increased anytime that the device is running. For these reasons, it is important to keep the people running the test and people viewing the experiment away from the experiment whenever possible. The test ramp will also include a railing and other safety precautions to keep the device from falling off the ramp. If someone needs to be near the device when running, sufficient testing of the functionality and safety of the general device should be done beforehand. This may include testing the device's capability of going forwards and backwards on flat ground and on the ramp with a test dummy at different speeds. The emergency stop should also be sufficiently tested beforehand and if possible have remote stops to the device so that the physical emergency stop does not need to be pressed. This will be helpful for any malfunctions that may occur in testing.

The next concern involves potential instability using the car jack to raise and lower the ramp. To avoid these issues, we will provide safety training on how to operate the apparatus. Having this training will mitigate safety concerns. Similarly, ramp stability within the car jack mating attachment is critical for testing conditions; therefore, ensuring and defining proper alignment of the ramp within the attachment is something we plan to include in training. If the metal tube on the bottom of the ramp sits within the mating attachment, stability should be ensured and safety concerns will be mitigated. This will be verified per test by the testing group. Stability checks of the ramp should occur frequently and ensure that the test ramp is safe to use particularly when a person using the wheelchair will be on the ramp.

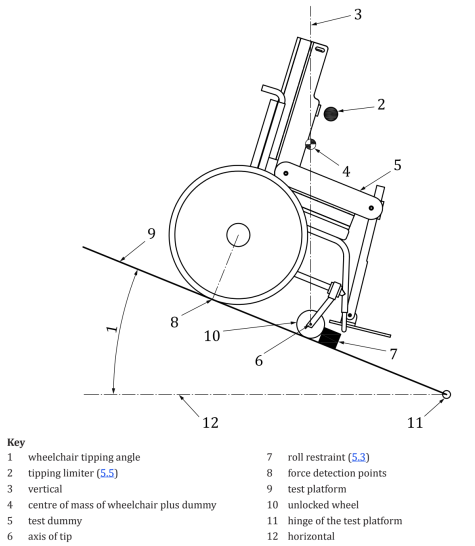
Generally, safety checks of the wheelchair, device and ramp will be done before any testing is conducted. This will help mitigate any mechanical or electrical failures during testing and keep participants, testers, and spectators safe.

3. Static Stability Test

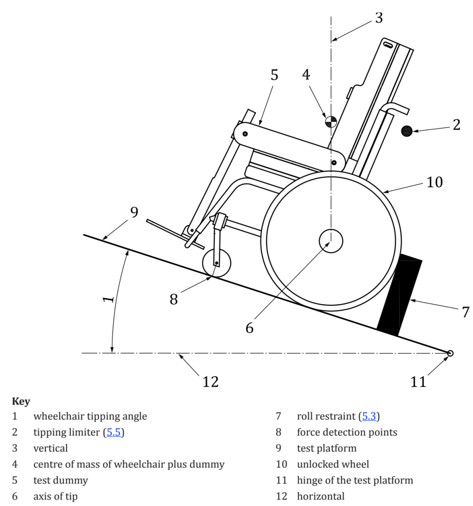
Goal of Test: The goal of the static stability test is to ensure stability of the wheelchair with the add-on on a ramp under varying inclination conditions. This test procedure is given by ISO standard 7176-1 referring to P3 [Appendix A]. This test will test for Specification G5 and P12 [Appendix A].

Procedure:

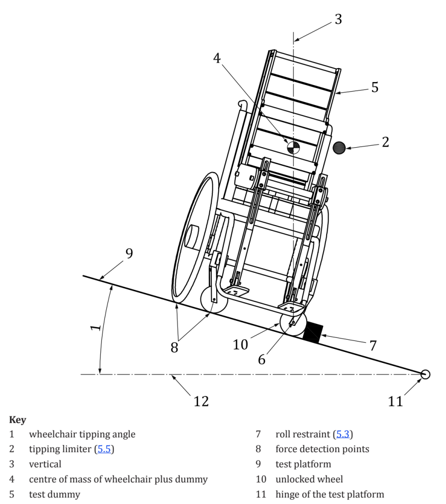
1. Prepare ramp for testing by positioning the ramp horizontally using the car jack.
2. Place the wheelchair on the test ramp. The test should be repeated 3 times for a forward (*Figure 1a*), backward (*Figure 1b*) and lateral orientation (*Figure 1c*). The following diagrams depict the orientation for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



a. Forward



b. Backward



c. Lateral

Figure 1. ISO diagrams for three different wheelchair positionings [2].

3. Place the roll restraint 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 at marked locations on the wheelchair.
6. Secure leveling device (or angle measurement device) to ramp near wheelchair.
7. Increase the angle of the platform by cranking the car jack until wheelchair tips. Record this angle to the nearest degree.
8. Lower the test platform using the crank on the car jack until it is in its lowest position.
9. Repeat steps 2-7 to ensure the wheelchair and add-on are tested with the three different orientations. Reference *Figures 1a, 1b,* and *1c*.

Required Equipment:

- 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*.
- Clamps
- Angle Measurement Device

Safety Concerns:

We are concerned with instability of the roll restraints. These restraints will be properly clamped in place per the specified location for different testing orientations. By ensuring stability, we will mitigate safety concerns as the ramp is raised and ensure valid testing results.

Clearing the area surrounding the ramp is important for bystander safety. We want to ensure that no one gets injured by the wheelchair or any of the setup. We will only have trained individuals touching the equipment and keep bystanders away during testing. The trained individuals will remain at the top of the ramp before and during the test.

Conducted By: Carolyn Pye, Drew Freeland, Emily Eng
Date of Test: 5/11/2021

4. 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 [Appendix A]. The test procedure is given by ISO standard 7176-3.

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.

Conducted By: Nick Moosic, Katie Rice, Matt Urban
Date of Test: 5/12/2021

5. <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. This test will test for Specification G8 and P8 [Appendix A].

Procedure:

I. General Test
   1. Prepare the wheelchair: have fully charged battery and test dummy, and place this system on the flat testing plane
   2. Set and secure obstacle on ramp using clamps
   3. Position wheelchair with the obstacle according to the descriptions listed in Section III
   4. Send full speed command to the motor
   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 (increase in increments of 5 mm) 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

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 ramp 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 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. Half power
      1. Repeat the general test, except instead of full power command being sent in step 4, send half power command to the motors
   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. 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. The obstacle should be placed at a lower elevation than the wheelchair

III. Positions
   1. Front wheels in contact, wheelchair facing forwards
   2. 500 mm away, wheelchair facing forwards
   3. Back wheels in contact, wheelchair facing backward
   4. 500 mm away, wheelchair facing backward
   5. 500 mm away, wheelchair going forward, but off of the obstacle
   6. 500 mm away, wheelchair facing backward, but off of the 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 5 mm 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.

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.

Conducted By: Charlotte Sullivan, Nicole Stanec, and Geoffrey Toth
Date of Test: 5/4/2021-5/11/2021

6. User Input Force Measurement Accuracy

Goal of Test: The goal of this test is to determine if the resolution of the user force measurement system based on the mathematical model calculations is within the percent error stated in the specification report. This will test for Specification ES1 [Appendix A].

Procedure:

All portions of this test will be performed with a human mass analog seated in the wheelchair. The propulsion system will briefly run at a known torque to kick the wheelchair forward and data will be recorded for the wheelchair coming to a stop. This data will be used to model the linear friction and angular damping on the system. Once a model of damping has been developed the propulsion system will run at a low, constant, known torque which can be fed into the mathematical model of the system along with the damping model and wheelchair angle data. As the wheelchair slowly moves forward under these conditions it will be pulled on with a spring scale so that the magnitude of the added force will be known and can be compared to the calculated force produced by the mathematical model.

Required Equipment:

- The wheelchair with the completed (or at least mostly functional) propulsion system
- A human analog with reasonable mass
- A spring scale

Safety:

The first step for safety is having the wheelchair be occupied by a test dummy rather than a human subject. That being said, the wheelchair will still be powered during this test which adds risk. To further mitigate this risk all testing speeds will be kept low and an emergency shut off will be available to stop the test should the wheelchair go out of control.

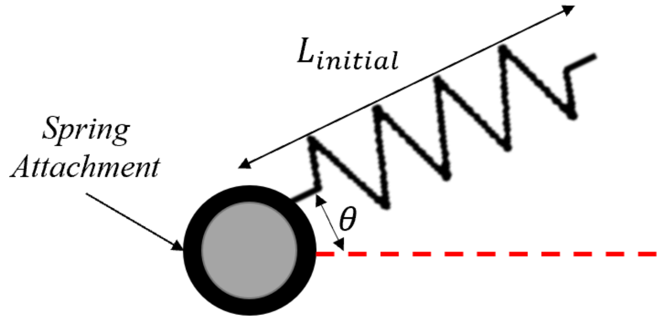
Conducted by: Drew Freeland, Nick Moosic
Data of Test: 5/11/2021

7. **Propulsion Force Measurement Accuracy**

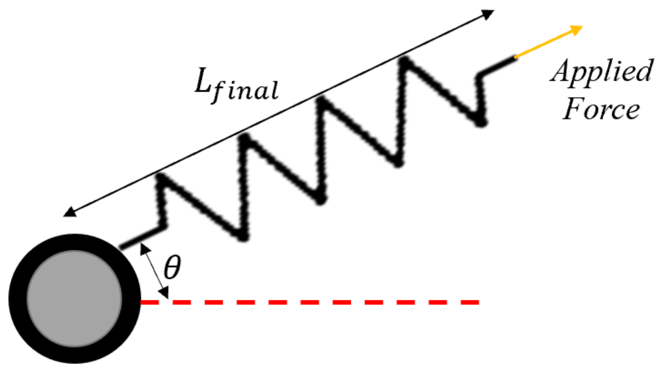
Goal of Test: The goal of this test is to determine if the propulsion force measurement using the strain gauge measurement apparatus is within the percent error stated in the specification report. Similarly, this will also ensure the horizontal bending force applied is being properly isolated by the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

Procedure:

1. Place the wheelchair including the strain gauge measurement system attachment in a clear testing area on flat ground.
2. Ensure propulsive add-on has been removed from the rod. If not, remove the subsystem so just the strain gauges and the left and right rod attachments are connected to the wheelchair.
3. Turn on the strain gauge measurement system.
4. Connect the spring using the spring mating attachment to the rod.
5. Position the spring at a known angle using the angle measurement device. Take a picture of the spring with the measurement angle device for documentation.
6. Use a ruler to measure and record the initial length of the spring.
7. Calibrate the strain gauge measurement system.
8. Pull the spring to apply a force. Record the strain gauge measurement taken by the subsystem. Take a picture of the final length of the spring that it's been pulled to. The following *Figure 2a* and *2b* depict how the spring attachment and spring should be positioned and pulled to apply the force.



a. Initial Position



b. Force Application

Figure 2. Diagram representing the spring attachment, force application, and important parameters to record during testing.

9. Return the spring to the starting position by releasing the tension from pulling.
10. Repeat steps 5-8 for 10 different angle and force combinations.
11. Using the known information about spring constant, initial and final lengths of the spring, the angle at which the spring was applied, and the pictures from each of tests, find the horizontal component of the force applied by the spring and compare it to the measurement of the strain gauge subsystem by calculating percent error.

Required Equipment:

- Spring (with a known k constant)
- Spring mating attachment
  - Specifically to attach to the propulsion rod to apply a known force to the rod
- Strain gauge measurement subsystem
- Angle measurement device
- Ruler
- Camera

Safety:
Overall, this test does not have extreme safety concerns. That being said, the wheelchair will still be powered during this test which adds risk. To further mitigate this risk all testing speeds will not exceed zero and an emergency shut off will be available to cut the test off short should the wheelchair experience issues.

Conducted by: Drew Freeland, Nick Moosic
Data of Test: 5/11/2021

8. Weight

The goal of this test is to weigh all of the added material to the wheelchair to ensure the added weight of the device does not exceed the max value of Specification G2 [Appendix A].
To accomplish this all components of the device including the propulsion, electro-mechanical, and effort sensing systems will be weighed using a scale.

9. Added Width

The goal of this test is 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 [Appendix A]. All parts of the device will be attached to the wheelchair and then the outermost protruding part of the device will be measured and recorded.

10. E-Stop

The purpose of this test is to make sure that pressing the E-stop button performs all actions described in Specification E4 [Appendix A]. To test this, the device will be turned on and put into all of its various modes. The E-stop will be engaged and show that it shuts off the motors.

11. Ability to Go Backwards

This test is performed to ensure that the wheelchair can go backward with and without help from the attachment with ease. This test reflects Specification P10 [Appendix A]. To test this specification the device will be attached to the wheelchair and the test dummy will be put in the wheelchair. The device will be turned on and the device will have a command to go backward.

12. Ability to Steer

The purpose of this test is to ensure that the motors can function independently of each other such that the user can steer easily using the wheelchair attachment. This tests Specification P11 [Appendix A]. The device will be attached to the wheelchair and the test dummy will be secured to the wheelchair. The device will then be turned on and various commands will be given to the device to test the steering including forwards, backward, left, and right commands.

13. Budget

The current cost of the prototype is about $1,957.85. This was calculated to include the cost of extra material including screws and scrap metal. This satisfies Specification G1, but we would still like to continue to work to minimize the cost without sacrificing functionality or safety. The team has spent an additional $811.62 for testing equipment and extra components that were for testing or replacement, excluding materials that may be returned. It is expected that the additional expenses total will increase to accommodate testing needs, including the cost of test dummy materials and safety equipment. This is expected to be at least $50, creating a total budget for the team of approximately $2,820.

14. Schedule

The current updated schedule can be seen below. Generally, the integrations of the different subteams will occur in mid-April, and testing and redesign will follow after integration. The first table (Table 1) shows the general schedule which involves dates regarding the integration of different subsystems and the deliverables of the course. The general team tasks are shown in blue and the team deliverables are shown in grey. The second table (Table 2) shows the subteam specific tasks. The propulsion team is shown in green, the electro-mechanical integration team is shown in pink, and the effort sensing team is seen in orange.

Table 1: General Team Task and Deliverables Schedule

Task	Duration (days)	Start Date	End Date
Complete Sub-team initial parts/software	7	4-Apr	10-Apr
Manufacture sub-team initial parts	14	4-Apr	17-Apr
Assemble sub-team initial parts	14	4-Apr	17-Apr
Test sub-team specific software	14	4-Apr	17-Apr
Test sub-team specific designs/parts	14	4-Apr	17-Apr
Adjust parts/software according to initial tests	14	4-Apr	17-Apr
Manufacture updated parts	14	4-Apr	17-Apr
Assemble and test updated parts/software	14	4-Apr	17-Apr
Update parts and software as needed	14	4-Apr	17-Apr
Integrate propulsion and EMI systems	13	10-Apr	22-Apr
Test propulsion and EMI integration	13	10-Apr	22-Apr
Update and Adjust Propulsion and EMI systems	7	16-Apr	22-Apr
Integrate EMI and Effort systems	23	12-Apr	4-May
Test EMI and Effort integration	23	12-Apr	4-May
Update and adjust EMI/Propulsion and effort integration	8	27-Apr	4-May
Test full assembly with test dummy	14	27-Apr	10-May
Adjust Full Assembly	14	27-April	10-May
Test Updated Full Assembly	11	8-May	18-May
Final Updates to parts	11	8-May	18-May
Final Assembly Testing and Documenting	25	1-May	25-May
Complete Final Draft of Prototype Evaluation and System Testing Report (4/12)	8	5-Apr	12-Apr
Complete Statement of Individual Goals (4/12)	3	10-Apr	12-Apr
Plan for Presentation 3 (4/19)	4	16-Apr	19-Apr
Complete Rough Draft of Final Report	6	15-May	20-May
Time for Utter to Review	2	20-May	21-May
Complete Final Draft of Final Report (5/25)	5	21-May	25-May
Plan Prototype Demonstration Rough Draft (TBD)	TBD	TBD	TBD
Time for Utter to Review (TBD)	TBD	TBD	TBD
Complete Prototype Demonstration Final Draft (TBD)	TBD	TBD	TBD
Plan poster/video presentation (TBD)	TBD	TBD	TBD
Time for Utter to Review (TBD)	TBD	TBD	TBD
Create Final Poster/Video Presentation (TBD)	TBD	TBD	TBD

Table 2: Subteam Team Task Schedule

Task	Duration (days)	Start Date	End Date
Manufacture components	14	4-Apr	17-Apr
Test complete system	14	4-Apr	17-Apr
Adjust system accordingly	17	4-Apr	20-Apr
Solder electrical components to circuit board	7	13-Apr	20-Apr
Test Circuit Board	14	13-Apr	27-Apr
Test all 3D printed components	7	13-Apr	20-Apr
Finish code for entire model	21	13-Apr	4-May
Waterproof housing	14	27-Apr	11-May
Assemble housing with electrical components	0	11-May	11-May
Test completed and assembled system	7	11-May	18-May
Develop Code to Take Data from Magnetometer	51	8-Feb	30-March
Understand Magnetometer and Data Received	51	8-Feb	30-March
Write Code to Calibrate the Magnetometer	36	30-March	4-May
Write Code to Implement Mathematical Model with the Sensor	22	13-April	4-May
Test Sensitivity of 9DOF Sensor to Electronics/Motor	36	30-Mar	4-May
Design Test Ramp	16	8-Feb	23-Feb
Complete Purchase Forms for Test Ramp	16	8-Feb	23-Feb
Manufacture and Assemble Test Ramp	22	30-March	20-April
Use Test Ramp to Calibrate and Test Angle/Mathematical Model Code	15	20-April	4-May
Pick Out Strain Gauges to Measure Force of Wheel Add-on on Chair	16	8-Feb	23-Feb
Pick Out Board to Attach Strain Gauge Sensors to	16	8-Feb	23-Feb
Complete Purchase Forms for Strain Gauge Measurement System	16	8-Feb	23-Feb
Soder/Wire/Assemble Strain Gauge Measuring System	15	13-April	27-April
Take/Interpret Data from Strain Gauge Assembly	15	27-April	11-May
Write Code to Measure the Force of the Wheel Add-on	15	27-April	11-May
Integrate Effort Sensing Code for 9DOF Sensor	15	4-May	18-May
Integrate Effort Sensing Code for Strain Gauge Assembly	15	4-May	18-May
Design Housing for 9DOF Sensor	15	23-March	6-April
Integrate Hardwiring for 9DOF Sensor	15	4-May	18-May
Design Housing for Strain Gauges	15	23-March	6-April
Integrate Strain Gauge Assembly/Hardwiring	15	4-May	18-May
Test Full System on Chair	15	4-May	18-May

**For the entire timeline for the team and each of the subteams, please follow this link.*

Research References:

1. Roland, J. (2019, March 7). How much does the average American man weigh? Retrieved November 24, 2020, from
2. Wheelchairs- Part 1: Determination of Static Stability. (2014). *International Organization for Standardization. International Standard, 7176*-1.
3. Wheelchairs- Part 3: Determination of Effectiveness of Brakes. (2012). *International Organization for Standardization. International Standard, 7176*-3.
4. Wheelchairs- Part 10: Determination of Obstacle-Climbing Ability of Electrically Powered Wheelchairs. (2008). *International Organization for Standardization. International Standard, 7176*-10.

Appendix A: Prototype Specification Report

1. Introduction

The purpose of the report 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 the general, 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 has developed, subteam specific metrics emerged. Some measurable quantities identified are the 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. All specifications will be further developed as prototyping and modeling continue, but the current specifications are found in the sections below for the full team's general specifications and subteam specific specifications.

The report is organized into four sections: 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.

2. General Specifications

The goal of the project is to make areas that are difficult to navigate more accessible to people with limited mobility by creating a device designed to assist manual wheelchair users in ascending and descending sloping surfaces. 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 1).

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 are intended to be met, but if not met a redesign may not be required. However, if a constrained value is not met, a redesign should be considered and discussed because the device is 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.

Table 1: 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 will not exceed $2500 to stay within competitive pricing of prior art (Table A1). 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 B1, Appendix B). Cost of manufacturing, and cost of parts are considered in determining the design of the device to ensure this specification is 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 exceed 25 lbs. Setting the total added weight to 25 lbs allows the user to push the wheelchair when the device is not in use and 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 A1 (Appendix A), the range of added weight of the four prior art is 13.5 lbs - 35 lbs. 25 lbs is currently the specified added weight as it is in the middle of the prior art range. To achieve this specification, lightweight materials are being used where applicable such as aluminum while also balancing Specification G1 to keep costs low.

G3. The device needs to 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 will be used to test the device and assess the device's ability to withstand different weather changes. To aid in weatherproofing, the device's electrical components are being waterproofed. Stainless steel and aluminum are 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 exceed 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. Additionally, the control interface has been designed to meet this width requirement.

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 will be carried out when the device prototype is fully assembled.

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 requires a full assembly prototype of the device attached to a wheelchair. This specification will be taken into account during the testing stage of our design after we complete our first prototype.

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 which will be tested using the ISO 7176-3 standards once the prototype is assembled.

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 will be completed on a fully assembled prototype.

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 will be used to confirm that the device's control and power system meet the requirements of the standard. The maximum speed will be 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 will be conducted on the fully assembled prototype.

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]. These testing methods will be used to test the full assembly prototype and ensure the batteries and chargers are safe and up to ISO standards. ISO 7176-31 is a standard under development concerning lithium based battery technology for electric wheelchairs. If it is published before the completion of the project, it may be used to further define this specification.

3. Propulsion Team Specifications

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 is a conservative design choice because the weight of an average American man is greater than the average weight of an American person.

Table 2: 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	

Table 2: ***Continued***

#	Metric/Specification	Target Minimum Value	Target Maximum Value	Unit	Maximize /Minimize /Target/ Constraint	Constrained Max/Min or Yes/No
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 A1). 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 will be 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 will be 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]. To put the stopping capabilities within the competitive range of other products on the market the current target incline grade is 8.3% for stopping without user intervention. 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 an 8.3% grade but changes to the spring strength may change to balance Specification P8, P9, and P10.

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. Electro-Mechanical Integration 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 3: 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.

5. Effort Sensing 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 4: Effort Sensing Team Specification and Metrics

#	Metric/Specification	Minimum Value	Maximum Value	Unit	Maximize /Minimize/ Target/Constraint	Constrained Max/Min
ES1	Sampling rate of 9DOF measurement system		∞		Maximize	
ES2	Sampling rate of strain gauge measurement system		∞		Maximize	
ES3	Response time to call to the propulsion system	0			Minimize	
ES4	Response time to register user input from user to the joystick	0			Minimize	
ES5	Percent error in strain measurement	0			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 response time to call the propulsion system must be fast enough to ensure the propulsion system can make adjustments based on input to operate efficiently. This ensures the propulsion system can use the data to respond as designed.

ES4. The response time of registering user input from the joystick must be fast enough to ensure the 9DOF measurement system can correctly implement the mathematical model based on the input to efficiently generate output. This ensures the effort sensing subsystem will be able to generate outputs quickly based on the input from the electro-mechanical integration subsystem.

ES5. The percent 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.

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Appendix B: Background Research and Prior Art

Table B1: Pricing, Weights, Range and Speeds of Different Wheelchair Add-On Devices currently on the market

	SmartDrive MX2 Power Assist [10]	**Firefly 2.5 [5]**	**E-Motion [1]**	**SMOOV One [9]**
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