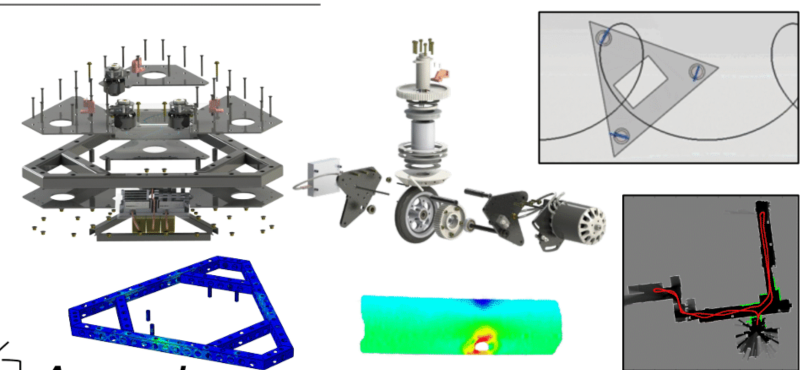
MEM P15

Swerve Robotic Platform

Background

There are many robotic platforms that are either nimble, high speed, lightweight, or have integrated autonomy, but there does not exist a commercially available robot platform that integrates all of these elements into one platform.

Approach



Objective

Unique Features

- Withstand Large Loads
- High Torque BLDC Motors
- Nimble with High Acceleration
- Integrated Autonomy
- Multi-Purpose Platform

Nimble | Support a Person | Lightweight | Human Machine Interface | High Speed

Solution

Multi-Purpose Platform for Various Industries

Warehouse Optimization | Personal Mobility | Entertainment

Members

(MEM) Harrison Katz Alexander Nhan (ECE)
(MEM) Frederick Wachter Matthew Wiese (MEM)

Head Advisor
Dr. Ajmal Yousuff

Co-Advisor
Dr. Tein-Min Tan

Stakeholder
Josh Geating

Sponsors

Josh Geating, SICK Sensors, Botstiber Senior Design Competition,
ASME Philadelphia, Drexel MEM Department

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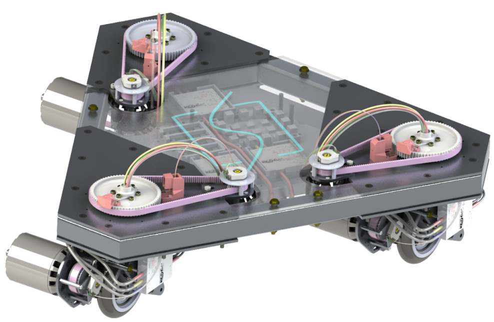
Abstract

The Swerve Robotic Platform is a three-wheeled, autonomy-enabled vehicle that is capable of carrying large loads while moving at high speeds and accelerations. This type of platform does not exist on the market today and is targeted for the entertainment, warehouse optimization, and personal mobility industries. This platform was designed, fabricated, and tested using modern tools including motion capture systems, advanced machining techniques, computer simulations and software, as well as state-of- the-art sensors. Additionally, the vehicle was designed and manufactured to be lightweight and robust by using finite element analysis, an analysis driven design process, and computer controlled tooling. The platform software was developed in the Robot Operating Systems (ROS) framework and utilized the Gazebo physics simulator in order to generate data sets and test autonomy algorithms in both simulation and on the physical platform. System models, sensors, as well sensing techniques were used to provide the platform with the ability to understand its local environment and its location within that environment. A human-machine interface is provided with the platform to allow for intuitive control of the system. The platform adheres to ASTM, AWS, and AISC standards pertaining to system design, analysis, and testing in addition to Google and ROC C++ style guidelines for software development. The project is successful as the test and validation results showed that the platform met all design criteria.



Introduction

Project Purpose

Robotic mobility platforms on the market today integrate one or two of the following four elements: lightweight, high speed, omni-directional, and integrated autonomy. None of these platforms have integrated all four of these elements onto one product. The purpose of this project is to create such a platform. This platform is called Swerve which incorporates the unique features of being able to withstand loads up to 300 pounds, have high torque brushless DC motors, be nimble with high acceleration capabilities, have integrated autonomy. This is a multi-purpose purpose platform targeted for the warehouse optimization, entertainment, and personal mobility markets.

Project Goals

The project's stakeholder, Josh Geating, will be using this robotic platform for the purpose of personal mobility. He wants a platform that is able to support payloads up to a 95th percentile male (300 lbs, 6’ 2”) that is able to move at speeds and acceleration faster than Usain Bolt. Additionally, this platform must have omni-directional and variable speed capabilities that is controlled using a human-machine interface provided with the platform. The platform must have a weight limit of 100 pounds. **Table 1** shows the success criteria based on the stakeholder's need with the four elements mentioned are of primary priority while the rest are secondary and tertiary priority. The courses for criteria 1 and 8 are described in the *Testing and Validation* section.

Table 1. Project Success Criteria.

#	Needs	Pri.	Metric	Value
1	Highly Nimble	1	Time to Complete Course	< 1 minute
2	Support Heavy Loads	1	Support Static Over-Weight Load	300 lbs
3	Lightweight	1	Weight of Vehicle (Without Power)	100 lbs ± 10 lbs
4	Human-Machine Interface	1	Remote Control by Human	Yes/No
5	Maintain Ability to be Disassembled	2	No Gross Permanent Connections	Yes/No
6	Faster than Usain Bolt Top Speed	3	Top Vehicle Speed	> 27.8 mph
7	Faster than Usain Bolt Accleration	3	Top Acceleration	> 19 ft/sec^2
8	Autonomous	3	Navigate Predefined Course	0 Collisions

Standards, Referenced Publications, and Practices

Table 2 lists the standards and practices that were referenced and implemented while developing the Swerve platform. The referenced standards and specifications are developed by various organizations and publications, influence multiple industries, and affect the design and analysis of every aspect of the Swerve platform.

Table 2. List of Standards and Specifications Used for Developing Swerve.

ASTM F2291-17: *Standard Practice for Design of Amusement Rides and Devices*
ASTM E855-08: *Bend Testing of Metallic Flat Materials for Spring Applications*
RCSC - 2009: *Specification for Structural Joints Using High-Strength Bolts*
ASIC 360-16: *Specification for Structural Steel Buildings*
AWS D1.2: *Structural Welding Code - Aluminum*
Google C++ Style Guide: *Programming Style Guidelines*
ROS C++ Style Guide: *Programming Style Guidelines*
Doxygen: *Automated Code Documentation*

Project Management

Personnel

The Swerve senior design team consists of three mechanical engineers (Harrison Katz, Frederick Wachter, Matthew Wise) and one computer engineer (Alexander Nhan) advised by two mechanical engineering professors (Dr Ajmal Yousuff, Dr. Tein-Min Tan) and an external stakeholder (Josh Geating). Harrison Katz and Matthew Wiese have experience with mechanical design and analysis and they form the mechanical team. Alexander Nhan and Frederick Wachter have experience with software development and algorithms and they form the software team.

Project Schedule

The original schedule, shown in **Figure 1A**, consisted of 10 weeks of mechanical design and analysis, 10 weeks of manufacturing, and the remaining time for testing.

After the initial platform analysis was performed by the team, it was determined that more time should be spent flushing out the mechanical design before beginning manufacturing. For this reason, the mechanical portion of the project was extended while the remaining portions were shortened as shown in the final schedule in **Figure 1B**.

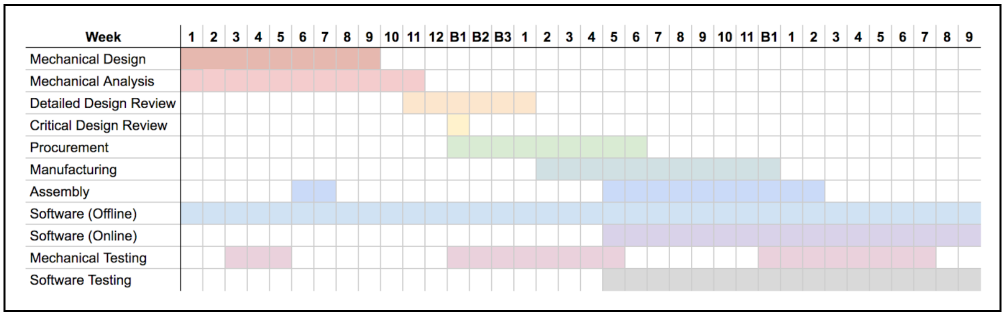


Figure 1A. Original Project Schedule.

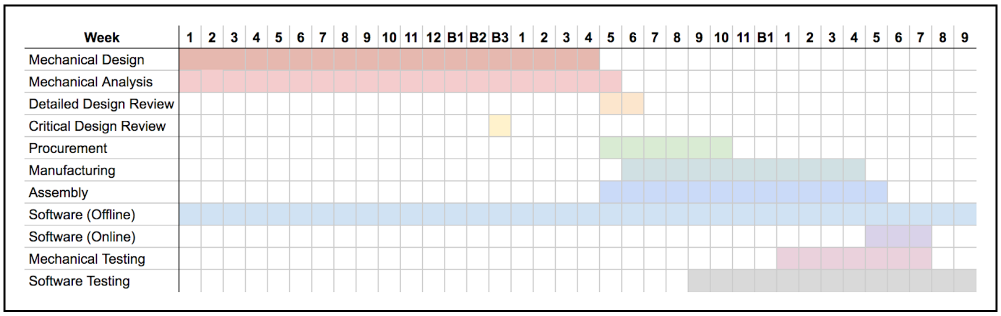


Figure 1B. Final Project Schedule.

Project Costs

Figure 2 shows the project expenses. The project costs $4,756.89 for all the autonomy sensors and computers and $3,100.62 for the platform. Overall, the project costs $7,857.51.

Mechanical Hardware							
2.0in. X 0.12in. SQ. and 0.25in Rad 6061-T6	$	38.33	3	$	-	$	114.99
24.0in. X 48.0in. X 0.19in. Sheet, 6061-T6	$	127.04	2	$	-	$	254.08
0.625in. OD X 0.125in Tube, 6061-T6	$	60.01	2	$	-	$	120.02
2.5in. Dia Bar, 8620 Hot Rolled Steel	$	95.13	1	$	-	$	95.13
1/4-20 X 3in. Flat Socket Cap Screw	$	0.68	114	$	-	$	77.47
1/4-20 Nylon Insert Lock Nut, Grade 5	$	0.29	200	$	-	$	58.38
1/4" X 0.625" Hardened Washer, Yellow Zinc	$	11.16	1	$	-	$	11.16
1/4" X 0.625" General Washer, Zinc	$	0.04	200	$	-	$	8.04
1/4-20 X 2in. Hex Cap Screw, Yellow Zinc	$	0.33	50	$	-	$	16.33
1/4-20 X 1in. Hex Cap Screw, Yellow Zinc	$	0.21	50	$	-	$	10.44
55mm ID, 80mm OD, Ball Bearing	$	280.13	6	$	9.98	$	1,690.76
55mm ID, 78mm OD, Thrust Bearing	$	85.91	6	$	9.98	$	525.44
5mm Pitch, 12mm Bore, 28 Teeth, Timing Pulley	$	16.04	6	$	-	$	96.24
5mm Pitch, 8mm Bore, 15 Teeth, Timing Pulley	$	7.38	3	$	-	$	22.14
Grand Total Mechanical Hardware:						**$**	**3,100.62**

Sensors and Electronics							
NVidia Jetson TX2	$	299.00	1	$	-	$	299.00
Teensy 3.6	$	29.25	4	$	-	$	117.00
High-Accuracy LIDAR	$	2,599.00	1	$	-	$	2,599.00
Ublox NEO-M8N GPS Module	$	19.99	1	$	-	$	19.99
ZED Camera	$	449.00	1	$	-	$	449.00
VESC Motor Controller	$	99.00	6	$	-	$	594.00
Xbee Xtend 900MHz	$	194.95	2	$	-	$	389.90
UpBoard Squared	$	289.00	1	$	-	$	289.00
Grand Total Sensors and Electronics:						**$**	**4,756.89**

Figure 2. Project Costs for the Platform and Autonomy Sensors/Computers.

Design Process and Review

As shown in **Figure 1B**, a Detailed Design Review (DDR) and a Critical Design Review (CDR) were hosted in order to receive feedback from advisors and external reviewers to ensure the assumptions made in the design of the platform were correct along with general design features. The team adhered to an analysis driven design process by utilizing simulations and advanced analysis in order to provide a high quality product within the nine-month timespan. Additionally the team validated all of the design assumptions through testing. Links to the DDR are listed below.

Links to Detailed Design Review Documents

swerveroboticsystems.github.io/DDR/Design
swerveroboticsystems.github.io/DDR/Analysis
swerveroboticsystems.github.io/DDR/Software

Mechanical Design and Analysis

Throughout the entire design process, the team adhered to an analysis driven design practice. The design of many elements was iterated after analysis to achieve a safe, reliable, and efficient design. **Figure 3** shows the exploded view models for the final chassis and wheel assembly designs. One thing of note is that the chassis is connected by gusset plates using countersink bolts as well as crush tubes that are welded within the chassis as shown below in **Figure 4**.

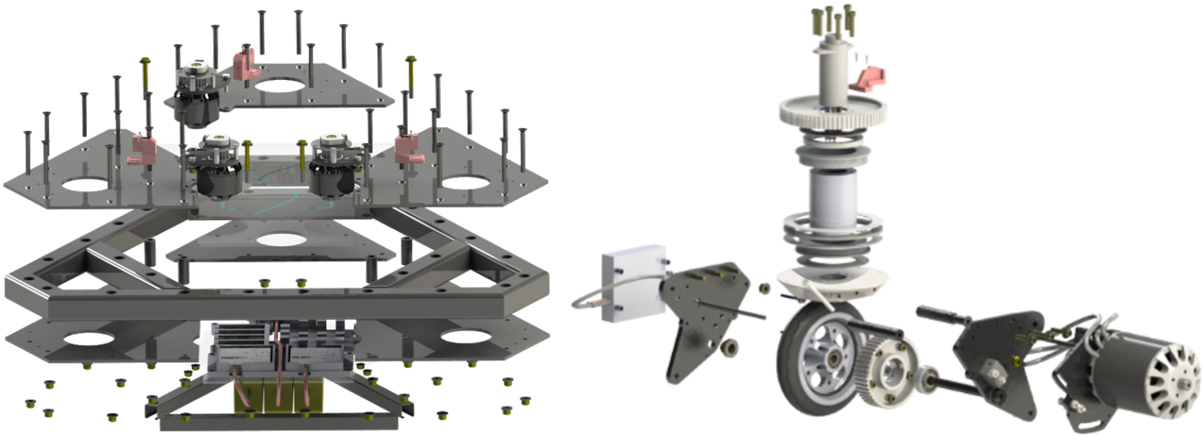


Figure 3. Chassis Assembly Exploded View (Left) and Wheel Assembly Exploded View (Right).

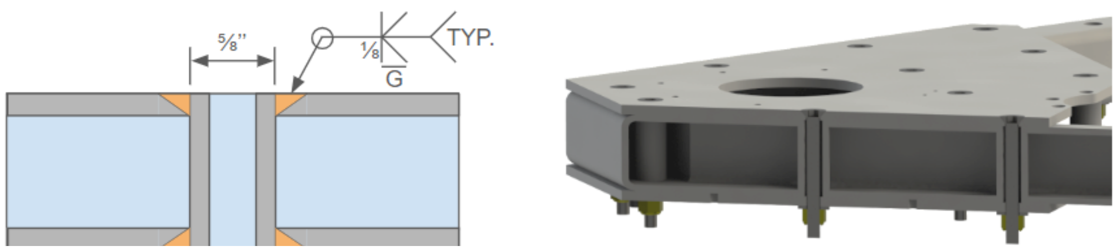


Figure 4. Typical Crush Tube Weld Detail (Left) and Chassis Cross Section (Right).

Structural and Mechanical Analysis

The design and analysis were based on a 1G (32.2 ft/sec^2) acceleration. This system is intended to be used for recreation, for short periods of time, and in dry as well as clean environments. Therefore, fatigue considerations and material corrosion are beyond the scope of the analysis. For analysis success, the mechanical and structural components were expected to pass conservative safety factors for strength load cases.

Per ASTM F2291 (Standard Practice for Design of Amusement Rides and Devices), the rider was assumed to be a 300lbs, 95th percentile male for all strength load cases. Using ABAQUS/CAE, a finite element model was created and analyzed. Additionally, supporting structural and mechanical calculations were completed to validate the proposed design. Considering that most of the vehicle structure is made from aluminum, the safety factors per the Aluminum Specification are shown in **Table 3**. Per the Aluminum Specification, Bridge type structures are defined as structures dominated by dynamic loading. Since the platform is subject to highly dynamic loading, the bridge type safety factors were considered for all analyses related to aluminum material.

Table 3. Applicable Safety Factors for Aluminum Material per the Aluminum Specification.

TABLE 6.1 Safety Margins in the Aluminum *Specification*

Type of Structure	Yield Strength	Ultimate Strength
Building Type	1.65	1.95
Bridge Type	1.85	2.20

The finite element model for the chassis, including the detailed bearing connection assembly, is shown in **Figure 5**. The stress distribution in the chassis under the worst case loading scenario in which the chassis is subjected to the weight of patron and a 1g acceleration is shown in **Figure 6**.

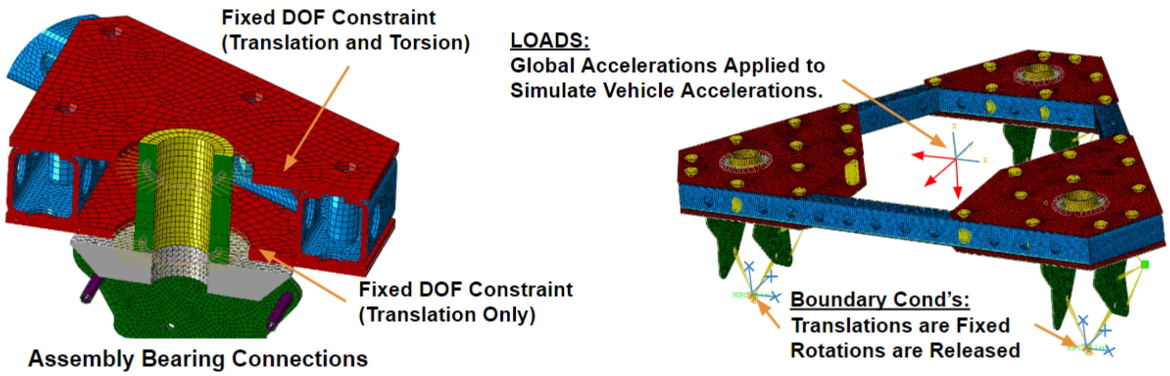


Figure 5. Finite Element Model with Boundary Conditions, Applied Loads, and Connections.

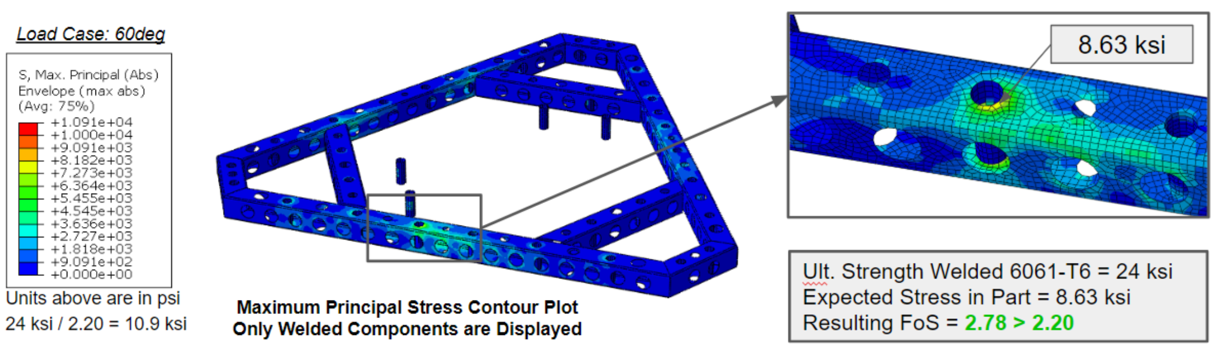


Figure 6. Stress Contour Plot of Chassis Welded Analysis (Principal Stresses Shown).

Additional mechanical and structural analyses for fabricated and consumer off the shelf (COTS) parts were conducted to confirm that all components have adequate capacity. Abridged variable derivations for beam and bolted joint analyses are shown in **Figure 7**. All analyzed components were proven to meet minimum required safety factors.

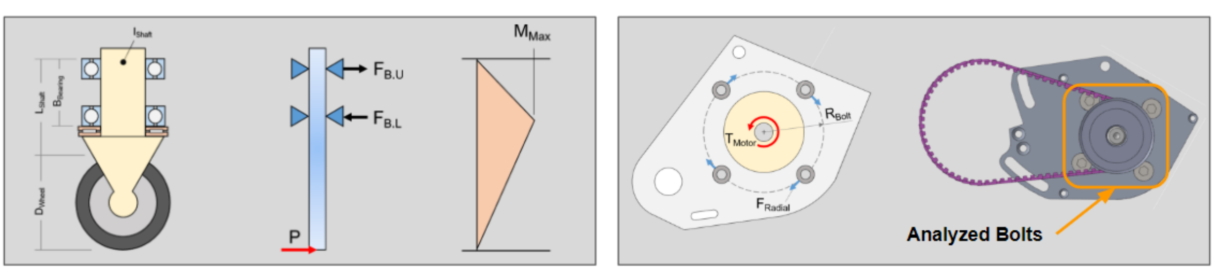


Figure 7. Shaft Bending Analysis (Left) Bolted Joint Analysis (Right).

Manufacturing

Critical Path to Manufacturing Success

All the mechanical components manufactured for the platform were either custom from stock metal or modified COTS parts in order to keep a compact and lightweight platform. 5-Axis water jet cutting, 3D CNC milling, aluminum welding, as well as manual lathe and milling processes were used to manufacture the components. All critical parts were held within 0.005" tolerance to ensure all parts could be assembled without introducing stresses. **Figure 8** shows the manufacturing flow chart used to track milestones and ensure the project would be finished within the designated time.

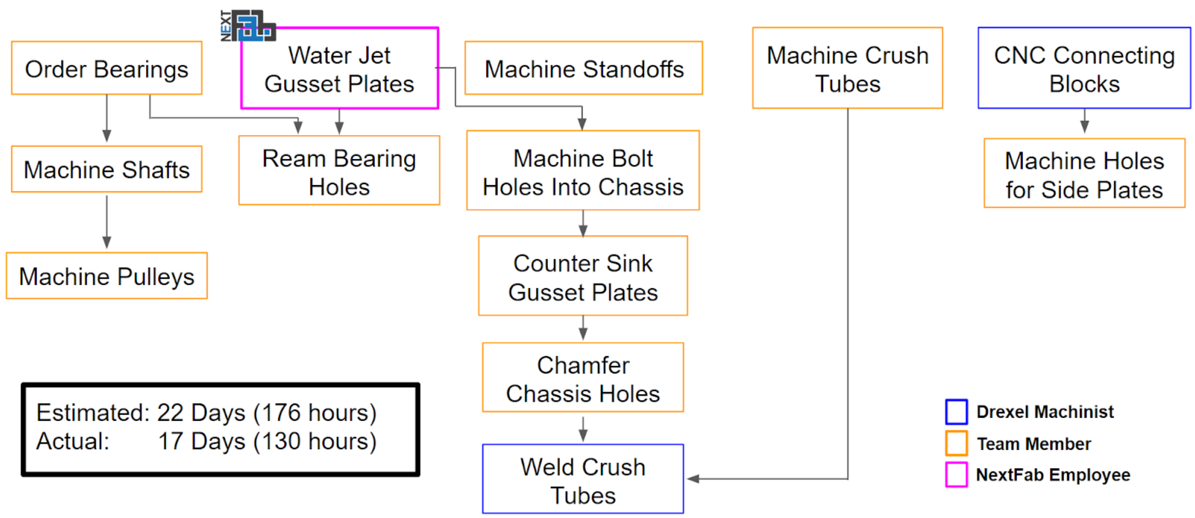


Figure 8. Completed Critical Path to Success for Manufacturing.

To reduce time for manufacturing, many components were designed so that the majority of the structure is two dimensional complex shapes joined by standoffs. This type of design is easy to manufacture with waterjet cutting technology, easy to assemble, as well as robust in strength.

Gusset Plates & Tolerancing

The gusset plates were manufactured using a waterjet and manual mill. Large holes in the gusset plates were undersized since the waterjet cuts left an undesirable surface finish and the flange bearings inserted in the holes required a tight tolerance. **Figure 9** shows the process used to manufacture this part including the coaxial centering indicator used to accurately find the center since the gusset plate holes were held to a 0.002" tolerance.

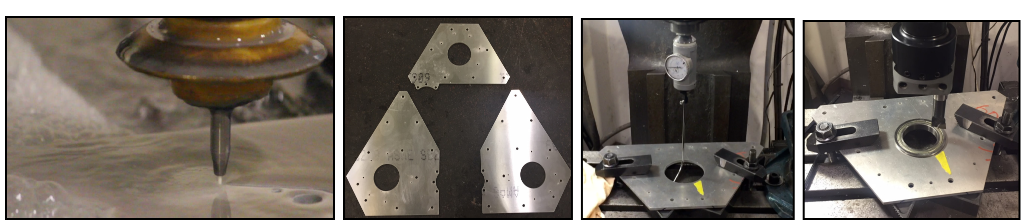


Figure 9. View of Waterjet Cutting Gusset Plates (Left), Plates Post Waterjet Cutting (Right).

Chassis Hollow Structural Tubes & Welding

The hollow structural sections were machined from 6061-T6 aluminum tube stock. Each aluminum member was cut to size and prepared for welding by inserting the crush tubes. Welding was performed by the Drexel Machine Shop and grinded down by the team members. **Figure 10** provides an overview of these processes.

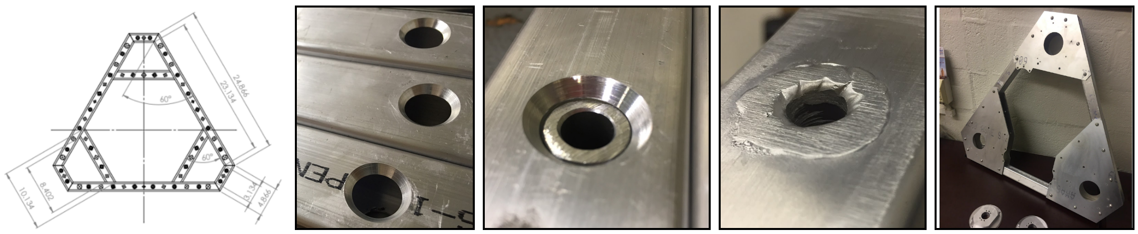


Figure 10. Crush Tube Welding Process.

Connecting Block

The connecting block was designed to remove weight and act as a mounting and locating surface for the wheel assembly thrust bearing. Autodesk's Fusion 360 was used to create a computer automated manufacturing simulation, the part was then mounted into the CNC mill and manufactured at the Drexel Machine Shop, seen in **Figure 11** (middle).

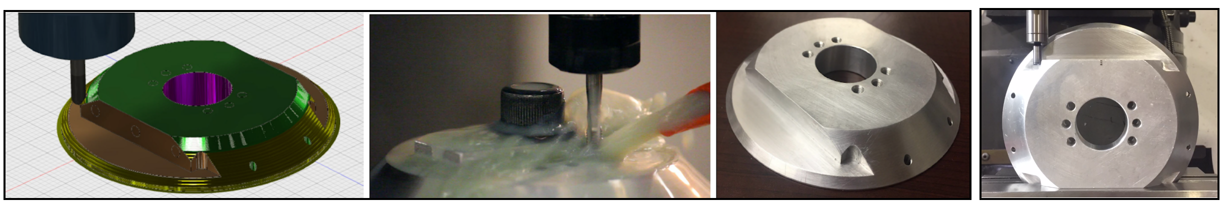


Figure 11. CAM simulation, Actual CNC Machining, CNC Part, Locating Feature.

After the CNC milling operation, threaded holes were added by locating the part using the specifically designed features. Next a center bit, tap drill, and tapped were used to create the threaded hole which connects the block to the wheel assembly side plates.

Electronics

The selection for the electronics was determined based on the hardware provided by the stakeholder and the requirements determined by the software architecture. The electrical layout is shown in **Figure 12**.

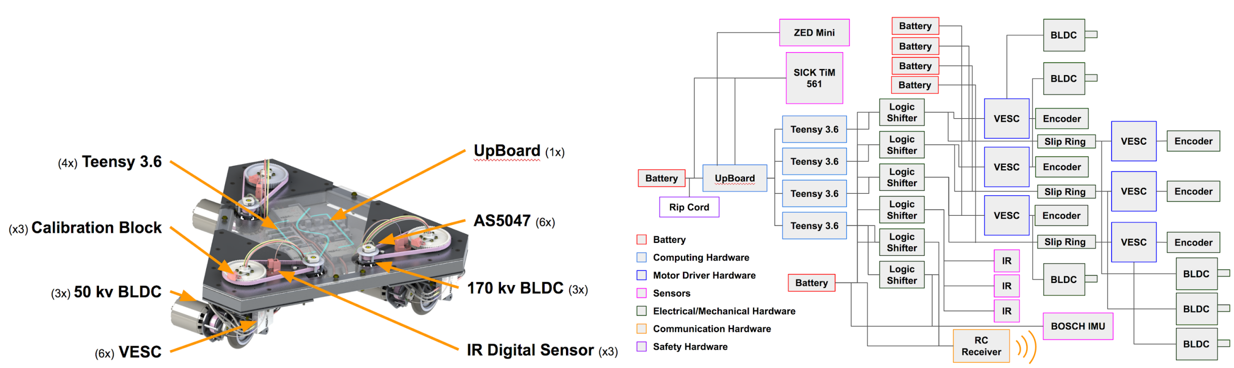


Figure 12. Electrical Hardware Locations (left) and Electrical Layout (right).

Motor Selection

The stakeholder previously purchased and provided the six brushless DC (BLDC) motors and controllers (called VESC) along with AS5047 14-bit magnetic motor encoders. Three BLDC's at 50kV were used to drive the wheel while the remaining three 190kV motors control the yaw mechanism.

Computing, Sensing, and Electronics

An UpBoard onboard computer with Linux was required to setup the communication network for the hardware on the platform. Teensy 3.6 microcontrollers are used to provide real time control to the motors through their motor controllers while also being able to receive/send data to and from the onboard computer. An RC controller was provided as the human machine interface to control the platform. Additionally, each wheel yaw mechanism is calibrated using an IR digital distance sensor used in conjunction with a 3D printed calibration block in order to zero the location of the motor each time the platform is powered. A SICK TiM561 2D scanning LiDAR, ZED Mini stereo camera, and a BOSCH BNO055 IMU are integrated on the platform to provide additional sensing for autonomy applications.

Software

Software Architecture Overview

The software was designed in consideration of the following elements:

1. The platform will not be manufactured/assembled until near the end of project timeline
2. Specific software implementations may change during the course of the project

For these reasons, the platform software was designed in order to provide an interface for both a simulated and existing robot along with being built as sets packages in order to allow for specific software implementations to be easily modified/changed. A visual depiction is shown in **Figure 13**.

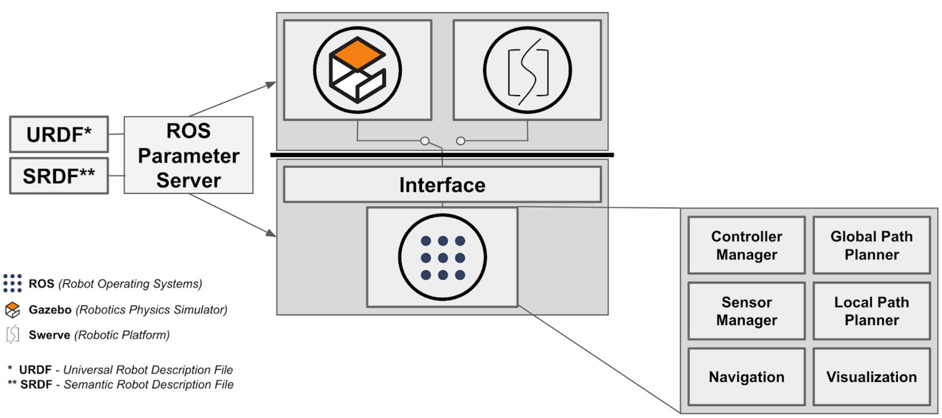


Figure 13. Software Architecture Visual Depiction.

Simulation Environment

The Gazebo physics simulator was chosen as the simulation software since it provides packages for generating sensor data along with having a visual interface for qualitative validation of software performance. This simulation is able to simulate all major components of the platform and was used to develop the software implemented on Swerve. **Figure 14** shows a Gazebo simulation.

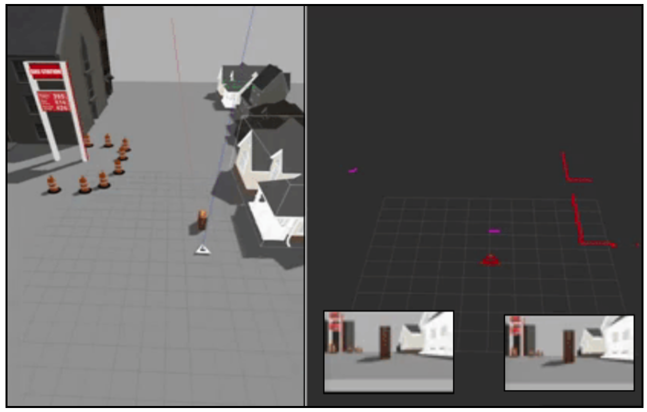


Figure 14. Simulated Platform in Gazebo (left) and Sensor Data Visualized in Software (right).

Software Tools

The core software for the platform utilizes Robot Operating Systems (ROS) as the middleware to provide communication interfaces between all of the onboard computing hardware. ROS also provides an extensive amount of software and visualizations tools in order to be able to validate software performance, decrease software development time with a suite of integrated software packages, and decrease debugging time. Git was used as the software version control tool which allows for collaborative software development environment, issue tracking, and code reviews by utilizing Git with a software hosting website like Github. Below is a link to the Swerve Github organization.

Swerve Github Organization Link: https://github.com/SwerveRoboticSystems

Algorithms and Autonomy

Kinematic and Dynamic Modeling

Kinematic and dynamic models of a system are required in order to accurately control and predict motions. Comparing these models to the sensor data allows for a robust understanding of the platforms state over time. The system was modeled using an energy approach utilizing the Euler-Lagrange formulation energy formulation. This model provides an understanding of the response time of the system and the system capabilities. The variable derivation for the kinematic model as well as a simulation of the wheel kinematics are shown below in **Figure 15**.

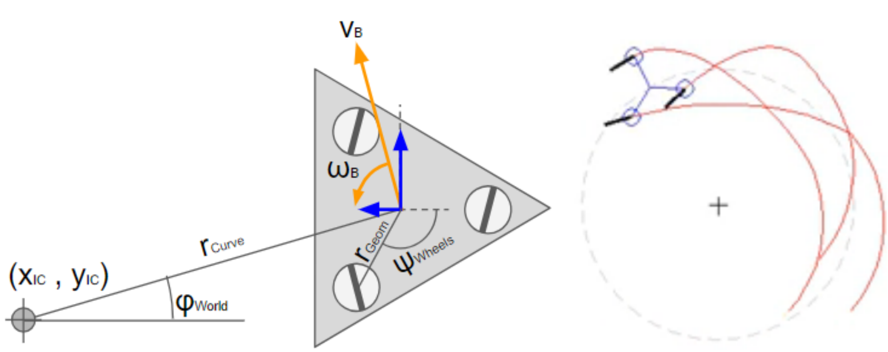


Figure 15. Visual Depiction of Platform Motion Capabilities Using Kinematics.

Laser Scan Matching

The robot receives 2D Light Detection and Ranging (LiDAR) data through a SICK TiM561 sensor which provides scan angles and ranges to the nearest object at those angles. Using successive LiDAR scan data, the change the in robots position and orientation in 2D space can be estimated by determine the translations and rotation required to match the two scans. This is done using a scan matching algorithm with the Normal Distributions Transform (NDT). The pose of the robot is then able to be estimated over time.

Occupancy Grid Mapping

Occupancy grids are often used as the 2D map representations of the environment. Occupancy grid maps can be visualized as a square grid that has been subdivided with evenly spaced cells of equal length. Each cell edge is represented as a unit of some predetermined distance. LiDAR scans were used to determine a pose estimate. Free cells and occupied cells can be determined by casting rays from the current pose using the corresponding scan angles and ranges. The potential free cells are determined using Bresenham's line algorithm. **Figure 16** shows how the cells in the map are updated, and the right show occupancy grids generation using MATLAB.

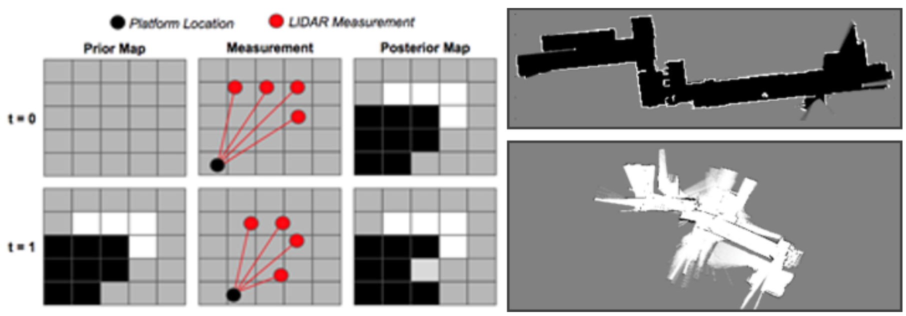


Figure 16. Occupancy Grid Visual Depiction (Left) Noisy and Clean Generated Maps (Right).

Particle Filtering

Given a known map, position over time can be estimated using a particle filter with sensor data like LiDAR scan angles and ranges. Particle filters are a Sequential Monte Carlo technique that samples potential new positions of the robot (particles) and weighting them in order to approximate the robot position. Particle filters have the advantage that the robot's dynamics do not need to be known, and that it makes no linear or Gaussian assumption that the Kalman filter would require. If the robot's dynamics are known, they can be used in conjunction with the particle filter to increase accuracy in position estimates over time which will require less particles. A visual representation of a particle filter can be seen in **Figure 17** along with the implementation performed in MATLAB.

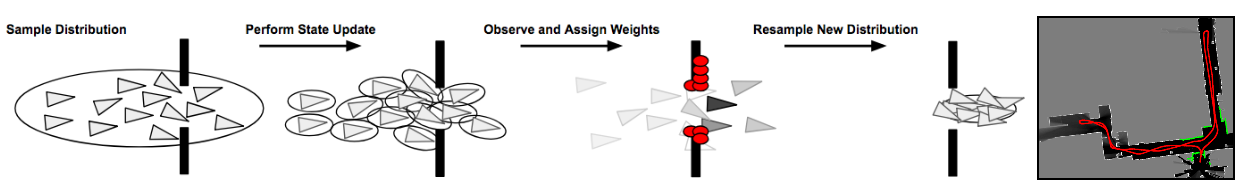


Figure 17. Visual Depiction of a State Update Using a Particle Filter and MATLAB Implementation.

Path Planning

With a known map and the ability to track the position of the robot over time, paths can be constructed and provided to the platform for autonomous operation. Valid paths can be generated using algorithms like A* which search through the known map for valid paths from the robot location to an end location and use a set of heuristics in order to determine the "optimal" path based on the sample paths that were generated and the criteria used to determine optimality. The robot can then follow this path in an open-loop manner in order to reach the end location autonomously. **Figure 18** shows a valid optimal path generated in MATLAB using the A* algorithm with a known map. Obstacles are represented in red with the robot location starting in the top left cell and the end location at the middle of the map.

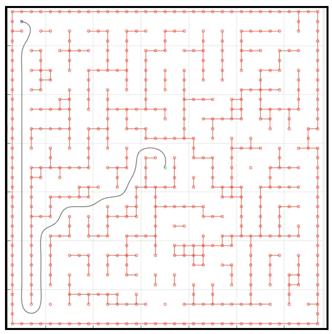


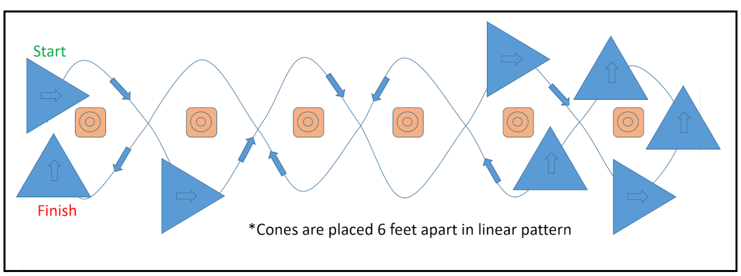
Figure 18. Valid Path Generated Using A* Algorithm and a Known Map (Obstacles in Red).

Testing and Validation

Table 1 above lists the criteria used to determine the success of the project.

Success Criteria 1 - Highly Nimble

In order to test the first criteria, an obstacle course was set up as shown in **Figure 19**. The course was completed in 52 seconds which meets the predetermined criteria for highly nimble.



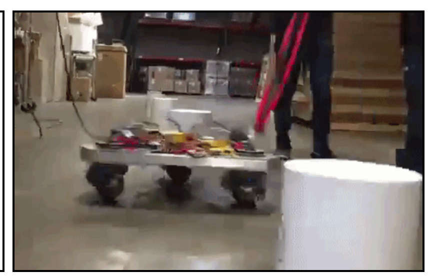


Figure 19. Nimble Test Overview (left) Still Image of Actual Nimble Test (right).

Success Criteria 2 - Support Heavy Loads

The quality of the welds on the chassis were tested in order to confirm the strength capacity of the vehicle. A four-point bend test was performed in cooperation with the Drexel Theoretical and Applied Mechanics Group (TAMG) in which Digital Image Correlation (DIC) was used to determine the strain field of a typical welded section found on the chassis. By comparing the stress at crack initiation on the test coupon and the published welded ultimate strength for 6061-T6 aluminum per the Aluminum Specification, the quality of the vehicle welds was confirmed. Although the nominal strength for the vehicle welds was determined to be 15.5 ksi as compared to the design strength of

24 ksi, the vehicle capacity is still sufficient since the analysis performed was highly conservative. Additionally, the fully assembled vehicle was loaded with 300 lbs to confirm the platform can sustain this weight without permanent deformation. The four-point bend test as well as the typical chassis beam cross section are shown in **Figure 20** while the fully assembled vehicle load test is shown in **Figure 21**.

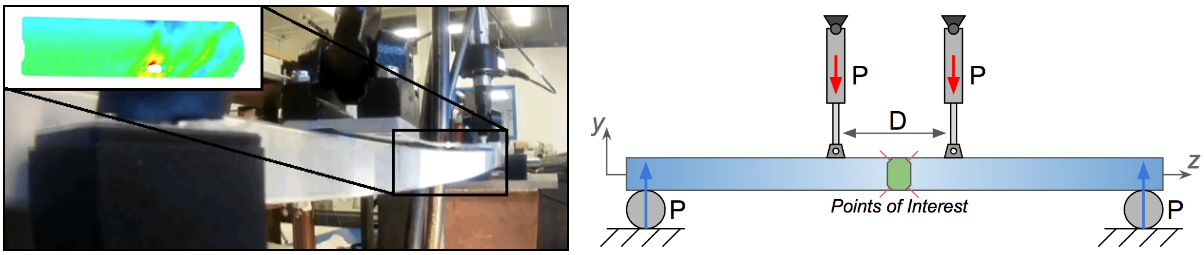


Figure 20. Welded Test of Chassis Beam Element (left) Test Setup of Loaded Coupon (right).

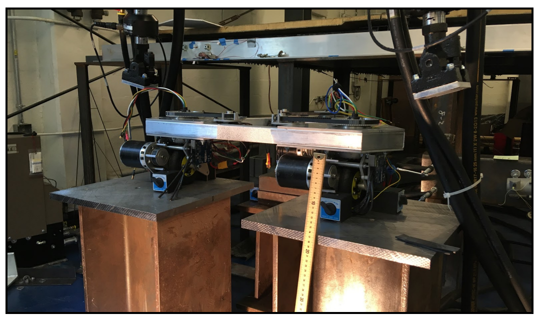


Figure 21. Fully Assembled Vehicle Load Test.

Success Criteria 3 - Lightweight

The final weight of the platform with all the batteries and electronics was determined to be 65 lbs which meets the success criteria of being under 100 lbs.

Success Criteria 4 - Human Machine Interface

The human-machine interface provided with the platform is a controller commonly used with RC drones. This interface was tested by having the operator be stationary in the room while sending commands over Drexel Wifi to guide the platform. LiDAR data from the platform was streamed back to the user in order to display the platforms environment. This is shown in **Figure 22**.

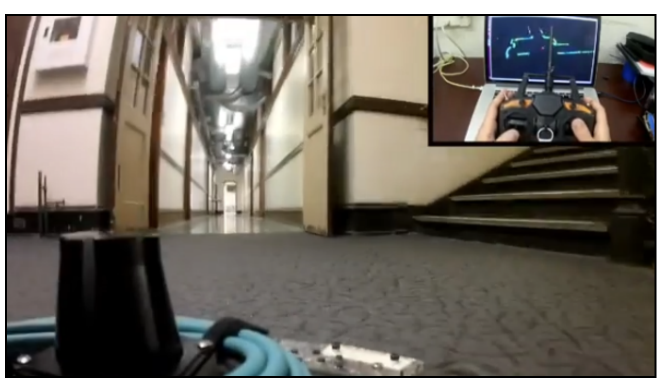


Figure 22. Implementing the Human Machine Interface Over Drexel Wifi.

Success Criteria 5 - Maintain Ability to be Disassembled

The chassis was constructed without any permanent connections meeting the desired criteria.

Success Criteria 6 and 7 - Faster than Usain Bolt Top Speed and Acceleration

During the week of testing, it was raining which forced the team to test indoors inside of a warehouse. With the limited space and many nearby obstacles, the platform was still able to reach a 13.7 mph speed and a 0.4g acceleration. Criteria 6 and 7 are deemed to be of third priority and will be tested in a larger open area pending good weather for the test.

Success Criteria 8 - Autonomous

A dataset was generated in order to test the autonomy algorithms developed for the platform. The robot was placed in a motion capture room to track the ground-truth location of the robot in order to compare it with our algorithms. This test was successful with the platform guided by a remote controller. An autonomous test run is planned pending the availability of the motion capture facility. This is shown below in **Figure 23**.

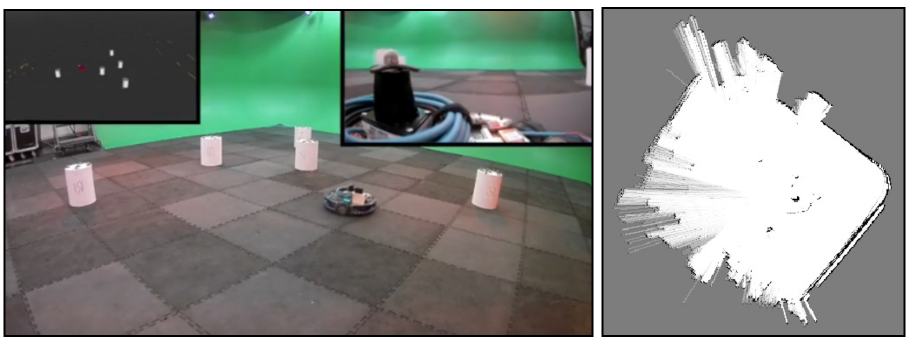


Figure 23. Controlling the Test Platform with Integrated Sensors in a Motion Capture Room.

In summary, all of the primary and secondary priority criteria have been met while the three third priority criteria have been partially met and will be fully tested. Thus, the project is deemed successful.

Closing Remarks

Lessons Learned

The team learned that we always need more time for mechanical design than expected, utilizing components that the team is not familiar with will cause more issues than expected, and that a metal chassis can easily short electronics unless the proper precautions are performed.

Future Work

The team would like to test this platform to failure in order to get statistics on the upper limits of the platform in respect to speed, max platform loading, and platform failure points. Additionally, the team would like to implement an advanced human machine interface where a human standing on the platform can use weight shifting to move the platform by using force sensors on the patron's shoes.