BINGHAMTON HYPERLOOP

BINGHAMTON UNIVERSITY
STATE UNIVERSITY OF NEW YORK

Final Design Package

January 11, 2019

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Our Team

Our team is comprised of 18 dedicated Binghamton University students studying mechanical, industrial, computer and electrical engineering. We are separated into five different subgroups. Together, we are designing an innovative, sustainable, and efficient new pod aimed at paving the way in the future of transportation.

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Design Description

Top Level Design Summary

The main objective of the design developed by Binghamton Hyperloop is to reach a maximum speed and successfully brake to a stop prior to the end of the test track. With an estimated weight of 472 lbs, our pod will be able to reach a max speed of approximately 220 mph before applying it's brakes.

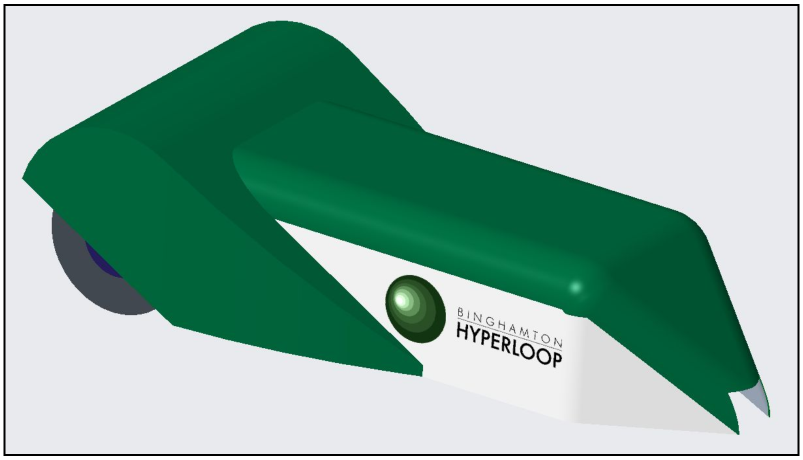


Figure 1. Binghamton Hyperloop's 2019 "Dragster Style" Pod

The structure of the pod has been designed to house several subsystems, including pneumatic braking systems and vertical and horizontal stability systems, as well as handcrafted battery packs. The frame is to be pushed by two high powered electric motors embedded in dragster-like rear wheels. The pod is held to the I-beam by spring loaded vertical and horizontal stability systems. The power for the motors is generated from a custom lithium-polymer battery pack. The carbon fiber skin will entirely encompass the subsystems of the pod during the test run.

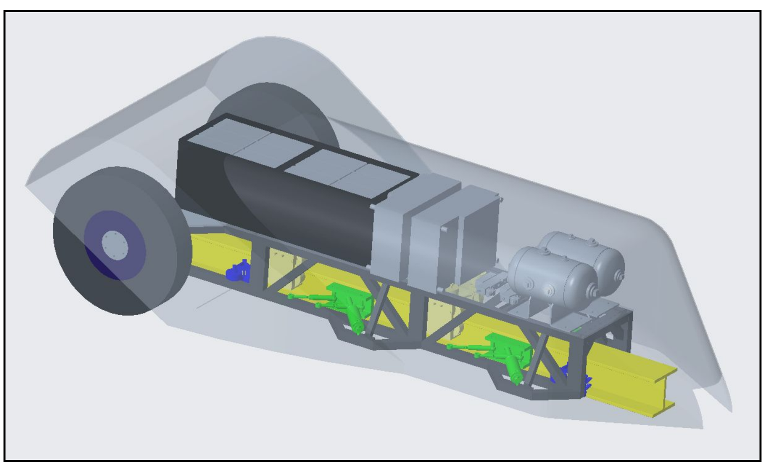


Figure 2. Binghamton Hyperloop's 2019 Pod (Transparent shell)

Pod Dimensions and Mass

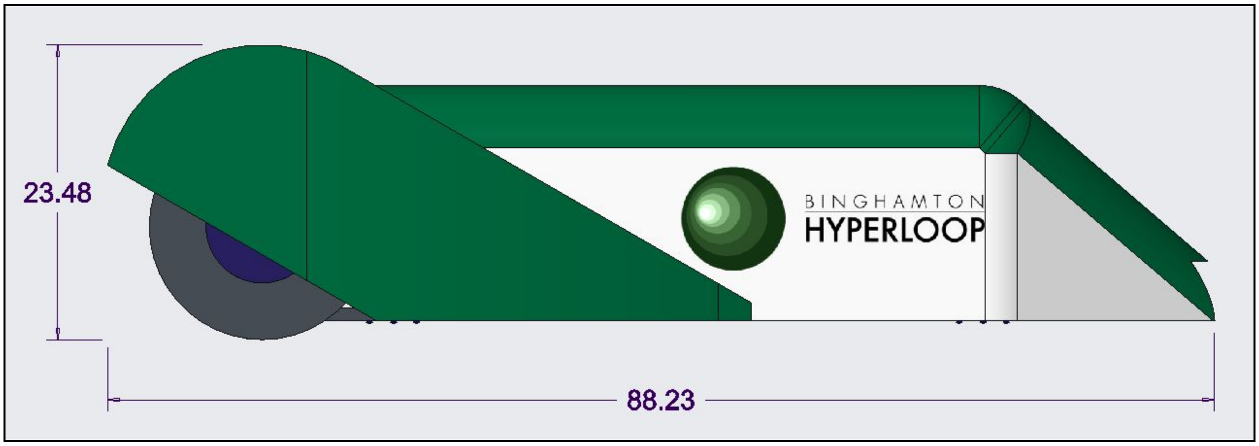


Figure 3. Length and Height of Binghamton Hyperloop's Pod

Table 1. Estimated Pod Dimensions

Estimated Pod Dimensions	Measure (in)
Length	88.23
Width	40
Height	23.5

Table 2. Estimated Mass of Pod by Subsystem

Estimated Mass by Subsystem	Mass (lbm)
Structure	55.0
Braking	43.0
Propulsion	101.0
Power	266.0
Navigation & Control	7.0
Total Mass	**472.0 lbm**

Pod Materials

Structure
Aluminium 6061
Rubber
Black-Oxide Carbon Steel
Steel

Propulsion
Aluminum 6061
Polyurethane Rubber
Stainless Steel

Power
Lithium-Phosphate Polymer
Copper-Aluminum
Copper
Varied Composite Materials

Navigation and Control
Silicon
Copper

Braking
Stainless Steel
6061 Aluminum
Brass
Rubber

Table 3. Materials used in each of Binghamton Hyperloop's Subsystems

Pod Power Source and Consumption

The Hyperloop Pod's, hereby called the HPOD, Power System consists of 2 independent power systems: a high voltage system to power the propulsion, and a low voltage system to power the Navigation and Control. These systems were designed to achieve a maximum power to weight ratio as they account for a large portion of the overall HPOD mass.

The high voltage system powers two EMRAX 228 High Voltage 100 kW motors. The Emrax 228 HV motor runs at 670 V so a high voltage custom battery module is needed. The high voltage system consists of two 182S1P Lithium Polymer High Discharge Prismatic Cell Battery packs wired together in parallel. A pack can be seen below in Figure 4.

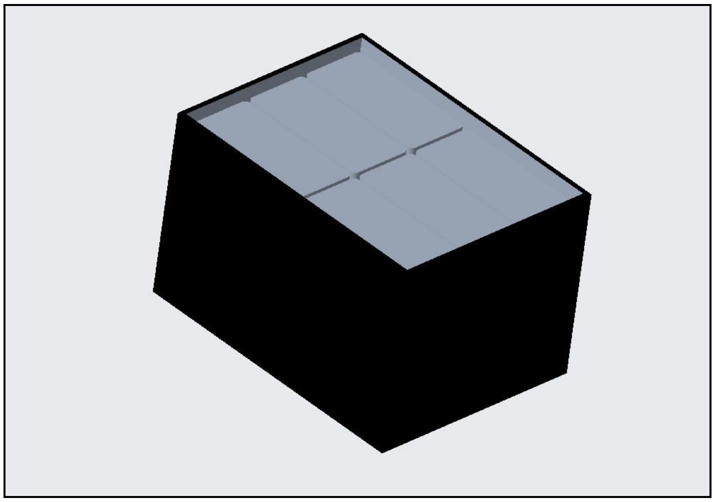


Figure 4. 182S1P Lithium Polymer High Discharge Prismatic Cell Battery Pack

These batteries will be assembled and tested by Charge CCCV [C4V], LLC in Binghamton, NY.. The packs will be vacuum certified to be able to run in the low pressure environment of the SpaceX testing site. Each pack current flow will be fed through a 700V 175A semiconductor fuse to prevent the cells from discharging more than their maximum rated discharge. The battery packs will also be monitored by an Elithion Battery Management System (BMS) to ensure the cell balance within the pack and to prevent the packs from discharging above the rated current of the wires and the O-rings. The BMS will also monitor the temperature of the cells to ensure they are only running within their specified temperature ranges. The ranges can be seen below in Table 4**.**

Table 4. Temperature Ranges for LiPO Prismatic Cells

State	Minimum Temperature (℃)	Maximum Temperature (℃)
Charging	0	45
Discharging	-20	60

An exterior mechanical cut-off switch will be mounted to each pack as a safety precaution when handling the pod to allow for power to be quickly cut from the HPOD during testing or an emergency. The current will be fed through the BMS with gauge 00 wire to the motor controllers and then into the EMRAX 228 motors. The current flow of the high voltage system can be seen in the schematic below in Figure 5.

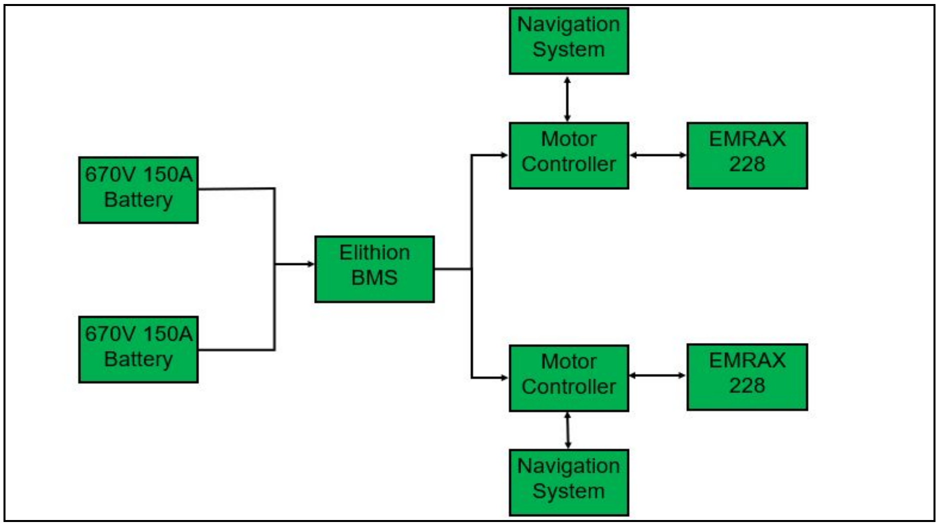


Figure 5. High Voltage Power System Schematic

Each LiPO Prismatic Cell is a 3.7 V 6Ah cell rated for continuous discharge at 25C. Each cell is 76mm x 156mm x 6.5 mm. The wiring of the cells together in the 182S2P configuration allows for ample voltage and current to be supplied to the motor. 182 * 3.7 V = 673.4 V which is greater than the required 670 V of the motors. The motors each require 150 A of current for the run. This battery configuration gives out 6Ah * 25C = 150 Ah per pack. The batteries will be wired in parallel, doubling the potential current output from 150 A to 300A. This is sufficient current to run both motors. A summary of the high voltages system can be seen in the below in Table 5.

Table 5. High Voltage Power System Specifications

Item	Max Discharge (A)	Voltage (V)	Capacity (kWh)	Weight (lbm)	Quantity
LPHD6578156 - 3.7V 6Ah Rated Continuous Discharge: 25C LiPO Prismatic Cells Config: 182S2P	300	670	8.04	103	1

The batteries used in the low voltage system will be comprised of the same cells as the high voltage system but wired in the 4S1P configuration. The system will be responsible for delivering power to the Arduino Yun and both Arduino Unos, which are used to control the

HPOD. The low voltage system will also power all pod sensors and the solenoid valves used in the pneumatic braking system. Of this list, the solenoid valves require the highest input voltage (12V) and current draw (~0.16667A) in order to activate. The 4SP1 configuration gives us 4 * 3.7V = 14.8V and 6Ah * 25C = 150 Ah per battery pack, which is ample voltage and current for the low voltage system power needs. To mitigate risk, a certain level of redundancy is designed into the system. This includes having two low voltage battery packs which each independently power an Arduino Uno. These two battery packs allow us to safely and sufficiently power the entire Navigation and Control system. A summary of the low voltage system can be seen below in Table 6**.**

Table 6. Low Voltage Power System Specifications

Item	Max Discharge (A)	Voltage (V)	Capacity (kWh)	Weight (lbm)	Quantity
LPHD6578156 - 3.7V 6Ah Rated Continuous Discharge: 25C LiPO Prismatic Cells Config: 4S1P	150	14.8	.0888	3	2

Table 7. Power Consumption of Components

Component	Min Supply Voltage (V)	Max Supply Voltage (V)	Current Draw (mA)	Quantity	Total (mA)	Max Power (mW)
Arduino Yun	5	5	100	1	100	500
Arduino Uno	5	12	100	2	200	2400
OBR1500-R2F-E2-L Photoelectric Sensor	12	24	50	4	200	4,848
DS18B20 Temperature Sensor	5	5	2	8	16	80
Total				15	516	7,828

Pod State Diagram

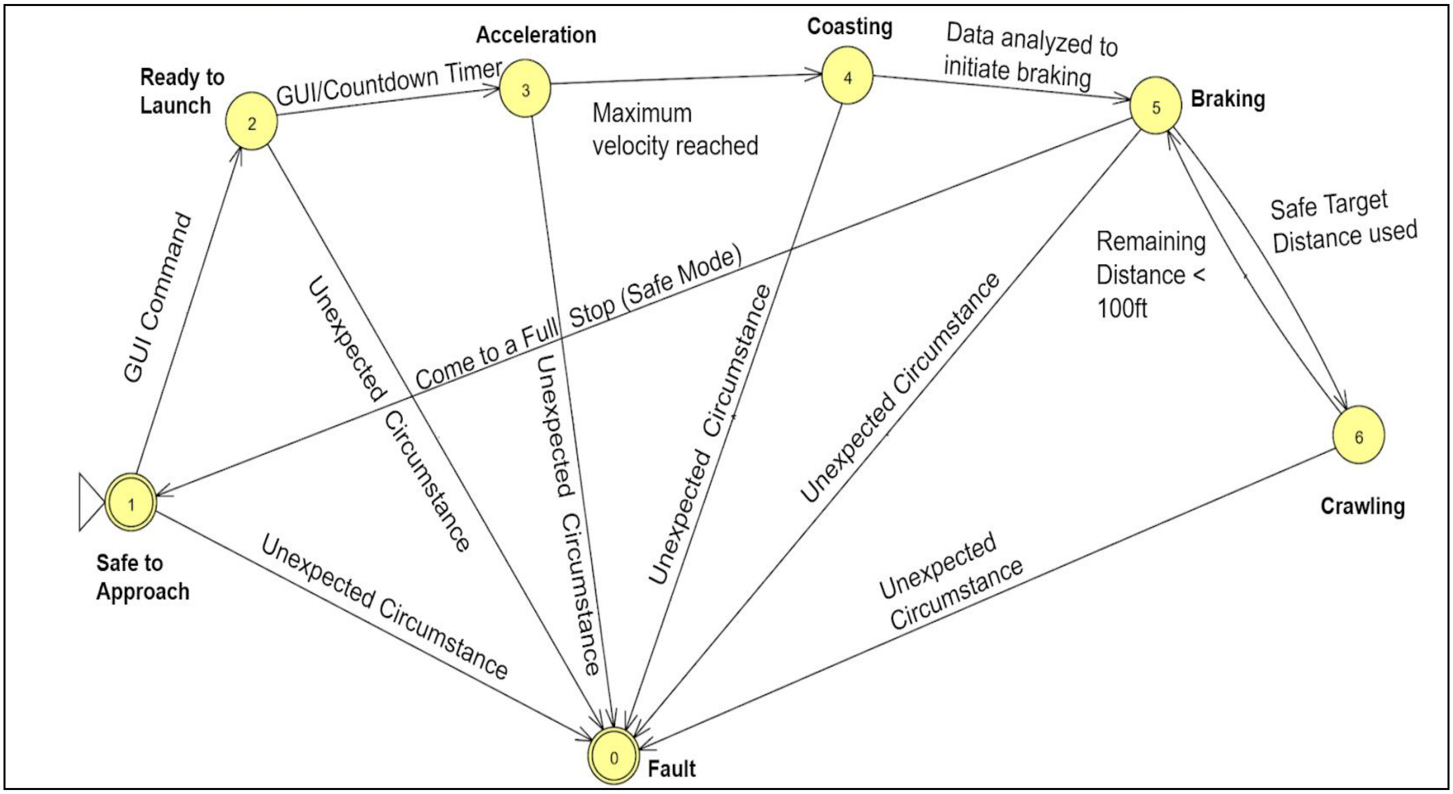


Figure 6. Binghamton Hyperloop Pod State Diagram

Figure 6, shown above, is a state diagram showcasing the lifecycle of the pod on a test track. State one serves both as the start and end state. The other end state is state zero, known as the fault state indicating something unexpected has occurred. The pod begins in a safe to approach state, and moves forward to the ready to launch state when a command from a GUI application is entered by the team laptop. Then, using either a GUI command or a countdown timer, the pod will transition to the acceleration state. Once the maximum velocity has been reached, the pod will transition into state 4 and begin coasting. After analyzing data collected by sensors, the pod will initiate braking when appropriate.

The intention is to analyze the distance and speed data to determine the accuracy of the distance sensors as it is crucial in determining the exact time to initiate the brakes. In the instance of high variation among the data received from the four distance sensors, the pod will use a pre-calculated safe-target distance to determine when to initiate the braking. If safe-target distance is used to apply the brakes, the pod will enter into the crawling state and crawl until it is within 100 feet. At this point, the pod will transition back into the braking state to come to a complete stop, and then into the safe to approach state. On the other hand, if safe-target distance is not used and if the pod comes to a complete stop less than 100 feet away from the end of the test track, it will immediately transition into the safe to approach state again in order to be removed from the track. Additionally, at any point during the run, if an unexpected circumstance such as a loss of power occurs, the pod will immediately transition into the fault state.

Pod Aerodynamics

Due to the fact the pod will operate in near-vacuum conditions (.125 psi), the aerodynamic drag coefficient is not the most pertinent design consideration, however it is still relevant enough to test. Thus, the pod shell, seen below in Figure 7, has been designed to minimize the drag coefficient, in order to reduce aerodynamic drag forces. The program ANSYS Workbench 19.2 was used to determine the drag coefficient of the pod shell at the pod's maximum projected speed of 220 mph, and the results are shown in Figure 8, below. According to the ANSYS results, the maximum drag coefficient of the pod was determined to be approximately .0053. In order to minimize the drag coefficient, the geometry of the front face of the skin was designed to closely resemble a cone. The geometry is also relatively smooth and avoids sharp edges. This geometry allows for streamlines to smoothly wrap around the pod during motion, which us shown below in Figure 9. The midsection and rear of the skin are also smoothly contoured in order to minimize the wake regions that develop at rear end of the pod during motion. The skin, made from carbon fiber, also houses the entirety of the pod and all its components, in order to eliminate any surface discontinuities or gaps.

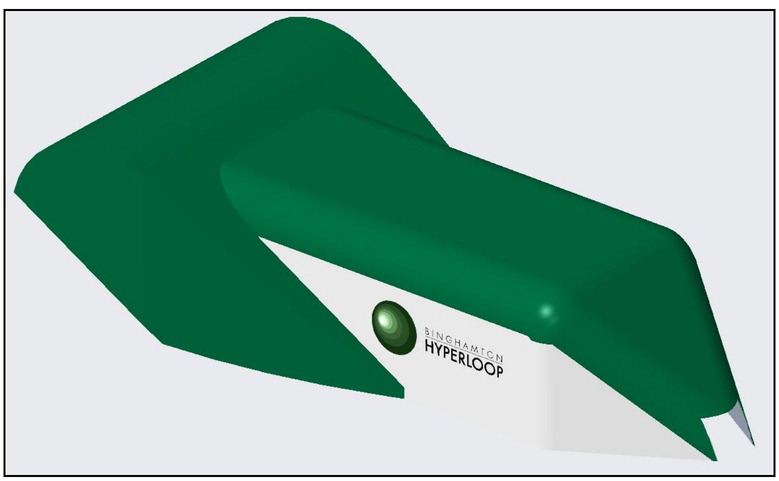


Figure 7. Binghamton Hyperloop's Pod Skin

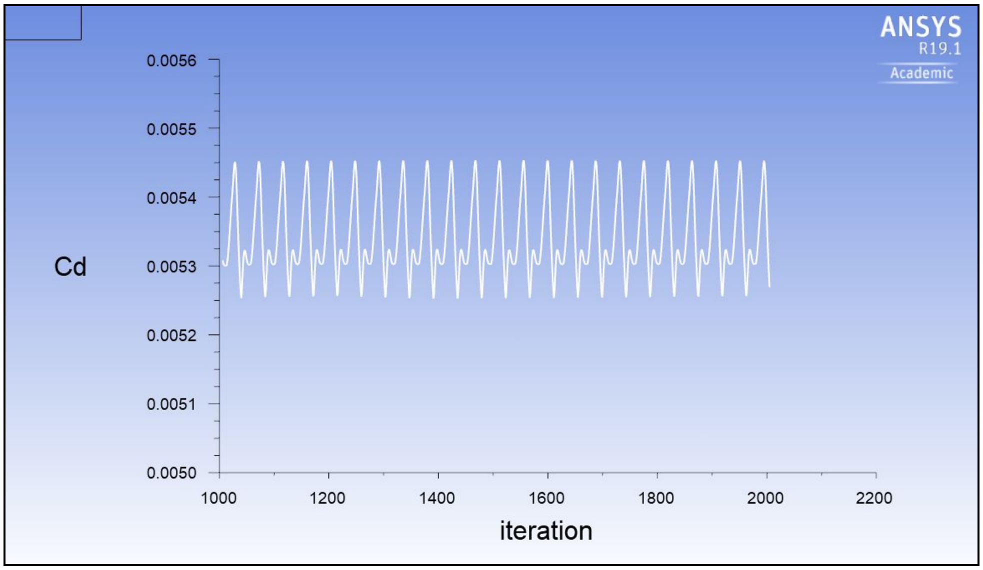


Figure 8. Drag Coefficient of Pod Skin

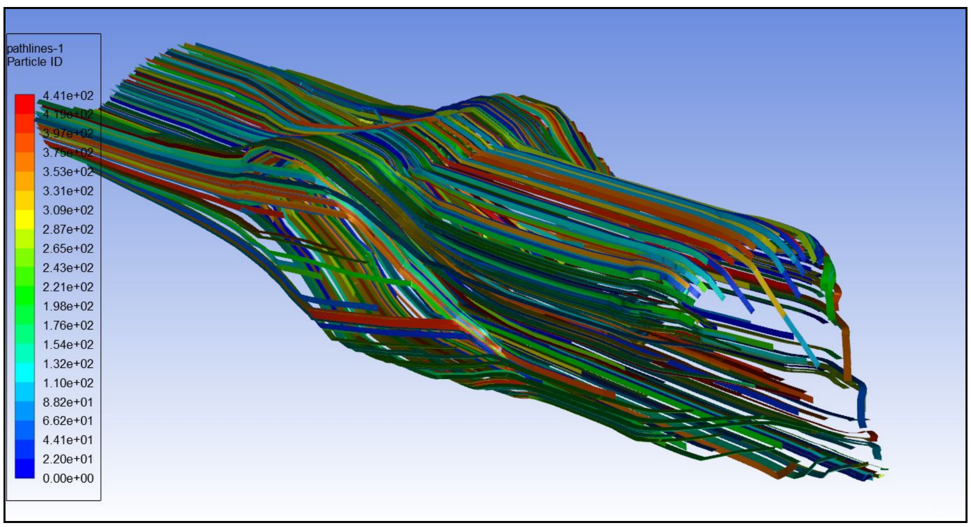


Figure 9. Particle Velocity Streamlines Over Pod Skin

Pod Stability Mechanisms

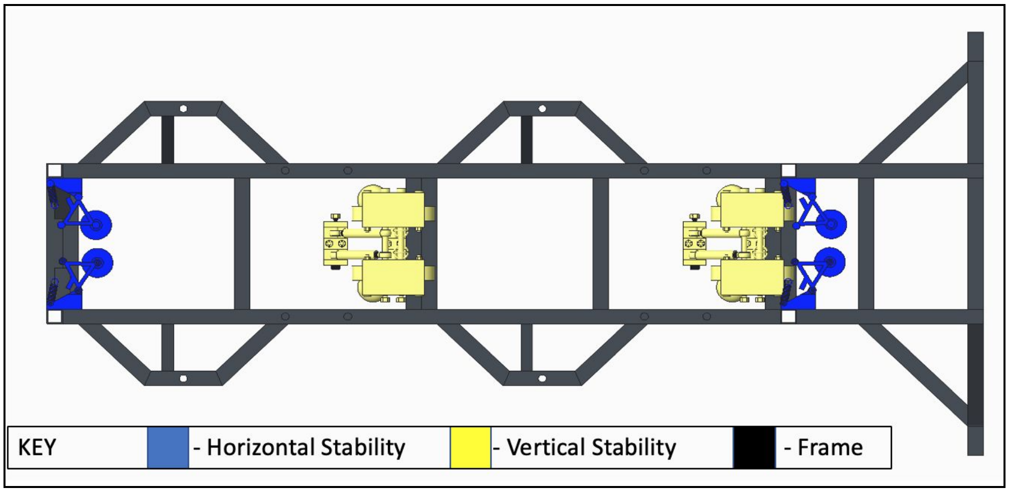


Figure 10. Binghamton Hyperloop's Stability Mechanisms - Bottom View

Binghamton Hyperloop has designed two seperate stability mechanisms: horizontal and vertical. The function of horizontal stability is to resist horizontal motion of the cart along the beam, or to keep the cart centered along the beam. The horizontal stability system, as shown in Figure 11 below, is four sets of spring-loaded wheel mechanisms. The mechanism keeps tension on the wheels in the direction of motion. To ensure that the pod has minimal horizontal translation, the wheels have been designed to be in constant contact with the track. The purpose of the horizontal stability wheels is to stop the cart from veering off the track. If this were to occur the rest of the frame would collide with the I-beam causing failure.

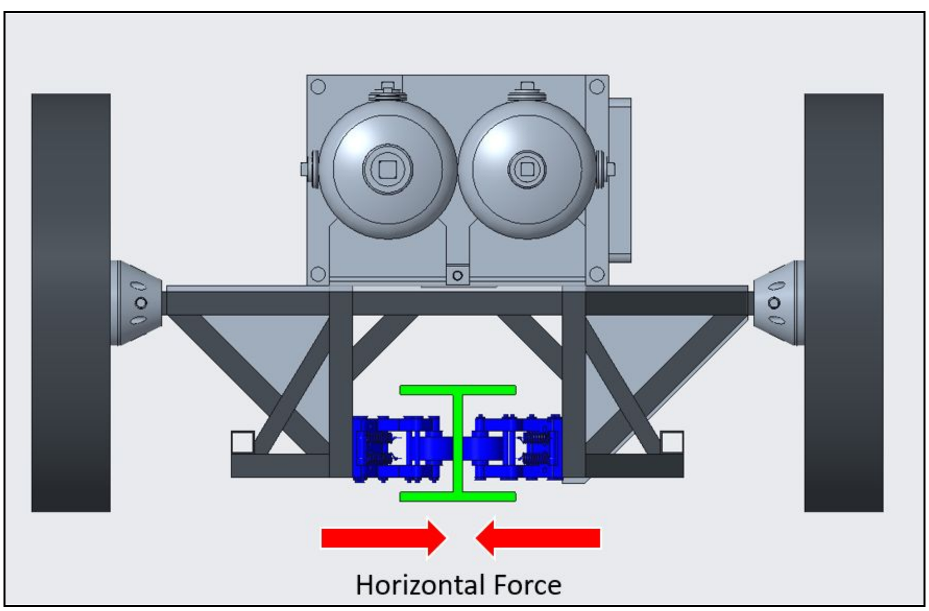


Figure 11. Horizontal Stability Wheels

When the cart is rolled into the beam the wheels on each side of the vehicle move into tension. When the cart is in the center of the beam, the springs will be displaced, creating horizontal force. This force will be equal on each side of the pod pushing the cart to the center of the I-beam throughout the run. Each horizontal assembly creates tension by 3 music wire springs with a rate of 24.3 lb/in. When the pod is in the center of the I-beam the springs will be stretched to 2.92 in. which dissipates 30.7 lb of force at an angle of 43.2 degrees of the triangular housing. The force creates a moment on the housing of the wheel. In the natural state each pair of horizontal wheels will push 10.6 lbf of force towards the beam. As the cart veers off center one side of the pod will get closer to the beam as the other gets further. As shown in Figure 12, if the beam gets closer to the pod, the pivot will stretch the springs creating more spring force, and therefore a greater wheel force reaction. For the side going away from the beam, the pivot will allow the spring to loose tension and react less. This creates a force imbalance which will push the pod back to its center position. At the maximum imbalance, the springs stretch to 3.16 in. which dissipates 48.114 lbf of force at an angle of 38.225 degrees to the triangular housing. The force creates a moment that is transferred to the wheels. At the maximum movement the force each wheel applies is 19.425 lbf.

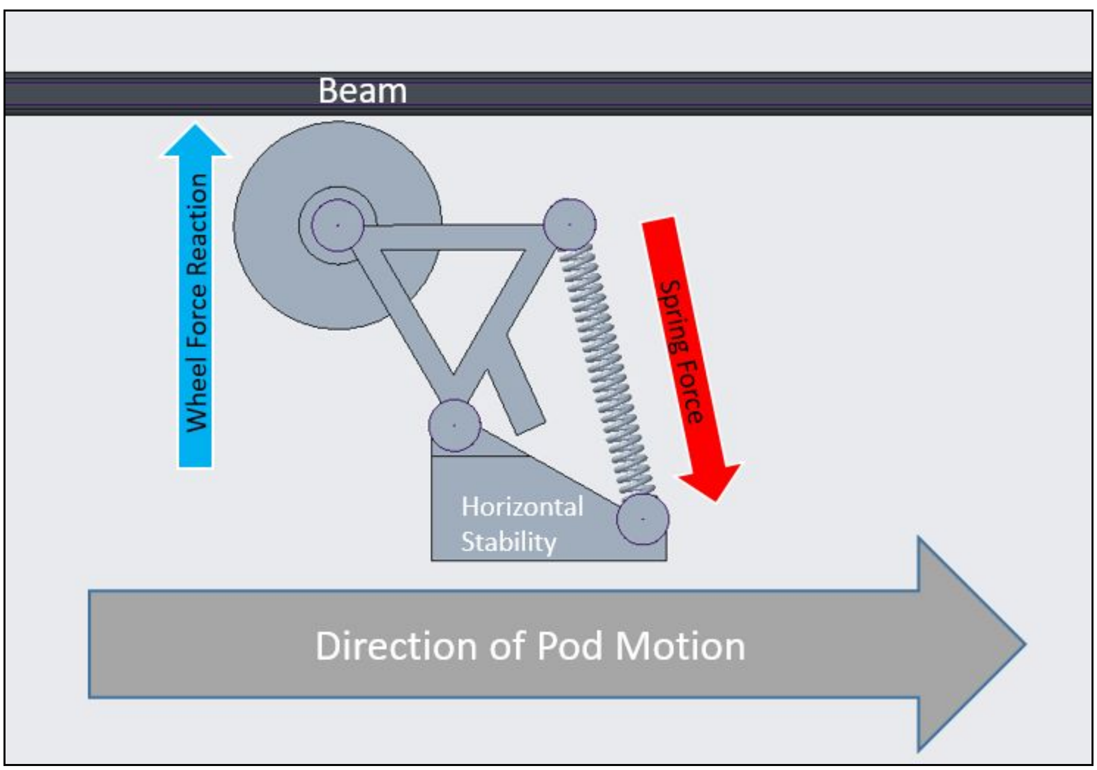


Figure 12. Horizontal Stability Assembly Function

Horizontal stability systems will be manufactured from vendor parts including the wheels, bearings, shoulder screw, washers, and bolts. Every part in the horizontal stability wheels can be found in Appendix A. The triangular base that houses the wheel and the base bolted into the frame will be custom made. The three pivot points of the triangular base are shoulder screws bolted down by hex nuts. This allows the parts to be assembled rather easily. The wheel used is an aluminum 6061 disc. Aluminum 6061 was chosen because SpaceX regulates that any part in contact with the I beam must have smaller hardness factor than the aluminum of the beam, and a rubber material could not withstand the rotational inertia of going 200+ mph. Figure 13 below shows the aluminum 6061 disk and speed rated bearing that will press fit together to create horizontal wheels. This wheel system will be able to rotate up to 39500 rpm and withstand a lateral force of 620 lbf.

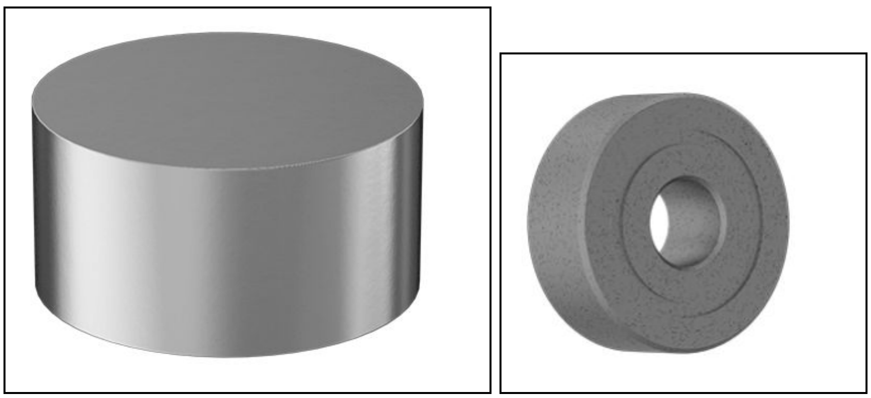


Figure 13. Horizontal Stability Parts

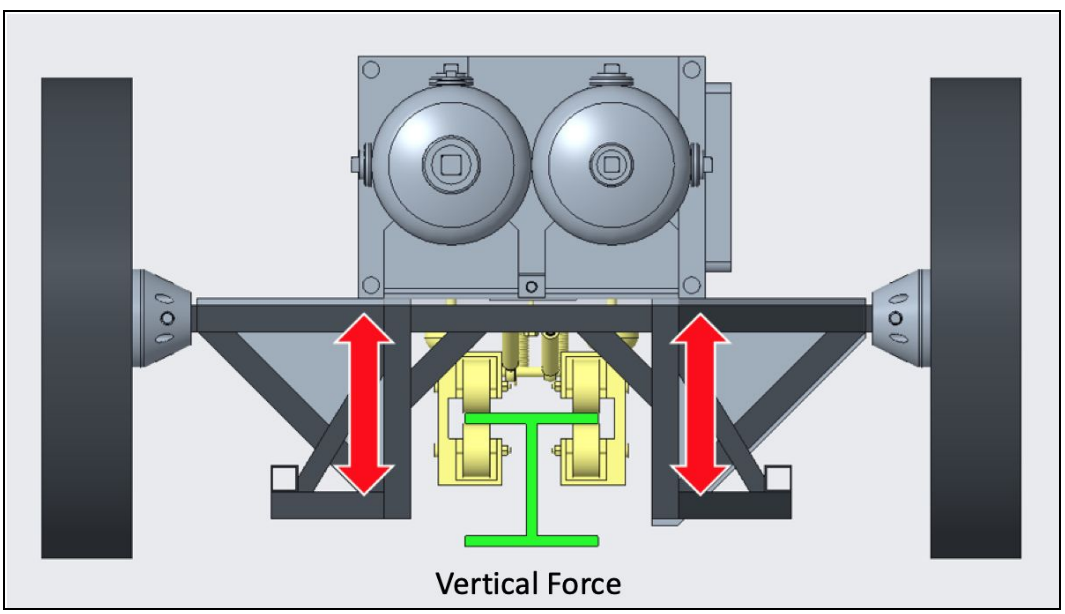


Figure 14. Vertical Stability Movement

The vertical stability system, shown in Figure 14, locks the entire cart vertically in place. The cart is supported by the back propulsion wheels and two sets of vertical stability wheels. The SpaceX track is known to have many bumps and holes and when the propulsion wheels run along the track, the cart is expected to bounce along the I-beam. The vertical stability wheels lock on each side of the I-beam with bearing filled aluminum 6061 wheels and shoulder screws as the axle. When the cart is bounced off the beam upward, tension springs pull the cart down to the beam, keeping it from jumping off the beam. When the cart hits a hole and goes downward on the beam the stability system hits rubber stoppers, which transfers the load to the frame. The system is held in place by rod end links that lock the translation of the system only allowing rotation. The links are bolted into the cart by a base. When running smoothly along the track the stability system will run against the rubber stoppers that are bolted into the frame.

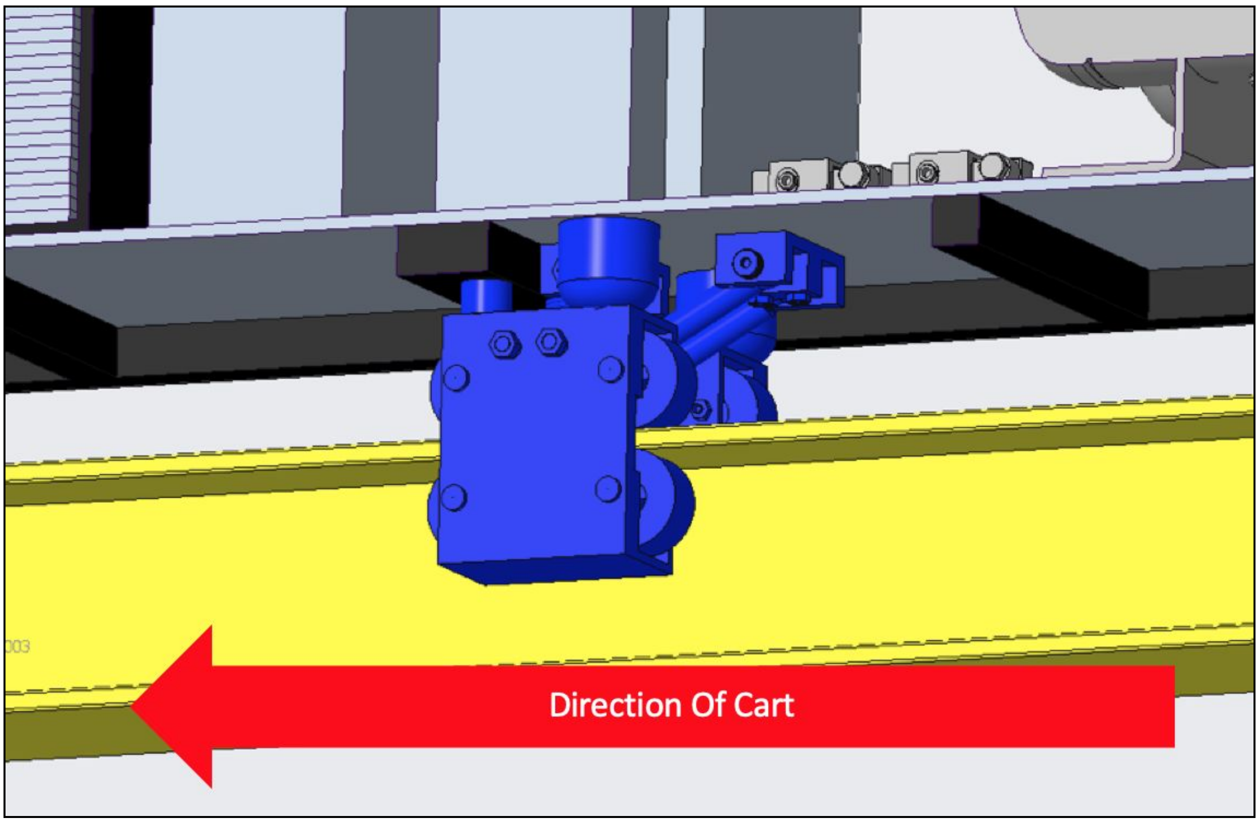


Figure 15. Vertical Stability Running

The vertical system also serves the purpose of stopping the braking system and horizontal wheels from hitting the top or bottom of the beam. If the propulsion wheels hit a hole or divot the vertical wheels in the front and back will make contact with the rubber bumpers and support the entire weight of the pod. If the propulsion wheels hit a bump or the torque of the engine tries to lift the pod, the springs within the system will pull it back to normal position. Each vertical assembly is made up of two 151 lb/in. springs. The pod can withstand a maximum deflection of .65 in. before any failure. If only once vertical assembly system is used and the pod moves .54 in. above its normal running location, the vertical assembly system will expel 130 lbf downward to push the pod back down. If the motors become locked into place and all of the torque is applied directly to the pod, the pod will not exceed .54 inches by a design factor of 4.1. This is due to the weight distribution on the top load and the power of one vertical assembly located in the middle of the pod.

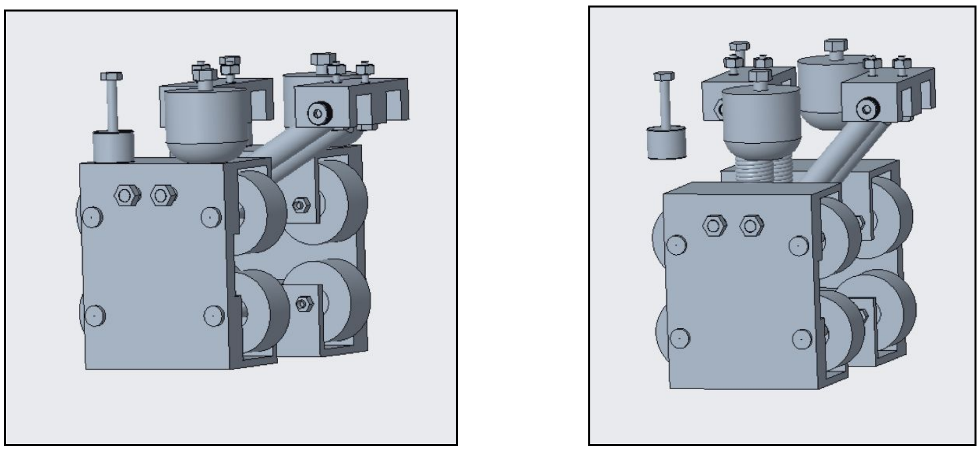


Figure 16. Vertical Stability Stages

The manufacturing of the vertical stability is completed by vendor and custom parts. The two parts that are custom machined are the base and the hinge. Both pieces are aluminum 6061 blocks machined for the vendor parts. Three different sized shoulder screws and hex nuts are used in the vertical assembly.

Pod Propulsion Mechanism

The pod has been designed to be propelled by two Emrax 228 motors. These are direct drive 100 kW AC induction motors that will be mounted into the two 18 inch rear propulsion wheels. The drive wheels will be connected together by a non-rotating 1 inch square solid Aluminum 6061 axle, welded at the rear of the frame. The system has 45 degree support struts to help resist the torsional force of the motors. The torsional force proved to be too much for the axel and supports alone so two custom pieces were designed for extra support and to redistribute the forces. One of these pieces is a ¼” sheet of Aluminum 6061 cut out into two pieces and welded together at a 90 degree angle. These sheets are then welded to the rest of the frame. The second custom piece is machined out of a singular 3’x3” block of Al 6061 into a conical shape and bolted to the rear axle. This piece is referenced as the axle sleeve. The arrangement can be seen below in Figure 17.

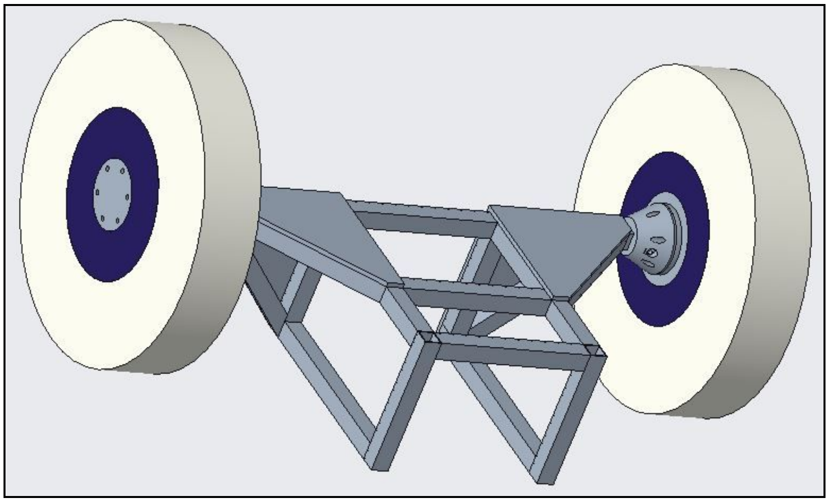


Figure 17. Propulsion System

The motors, in tandem, provide an acceleration of 19.7 ft/s^2 reaching a projected top speed of 219.9 mph at .5 miles into the run. The propulsion specifications of two motors running in tandem can be seen below in Table 8.

Table 8. Propulsion System Specifications

Acceleration (ft/s^2)**	Projected Speed @ .5 miles (mph)**	Time to .5 miles (s)**	Continuous Torque (ft-lb)**	Continuous Power (kW)**
19.7	219.9	16.3	177.0	110.0

The two custom pieces are essential to the rear frame assembly. Without each piece the axle will snap due to the moment created by the twin motors. The inner walls of the axle sleeve are lined with pieces of a ⅛" thick vibration dampening rubber sheet. This sheet absorbs the vibrations created by the motor and helps improve the longevity of the welds on the frame assembly itself. Each bolt connection is also fitted with a rubber, vibration dampening washer to further amplify this effect. The design of the axle sleeve allows it to slide over the axle itself and fit up against the 45 degree supports taking away any torsional forces applied solely to the axle which helps maintain its integrity.

The aforementioned Emrax 228 is a permanent magnetic synchronous three phase sinusoidal motor that achieves high torque at relatively low RPMs. By being an in wheel-drive motor, the need for drives shafts or gear belts is removed thus simplifying the system. The motor's power is supplied by a custom lithium-polymer battery pack, and will be controlled by two Unitek Bamocar controllers, one per motor. The controller has adjustable output parameters for voltage and current that can be changed through Unitek's provided software.

To achieve desired RPM, each motor will operate in its high-voltage state. The controller will draw DC voltage from the batteries, convert it to a 670VAC signal, and output three voltage signals, each out of phase by 120 degrees, to its motor. Feedback from the controller will be sent and regulated in real-time by an on-board computer, communicating over a common CAN bus line. Feedback data will include measurements of voltage, current, RPM, and distance traveled. Technical specifications of the propulsion system can be seen below in Table 9**.**

Table 9. Propulsion Technical Specifications

Item	Max Current (A)	Voltage (V)	Weight (lbm)	Quantity
EMRAX 228 HV/LC Motor	150	670	27	2
Unitek Bamocar D3 Motor Controller	400	700	13	2

Pod Braking Mechanism

The braking subsystem, seen below in Figures 18 and 19, was designed to decelerate the hyperloop pod as fast as possible in order to maximize the time the propulsion subsystem is able to accelerate the pod to its top speed. This was to be accomplished in a safe manner so that the central I-beam and HPOD are not damaged during the deceleration process. For this reason, a pneumatic working system was chosen to provide the main source of braking force.

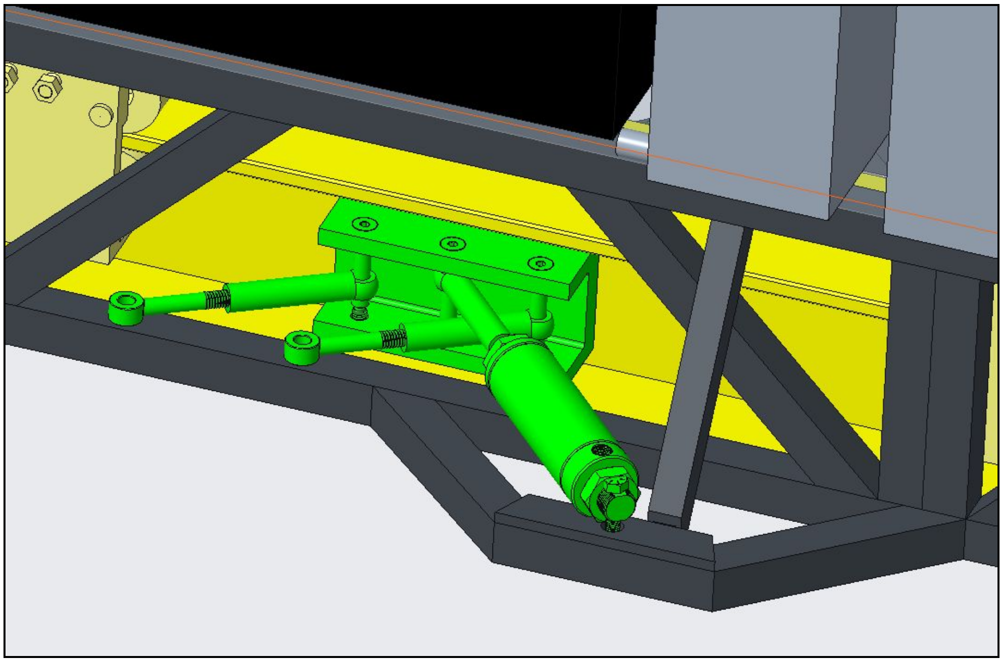


Figure 18. Isometric View of the Braking Subsystem

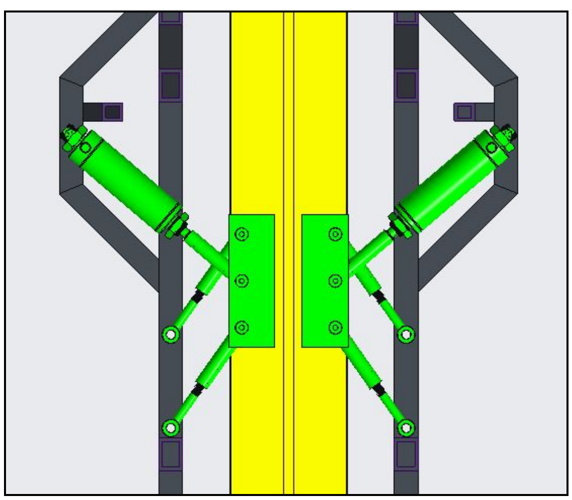


Figure 19. Top Down View of the Braking Subsystem

The five bar linkage attached to the brake pad was designed to minimize the shear stress acting on the pneumatic cylinder during the braking process. When force is applied, the linkage will swing along the x-y plane to pinch the I beam between two brake pads. The direction of motion of the pod in combination with the angle of the brake links will serve to exaggerate the total force exerted during braking. The motion of the linkage is illustrated in the free body diagram in Figure 20.

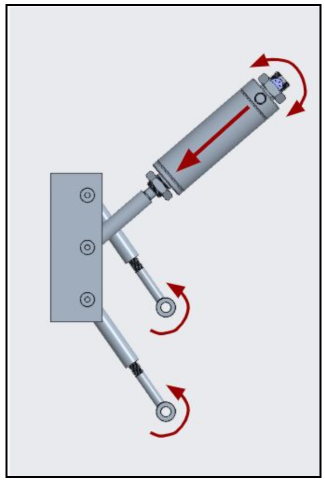


Figure 20. Braking Linkage Free Body Diagram

Air is stored in a reservoir until it is needed to stop the HPOD. When braking is needed an electronic signal is sent to a servo valve telling it to reroute the gas to the brakes. Once pressure is applied, a pneumatic cylinder is actuated which swivels the brake pad along a linkage to press against the central I-beam. When the braking process is complete, another signal is sent to the servo valve and the air in the cylinders is vented to atmosphere. This process is laid out in the schematic diagram shown in Figure 21.

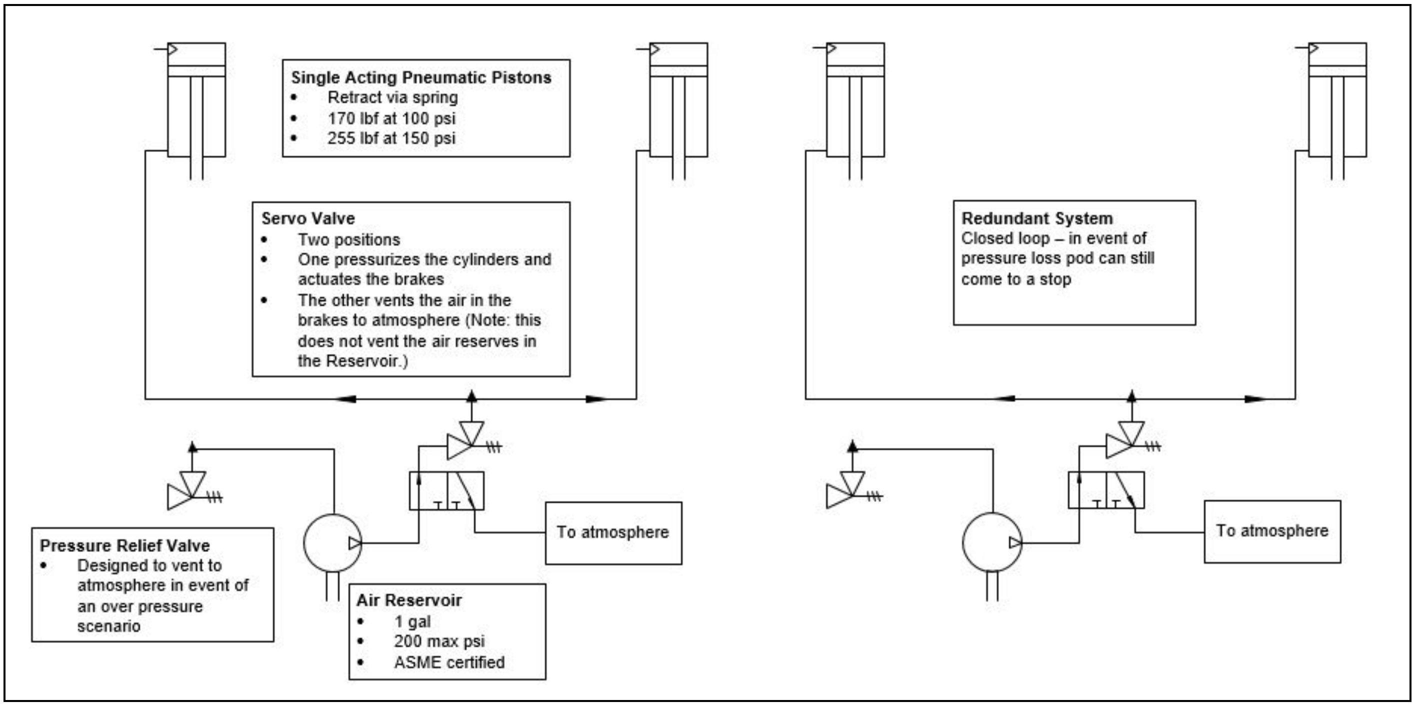


Figure 21. Pneumatic Schematic

A pneumatic system was chosen for its reliability and simplicity. The four bar linkage design was chosen in an effort to combat the unacceptably high shear stress present in earlier designs. Together they make a system that is able to deal with multiple contingencies.

Analysis and calculations were performed to ensure each part in the braking subsystem will work as expected. The majority of the parts used are being purchased from a vendor and therefore have a rated maximum yield strength or maximum pressure rating. The maximum applied stress was then calculated using the part's cross sectional area and the force applied during braking (this was increased from 255 lbf to 500 lbf due to the nature of the braking process). The factor of safety for each part was then calculated by dividing the rated yield strength by the maximum applied stress. The part with the lowest factor of safety is the steel guide rod attached to the end of the pneumatic cylinder. It has a rating of 3.2. This is well within acceptable limits.

In addition, the part with the lowest maximum pressure rating is the air reservoir with an MAOP of 200 psi (or 186 psi in a vacuum). This then sets the MAOP of the entire pneumatic system at 186 psi, which is well above the operating pressure of 150 psi. These pressures, yield strengths, and factors of safety can be viewed below in Table 10.

Table 10. Braking Part Analysis

Part	Rating psi	Yield Strength (psi)	Max Stress (psi)	Applied Force (lbf)	Rated FOS
Air Reservoir	200	-	-	-	-
Piston	250	-	-	-	-
Servo Valve	250	-	-	-	-
Flex Tube	4000	-	-	-	-
1/2 - 1/8 Adapter	3000	-	-	-	-
1/2 - 3/8 Adapter	1200	-	-	-	-
Manifold (3/8 - 1/2)	1000	-	-	-	-
Male Threaded Rod	-	75000	1131.8	500	66.3
Female Threaded Rod	-	75000	1131.8	500	66.3
7/16 -20 Fem Rod	-	1610	503.0	500	3.2
PSV 175 Set Pressure	175	-	-	-	-
T Joint 1/2 NPT	2500	-	-	-	-
5/16 - 24 Hex Nut	-	68000	2546.5	500	26.7
5/16 - 24 Bolt	-	150000	2546.5	500	58.9
Shoulder Screw	-	140000	4527.1	500	30.9
5/16 - 18 Hex Nut	-	68000	2546.5	500	26.7
Manual Shut Off Valve	600	-	-	-	-

To summarize, the pod uses pneumatically actuated high friction brakes to pinch the center rail at four points of contact. In an effort to reduce the shear stress acting on the system, a five bar linkage pivots in the x-y plane and swings the brake pad against the central I-beam. The system was designed to maximize braking force while minimizing shear stress.

Electronics System Overview

The navigation and control subsystem is comprised of three main components: the off-board computer, the high-level interface board, and the low-level interface board.

The off-board computer is responsible for wirelessly communicating data to/from the pod as well as displaying information on the pod's status to the user. Wireless communication is achieved through the use of Ubiquiti Rocket M900 radios. One radio will be connected via ethernet to the team laptop, and the other will be connected via ethernet to the Arduino Yun on the pod. In addition, the stage radio is connected to SpaceX base station radios, thus providing a wireless point-to-point communication. Telemetry data displayed on the team laptop through a web application accepts data requests sent from the pod. The data is stored and analyzed on the laptop. Additionally, a telnet server exists on the pod to listen to requests sent from the laptop, process to the requests, and send back the appropriate responses.

The high-level interface board is responsible for handling the more complex communication methods and processing required on the pod. With specialized software, the board has the ability to wirelessly communicate with the off-board computer, allowing the pod to send and receive data. The board also will be required to interface with higher level peripherals such as the VN100 IMU, which communicates via USB 2.0, as well as pulling data from the low-level interface board. Additionally, this board will perform a considerable amount of data processing and filtering on the incoming sensor data so that the pod may operate autonomously.

The low-level interface board is responsible for communicating with the low-level peripherals and relaying their data to the high-level interface board. This board is necessary because components such as temperature sensors and photoelectric sensors require very low level control, which higher level boards cannot properly interface with.

Figure 22 below shows a detailed diagram on the flow of data in the system. Figure 23 below shows the interactions of the Navigation & Control system with other pod systems in detail.

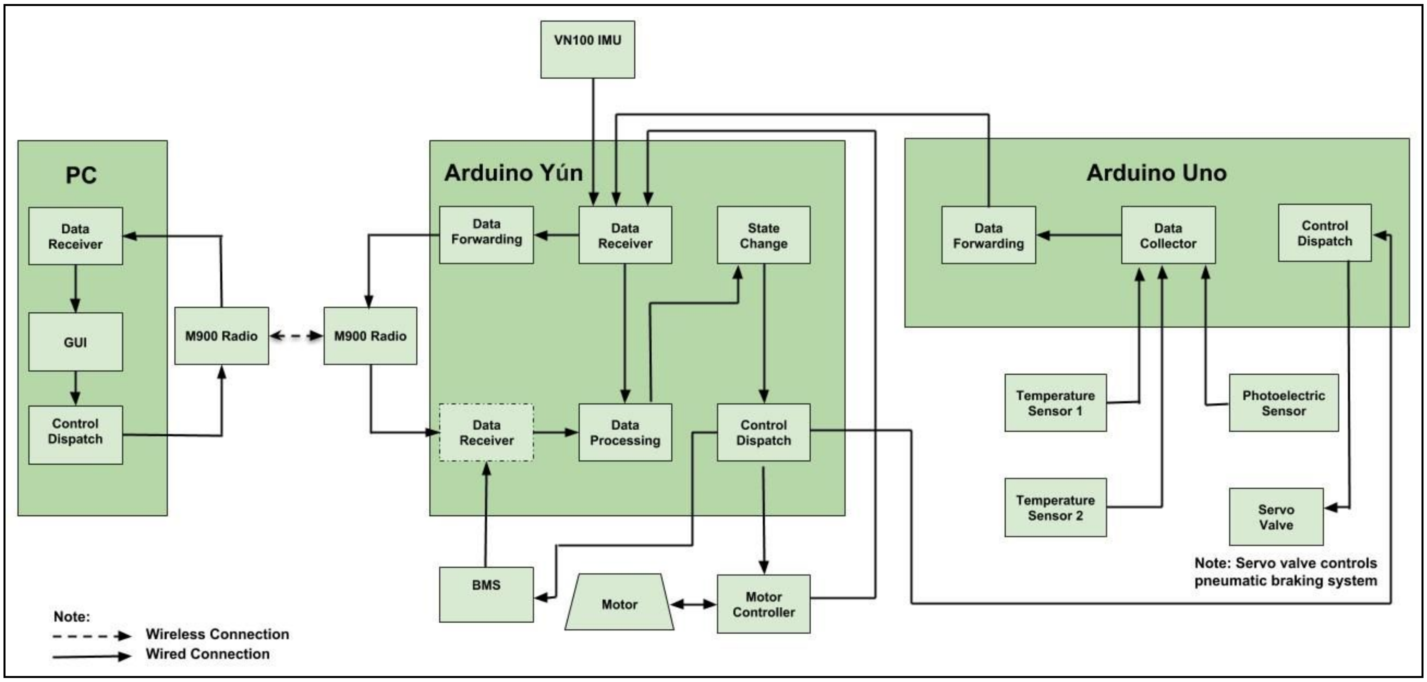


Figure 22. Detailed Data Flow Diagram

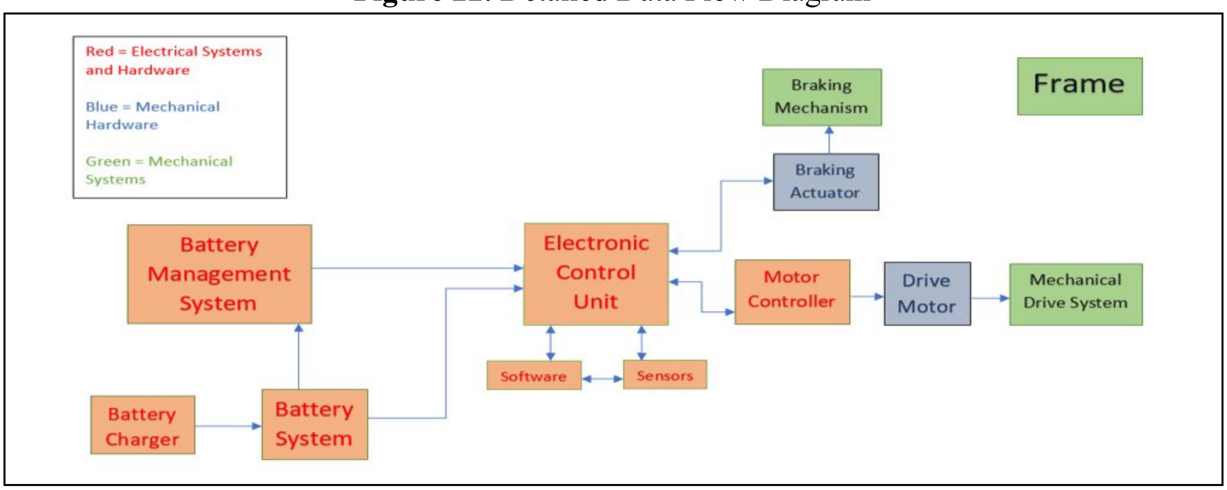


Figure 23. System Diagram

Figure 24 below is a wiring diagram consisting of the complete on pod Navigation & Control Electrical system. A high-level interface system will be composed of the Arduino Yun, VN1000 IMU, M900 radio, and a battery management system (BMS). The Arduino Yun will derive position and velocity from the IMU, communicate with the team laptop via the M900 radios, control the motor controllers, and monitor the BMS. There will also be two low-level interface systems composed of the Arduino Uno, photoelectric, and temperature sensors. In each low-level system, when the Arduino Uno receives a call from the Arduino Yun, the Uno will delegate the call to the appropriate sensor and fulfill the callback initiated by the Yun. This is done by sending a response with the collected data to the Yun. As a result, the two low-level interfaces are connected to the Arduino Yun that is also responsible for delegating calls to the appropriate modules. The delegation enforces the concept of sharing responsibilities instead of having a single module doing all the work. Both low voltage batteries are directly connected to a buck converter before connecting to any of the Arduino Boards so that an acceptable input voltage can be ensured. They are additionally wired to the relays and therefore the servo valves that operate the pneumatic braking. The wiring diagram below uses the same color code as the system diagram above.

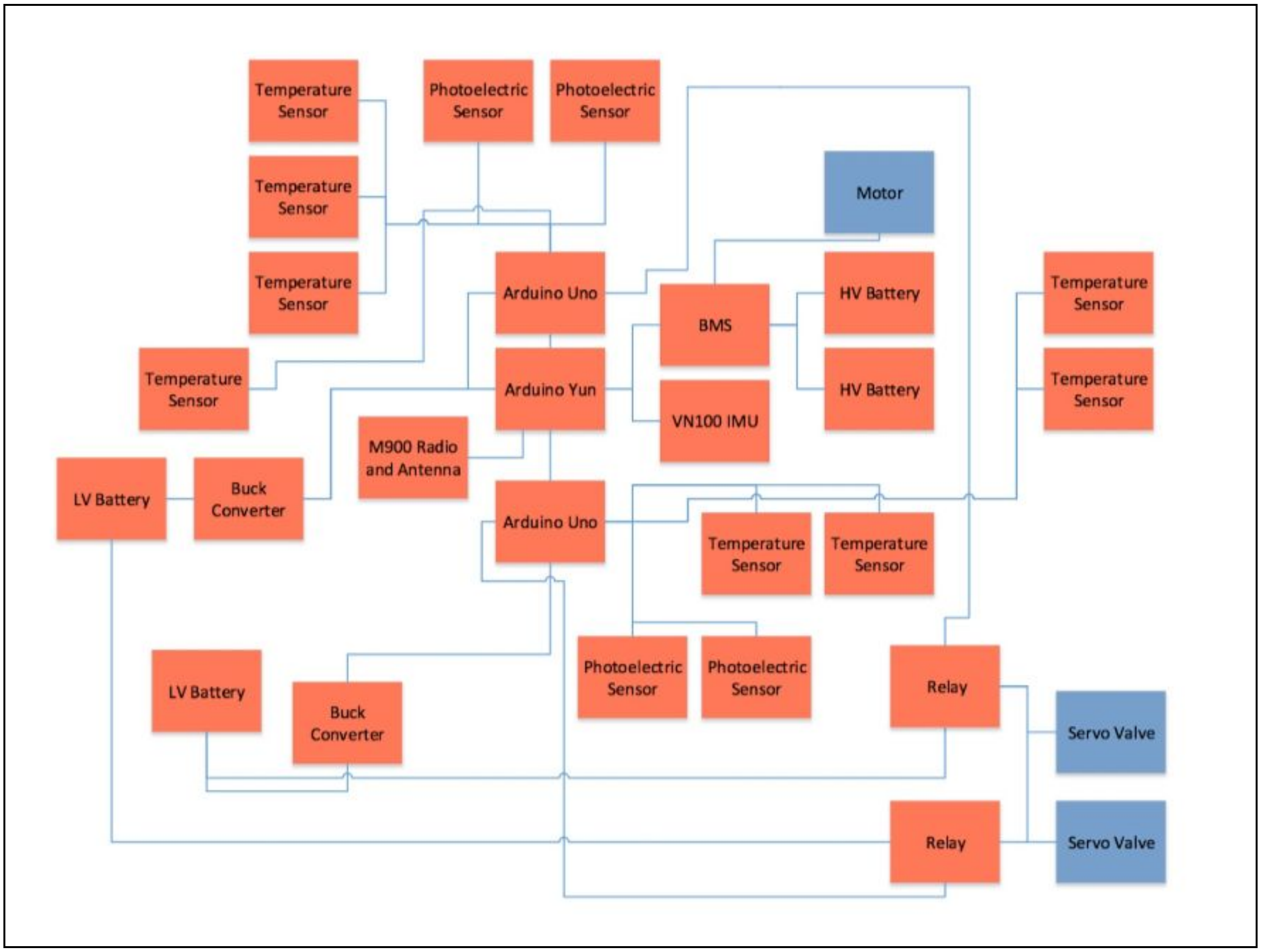


Figure 24. Wiring Diagram

In order to ensure that the dual motors will run synchronized, we are implementing a control system with a closed feedback loop. The encoders in each motor will send each uptick to the arduino yun and the yun will compare the encoder values to one another and adjust the speed of the motors so that they are synchronized.

```
int main (void){
  while(1){
    while(!wirelessDataReciever());
    while(!dataReciever());
    while(!dataProcessing());
    while(!stateChange());
    while(!controlDispatch());
    while(!wirelessDataForwarding());
  }
}
```

Figure 25. Driver Program for High-Level Interface Board

```
#include <stdbool.h>
enum state{Idle, Test};

//When called, pulls data from wireless link and updates values
//Returns true if successful
bool wirelessDataReciever(void){/*TODO*/}

//Filters control input and recieved data
bool dataProcessing(void){/*TODO*/}

//Calls functions to pull data from mega/motor controller/IMU
//Returns true if successful
bool dataReciever(void) {
       return imuReciever() && yunReciever();
}

//Receives data from IMU
//Returns true if successful
bool imuReciever(void) {/*TODO*/}

//Receives data from arduino Yun
//Returns true if successful
bool yunReciever(void) {/*TODO*/}

//Uses current data values and sets state
bool stateChange(void) {/*TODO*/}

//sends control signal to motor controller and Yun
//calls the 2 other methods
bool controlDispatch(void) {
       return yunControlDispatch();
}

//sends control signal to motor controller and actuators
bool yunControlDispatch(void) {/*TODO*/}

//sends data in a packet to PC
bool wirelessDataForwarding(void){/*TODO*/}
```

Figure 26. Header File for Driver Program

```
// send sensor data request using write and reference to socket
void sendRequest (char** message, int* socket_ref) {
    unsigned int total = strlen(*message);
    unsigned int sent = 0;
    int bytes;

    do {
        bytes = write(*socket_ref, *message + sent, total - sent);
        if (bytes < 0) {
            Serial.print("Error writing to socket");
        }
        if (bytes == 0) break;
        sent += bytes;
    } while (sent < total);
}
```

Figure 27. Code Snippet to Send Telemetry Data to Server Running on Team Taptop

```
function doWriteTemp (app) {
  return errorWrap(async function(req, res) {
    try {
      if (req.query.sensorId === null || req.query.sensorId.length === 0
        || req.query.value === null || req.query.value.length === 0) {
        throw {
          isDomain: true,
          errorCode: `BAD_REQUEST`,
          message: `Incorrect url, try like so temp?sensorId=1&value=26`,
        };
      }

      const [sensorId, value] = [req.query.sensorId, req.query.value];
      await app.locals.processor.writeFile(sensorId, value);
      res.send("GOOD");

    } catch(err) {
      console.log(err);
      res.send("BAD");
    }
  });
}
```

Figure 28. Code Snippet of Node.js Express Server to Receive Request Sent From the Pod

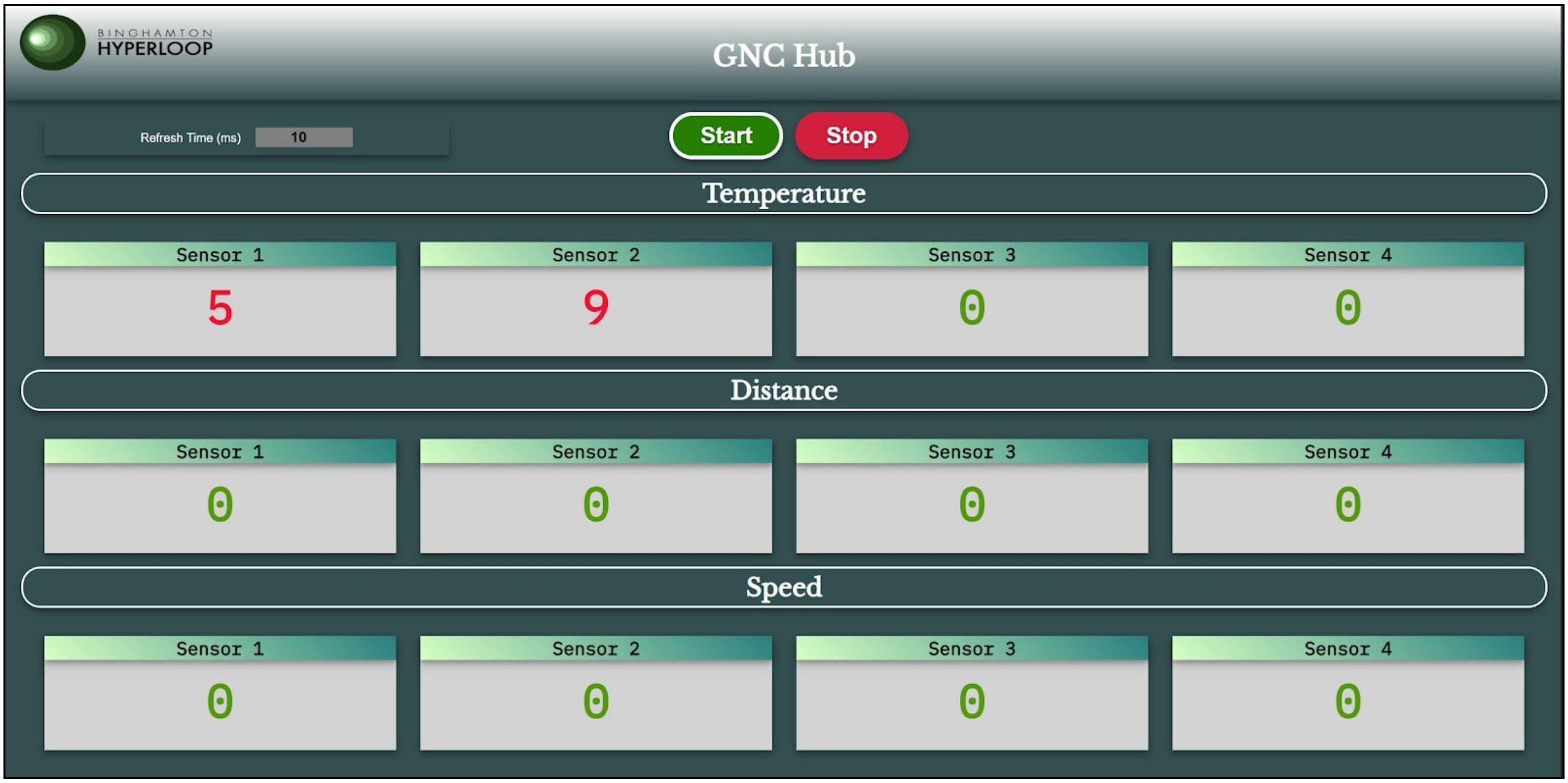


Figure 29. Preview of Navigation and Control Hub

Telemetry Data Processing

A web server running on the team laptop is utilized to retrieve telemetry data from the pod. Specifically, the pod contains an Arduino Yun connected to the same network through which the web server is accessible. Through persistent http connection and protothreads, data from the Arduino Yun are delivered constantly and quickly. A telnet server also exists on the Arduino Yun to respond to requests sent from the team laptop, such as sending a request to make the pod enter its start state or manually force the pod to enter its brake state. Through two servers running on two different hardware, two levels of abstraction are obtained. As a result, there exists separation of responsibilities allowing accurate and quick handling of information.

Once data is retrieved from the pod, data is viewable on the web application shown above in Figure 29. Data is also processed to determine their accuracy. For instance, if the average distance data for one sensor is below or higher than a specific margin when compared to that of the other three sensors, this information will be used to notify the pod the appropriate time to slow down and come to a stop.

Predicted Pod Thermal Profile

The brake pads used to stop the pod are Hawk Performance HB110U.654 Disc Brake Pads. These will heat up when applied to the I-beam. Over time the brake pads will continue to heat up to a maximum temperature of 1328 degrees fahrenheit. The exact properties of the pads are not disclosed by the company that produces them.The found temperature distribution is based on the velocity of the pod when the brakes are applied, the force applied by the pneumatic cylinders and the estimated frictional coefficient. The pads themselves were simulated to see the distribution through them. This was done to find the point of heat contact with the custom made aluminum casing. Figure 30 below shows the profile of the brake pads.

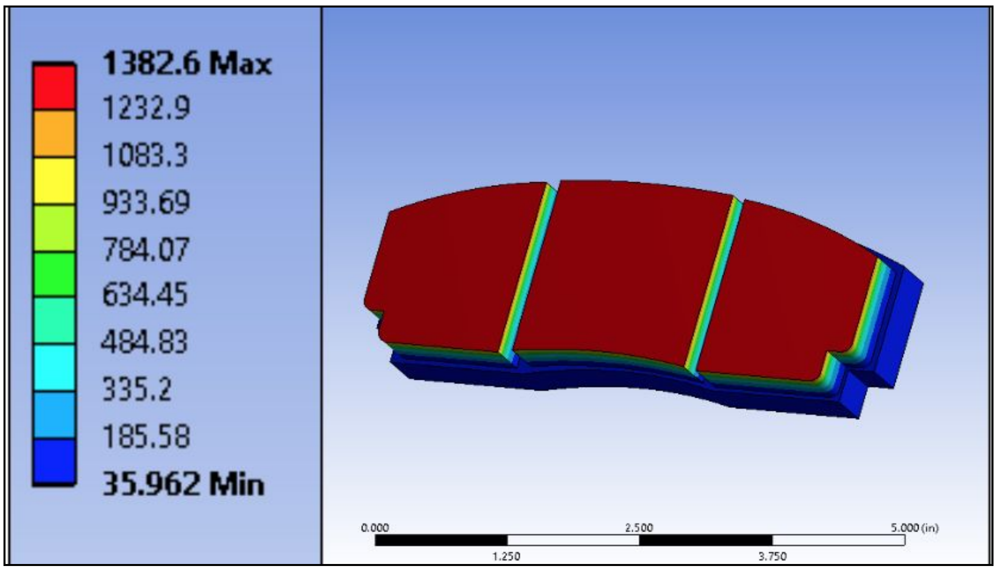


Figure 30. Brake Pad Thermal Profile

The company that produces the pads have specifications of speed and force they can handle. The pad does not exceed the maximum temperature of 1600 degrees which is what the rated maximum heat is. The casing for the brakes was also simulated in Ansys to see the thermal profile of the aluminum custom part. This is important to see the flow of temperature based on the heat generated by the pad. Figure 31 though 33 below, shows the initial distribution at 1.2 second into braking, the distribution at maximum heat of the brake pads which occurs at 7.5 seconds, and the final distribution 20 seconds after initial braking respectively.

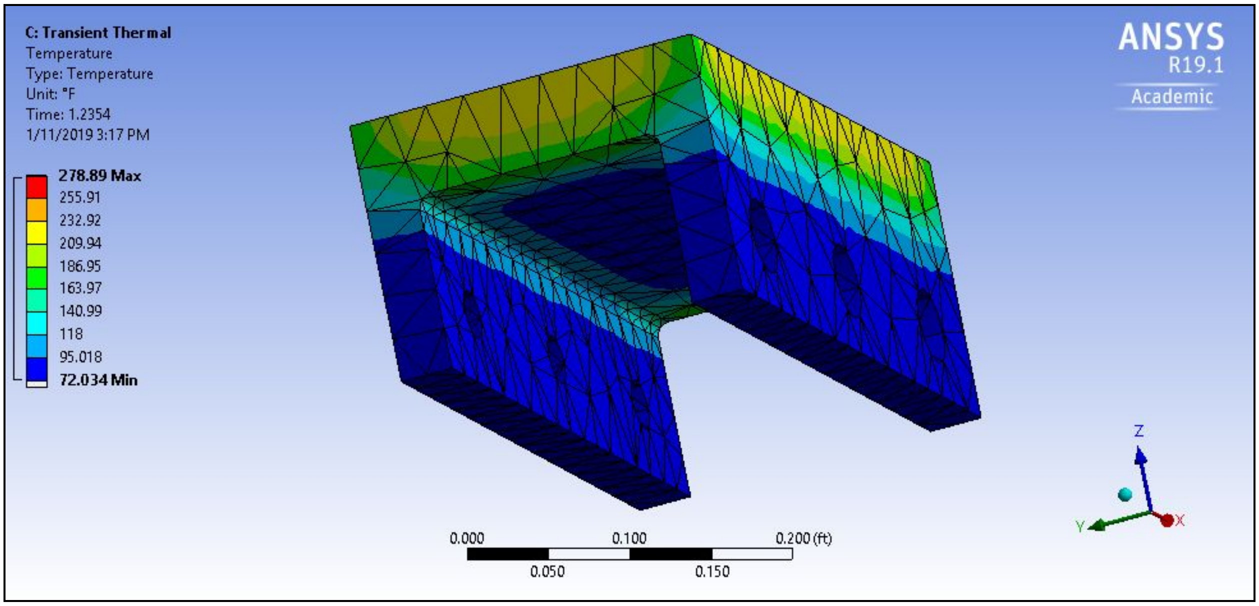


Figure 31. Temperature Profile of Heat Casing at 1.2 Seconds

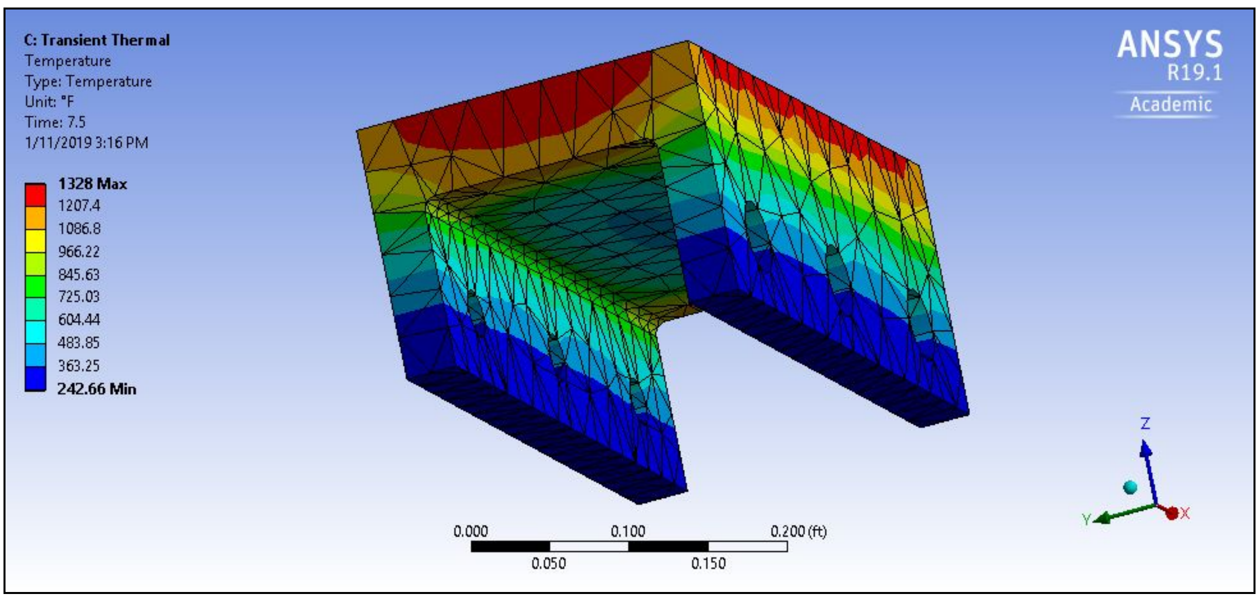


Figure 32. Temperature Profile of Heat Casing at 7.5 Seconds

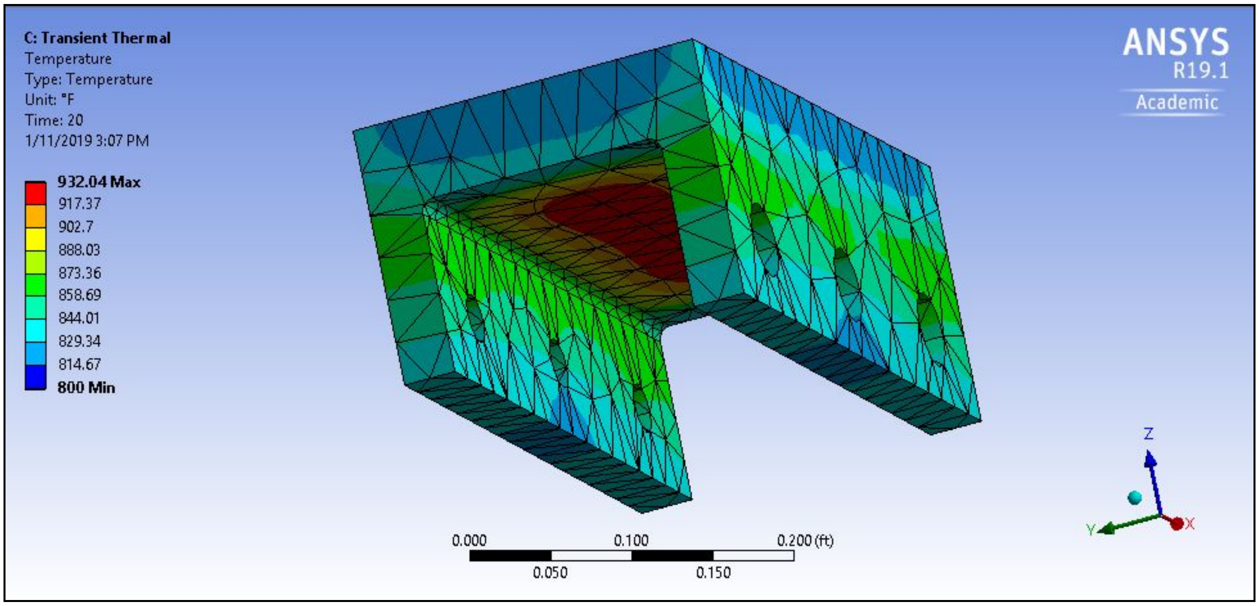


Figure 33. Temperature Profile of Heat Casing at 20 Seconds

Predicted Pod Trajectory

The HPOD's projected trajectory takes it from 0 to 220 mph in half a mile while accelerating for 16.4 seconds. The state of the HPOD changes from accelerating to coasting and the pod remains at its top speed for 0.4 seconds. At this point the pod changes states from coasting to braking and the pneumatic braking commences. The pod brakes for 7.5 seconds before reaching a complete stop within 100 feet of the end of the tunnel. A timeline of the HPOD's trajectory can be seen below in Figure 34.

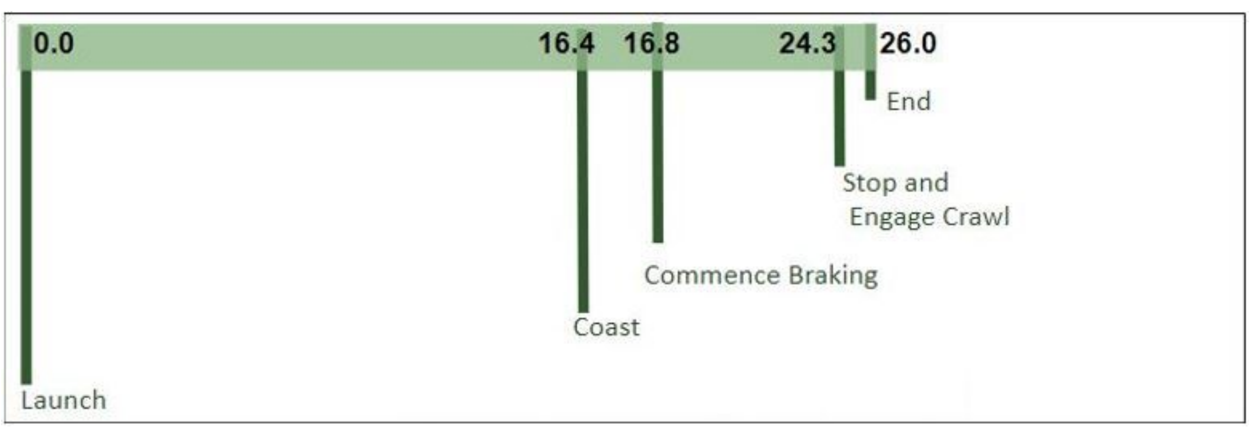


Figure 34. Timeline of Mission Profile

The preliminary position, velocity and acceleration plots can be seen in Figures 35 through 37**.** To create the pod trajectory the possible accelerations had to be calculated. Once the possible acceleration of the braking system and propulsion system is known the the maximum velocity the pod can achieve before it must start breaking can be calculated. The motors have an acceleration of 19.7 ft/s^2 and the brakes have a deceleration of 41 ft/s^2.

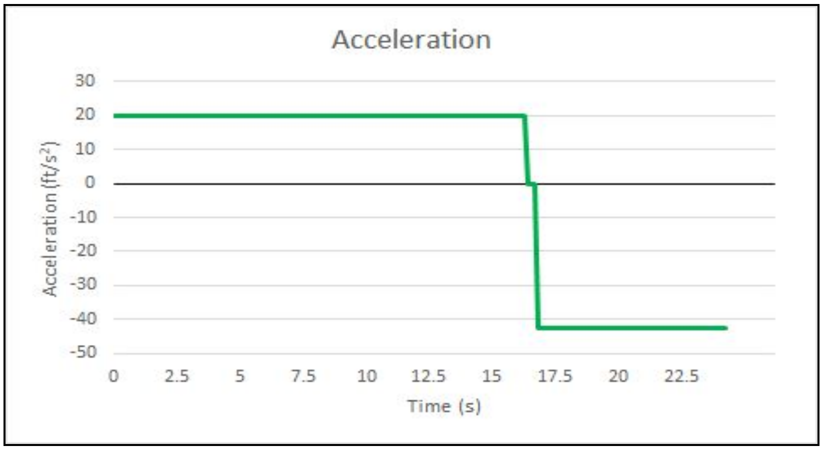


Figure 35. Pod Acceleration Profile

During the launch phase the motors constant acceleration propels the pod at an increasing linear velocity as shown. Once reaching about 322 ft/s the coast phase can then be seen below when the acceleration is 0. Then brakes are applied and starts the deceleration of the pod. At the end of the cycle the velocity is 0.

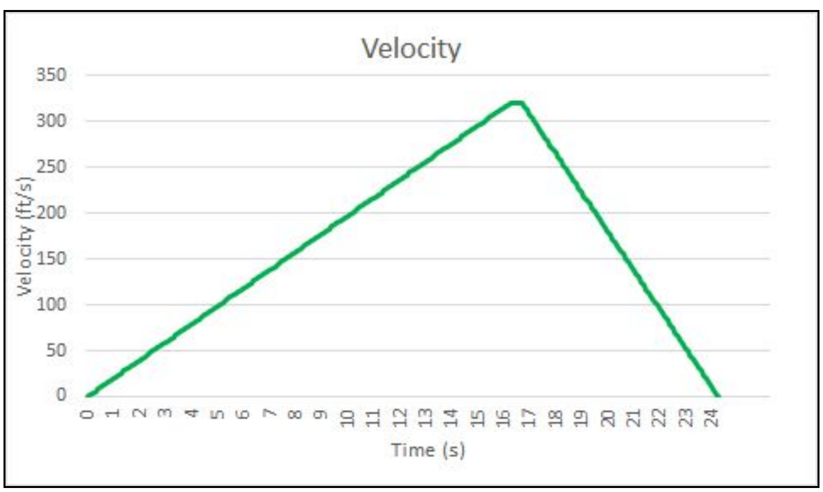


Figure 36. Pod Velocity Profile

The overall position can be found using the acceleration and taking the derivative. Figure 37. below shows the entire position of the pod over time.

Figure 37. Predicted Displacement Profile

A summary of the Trajectory details can be seen below in Table 11.

Table 11. Pod Trajectory Details

Maximum Velocity	322.6 ft/s 220.0 mph
Peak G-Force	19.7 ft/s^2
Braking Force	555.9 lbf
Braking Time	7.5 s
Total Travel Time	24.3 s
Total Travel Distance	3960 ft 0.75 mi

Predicted Vibration Environments

As the pod accels along the Hyperloop track, there are many different sources of vibration. These vibrational environments can cause deformation and failure if not accounted for correctly. A small source of vibration is the large propulsion wheels that propel along the concrete. Also, the motors that sit within the wheels is a source of vibration. For these cases the displacement of vibration will be random and not cyclic in nature. The rubber inserts within the wheel connection mitigates the risk of vibrational failure by reducing the vibration distribution through the frame.

The main source of vibration failure comes from cyclic motion. One source of cyclic vibration is that every 12.5 ft there is a new ibeam to run over. At the intersection of the new beam and old, there could be a step raise as high at .125 in. Based on the velocity of the pod, a driving frequency will be put on the vertical stability wheels that contact the I-beam. The driving frequency can be theorized by using the velocity profile shown in the pod trajectory and the fact that at every 12.5 ft there will be a displacement. Figure 38 below displays the driving frequency applied to the pod during its run.

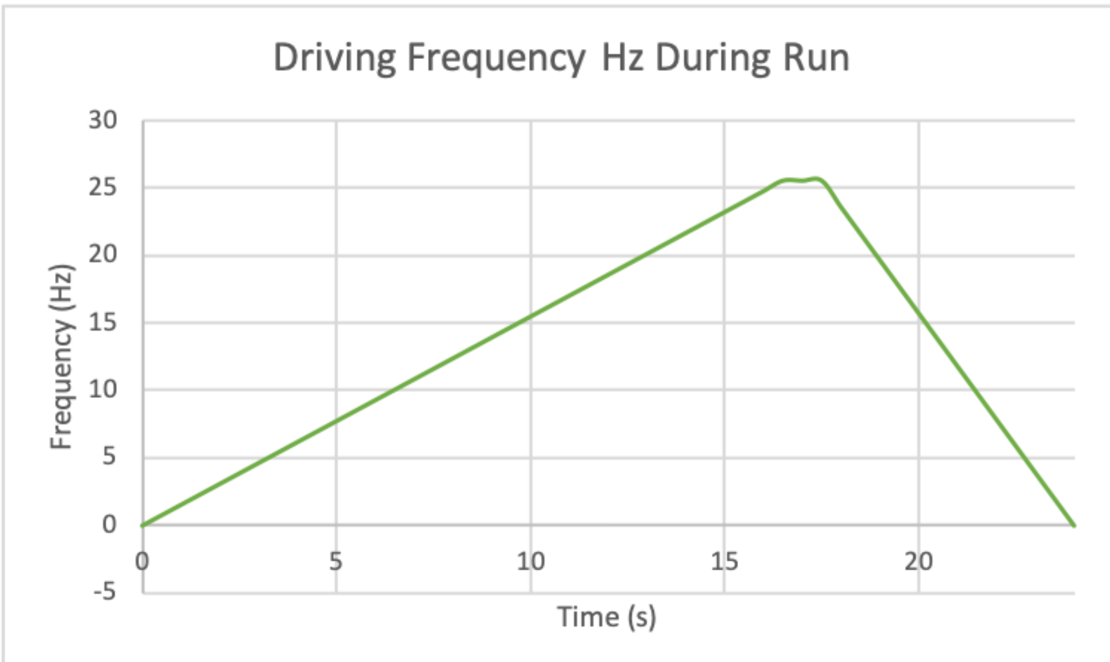


Figure 38. Pod Driving Frequency

The worst case vibration response is when every new I beam is raised .125 in. and then lowered .125 in. Figure 39 below shows the worst case displacement of the pod at the maximum speed of 322.6 ft/s.

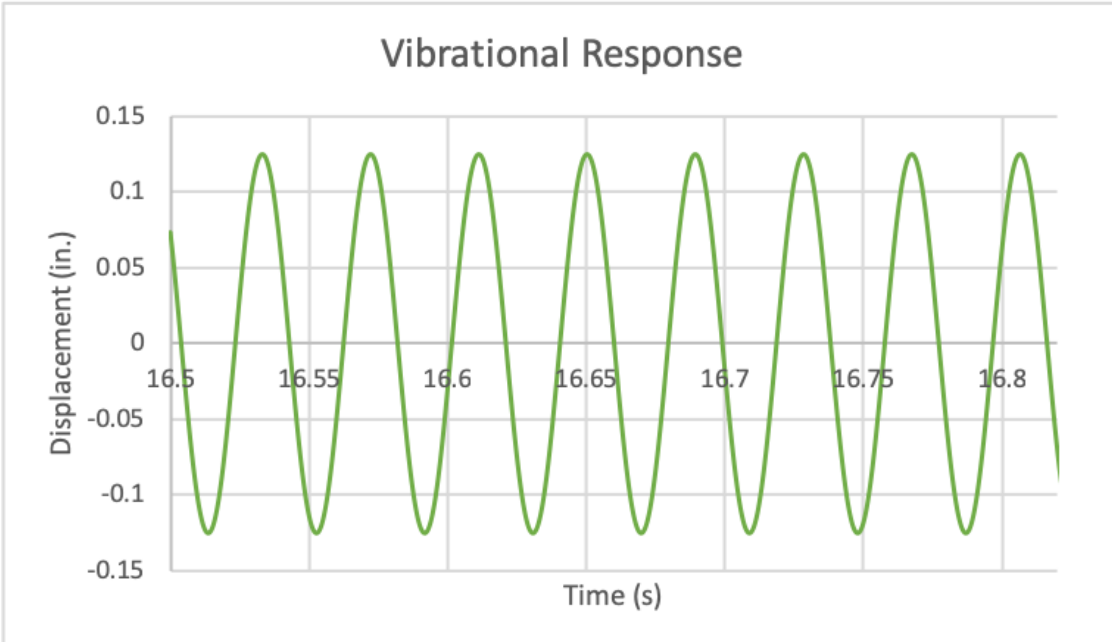


Figure 39. Predicted Vibration Response at 322.6 ft/s

The frame's resonance modes was found in Ansys 19.1 to verify if the driving frequency was held at one of the frames resonance frequencies. Figure 40 below shows the deformation at the first resonance of the frame as well as the remaining modes.

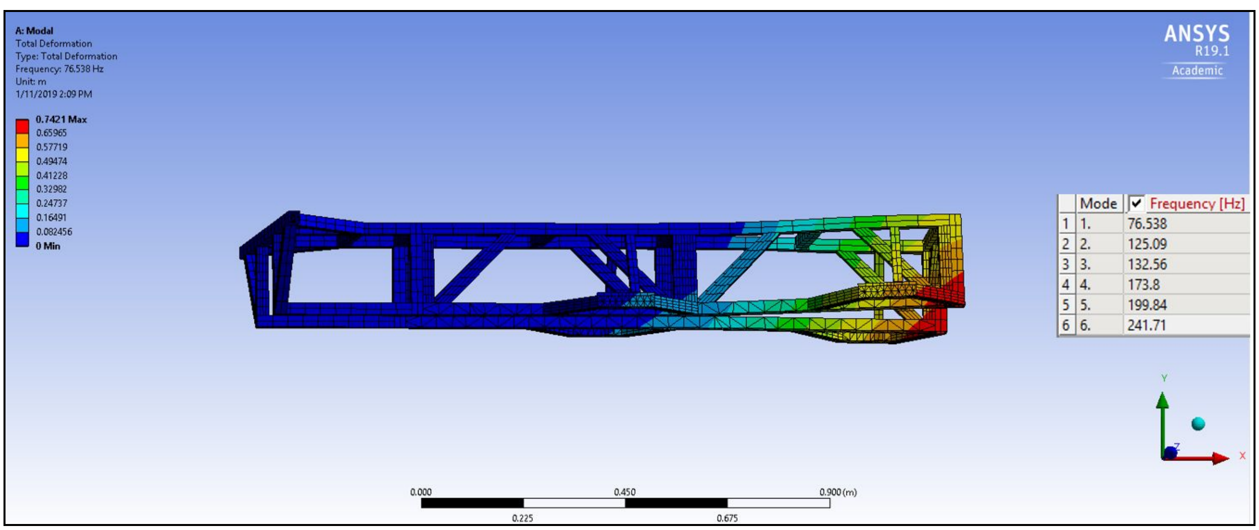


Figure 40. Frame Deformation at Resonant Frequencies

This figure shows that the frame can withstand the driving frequency shown because the driving frequency does not sit at any of its resonance nodes. To further protect the pod from deformation damage from vibration the vertical stability system transfers its energy through rubber load rated bumpers. The bumpers attach to frame to then transfer the structural load on the the frame. The specific bumpers chosen are designed to dampen vibration and shock.

Another source of cyclic vibration is the horizontal stability wheels. The pair of spring loaded systems on each side will oscillate once displaced. The natural frequency of this oscillation can be found by the spring rates used in the sub system and the mass of the pod. The natural frequency of one pair of horizontal stability wheels is 1.68 Hz. This assumes that the propulsion wheels touching the concrete will not stop the pod from oscillation. Therefore, this is the worst case vibration response of the horizontal stability system. Figure 41 below displays the worst case oscillation of the cart if only one set of horizontal wheels were constraining it. It shows a maximum displacement of .24 in. because that is the maximum allowable motion the system allows from center displacement of 0. This oscillation is within the bounds of the other systems. The correction by the system should keep the pod centered during its run.

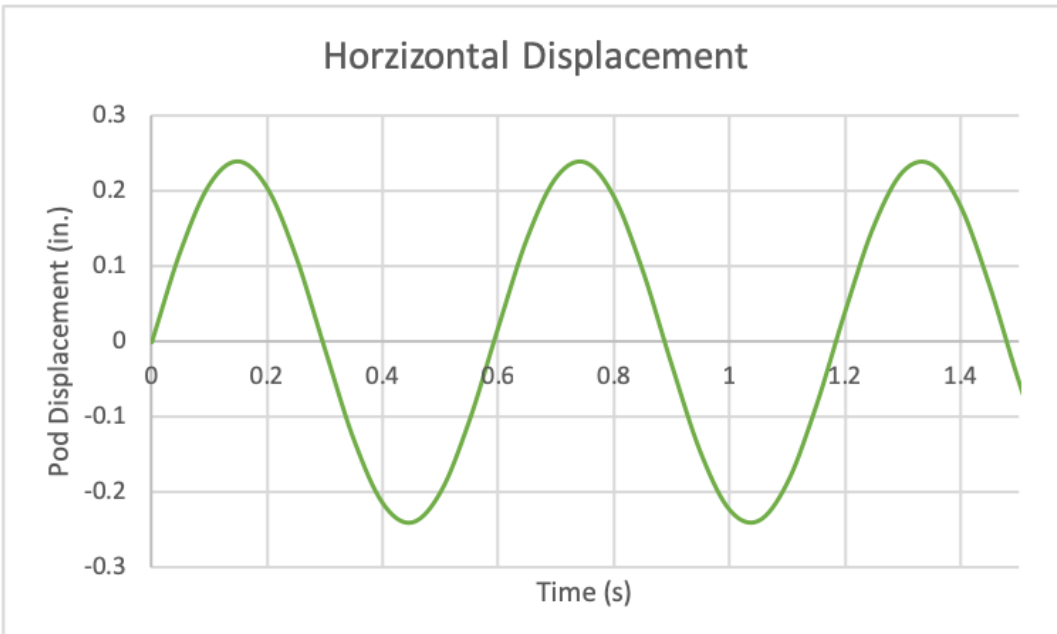


Figure 41. Worst Case Pod Oscillation

Pod Structural Design Cases

The frame, seen below in Figure 42, was designed to house all of the subsystems present within the pod, while allowing for all necessary degrees of freedom for the operation of these subsystems. The pod was based off of a dragster design, with two wheels in the rear flanking each side of the I-beam and a low profile frame extending forward. The frame design takes into account the expected loadings from the battery packs, stability systems, and pneumatic braking systems, as well as the loadings resulting from the front drive wheels and braking. The frame is simple and sturdy, allowing for easy placement of subsystems and for an relatively easy assembly process. The piping from which the frame is constructed is a 1-inch side square tubing with ⅛ inch thick walls. The total length of the frame is approximately 60.5 inches.

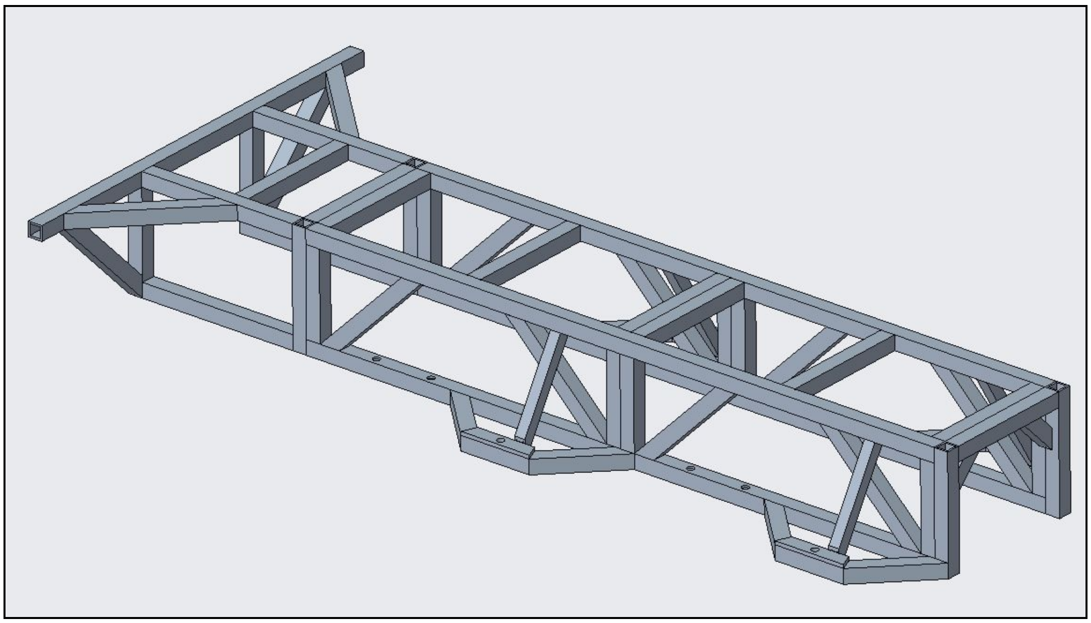


Figure 42. Hyperloop Pod Frame

The three main cases that the frame will undergo are as follows: the force due to rapid acceleration of the pod, the force due to nominal braking of the pod, and the forces involved in an off-nominal crash. All three cases were simulated in ANSYS and returned the following results.

For the case of rapid acceleration, a 171 pound force was applied to the top of the frame in the direction opposite of motion. This force is equivalent to the pod accelerating while holding the weight of all other components. Under these conditions, the maximum stress was 722 psi, well under the yield strength of the aluminum tubing, 35000 psi. Since our frame will be welded together, some sections will become weaker due to the heat required to bond the material. In these heat affected zones, it can be estimated that the aluminium will lose about 15% of its strength, bringing it's yield strength down to 29750 psi. With this in mind, the frame still has a safety of factor of around 40. The stress concentration for these conditions are shown below in Figure 43.

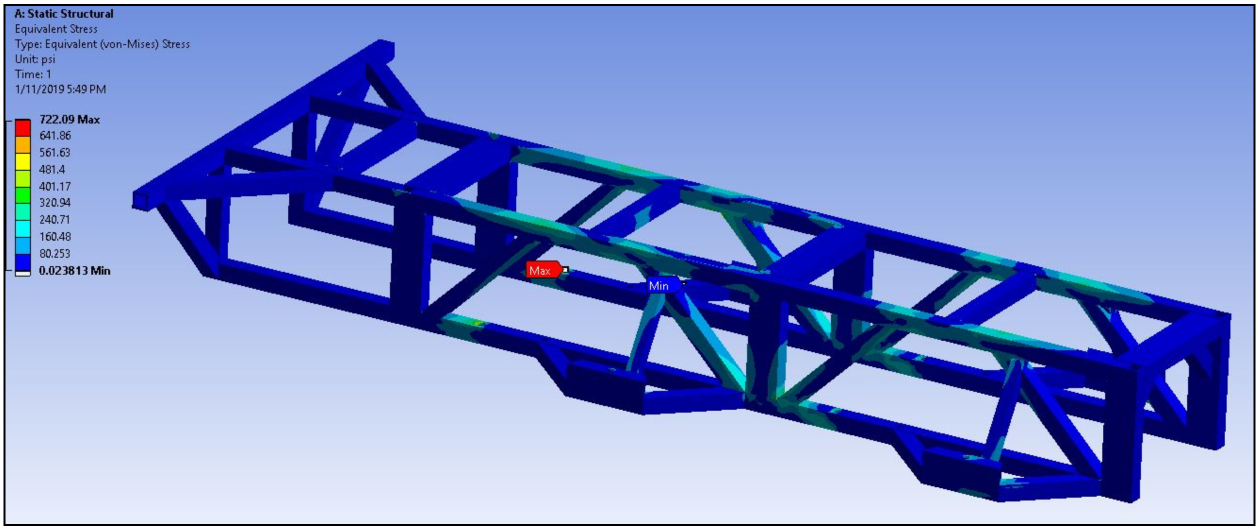


Figure 43. ANSYS Stress Results for Pod Acceleration

When the HPOD is braking, a different set of conditions will be applied. All of the weight will be sent forward in respect to the frame. In addition, since the HPOD decelerates at a higher rate than it's acceleration, a force of 405 pounds was applied in ANSYS. Under these conditions, the maximum stress endured by the HPOD was 1981 psi, which compared to the 29750 psi estimated yield strength calculated above, gives a Factor of Safety of 15.

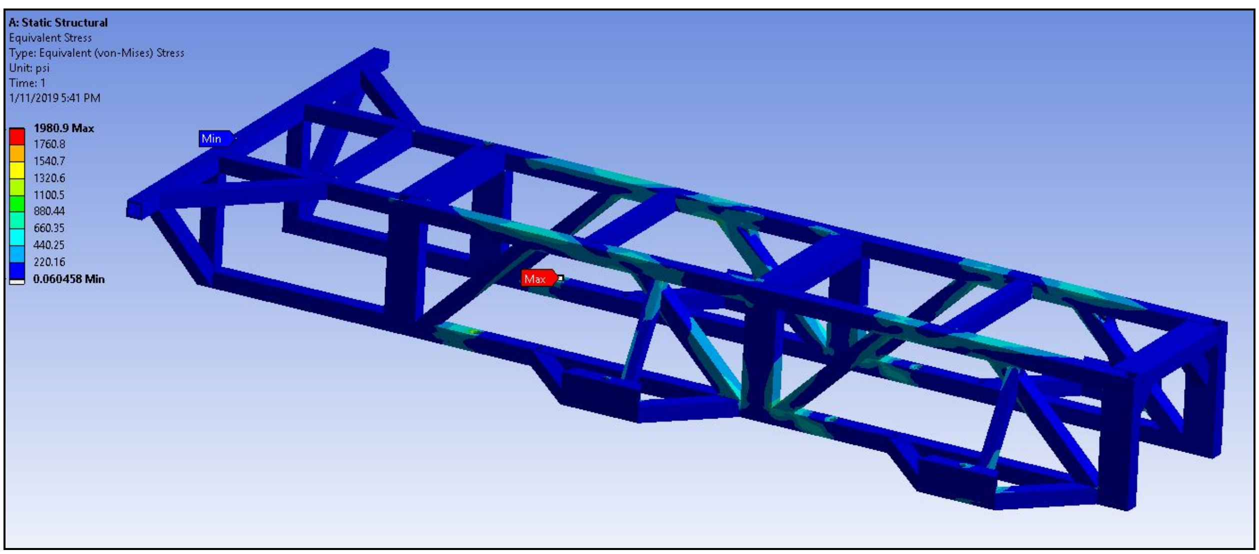


Figure 44. ANSYS Stress Results for Pod Deceleration

The third and final case that the frame was put under was a crashing case. Since this is off nominal, the integrity of the frame is not as important. What becomes important is the rate at which the HPOD comes to a halt. During the analysis, it can be found that the aluminium tubing fails almost immediately after it comes in contact with the wall. Figure 45 shows this failure in red. Since this failure uses up energy, the HPOD begins to slow down. As the frame buckles more and more, the HPOD loses velocity, making the stop less immediate.

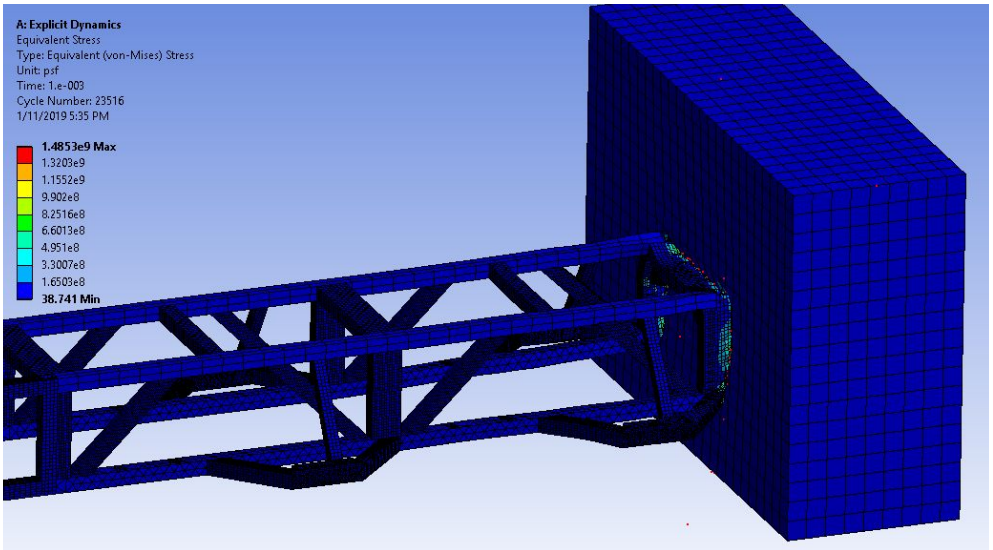


Figure 45. ANSYS Stress Results for Off-Nominal Crash

Analysis and calculations were completed to verify that the horizontal stability wheels will work properly and effectively. The vendor parts selected for the system have rated load and lengths. The shoulder screws, and bearings are rated much higher than the stress induced by the system. The set of springs are rated to reach a length of 3.6 inches, which at that length will induce 27.6 lbf. The custom upper and lower housing were simulated in ANSYS Workbench 19.2. Figures 46 and 47 below show the stress found on the custom parts when simulated with greater force than expected. The aluminum 6061 sheet used to create both custom parts has a yield strength of 35,000 psi. The greatest stress found on the custom aluminum is 1518 psi, having a factor of safety of over 23.

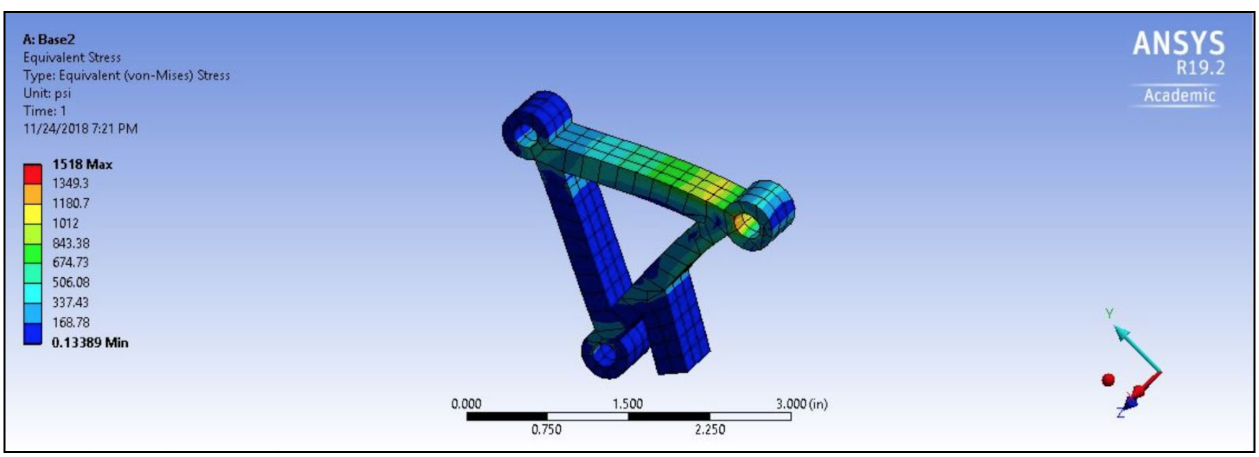


Figure 46. Upper Base Maximum Stress

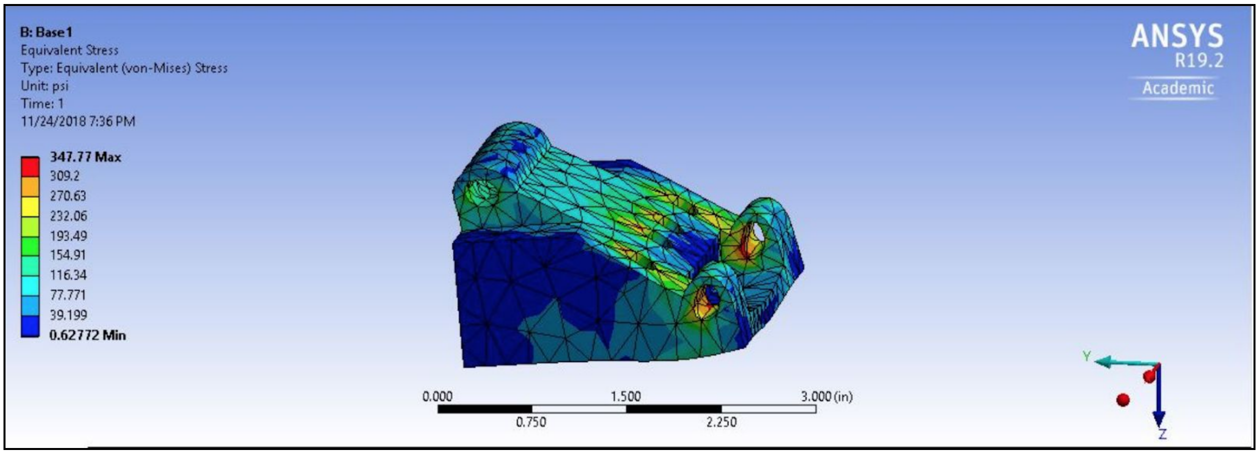


Figure 47. Lower Base Maximum Stress

Table 12. Horizontal Stability Analysis of Parts

Part	ANSYS	Yield Strength	Max Stress	Force (lbf)	Rated FOS
Base	Ansys	35000	347.77	35	100.644
Upper Base	Ansys	35000	1518	35	23.059
Dowel1	Rating	140000	1629.74	80	85.902
Existing Wheel	Rating	35000	1426.02	70	24.541
R4A-2Z Ball Bearing	Rating	1000	35	70	28.577

The Vertical Stability Assembly supports the entire front of the pod. For that reason the system must be capable of supporting extreme loads up to 500 lb's. The system was analyzed through FEA and excel calculations to ensure it would be able to support this stress. The vendor shoulder screws and bearings have rated stresses they can endure. All vendor parts used in the vertical assembly can endure the stresses applied to them by a factor of safety of at least 6. The custom lower hinge, made of block aluminum, will have a high stress applied to it when supporting the cart as well as when the cart hits a higher point and must hold the cart down. To ensure that this custom part could safely perform the function needed it was simulated in ANSYS Workbench for its stresses. Figures 48 through 50 show the results of the analysis performed when a worst case scenario occurs or only one hinge out of the four is constraining the cart vertically. Table 13 displays all of the analyses performed on the parts of the vertical assembly. The custom parts were validated in Ansys and the vendor part's factor of safety were found using the rated yield strengths. Even though that is highly unlikely, it must be shown that the system can perform at that condition. As shown below, even when only one hinge is supporting 500 lbs in the direction that causes the maximum amount of stress, the factor of safety for the hinge is over 12.

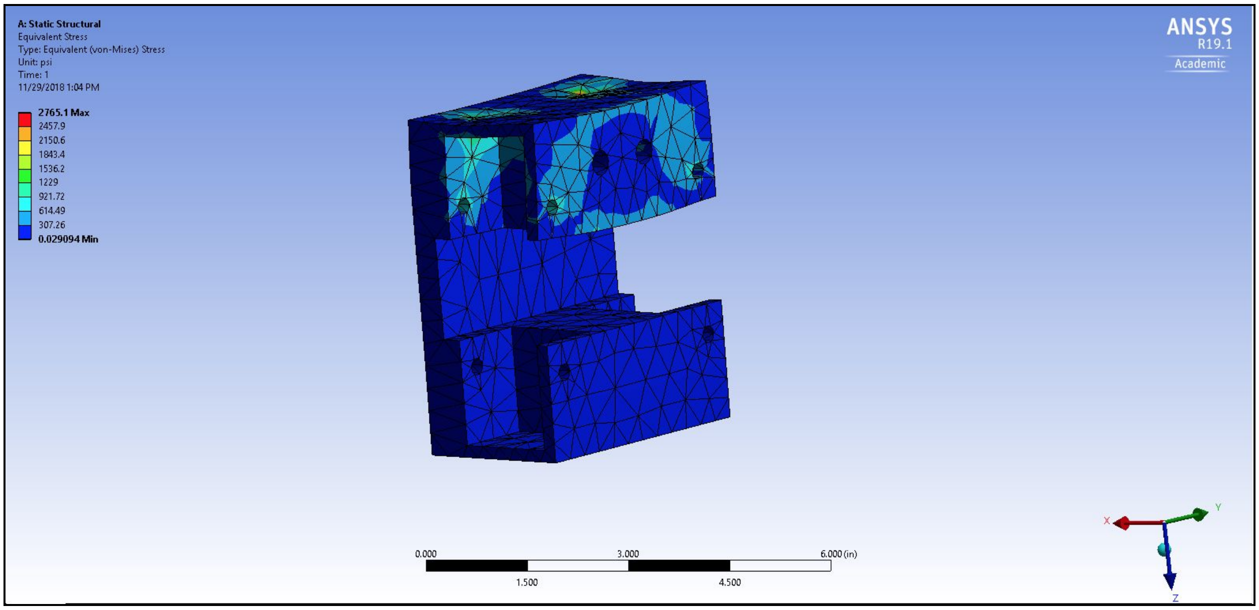


Figure 48. Lower Hinge Stress Under Compression

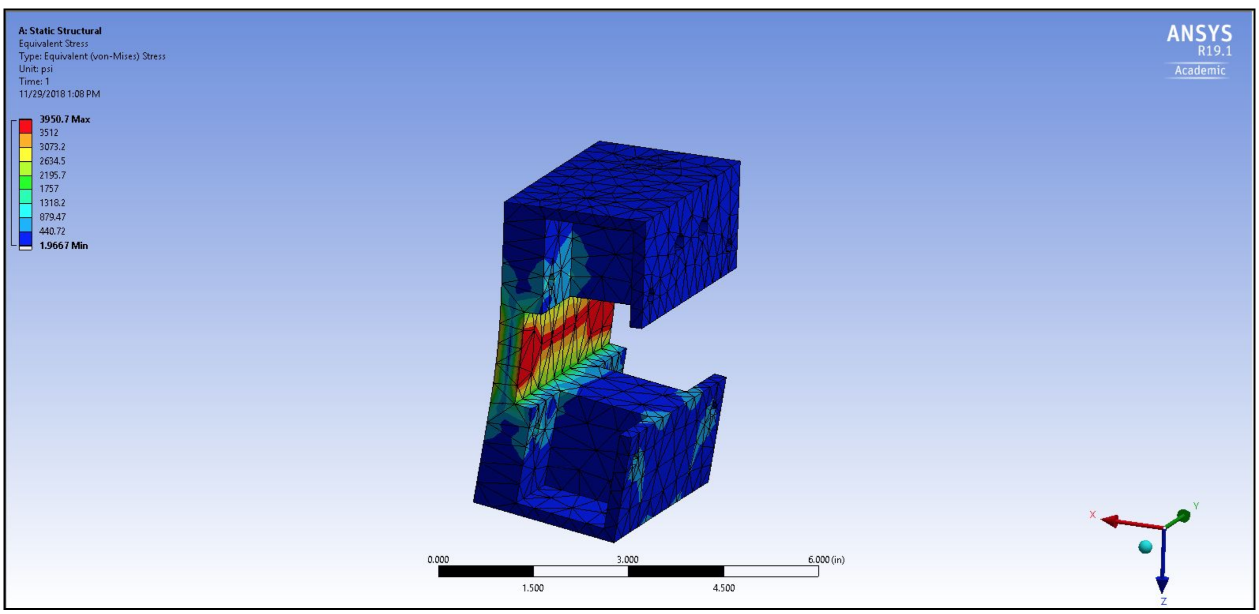


Figure 49. Lower Hinge Stress Under Tension

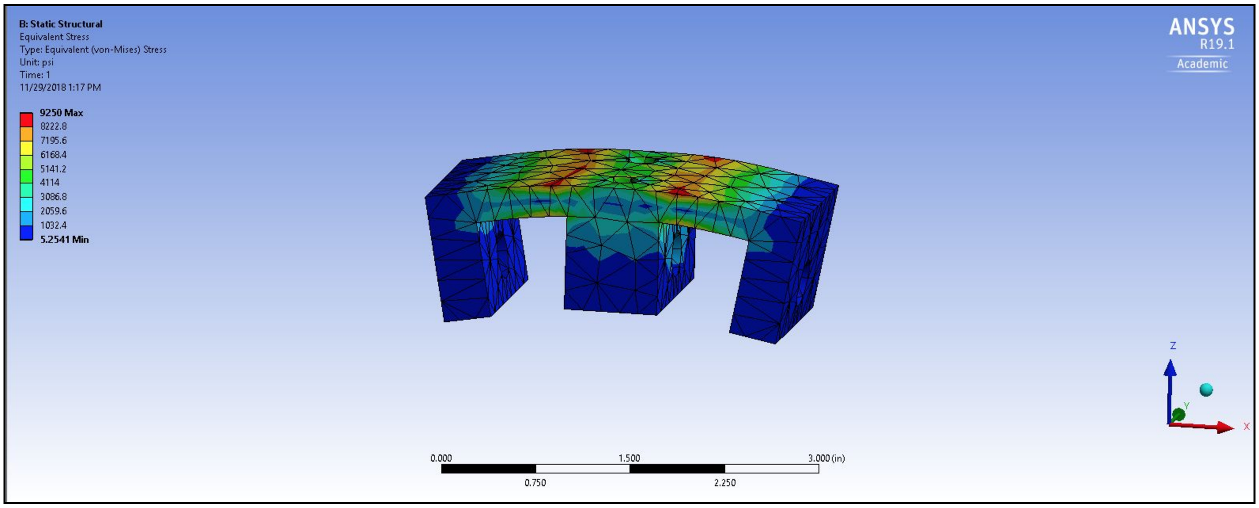


Figure 50. Base Vertical Stress While Holding Cart

Table 13. Vertical Stability Analysis of Parts

Part	ANSYS	Yield Strength	Max Stress	Force (lbf)	Rated FOS
Rubber Stopper (7/4)	Rating	2000	200	200	10.00
Rubber Stopper (3/4)	Rating	830	200	200	4.15
Base Vertical	Ansys	35,000	9,250	700	3.78
Rode Male (1 use)	Rating	60,000	4,527	500	13.25
Rode Female (1 use)	Rating	60,000	4,527	500	13.25
Bolt 3	Rating	84,000	4,527	500	18.56
25 Bolt	Rating	150,000	14,260	700	10.52
LowerHinge	Ansys	35,000	3,950	700	8.86
Dowel 1	Rating	140,000	14,260	700	9.82
R4A-2z Ball Bearing(same)	Rating	1,000	150	150	6.67
Existing Wheel (same)	Rating	35,000	3,055	150	11.45
Vertical Bolt 2	Rating	35,000	3,168	350	11.04

The function of the braking stability system is to support the braking cylinder and give the cylinder enough space without widening the main frame.

The braking stability system, as shown in Figure 51 below, includes four sets of trapezoidal support mechanisms. Each mechanism helps to support one of the four braking cylinders. To ensure that the pod will be able to fully support the braking systems, the supports have been designed to handle all of the forces acting upon them during the braking process. Each of these supports also has an extra strut connecting to the top of the frame to help distribute the loading forces to more members.

The braking stability system will be able to be easily welded onto the frame itself. Each bracket will consist of three aluminum tubes with 45 degree angles. These angles will reduce the amount of shear stress on the support as the pod undergoes braking forces. The extra strut will have a 60 degree cut on the top end and a 30 degree cut on the bottom end in order to correctly fit onto the frame.

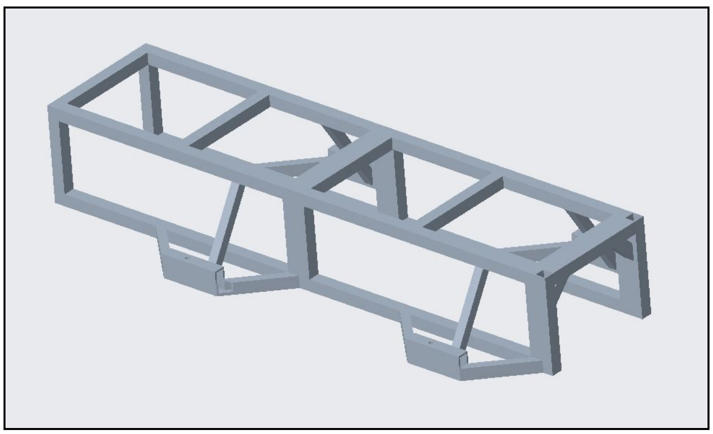


Figure 51. Frame Assembly With Braking Support

The braking support mechanism was analyzed using ANSYS to ensure that it will work properly. This takes into account the peak braking forces that will be acting upon it. Aluminum tubes will be used as they have a high enough tensile strength to handle the largest stresses that will be applied to them during braking.

Figure 52 below shows the stress applied to the braking supports when a greater force than expected is applied to them. Figure 53 below shows the factor of safety when this same force is applied to the braking supports. The aluminum 6061 tubes used to create the supports have a yield strength of 35,000 psi. The greatest stress found on the custom aluminum is 12460 psi. The factor of safety of the supports is 2.65.

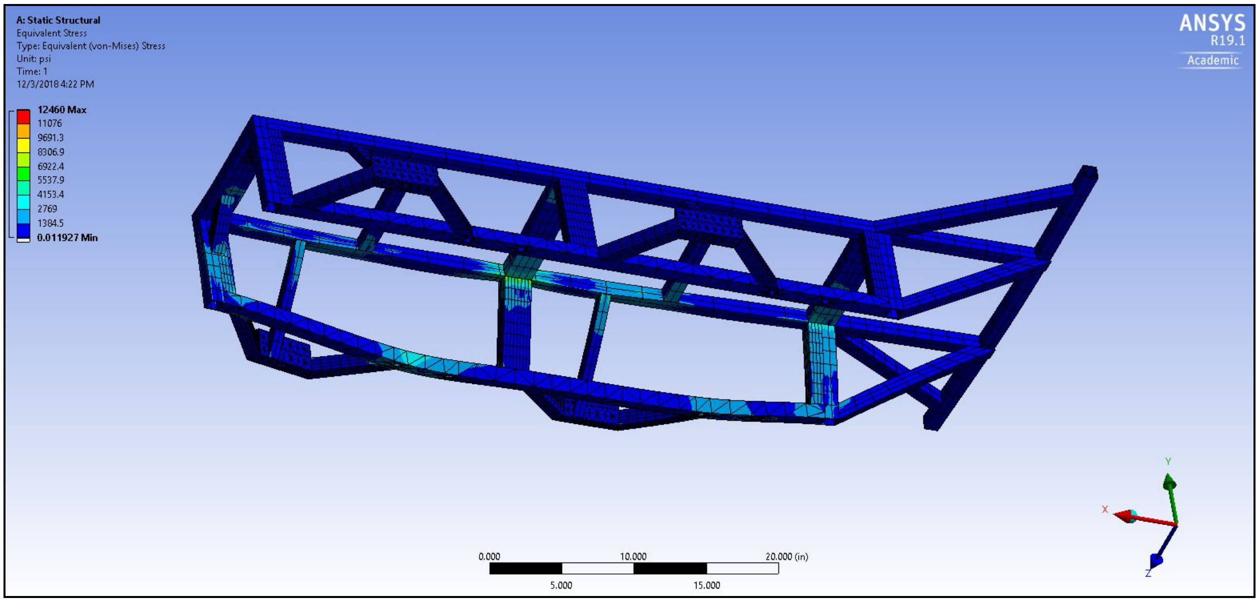


Figure 52. Stress From Applied Brakes

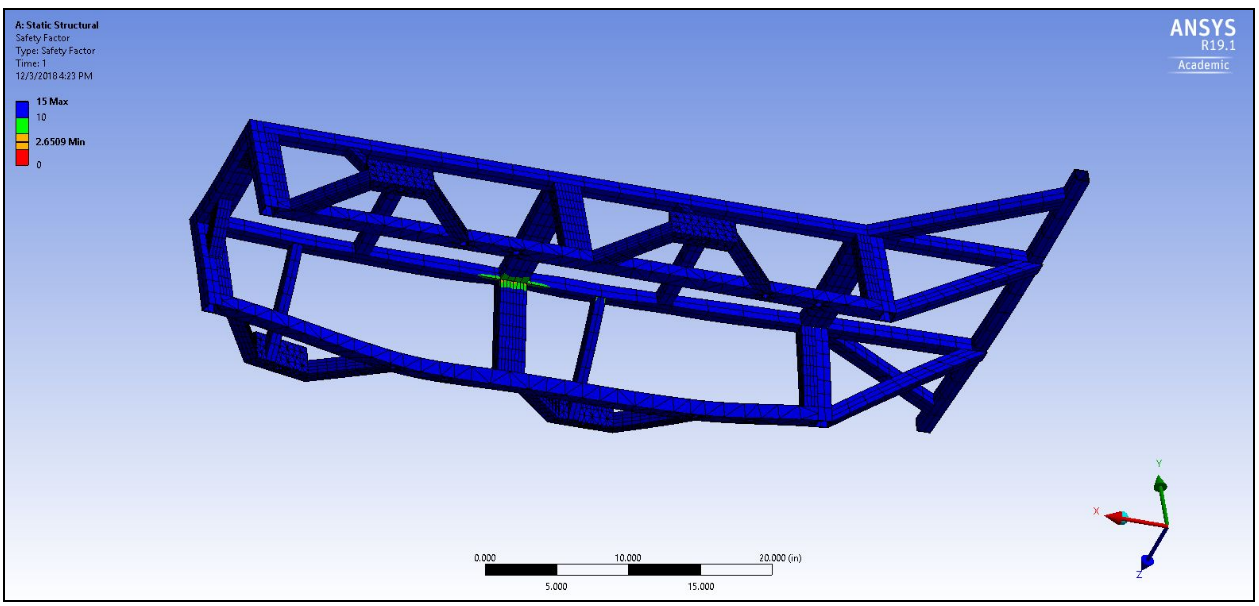


Figure 53. Factor of Safety From Applied Brakes

Structural analysis was conducted on the rear propulsion structure to ensure stability during motor acceleration. With an applied torque of 120 N-m from each motor during acceleration, the lowest safety factor experienced by the propulsion system was 5.62 with a max stress of 3100 psi as seen in Figure 54 below.

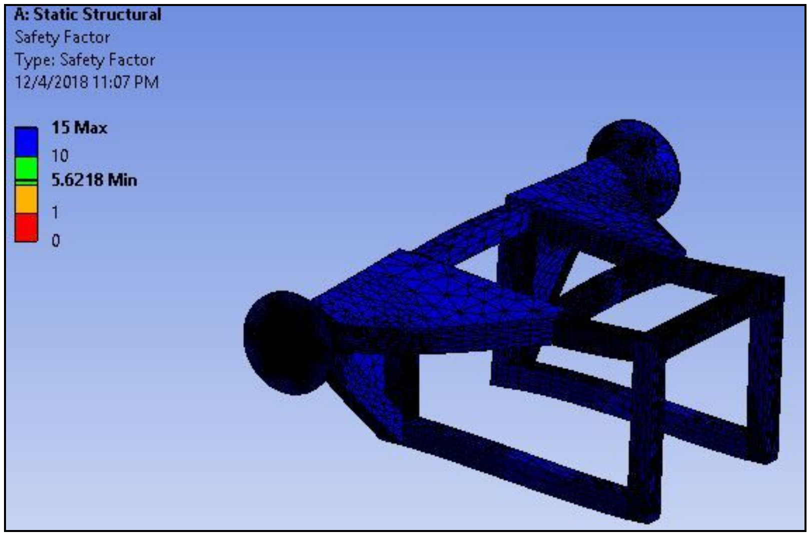


Figure 54. ANSYS Stress Results for Drive Wheel Links

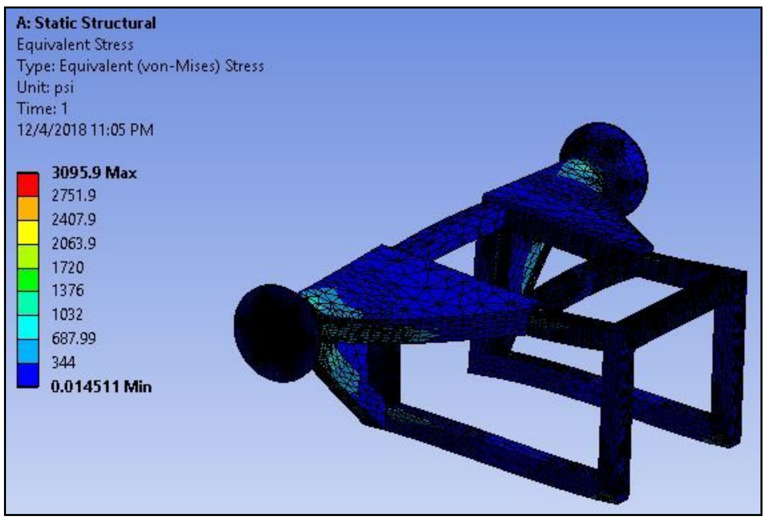


Figure 55. ANSYS Factor of Safety Results for Drive Wheel Links

The bolt connections between the sleeve and the motor were also analyzed to ensure the motor would remain in place during acceleration. These bolts are paramount to the overall success of the pod and must be able to withstand the high acceleration forces without coming loose. The motor bolts can be seen in the exploded view below in Figure 56.

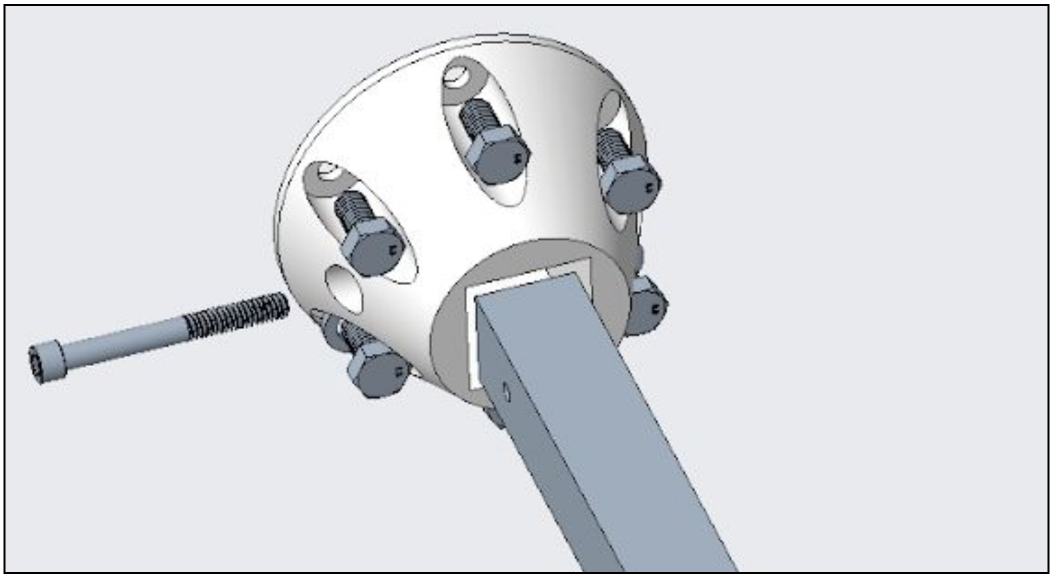


Figure 56. Propulsion Sleeve Exploded View

Table 14. below shows the maximum stress and factor of safety of the bolts under the acceleration conditions.

Table 14. Propulsion Bolt Analysis

Part	Yield Strength (psi)	Max Stress (psi)	Max Force (psi)	Factor of Safety
Axel Sleeve Bolt	70000	157885	3100	4.43
Motor Bolt	70000	10526	516.7	6.65

Pod Functional Test Programs

Structural Test Program

A horizontal stability system test plan will be conducted to ensure every horizontal system used on the pod performs correctly and safely. The following test procedures will be carried out and verified for the system.

- All bearing wheel assemblies will be tested at 30,000 rpm
  - To verify it can go the speed required
- All bearing wheel assemblies will be given a static load of 150 lbf
  - To verify the wheels used can support the pod
- The full sub assembly will be simulated by pulling on the wheel in the tension direction
  - To verify the entire sub assembly will function correctly

Vertical Stability test plan will be conducted to ensure the vertically system used on the pod performs correctly and safely. The following test procedures will be carried out and verified for the system.

- All bearing wheel assemblies will be tested at 30,000 rpm
  - To verify it can go the speed required
- All bearing wheel assemblies will be given a static load of 150 lbf
  - To verify the wheels used can support the pod
- The full sub assembly will be pulled down 0.125 in. simulating a bump
  - To verify the spring and arm action works as designed
- Once attached to the frame the 300 lbf of force will be applied to the wheels
  - To verify the rubber stoppers and frame transfers the load of the vertical stability

A frame test plan will be conducted to ensure the frame used for the pod performs correctly and safely. The following test procedures will be carried out and verified for the system.

- All weld points will be visually inspected
  - To verify the welds are completed correctly and no more than 15% of strength is lost due to weld
- The fully assembled frame will be constrained at the contact points of the wheels and vertical stability while 500 lbf is applied on top of it
  - To verify the frame once assembled can safely hold the batteries and other subsystems
- The fully assembled frame will be constrained at the braking contact points while 600 lbf is applied in the direction of motion from the top of the frame
  - To verify the frame can withstand the force the braking system will transfer to it.

Propulsion Test Program

Propulsion Function Testing:

- One of the requirements set forth for the propulsion system was that the pod must be self propelled. The pod is fixed with two High Voltage Emrax-228 motors connected to the high voltage power supply. The ability of the functionality of the motors will be verified by testing the motors in house once the pod is constructed.
- Emrax is aware of the motors intended use in a vacuum as part of the HPOD and will ensure the motor is sealed and tested under vacuum conditions prior to shipping to Binghamton Hyperloop.

Propulsion Dimension Testing:

- The next requirement is that the system will be compatible with the dimensions of the SpaceX test track. An I-beam with the SpaceX specified dimensions will be purchased and the systems will be constructed upon the test track to ensure there are no unexpected contact points. The distance to the outermost point of the rear propulsion will also be measured to ensure it will run within the vacuum tube.

HPOD Movement Testing:

- When the HPOD is not powered, the EMRAX motors are able to rotate freely and with little resistance. The EMRAX motors are brushless DC motors and when the power supply is cut from the motors there is no magnetic field opposing the motion allowing for the tires to rotate when a force is applied by a human. This will be verified through testing once the motors are assembled in the wheels.

Power Test Program

LiPo Cell Capacity Testing:

- Several LiPO Prismatic cells will be placed in vacuum like conditions overnight and their capacities will be measured. Through research, our team found that LiPO prismatic cells have a lower capacity in vacuum conditions however do not experience leaks. The capacity of the cells will be measured before during and after they are placed in the vacuum chamber and these values will be compared to ensure battery functionality is not lost. The capacities and states of the cells will be examined and verified to work in the expected SpaceX test environment.

LiPO Cell Discharge Testing:

- The pack will be tested by Charge CCCV to ensure there is not unexpected arcing of the individual cells. The battery pack will also be monitored by the BMS and will help prevent unexpected electrical outputs. The discharge rates and overall voltages will be measured and compared to the anticipated values for the battery pack.

Braking Test Program

Pneumatic System Test Plan:

- The pneumatic system and all associated tubing and parts will be individually tested at the 150 psi working pressure and then monitored to ensure there are no leaks in any aspect of the system.
- The pressure relief valves will be individually tested at their working pressure of 175 psi to ensure they will be able to vent excess air to atmosphere in an overpressure scenario.
- The servo valve will be tested at the operational pressure in both the open and the closed position to ensure it will not leak.
- The venting process will be performed and the temperature of the relevant components will be monitored to ensure the loss of pressure will not compromise any essential components.
- The pneumatic filling procedure will be performed and practiced in advance to ensure all relevant personnel are trained in its use.
    - Note that all pneumatic filling equipment including the air compressor and manual pressure gauge must be tested at the working pressure of 150 psi before use.

Braking Linkage Test Plan:

- Each guide rod will be tested using a compressive load of 500 lbs to ensure no buckling will occur during the braking process.
- Each brake pad will be tested by being placed against an Aluminum 6061-T6 sample and oscillated with comparable force and duration as will be experienced during the braking process.
    - The temperature of both samples will be monitored to ensure they do not go above expected limits.
    - Both samples will then be checked for damages afterwards to ensure the test track will not be harmed during the braking process.
    - The thickness of the brake pad will be measured before and after the testing process to estimate the degree of material loss during the braking process.
- The springs in the pneumatic cylinder will be removed and tested to find out how much force is going to be exerted when disengaging the brakes. If the spring force is inadequate, replacement springs with a higher spring constant will be purchased and the above process will be repeated until the spring force is sufficient in disengaging the brakes.

Navigation Test Program

Photoelectric Sensor Testing:

- Apply SpaceX test track tape (double up to make it 4 inches in width, as it will be in the test track) in a small test track
- Initiate a test run of the pod to determine if the stripe count matches to that of the distance count
  - For instance, if the width of each stripe is five feet then as the pod passes the 50, 100, 150, and 200 feet mark from the start of the track the total stripe count is expected to be 10, 20, 30, and 40, respectively
  - This will ensure the sensors are recognizing the test track tape and determining the correct count as they are constantly in motion

Temperature Sensor Testing:

- Apply a heat source to the temperature, and measure the voltage output
- Verify sensor measurement by checking temperature with thermometer

Radio Connection Test:

- Establish wireless point-to-point connection between the two radios
- Send command from team laptop that should send back a good response to the team computer

Communication System:

- GNC Hub web application will output initial pod conditions, and all data collected during the run
- In order to ensure everything on the pod is functioning correctly, limits will be set for each measurement
- If a limit is reach, the web application will alert the user and display warning signs

Lost Connection:

- Several requests will be sent from the laptop to the server running on the pod and from pod to server running on the laptop. If any response results in timeout or is a bad response, the occurrence of lost connection will be displayed on the Navigation and Control Hub web application.
  - If the sending of requests from pod to laptop is successful but not vice versa, the Arduino Yun will be programmed to constantly check for specific incoming requests from the laptop. If such requests are not found, the Yun will trigger internal code to apply the brakes to bring the pod to a complete stop.
  - If the sending of requests from laptop to pod is successful but not vice versa, the team laptop will be programmed to constantly check for specific incoming requests from the pod. If such requests are not found, the laptop will

automatically send a request to the pod where the arduino will trigger internal code to apply the brakes to bring the pod to a complete stop.

Full Pod Test Program

The overall structure of the pod must meet size requirements for SpaceX. These specifications will be tested by measuring the full pod. An example of the requirements that will be physically measured are as follows.

- The weight of the full HPOD assembly shall not exceed 3,300 lbs
- The length of the HPOD, along the axis of motion, shall be no less than 5 ft. and no greater than 24 ft
- The cross-sectional profile of the HPOD shall not exceed the inner dimensions of the SpaceX testing tube

The overall function of the pod will also be tested to verify that it will work in the SpaceX test. Once fully assembled a test run will be conducted on the entire pod. This will be done many times to check for errors. This mock test will go in the following order in Binghamton University using the exact I beam specifications.

- Load the pressure tank using the filling procedure at a lower psi.
- Put power to the motor using Navigation and Control system to ensure that it has propulsion forward.
- Disengage the power to the motors to ensure they will stop accelerating when told
- Physically bounce the pod in all directions to ensure the stability systems are reacting correctly.
- Engage the brakes using the Navigation and Control system to ensure the brakes deploy when told.
- Disengage the brakes using the Navigation and Control system to ensure the brake system depressurizes

Pod Production Schedule

WBS	Task Name	Sub Task	Task Lead	Duration	Start	December	January	February	March	April	May	June	July
5	**Build Pod**												
5.1		Work out Potential Design Bugs	Perry	1.5 months	November								
5.2		Finalize Fundraising	Gioia	2 months	December								
5.3		Order Parts	Gioia	3 months	January								
5.4		Pod Construction	Perry	4 months	January								
5.5		Parts Deadline	Gioia		April								
5.6		Construction Deadline	Perry		May								
6	**Finalize Pod**												
6.1		Test Pod Functions	Joseph	1 month	May/June								
6.2		Prepare Pod for Transportation	Clare	1 month	June/July								
6.3		Ready to Compete			July								

Figure 57. Preliminary Spring 2019 Production Schedule

During the Spring 2019 semester, the main focus of the team will be to fabricate pod parts, assemble the pod, run verification testing on the pod to ensure requirements are met, and continue providing SpaceX with documentation required for Hyperloop Competition qualification. At the start of the Spring 2019 semester, Binghamton Hyperloop will begin by evaluating the status of the project and formulating a detailed fabrication and build schedule that will guide the pod build process to be complete by the end of the Spring 2019 semester. As the subsystems of the design take shape and are assembled to the point of usability, they will undergo physical testing processes to ensure that they are functioning as the team expected them to. After the subsystems are tested, they will be fastened to the frame and the assembly will be completed.

The team will also prepare a Final Design Presentation for SpaceX and present it via online conference call on a to-be-announced date in late January or early February 2019. If Binghamton Hyperloop qualifies, a Safety Briefing document will be created and sent to SpaceX by a currently unannounced date in late May 2019. Travel and housing considerations for the trip to the competition in California would then be prepared by the Logistics and Outreach team. Binghamton Hyperloop would then continue making final preparations prior to the 2019 Hyperloop Competition, pass the SpaceX safety checks, and run the pod on the test track.

Pod Finances

WBS	Task Name	Sub Task	Task Lead	Duration	Start		November	December	January	February
7	Fundraising									
7.1		Finalize Fundraising Plan with Administration	Gioia	1 month	November					
7.2		Leverage On-Campus Resources	Gioia	1 month	December					
7.3		Reach out to Local Companies	Clare	2 months	December					
7.4		Acquire Funding from Coporate Sponsor			February					

Figure 58. Preliminary Spring 2019 Finances Schedule

Funding Plan

The Binghamton Hyperloop team was allotted a $10,000 project budget from our University. However, due to the need to meet the requirements outlined in the SpaceX Hyperloop Competition rules, the overall cost of the project is projected to exceed this amount by a significant margin. Due to this deficit, the team has been reaching out to Binghamton University departments in search of extra funding. The team has scheduled (or is in the process of scheduling) meetings with engineering departments to help raise funds for this project. Our team is also planning to meet with potential third-party corporate sponsors (former sponsors and new sponsors) during the Spring 2019 academic semester to meet our budgetary goal. To promote the productivity and satisfactory outcome of these meetings, the team has prepared the necessary Hyperloop sponsorship documents and presentations to adequately demonstrate the goals of the project and the benefits we will be providing to the sponsors. The team expects to require a minimum total of $22,510 to successfully complete the Hyperloop pod. These estimates are based on previous sponsorships this team and other Binghamton University Engineering Project teams have held. Our Hyperloop team is confident that upon admission to the final phase of the competition, the funding to complete our pod design will be acquired.

Pod Cost Breakdown

Table 15. Financial Estimation Spreadsheet

Items	Original Estimate ($)	Actual to Date ($)	Estimate to Completion ($)	Estimate at Completion ($)
Controller	4,000	0	4,000	4,000
Motor	7,500	0	7,500	7,500
Testing Apparatus	50	0	50	50
Metals	3,000	0	3,000	3,000
Skin	2,000	0	2,000	2,000
Fasteners	1,800	0	1,800	1,800
Custom Bearings	1,500	0	1,500	1,500
Wheels	1,500	0	1,500	1,500
Frame	600	0	600	600
Battery	3,000	0	8,500	8,500
Battery Mgmt. System	1,500	0	1,500	1,500
Misc. Electronics	900	0	900	900
Logo	60	60	0	60
Total	27,410	60	32,910	32,910
Funding Limit	10,000		-32,910	-22,910

Electronics System Overview

Sensor List and Location Map

a.

1. **Arduino Yun/Uno**

   There is one Arduino Yun and two Arduino Uno boards that maintains network communication with team laptop, collects sensor data, and controls the course of path for the pod. They are installed to model the master/slave architecture where the Arduino Yun serves as the main-controller and the two Uno boards as the sub-controller.

2. **M900 Radio**

   There are two M900 radios that provide point-to-point communication between the team laptop and the pod. The radios are configured with specific settings to allow network connection with the network provided by SpaceX. The radios allow the pod to be network connected at all times during its run on the track through which telemetry data is retrievable from the pod and requests can be sent to the pod.

3. **DS18B20 temperature sensor**

   Eight temperature sensors are placed within the pod to measure the temperature of different components and areas of the pod. For instance, one sensor is reserved to record the ambient temperature of the outer body of the battery module and another to measure the ambient temperature of the circuit layout composing of Arduino chips, transistors, and capacitors.

4. **OBR1500-R2F-E2-L photoelectric sensor**

   There are four photoelectric sensors on the pod that are used to determine the number of reflective stripes the pod has passed during its run on the track. The number of stripes are constantly sent to the team laptop for analyzing and sending the data to a SpaceX server. Additionally, the number of stripes determined from these sensors play a minor role in determining the accuracy of the distance data collected.

b.

One M900 radio is installed on the stage area next to the team laptop and the other is installed on the pod. In addition to the stage radio connected to team laptop via an Ethernet cable, the radio is connected to a communication network provided by SpaceX via an Ethernet cable. As a result of the two radios being linked, the stage radio is able to provide or extend the network connectivity to the pod radio, basically providing a wireless bridge network.

The Arduino boards are setup in master/slave architecture, the Yun is the main-controller and the Uno boards are the sub-controllers. The Arduino Yun achieves network connectivity through an Arduino Ethernet Shield which is connected to the pod radio via an Rj45 Ethernet cable. The Yun is responsible for sending and listening to specific network requests. The Yun directs the received requests to the appropriate destination and collects data from the two Arduino Uno boards that are programmed to operate specific sensors. The Uno boards are connected to the Yun via a USB hub allowing the Yun to talk to each Uno boards through the standard Serial classes.

The Arduino Uno boards are responsible for controlling all the sensors, such as photoelectric, temperature, distance, and speed. As the Uno boards receive data from the sensors, they will constantly relay the information to the Arduino Yun which is in charge of relaying that information to the team laptop.

The figure below shows the placements of the sensors. Two temperature sensors will be placed on the batteries, and one on each motor. Additionally, two retro-reflective photoelectric sensors will be placed on the top of the shell to count the reflective strips and calculate distance. The blue dots on the figure are temperature sensors and red are photoelectric sensors. Because there will be two redundant systems, there are actually two sensors at each dot.

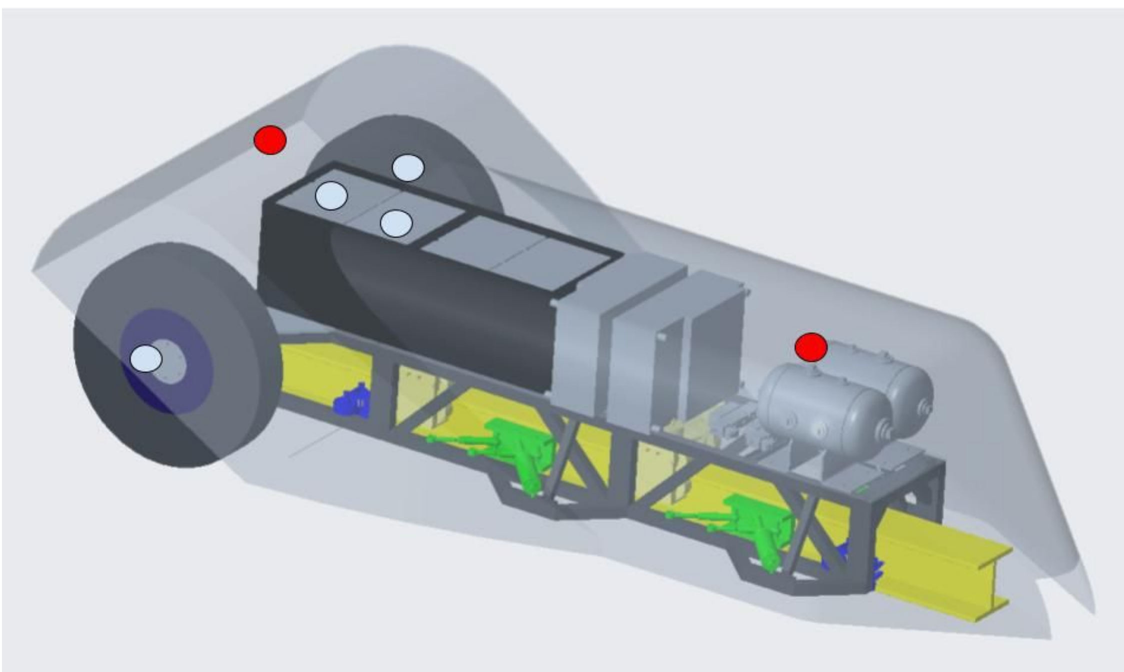


Figure 59. Sensor Location Map

Scalability

Table 16. Estimated Commercial Pod Dimensions

Estimated Pod Dimensions	Measure (ft)
Length	35
Width	6
Height	7

Table 17. Estimated Mass of Commercial Pod by Subsystem

Estimated Mass by Subsystem	Mass (lbm)
Structure	2100
Braking	1200
Propulsion	510
Power	730
Navigation & Control	50
Total Mass	**4590 lbm**

When scaled up for commercial use the Binghamton Hyperloop Pod is estimated to comfortably seat 18 passengers in 9 rows of 2 with approximately 40 inches of legroom per passenger. The pod will be pressurized to 6000 feet following the passenger comfort standards set by the Boeing 787 Dreamliner. Exits on each side allow for flexibility in station design, pod utilization, and decrease in turnaround time. Passenger storage will be available under each seat, similar to modern commercial aircraft. An emergency exit is located at the rear of the pod, allowing passengers to disembark into the tube once re-pressurized. Each pod will also be equipped with an emergency stop button. All planned design features focus on passenger comfort and safety.

The pod propulsion system will be upscaled to six in wheel motors located at the rear of the pod. Pneumatic braking systems and pod stability systems will be spaced every couple of feet along the rail to ensure pod stability and control.

Pod maintenance will be based on maglev trains and aircraft. However, the pod will not be impacted by weather and wear will occur primarily due to pressurization/depressurization of the transportation tubes. Expected pod lifespan will be around 25 years and it will comply with all FAA Maintenance guidelines. Daily checks should verify emergency equipment onboard and every 200-300 cycles (takeoff/landing) pod should be visually examined for wear. Brake pads will be replaced every 500 miles of travel or approximately 5300 cycles and the LiPo battery system will be replaced every 200-300 charging cycles.

Expected Pod costs were estimated based off of a scaled version of our design. By determining the rough amount of materials used in the scaled up design, the team was able to come to the number of $596,000. Due to the ease of expanding the size of the pod to increase cabin capacity along with a relatively low increase in weight, our team was able to create a large seating area within the pod with a minimal cost increase. We believe that creating a system that incorporates power being supplied to the pod during operation would drastically reduce costs and the required size of the battery. If this pod was to be scaled up for commercial use, our team believes that the most important redesign would be adjusting the current power system to reduce cost and improve the total performance of the pod.

The maintenance for the full scale pod we estimate to be around 5 percent of the total pod cost annually which amounts to $29,800. This cost is rather low due to the minimal weathering expected to occur during pod operation.

Loading and Unloading Plan

Staging Area to Test Track

- Once tests and procedures are completed at the SpaceX Staging Area, the front of the Hyperloop Pod will be lifted up onto a four-wheeled moving dolly to assist with transportation.
    - Note that the Pod's back wheels are able to roll freely when the two motors are powered off, so the dolly will only need to be placed underneath the front horizontal stability system in order for the Pod to be able to be transported along flat ground.
- The Hyperloop Pod will then be hand carted from the SpaceX Staging Area to the Test Track.
    - There must be at least six team members with a hand on the Pod at all times when it is being transported to ensure it does not rock back and forth and slip off the dolly.
- From there, the Pod may then be lifted off of the moving dolly and loaded onto the SpaceX Test Track.

Pneumatic Filling Procedure:

- Only personnel trained in the pneumatic filling procedure are authorized to carry out the below steps
- All equipment used in the pneumatic filling procedure are to be owned by Binghamton University or the Binghamton Hyperloop Team. Outside equipment is not to be used.
- All equipment must have been tested and verified before use.
- Inspect air reservoir casing for damage. If damage found, do not proceed with filling procedure.
- Verify all ports on air reservoir are closed
- Attach air compressor to air reservoir by use of the ½ in. flex tube fitting. This piece should be checked for leaks prior to use.
- Turn on the air compressor.
- Monitor the pressure gauge located on the left hand side of the air compressor. DO NOT LEAVE AIR COMPRESSOR UNATTENDED WHILE IT IS RUNNING.
- Turn off the air compressor when the gauge reads a pressure of 150 psi.
- Detach the air compressor from the reservoir.
- Double check the pressure on the air reservoir by means of a separate pressure gauge.
- Verify that no air is escaping the reservoir by monitoring the pressure gauge for 5 minutes. If pressure on gauge does not remain constant at 150 psi the tank should be safely depressurized immediately and should not be used with the hyperloop pod.
- Once all checks are complete, the tank may be safely hooked up with the rest of the pneumatic system.

Ready-to-Launch Checklist

Power:

- Electrical subsystems power on
- Electrical subsystems read data
- Power supply is sufficient for completion of the run
- Temperature of batteries are safe for the run

Braking System:

- Brakes have been tested and engage when command is given
- Tank Filling Procedure has been carried out by trained personnel
- System pressure is holding steady at 150 psi.
- All fittings are checked to ensure they are properly secured
- All linkages are lubricated to ensure ease of rotation

Environmental Conditions:

- Tube is the correct pressure and temperature

Pod:

- Pod skin is fully secured to the frame
- Wheels are aligned to the test track

Communication:

- Data from sensors are sent from the pod and viewable on team laptop
- Requests sent from team laptop is retrieved by the pod and sends back a good response

Ready-to-Remove Checklist

- Battery temperature is low enough for safe handling
- Servo valve is set in the open position
- All pneumatic components downstream of the valve are at atmospheric pressure
- All air reservoirs are safely depressurized to atmospheric pressure.
- All electronics are powered down
- All electronics are securely attached
- All screws are securely attached
- Brakes are disabled
- Pod has been checked for exterior damage
- All wheels are securely attached

Test Track to Exit Area

- Once the run is completed and the Hyperloop Pod is safe to approach, it will be rolled off the central I-beam and the front Horizontal Stability System will be placed onto the

four-wheeled moving dolly used to transport it from the Pod Staging Area to the Test Track.
- The Hyperloop Pod will then be hand carted from the SpaceX Test Track to the Exit Area
    - There must be at least six team members with a hand on the Pod at all times when it is being transported to ensure it does not rock back and forth and slip off the dolly.
- From there, the Pod may then be lifted off of the moving dolly and prepared for transportation

Stored Energy

The stored energy of the pod consists of the high and low voltage battery packs and the two pressurized air reservoirs. The Low voltage system consists of two 4S1P LiPO prismatic cell battery packs. The high voltage system consists of two 182S1P LiPO Prismatic cell battery packs. The air reservoirs are compliant with ASME standards. The energy specifications of the battery packs and the reservoirs can be seen in Table 16 below.

Table 18. Battery Stored Energy Specifications

Item	Description	Stored Energy (kJ)
LPHD6578156 - 3.7V 6Ah Rated Continuous Discharge: 25C LiPO Prismatic Cells Config: 4S1P (Low Voltage)	Minimum Capacity = 6000mAh Configuration = 4S1P/14.8V/4 Cell Constant Discharge Rate = 25C Pack Weight = 3.0 lbm	640
LPHD6578156 - 3.7V 6Ah Rated Continuous Discharge: 25C LiPO Prismatic Cells Config: 182S2P (High Voltage)	Minimum Capacity = 12000mAh Configuration = 182S2P/670V/364 Cell Constant Discharge Rate = 25C Pack Weight = 260 lbm	28944
Steel ASME-Code Horizontal Compressed Air Tank (x2)	Tank Capacity = 1 gallon Tank Material = Steel Working Fluid = Air Maximum Pressure = 200 psi Working Pressure = 150 psi Temperature Range = -20° F to 400° F	17.6

Hazardous Materials

The hazardous materials of the hyperloop pod are the LIPO battery packs and the compressed air tanks. LiPO battery cells when mishandled can lead to fires, explosions or an unexpected discharge. Overcharging, mismanagement or excessive vibrations can result in damage to the cells and must be avoided. A damaged cell is unfit for use and dangerous. The compressed air tanks must be filled and emptied by trained personnel as any mistreatment or damage to the vessel can result in rapid depressurization or explosion.

Table 19. Binghamton Hyperloop Hazardous Materials

Material	Hazard	Item Description	Use	Qty
Lithium Polymer Battery Packs	Explosions/fire when crushed, pierced, short (+) and (-) battery terminals with conductive (i.e. metal) surfaces.	LiPO Battery 14.8V 4S 6000 mAh	Control System	2
		LiPO Battery 8.04 kWh Module	Power Drive	1
Compressed Air Tank	Explosion if damaged while pressurized.	Steel ASME-Code Horizontal Compressed Air Tank (11.75” x 6” x 8”) 200 psi, 1 gal capacity.	Brakin g System	2

Safety Features

The Binghamton Hyperloop pod is fitted with multiple safety features to account for many of the predicted problems in constructing a vehicle of this complexity. These features range from a Battery Management System (BMS), to regulate the battery cells, to Pressure Relief Valves (PSVs), to ensure the pod is always in a safe approachable state. Below in Table XXX. are the safety features to be implemented in the Binghamton Hyperloop Pod.

Table 20. Binghamton Hyperloop Pod Safety Features

Item	Description	Added Safety Feature
Multiple Voltage Rails	Separate high voltage and low voltage systems.	Helps ensure control and braking systems can operate in the event high voltage system encounters error during operation. Also mitigates risk of overloading control components.

Battery Management System (BMS)	Controls and monitors battery cells	Prevents over discharge of the cells and prevents the battery from discharging above the rated current.
Battery Safety Systems	Fuses and chassis grounding	In the event of a short circuit, on board fuses connected to each battery blow. Chassis grounding also provides a safe path to ground should a wire connection come loose.
Mechanical Battery Cutoff Switch	On board key switch physically connects and disconnects power.	Prevents accidental power on/off, and provides a safe means of ensuring power is fully disconnected from the system when desired.
Corona Discharge	Insulation protection against arcing in a low pressure environment.	Electrical contacts are to be sufficiently insulted to mitigate potential risks. Additionally, extra precautions are being researched to ensure the system is protected against potential arcing.
Unitek Bamocar-D3	Motor Controller	IP65 Casing used ● Provides near-perfect isolation from outside environment Redundant Kinematic Data ● Assists the Gyroscope in deriving position, velocity, and acceleration ● Ensures we do not transition from rest, accelerate and decelerate states at improper moments
Emrax 228	AC Induction Motor	Direct Driven to Drive Wheel ● Motor itself rotates and will be used as inner wheel ● No need for a drive belt or chain
Pressure Relief Valves (PSV's)	Safety valves preventing over pressurization of the pneumatic system	Pop off valves set to 175 psi (system operating pressure is 150 psi and maximum pressure is 200 psi in atmosphere and 186 psi in a vacuum). If system pressure reaches set pressure PSV's pop off and vent excess air to atmosphere.

These safety features will be implemented to handle the safety concerns described by the SpaceX Hyperloop Rules and Regulations. The implementation plan can be seen below.

Hardware and Software Inhibits on Braking During Acceleration Phase

During acceleration the servo valves are closed preventing pressurization of the pneumatic cylinders. High strength springs located in the body of the cylinders are extended preventing them from actuating prematurely.

As soon as the pod enters the acceleration state, distance and speed sensor data are constantly analyzed to find variance among each group of sensors. If there exists a high variation among the data from distance sensors, the pod utilizes a pre-calculated safe-target distance to initiate braking. The braking initiation is done through the sending of a high voltage signal (12V) from the Arduino Yun to servo valves responsible for releasing the breaks. The Arduino Yun is programmed to do the data analyzing as well as the team laptop which receives and stores all telemetry data sent from the pod. When data is analyzed on the laptop, the user will be alerted when high variation of distance data is found as well as notified that a request has been automatically sent to the pod to initiate the brakes. Additionally, the user has the option to initiate a manual request from the laptop to the pod to apply the brakes at any moment during the run.

Mechanisms to Mitigate a Complete Loss of Pod Power

A relay will be connected to both low voltage batteries. When the main battery turns on, the relay will also turn on, and when the battery is switched off the relay switches off and completes the backup battery circuit. Through this, a complete power loss is avoided and the emergency brakes can be activated.

Mechanisms to Mitigate a Pressure Loss for Pneumatic Braking

In order to mitigate a pressure loss for the pneumatic braking system, there will be two pneumatic systems operating independently on a closed loop. The dual redundant systems will be used in case there is a pressure loss in one of the systems, the second system will still be capable of bringing the pod safely to a complete stop.

Pod Robustness to a Tube Breach Resulting in Rapid Pressurization

In the case of a tube breach and rapid re-pressurization, a large force will be applied to the carbon fiber skin. Once a breach is detected, the emergency brake command will be given. The pneumatic brake system will engage slowing the pod to a stop before depressurizing. The bolts that hold the skin to the pod prevent it from detaching during rapid pressurization and have been structurally analyzed to ensure integrity during a breach scenario. Thus, the bolts that secure the skin to the frame have been structurally analyzed a factor of safety of at least 2, in the instance of a breach scenario. Once the pod is Safe-To-Approach, it may be retrieved from the SpaceX test tube.

Fault Tolerances

Braking:

In the case of an over pressurized system, Pressure Safety Valves (PSVs) activate to relieve extra pressure to the environment.

Dual redundant pressure systems mitigate the potential harm in the event of pressure loss. Two pneumatic systems operate independently and on a closed loop. Should one system become depressurized the second will still be capable of bringing the pod to a complete stop.

In the case of a loss of pod telemetry, the braking system is coded to be independently pressurized, slow to a stop, wait 1-2 minutes, and then depressurize the system making it safe to approach the pod.

In the event of a loss of power to the servo valve, there is a second control unit set up to tell the secondary brake system to pressurize, slow to a stop, then depressurize. The likelihood of a loss of power to both servo valves at the same time is low since they are running on separate power sources.

It should be noted that the use of pneumatic cylinders that use springs to extend and compressed air to retract would solve the issue of a loss of power to both servo valves. This is because the brakes could be applied and the pod could be stopped without the need for the system to be pressurized. However, due to the fact that the spring force (and therefore braking force) inside of the cylinder would not be known until the part could be purchased and tested this solution will not be put into effect until a later date. At the time that the spring force is known and acceptable the pneumatic braking system will be reworked to include spring-extend cylinders.

Loss of Power:

During a loss of high voltage power scenario the pod would default to a fault state, at which point the pneumatic braking system would engage and bring the pod to a stop. The pod is then coded to wait 1-2 minutes and depressurize the pneumatic system. The pod would then be Safe-To-Approach and able to be retrieved from the Test Track.

The event of a complete loss of low voltage power is covered above in the Braking Fault Tolerance section.

Single Point of Failures Within the Pod

Arduino Yun: The Arduino Yun functions as the on-board computer for the communication system. If the Yun were to fail, the communication system between the Arduino Unos and the sensors would no longer be able to operate, causing a failure of the entire communication system.

Arduino Uno: If one of the Arduino Unos were to fail, The Arduino Yun will send the pod into a fault state in which the emergency pneumatic braking system is applied and then depressurized. The pod would then be in a Safe-To-Approach state and ready for retrieval.

Power Supply: The power supply is used to power the entire communication system. A failure of the power system would cause all electrical and communication systems to fail.

Recovery Plan if Pod Becomes Immovable Within Tube

Once the pod has been designated Safe-To-Approach within the tube the pneumatic braking system should be completely depressurized and unclamped from the central I-beam. The pod would then be free to crawl to the end of the Test Track if electronic communication can be reestablished with the on-board systems.

If communication cannot be reestablished, the pod may need to be manually wheeled out of the tube.

If for some reason damage occurs to the braking linkage and the pod brakes cannot be unclamped from the central I-beam, the shoulder screws connecting the brake pad casing to the steel guide rods may be unscrewed and removed. This would disconnect the brake pads from the rest of the pod unclamping the pod from the I-beam. The above steps may then be carried out to remove the pod from the test tube.

Implementation of the Pod Stop Command

The off-board computer and the on-board Arduino Yun can communicate wirelessly via the Ubiquiti Rocket M900 Radios. Once the requirements to stop the pod are met, the command is sent to the servo valves to reroute the air in the reservoirs to the brakes, enabling braking.

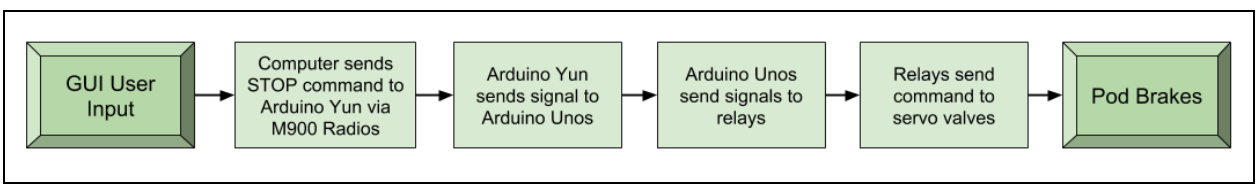


Figure 60. Pod Stop Command Flowchart

Vacuum Compatibility Analysis

There are several components that require vacuum testing before they are safe for use on the Hyperloop pod; the LiPo battery cells, the EMRAX motors and the low voltage hardware.

To ensure the LiPO battery cells will function as expected in a vacuum, research about LiPO cells behavior in a vacuum was conducted. Through research, our team found that LiPO prismatic cells tend to have a lower capacity in vacuum conditions however do not normally experience leaks. Experiments on individual cells, and a few cells wired together and left overnight in a Binghamton University Vacuum chamber will be conducted to verify or disprove the research for the specific LiPO cells to be used in the Binghamton Hyperloop battery packs. Based on previous LiPO cell testing done by past Binghamton Hyperloop teams, it is anticipated that the functionality of the LiPO cells will not be lost however, the vacuum testing on these LiPo Prismatic Cells has not be completed by the date of this submission.

Discharge Arc testing and overall voltage level testing will be conducted by Charge CCCV. LLC on the completed battery packs. This will ensure the batteries meet the design specifications regardless of the external pressures.

The Emrax motors being used are designed to work in low pressure scenarios. Emrax is aware of the motors intended use in a vacuum as part of the HPOD and will ensure the motor is sealed and tested under vacuum conditions prior to shipping to Binghamton Hyperloop.

The low voltage hardware must also be tested for vacuum compatibility prior to the Hyperloop competition. The components of the low voltage system depicted in the schematics and lists above, such as the Arduinos and sensors, can be tested through the use of the vacuum chamber in the Physics department at Binghamton University to ensure they are safe for use.

Appendices

Appendix A: Bills of Materials

Table 21. Bill of Materials for Pod Structural Frame

Item Name	**Quantity** (Finished Units)	**Material**	**Total Price** (All Units)	**Manufacturer** (Part Number)
1” square tubing, 1/16” wall thickness (6 ft tube)	6	6061 Aluminum	$187	McMaster Carr (6546K53)
Custom Unibody Pod Skin	1	TBA	TBA	Special Order

Table 22. Bill of Materials for Horizontal Stability System

Item Name	**Quantity** (Finished Units)	**Material**	**Total Price** (All Units)	**Manufacturer** (Part Number)
Base	4	6061 Aluminum	207.28	McMaster Carr (1643t51)
UpperBase	2	6061 Aluminum	41.68	McMaster Carr (975k215)
Dowel1	16	Alloy Steel	27.84	McMaster Carr (91259a105)
Nut 1	16	Alloy Steel	3.77	McMaster Carr (91841a011)
Existing Wheel	4	6061 Aluminum	161.52	McMaster Carr (7775t21)
9044k211 Spring	12	Music Wire	37.76	McMaster Carr

				(1920n470)
Washer 1	8	Alloy Steel	13.84	McMaster Carr (92510a491)
R4A-2Z Ball Bearing	8	Alloy Steel	57.28	McMaster Carr (60355k44)

*Indicates that part was inherited from previous iteration of Binghamton Hyperloop pod

Table 23. Bill of Materials for Vertical Stability System

Item Name	Quantity (Finished Units)	Material	Total Price (All Units)	Manufacturer (Part Number)
Bolt (1/2) Nut	4	Alloy Steel	7.84	McMaster-Carr (95462a031)
Bolt Stopper (1)	4	Alloy Steel	6.34	McMaster-Carr (92620a628)
Rubber Stopper (7/4)	4	Rubber	13.64	McMaster-Carr (9540k81)
Bolt Stopper (1 1/2)	4	Alloy Steel	12.32	McMaster-Carr (91257a535)
Rubber Stopper (3/4)	4	Rubber	10.2	McMaster-Carr (93115k171)
Spring Mcmaster	4	Music Wire	10.8	McMaster-Carr (9654k525)
Base Vertical	1	6061 Aluminum	9.14	McMaster-Carr (8975k52)
Rode Male (1 use)	4	Alloy Steel	27.12	McMaster-Carr (3798k48)
Rode Female (1 use)	4	Alloy Steel	86.16	McMaster-Carr (1581k21)
Bolt 3	4	Alloy Steel	8.08	McMaster-Carr (91259a636)
Nut 3	4	Alloy Steel	7.03	McMaster-Carr (98797a030)
25 Bolt	8	Alloy Steel	7.15	McMaster-Carr (92620a546)
25Nut	8	Alloy Steel	5.95	McMaster-Carr

				(98797a029)
LowerHinge	1	Alloy Steel	199.64	McMaster-Carr (8975k275)
Dowel1 (same)	16	Alloy Steel	1.74	McMaster-Carr (91259a105)
Nut1 (same)	16	Alloy Steel	0	McMaster-Carr (91841a011)
R4A-2z Ball Bearing(same)	16	Alloy Steel	114.56	McMaster-Carr (60355k44)
Washer 1 (same)	32	Alloy Steel	55.36	McMaster-Carr (92510a491)
Existing Wheel	16	6061 Aluminum	650.88	McMaster-Carr (1610t13)
Vertical Bolt 2	4	Alloy Steel	122.44	McMaster-Carr (90298a653)

Table 24. Bill of Materials for Pod Propulsion System

Item Name	Quantity (Finished Units)	Material	Total Price (All Units)	Manufacturer (Part Number)
Emrax 228 Linear Electric Motor	2	Varied (Mainly 6082 Aluminum)	$7,500	Emrax Innovative E-Motors (228)
Hamilton 18 Inch Diameter Wide, Rubber Caster Wheel	2	Rubber	$1,500	MSC Industrial Direct Co.
6061 Aluminum 7/8" Thick, 6" x 6"	2	6061 Aluminum	$ 63.88	McMaster-Carr (9246K573)
Medium-Strength Class 8.8 Steel Hex Head Screw	1	Zinc-Plated Steel	$10.16 (per 50)	McMaster-Carr (91280A526)

Unitek Bamocar D3 Motor Controller	2	Varied	$4,000	Unitek
Alloy Steel Thread-Locking Socket Head Screw	1	Black Oxide Alloy Steel	$6.61 (per 10)	McMaster-Carr (91205A552)
Moisture-Resistant Cushioning Washer	2	Polyurethane Rubber	$12.20 (per 10)	McMaster-Carr (93650A165)
6061 Aluminum 1" x 1"	1	6061 Aluminum	$21.49	McMaster-Carr (9008K14)
High-Strength Steel Nylon-Insert Locknut	1	Steel- Nylon	$3.22 (per 25)	McMaster-Carr (90630A110)
Vibration Damping Pad	1	Black Nitrile Rubber	$37.54 Per 12"x12" square	McMaster-Carr (5940K57)
6061 Aluminum 3" Cube	2	6061 Aluminum	$59.56	McMaster-Carr (9140T273)

Table 25. Bill of Materials for Pod Power System

Item Name	Quantity (Finished Units)	Material	Total Price (All Units)	Manufacturer (Part Number)
LPHD6578156 - 3.7V 6Ah LiPo Prismatic Cells	372	Lithium-Polymer	$23 (per cell)	LiPol Battery
C4V Battery Casing	2	Varied	$200	C4V
Elithion Battery Management System	1	Varied	$1,500.00	Elithion

JacobsParts 2/0 AWG Insulated Ring Terminal 00 Gauge, 3/8" Connector	12	Copper	$5.95	Amazon
4/0 AWG THHN Stranded Copper, Black, 1000'	20	Copper-Aluminum	$4.40 (per ft)	PLATT
MEV70A Round Body Fuse	2	Semiconductor	$ 32.00	Mersen (MEV70A175-4)

Table 26. Bill of Materials for Pod Braking System

Item Name	**Quantity** **(Finished Units)**	**Material**	**Total Price** **(All Units)**	**Manufacturer** **(Part Number)**
Air Reservoir	2	Steel	$461.06	McMaster Carr (9888k9)
Pneumatic Piston (extend)	4	Stainless Steel	$217.72	McMaster Carr (6498k544)
Servo Valve	2	Aluminum	$223.60	McMaster Carr (6124k281)
Manual Shut Off Valve	1	Brass	$10.73	McMaster Carr (47865k43)
½ - ⅜ Adapter	5	Brass	$40.05	Fastenal
Flex Tube (1/2in fittings)	15	Rubber	$264.00	JME Sales

½ - ⅛ Adapter	9	Steel	$91.80	Fastenal
Manifold (½ - ⅜)	2	Anodized Aluminum	$72.66	McMaster Carr (1023N19)
Shoulder Screw	8	Alloy Steel	$12.48	McMaster Carr (91259a630)
5/16 - 18 Hex Nut	1 (pack of 100)	Zinc Yellow-Chromate Plated Steel	$5.12	McMaster Carr (94895a030)
Male Threaded Rod	8	Black-Oxide Carbon Steel	$57.92	McMaster Carr (6066k41)
Female Threaded Rod	8	Black-Oxide Carbon Steel	$191.76	McMaster Carr (1581k12)
7/16 -20 Fem Rod	4	Steel	$46.48	MSC Direct
PSV 175 Set Pressure	4	Brass	$181.16	McMaster Carr (9889k39)
T Joint 1/2 NPT	4	Brass	$76.60	McMaster Carr (45525k544)
5/16 - 24 Hex Nut	1 (pack of 100)	Zinc-Plated Steel	$6.76	McMaster Carr (95462a510)
5/16 - 24 Bolt	1 (pack of 100)	Zinc Yellow-Chromate Plated Steel	$10.13	McMaster Carr (91257a609)
Brake Pads	1	Ferro-Carbon	$391.72	Amazon
Brake Casing	1	Aluminum	$96.53	McMaster Carr

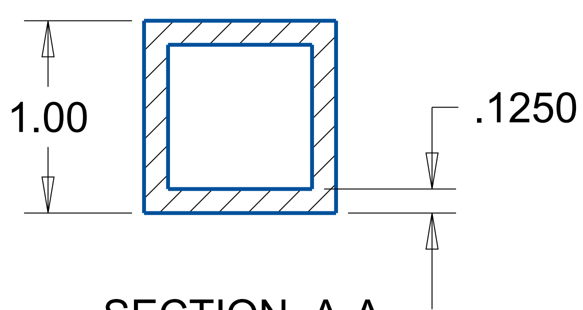
Table 27. Bill of Materials for Pod Navigation & Control System

Item Name	Quantity (Finished Units)	Material	Total Price (All Units)	Manufacturer (Part Number)
Digital Thermometer*	8	Aluminum	$19.20	Elenker DS18B20
Controller Area Network Bus	1	Aluminum	$20.00	Makerfocus
CAN-bus shield*	1	N/A	$29.50	Arduino
M900 Radio	2	N/A	$358.00	Ubiquiti Networks Rocket M900
Accelerometer*	1	N/A	$1000.00	VectorNav VN100 IMU
Photoelectric Sensor	4	N/A	$687.88	Pepperl + Fuchs OBR1500-R2F-E2-L
Antenna	2	N/A	$100.00	Ubiquiti Networks
Solid State Relays	2	N/A	$5.51	Omron Automation and Safety
Buck Converter	2	N/A	$19.90	MPS (MP2307)
Arduino Yun *	1	N/A	$59.00	Arduino
Arduino Uno*	2	N/A	$44.00	Arduino

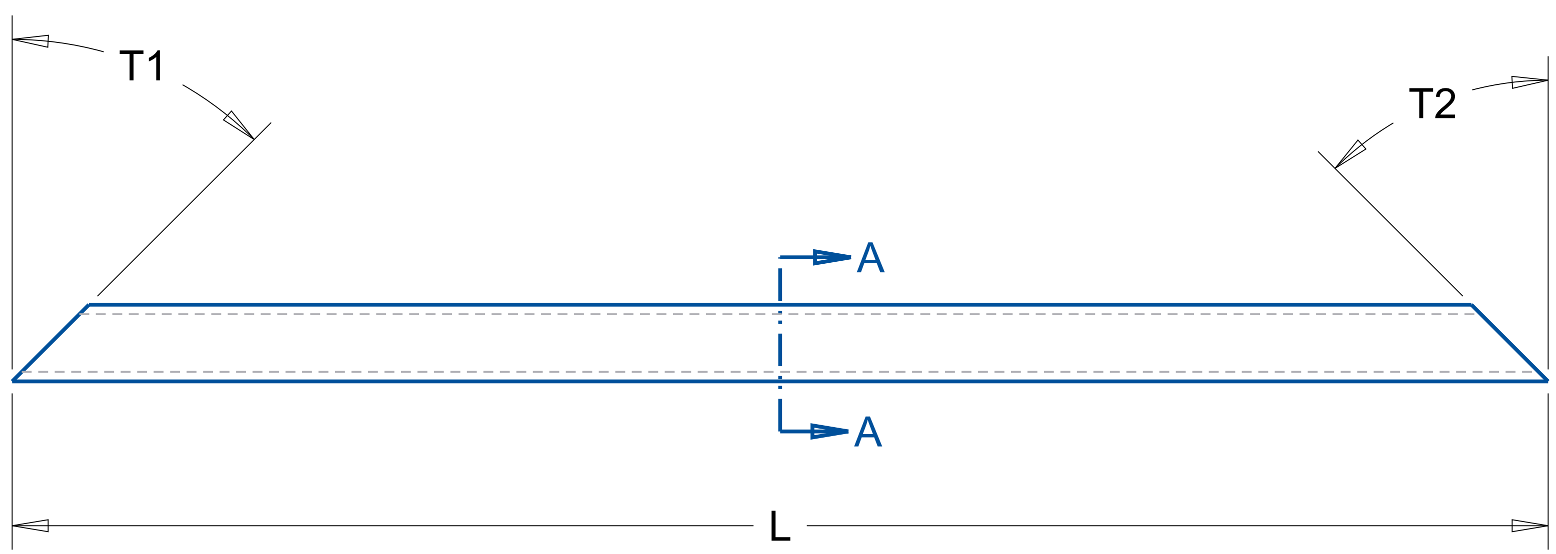
*Indicates that part was inherited from previous iteration of Binghamton Hyperloop pod

Appendix B: Technical Drawings

GENERIC PART NAME: SQUARE_TUBE					
	MODEL PARAMETERS				
INSTANCE NAME	L	T1	T2	THETA_1	THETA_2
SQUARE_TUBE_BRK_SPT_ANG	6.00	22.50°	45.00°	Y	Y
SQUARE_TUBE_BRK_SPT	5.00	22.50°	22.50°	Y	Y
SQUARE_TUBE_AXLE	29.00	-	-	N	N
SQUARE_TUBE_WHEEL_SUPPORT	9.90	45.00°	45.00°	Y	Y
SQUARE_TUBE_BACK_RAIL_TOP	11.00	-	-	N	N
SQUARE_TUBE_BACK_RAIL_BTM	12.00	-	-	N	N
SQUARE_TUBE_RAILS	46.00	-	-	N	N
SQUARE_TUBE_TOP	9.00	-	-	N	N
SQUARE_TUBE_CORNER	8.00	-	-	N	N
SQUARE_TUBE_SIDES	6.00	-	-	N	N
SQUARE_TUBE_FRT_SPT	4.00	45.00°	45.00°	Y	Y



SECTION A-A
SCALE 1.000



Binghamton University Hyperloop

Part Name: SQUARE_TUBE

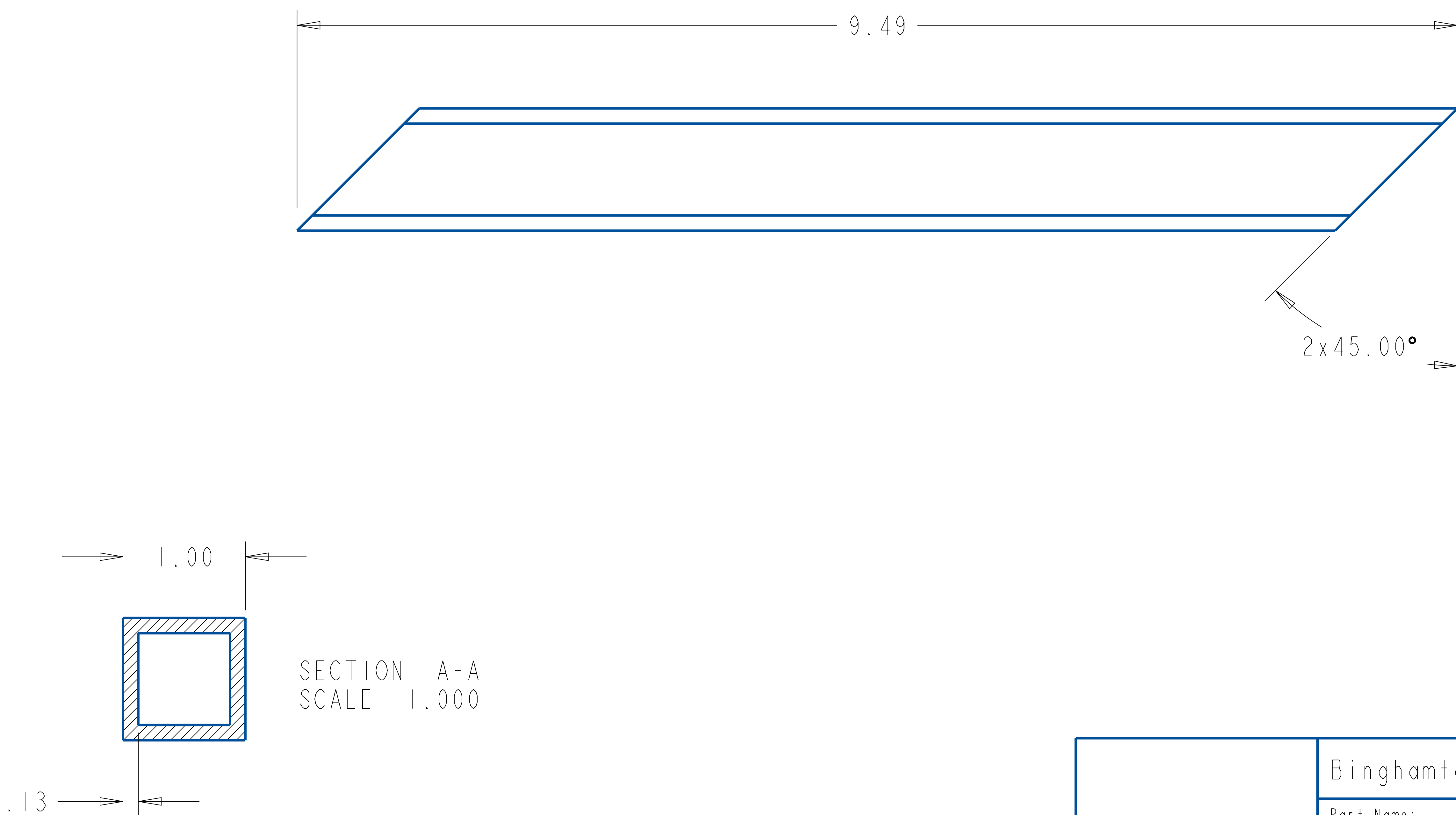
Scale: 0.400

Material: Al 6061

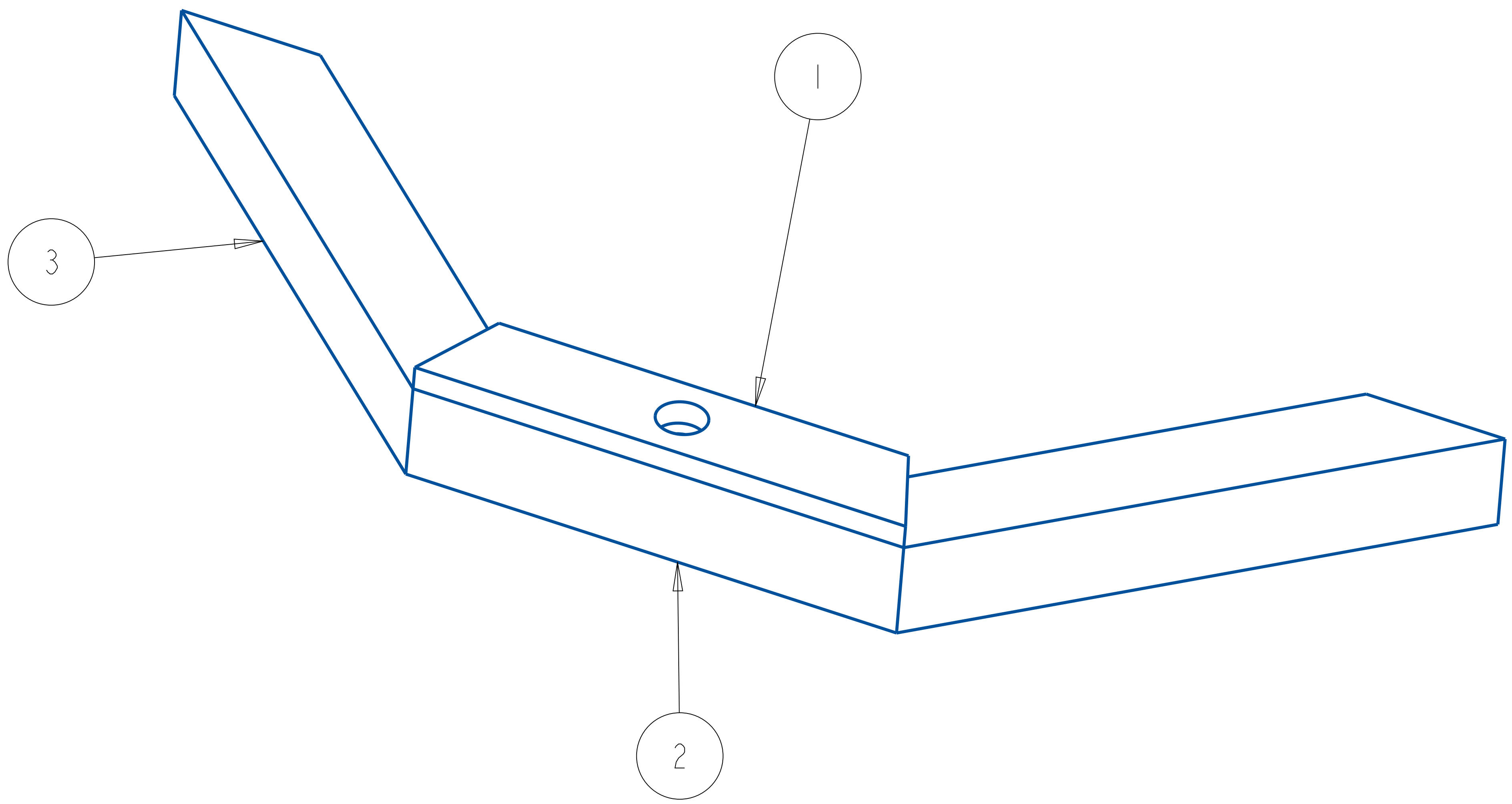
All units are in inches

Author: Perry Thomson

Date: 11/30/2019

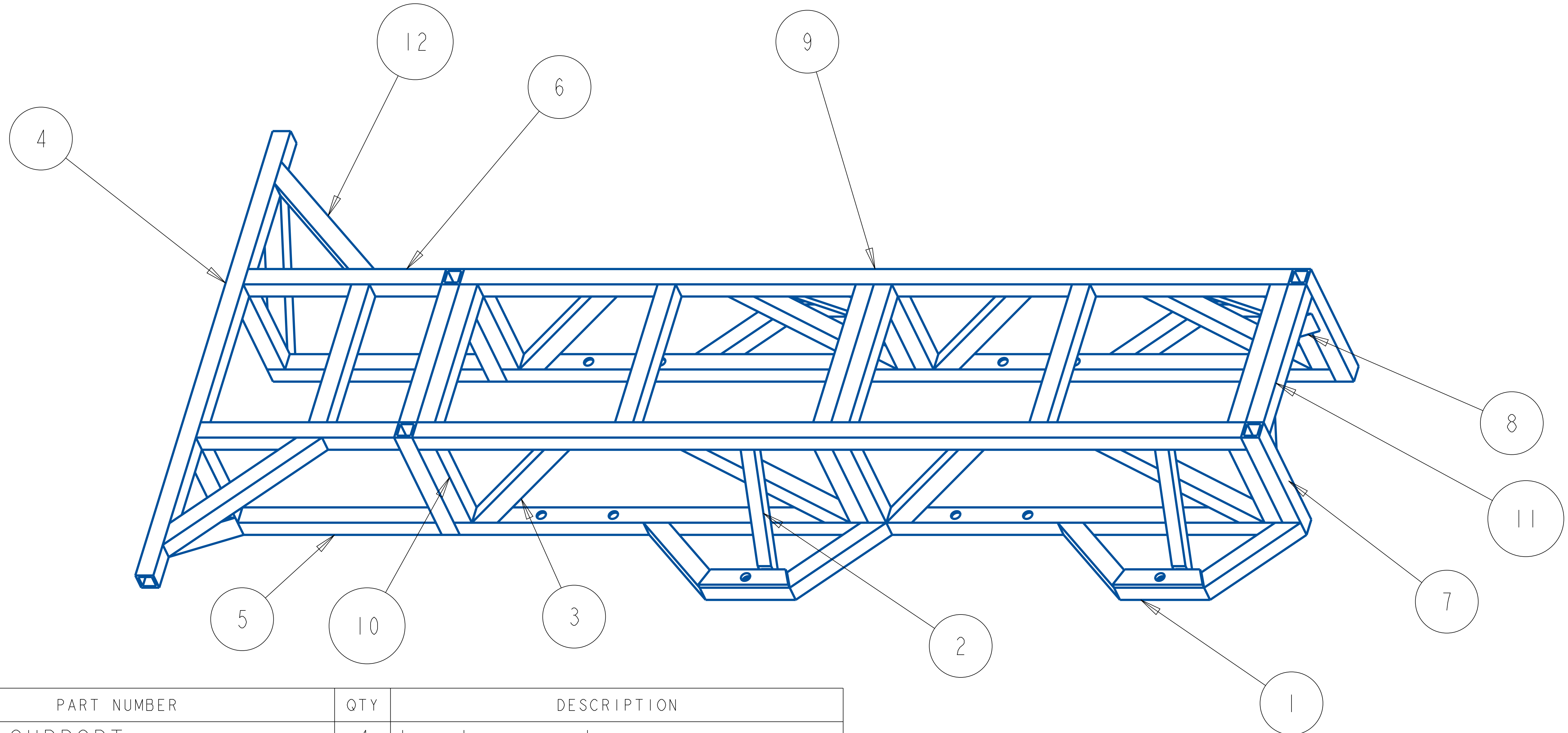


	Binghamton University Hyperloop		
	Part Name: SQUARE_TUBE_SIDE_SUPPORT		
Scale: 1.000			
Material: Al 6061	Author:	Perry Thomson	
All units are in inches	Date:	11/30/2019	



ITEM NO	PART NUMBER	QTY	DESCRIPTION
1	BRAKE_SPACER	1	brake_spacer.prt
2	SQUARE_TUBE_BRK_SPT	1	square_tube.prt_brk_spt
3	SQUARE_TUBE_BRK_SPT_ANG	2	square_tube.prt_brk_spt_ang

	Binghamton University Hyperloop
Scale: 0.700	Part Name: BRAKE SUPPORT SUBASSEMBLY
Material: N/A	Author: PERRY THOMSON
All units are in inches	Date: 12/1/2018



ITEM NO	PART NUMBER	QTY	DESCRIPTION
1	BREAK_SUPPORT	4	break_support.asm
2	EXTRA_BRAKE_SUPPORT	4	extra_brake_support.prt
3	SIDE_SUPPORT	8	side_support.prt
4	SQUARE_TUBE_AXLE	1	square_tube.prt_axle
5	SQUARE_TUBE_BACK_RAIL_BTM	2	square_tube.prt_back_rail_btm
6	SQUARE_TUBE_BACK_RAIL_TOP	2	square_tube.prt_back_rail_top
7	SQUARE_TUBE_CORNER	4	square_tube.prt_corner
8	SQUARE_TUBE_FRT_SPT	2	square_tube.prt_frt_spt
9	SQUARE_TUBE_RAILS	4	square_tube.prt_rails
10	SQUARE_TUBE_SIDES	10	square_tube.prt_sides
11	SQUARE_TUBE_TOP	9	square_tube.prt_top
12	SQUARE_TUBE_WHEEL_SUPPORT	4	square_tube.prt_wheel_support

Binghamton University Hyperloop

Part Name:

FRAME ASSEMBLY

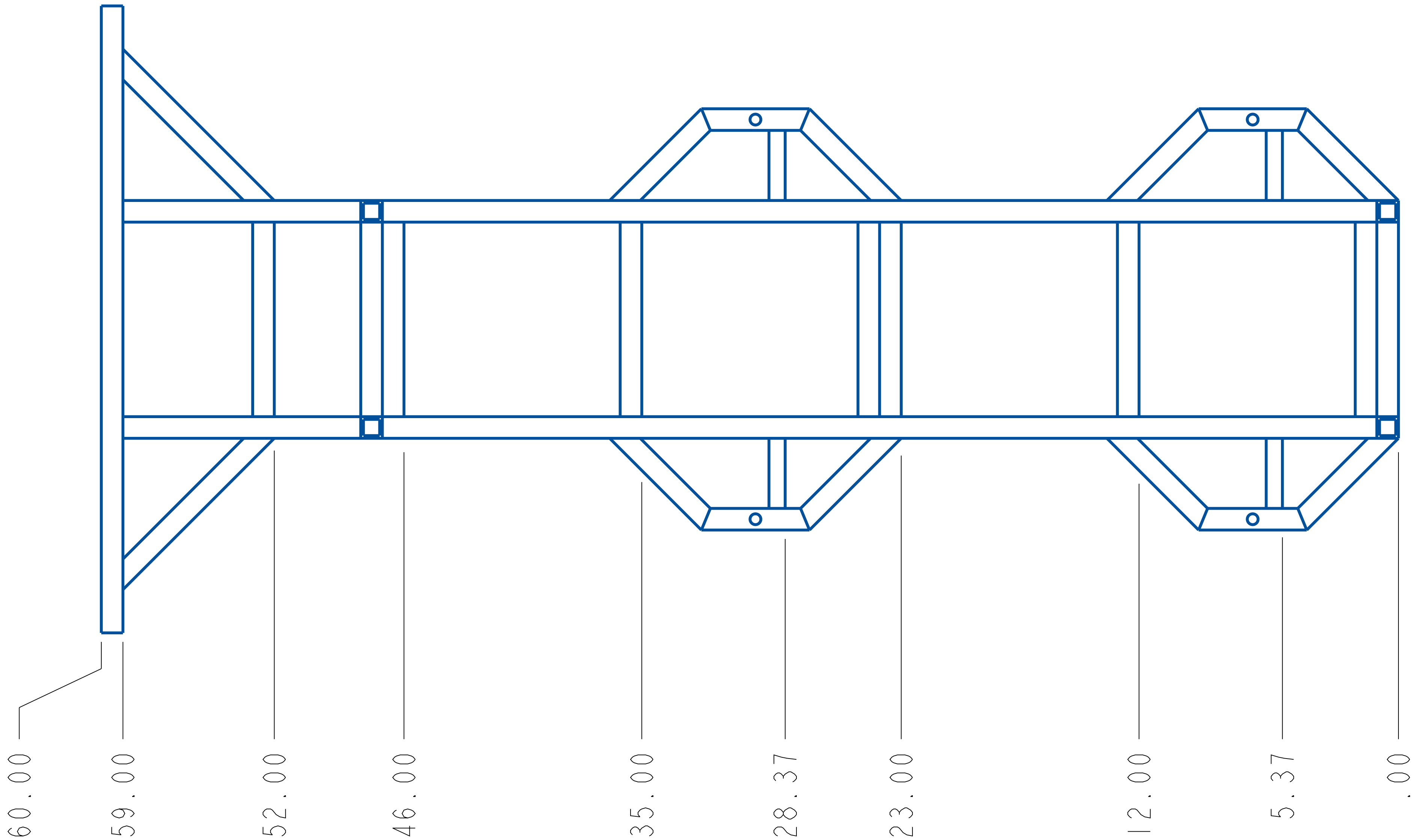
Scale: 0.175

Material: N/A

All units are in inches

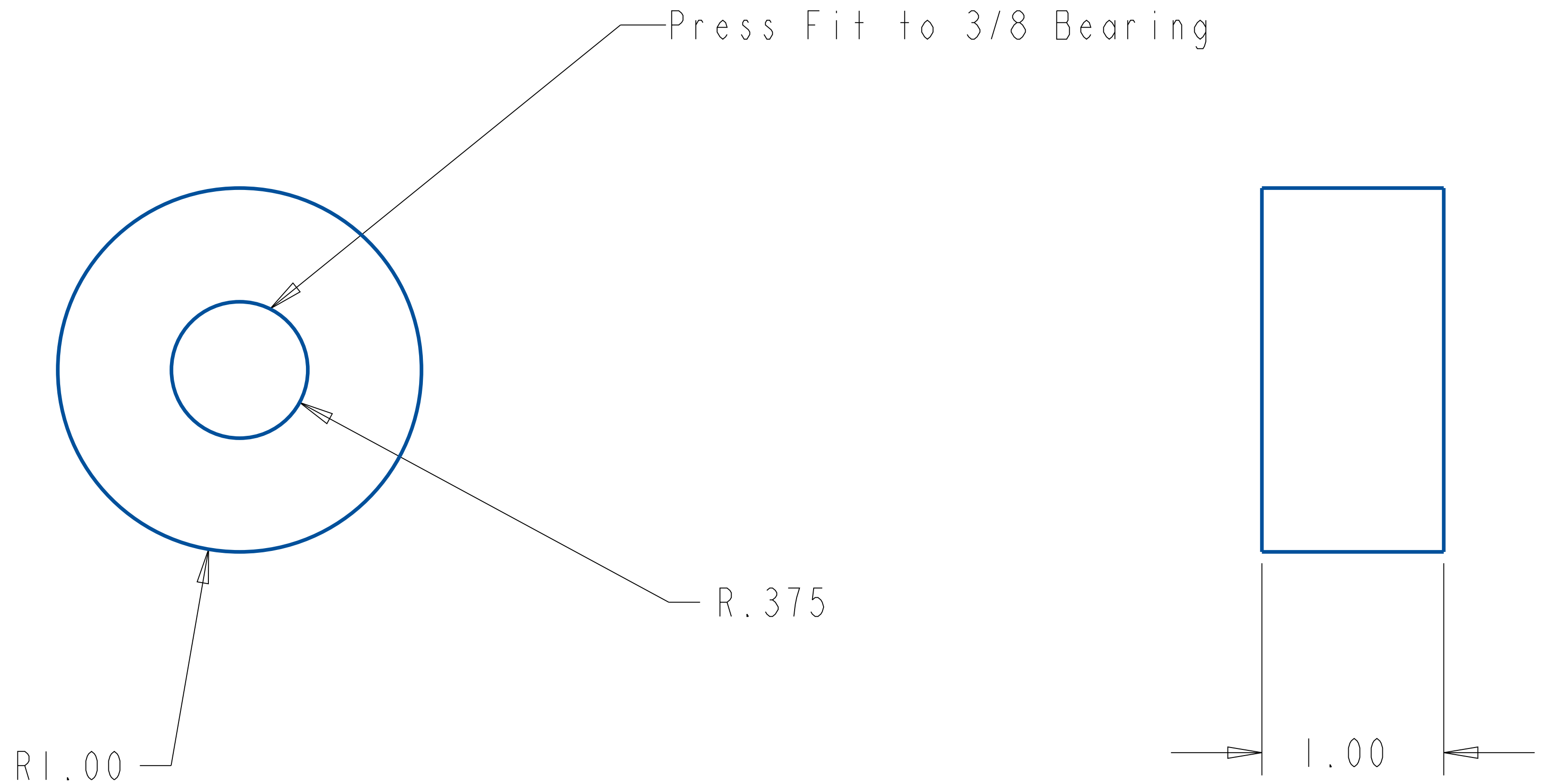
Author: PERRY THOMSON

Date: 12/1/2018

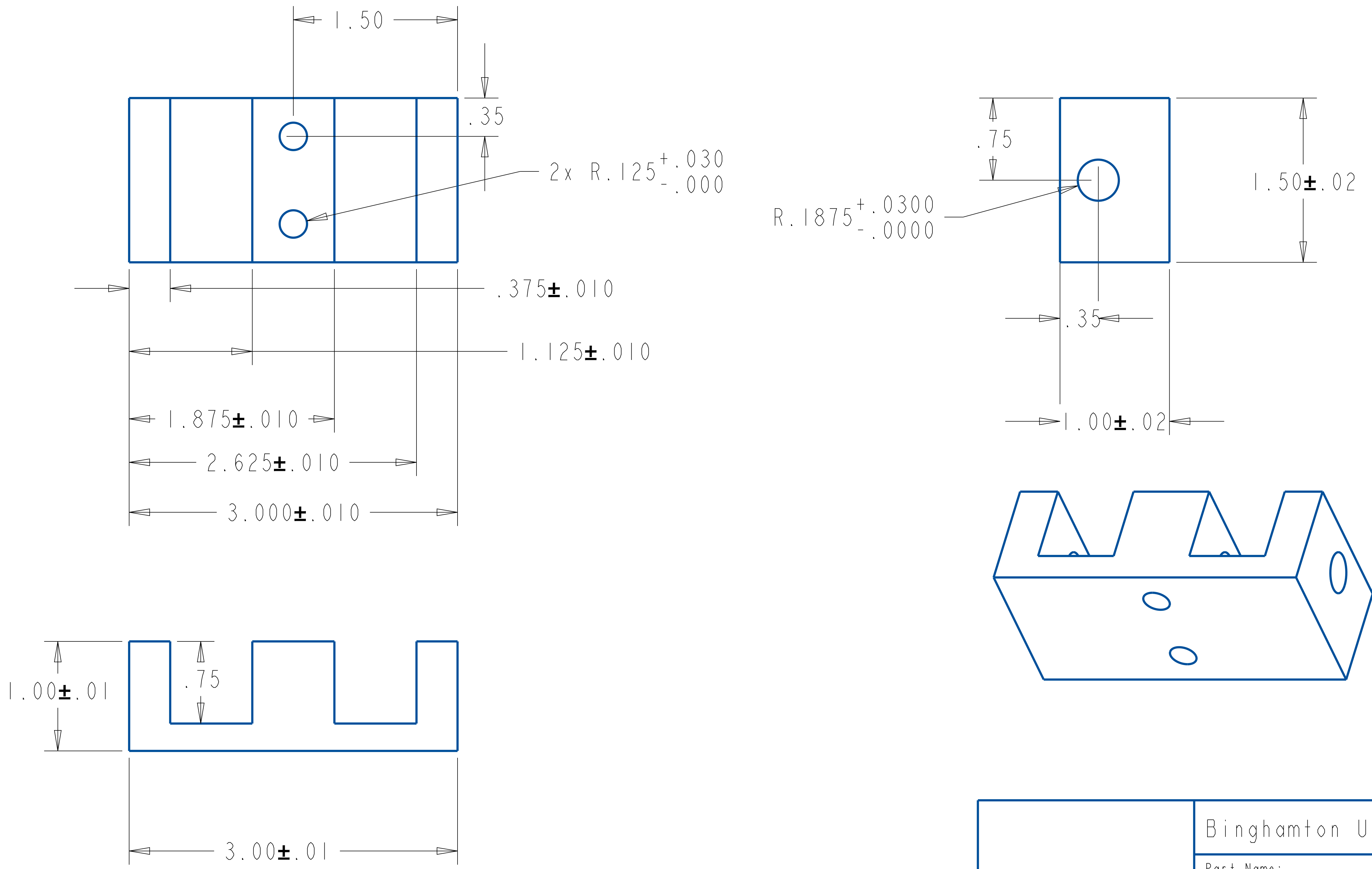


	Binghamton University Hyperloop		
Scale:	Part Name: FRAME ASSEMBLY		
Material: N/A	Author:	PERRY THOMSON	
All units are in inches	Date:	12/1/2018	

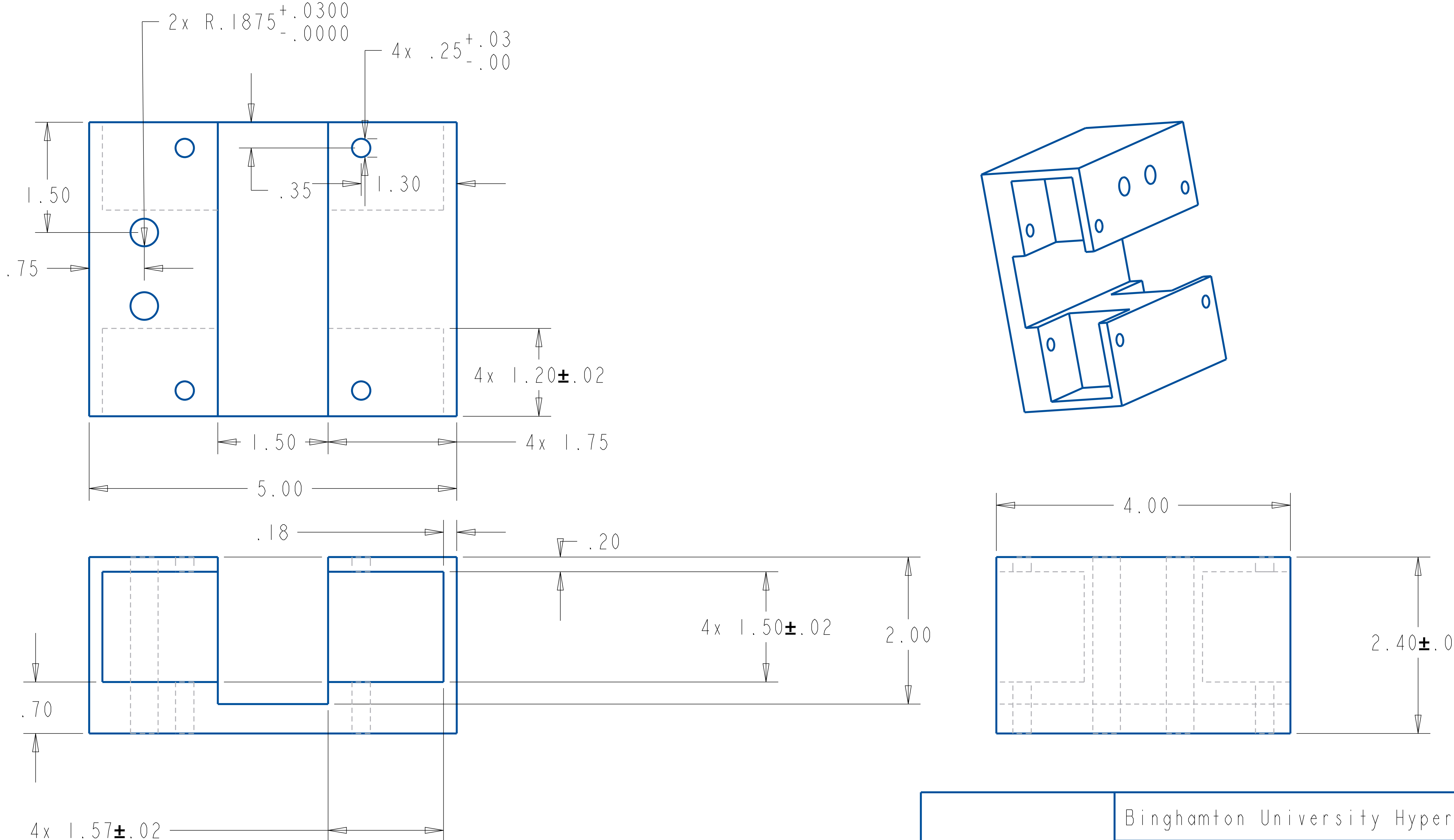
Vendor purchased part / hole drilled for bearing



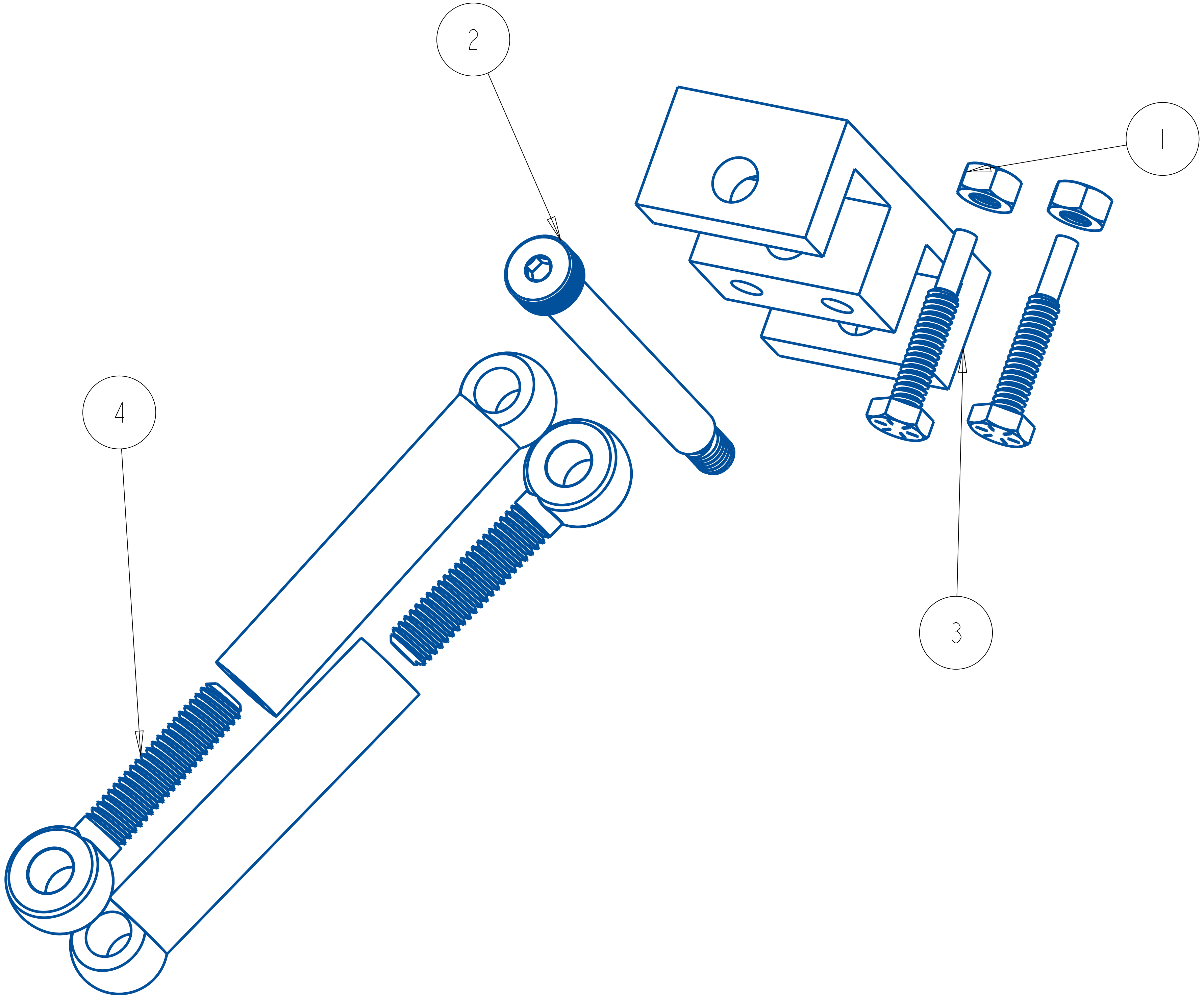
	Binghamton University Hyperloop
Scale: 1.000	Part Name: Aluminum Disk Wheel
Material: 6061 AL.	Author: Austin J Lallier
All units are in inches	Date: 11/30/2018



	Binghamton University Hyperloop
	Part Name: Vertical Base
Scale: 1.000	
Material: 6061 AL.	Author: Austin J Lallier
All units are in inches	Date: 11/30/2018

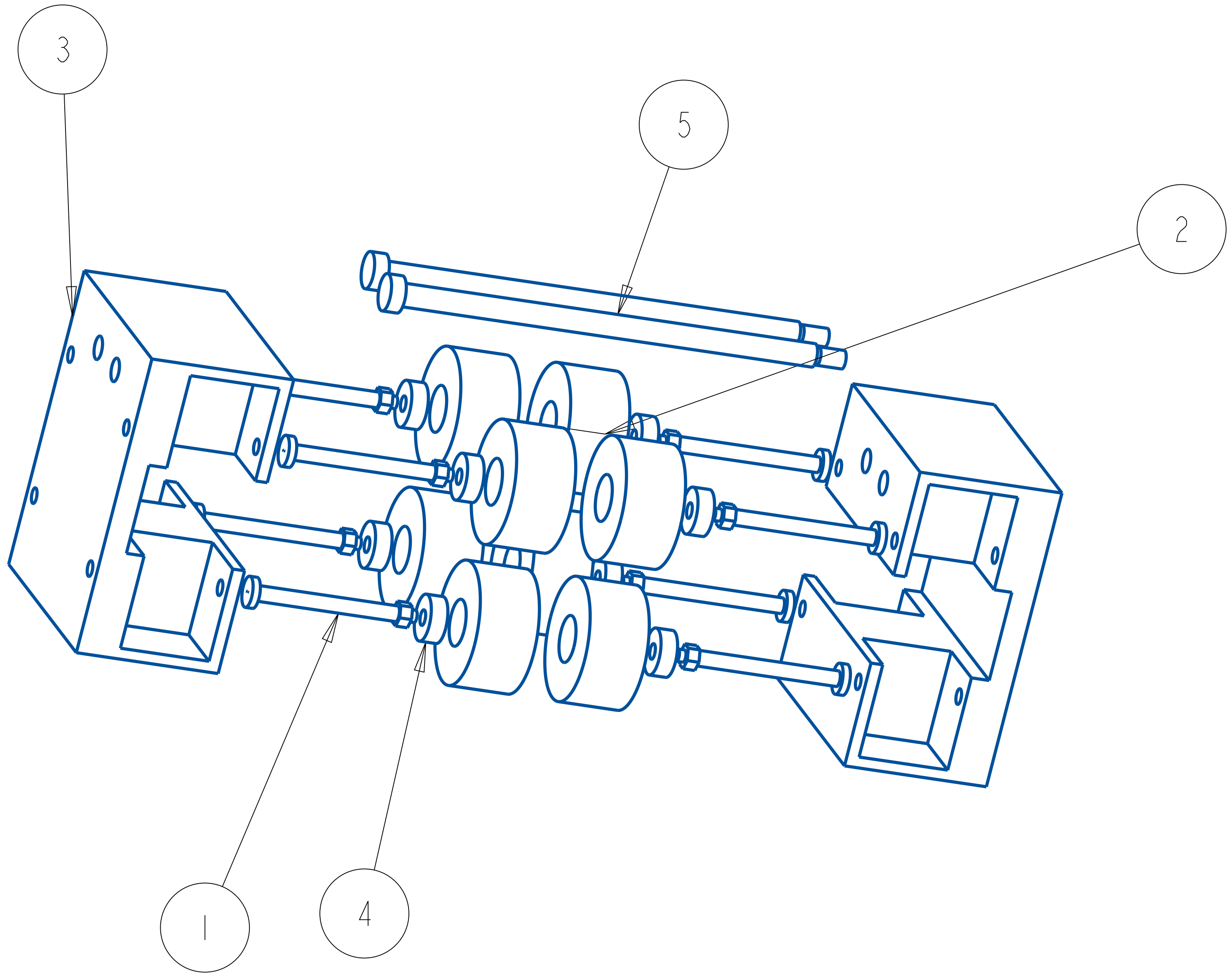


	Binghamton University Hyperloop	
	Part Name: Hinge- Vertical	
Scale: 0.750		
Material: 6061 AL.	Author:	Austin J Lallier
All units are in inches	Date:	11/30/2018



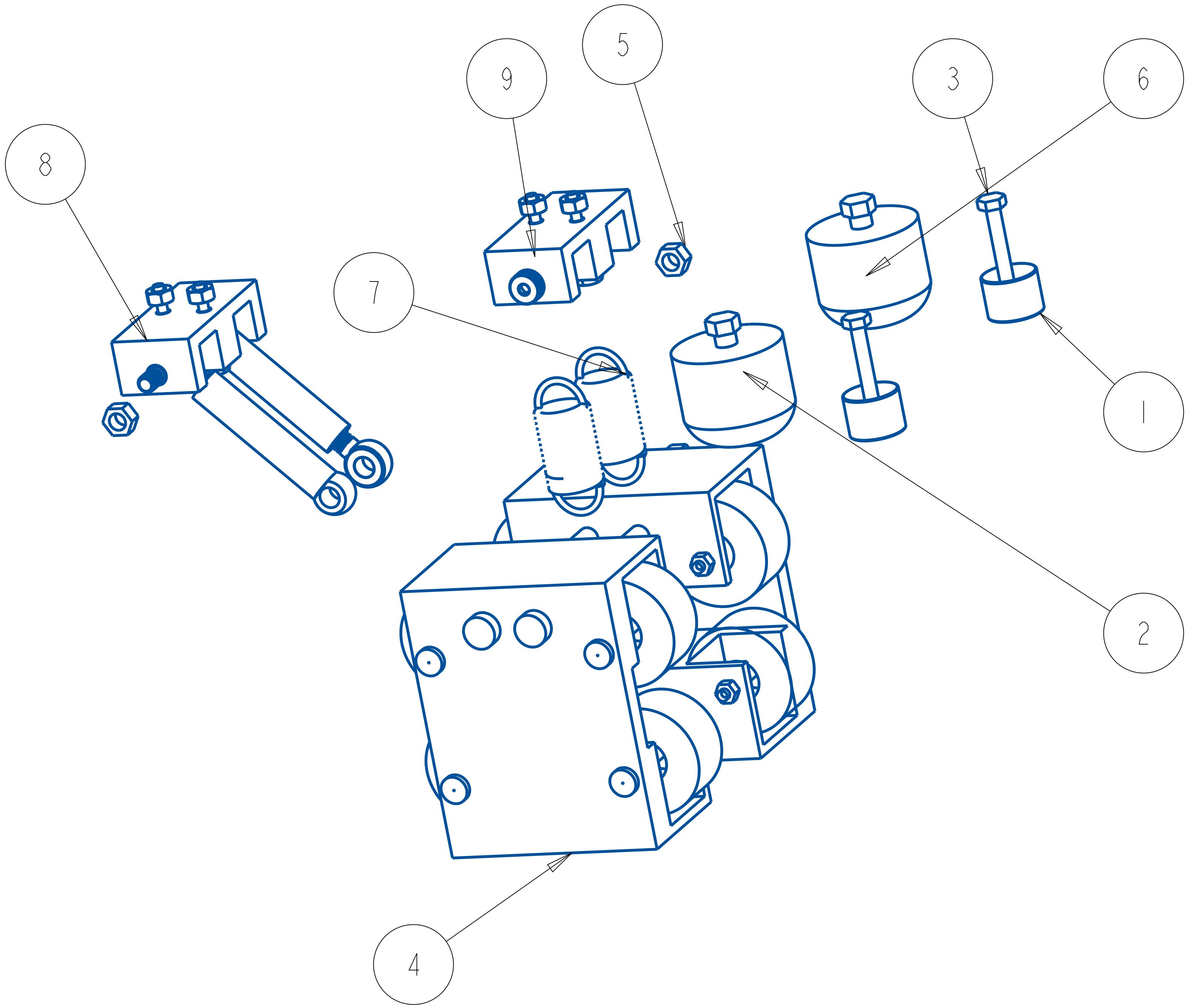
ITEM NO	PART NUMBER	QTY	TYPE
1	25NUTBOLT____	2	Vendor
2	91259A636_BOLT3__	1	Vendor
3	BASE_VERTICAL_____	1	Custom
4	ROD__	2	Vendor

	Binghamton University Hyperloop		
	Part Name: Vertical Stability Base		
Scale: 1.000			
Material: 6061 AL.	Author:	Austin J Lallier	
All units are in inches	Date:	11/30/2018	



ITEM NO	PART NUMBER	QTY	TYPE
1	DOWEL1_______	8	Vendor
2	EXISTINGWHEEL2__	8	Custom
3	LOWERHINGE_____	2	Custom
4	R4A-2Z_BALLBEARING__	8	Vendor
5	VERTICALBOLT2__	2	Vendor

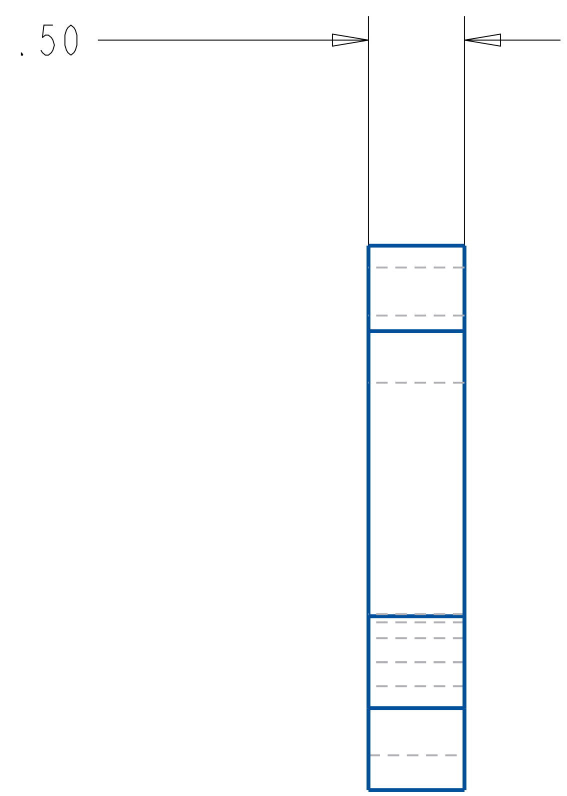
	Binghamton University Hyperloop		
	Part Name: Lower Hinge Sub - Vertical		
Scale: 0.400			
Material: 6061 AL.	Author:	Austin J Lallier	
All units are in inches	Date:	11/30/2018	

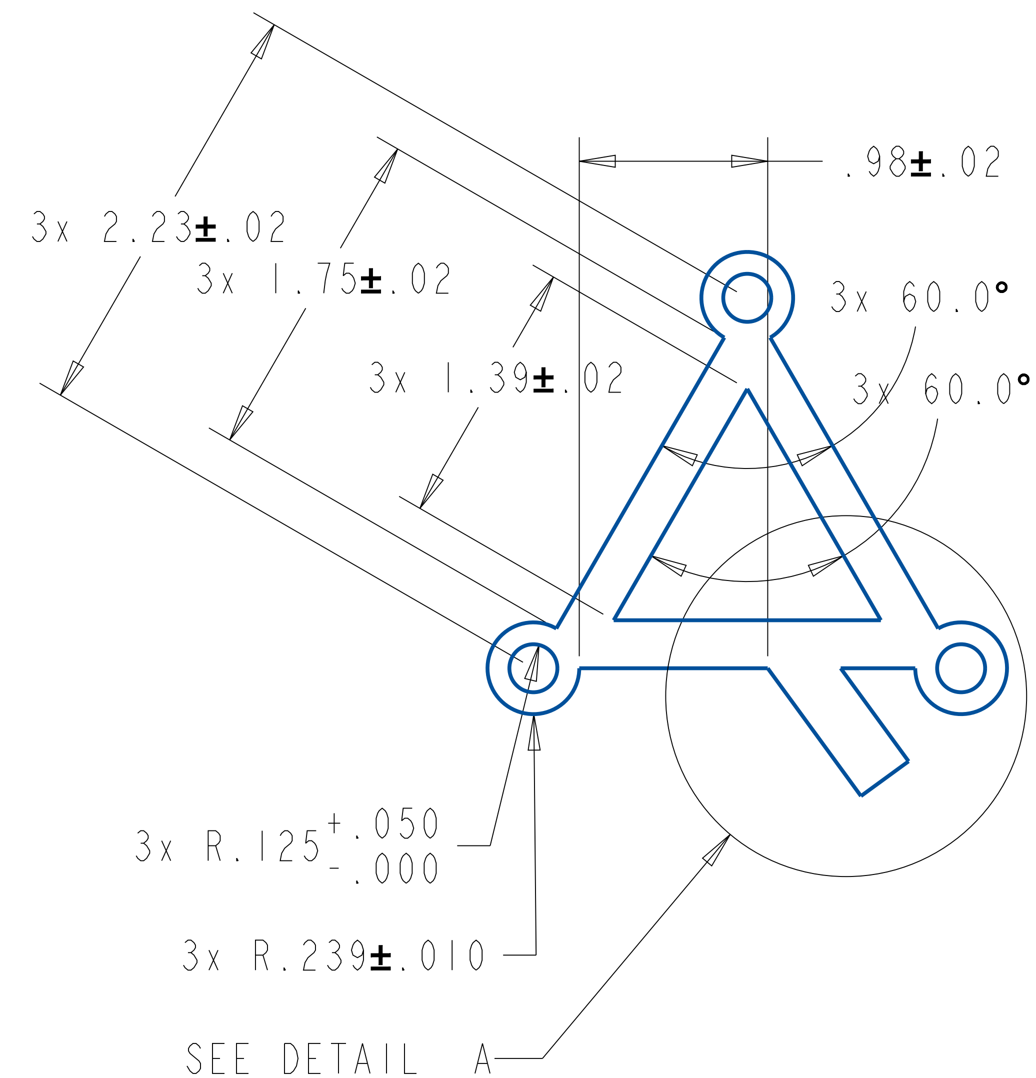


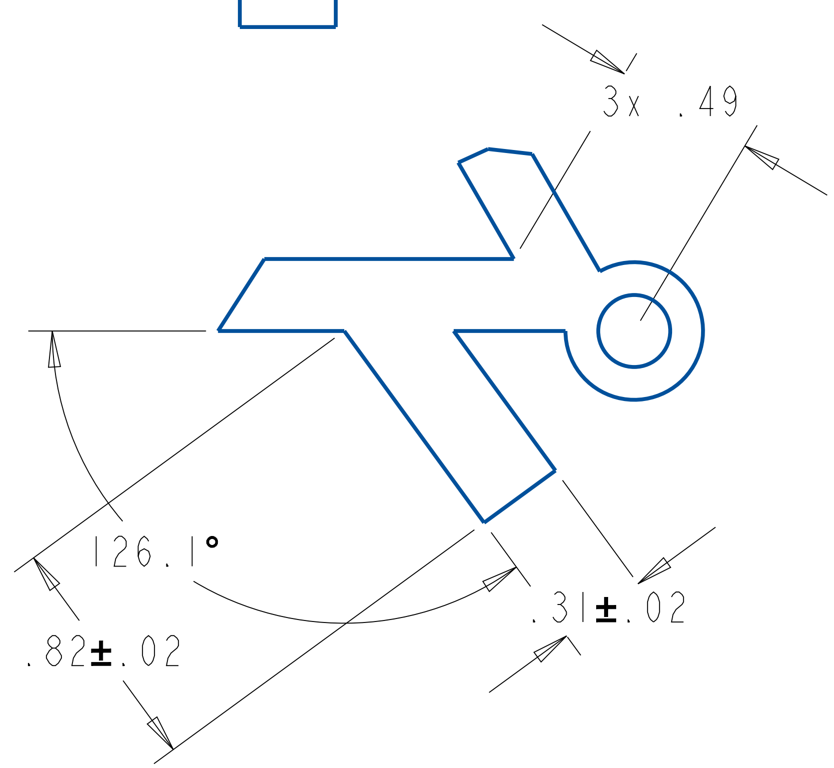
ITEM NO	PART NUMBER	QTY	TYPE
1	93115K111_RUBBER__	2	Vendor
2	BOLTSTOPPER_1__	2	Vendor
3	BOLTSTROPPERII_2__	2	Vendor
4	LOWER_HINGER__	1	Sub-Assembly
5	NUT3__	4	Vendor
6	RUBBERSTOPPER7_4__	2	Vendor
7	SPRINGMCMASTER_____	2	Vendor
8	VERTICALWHEELASSY______	1	Sub-Assembly
9	VERTICALWHEELASSY2__	1	Sub-Assembly

	Binghamton University Hyperloop
	Part Name: Vertical Master Assembly
Scale: 0.400	
Material:	Author: Austin J Lallier
All units are in inches	Date: 11/30/2018

Aluminum .5" block cut of demensions

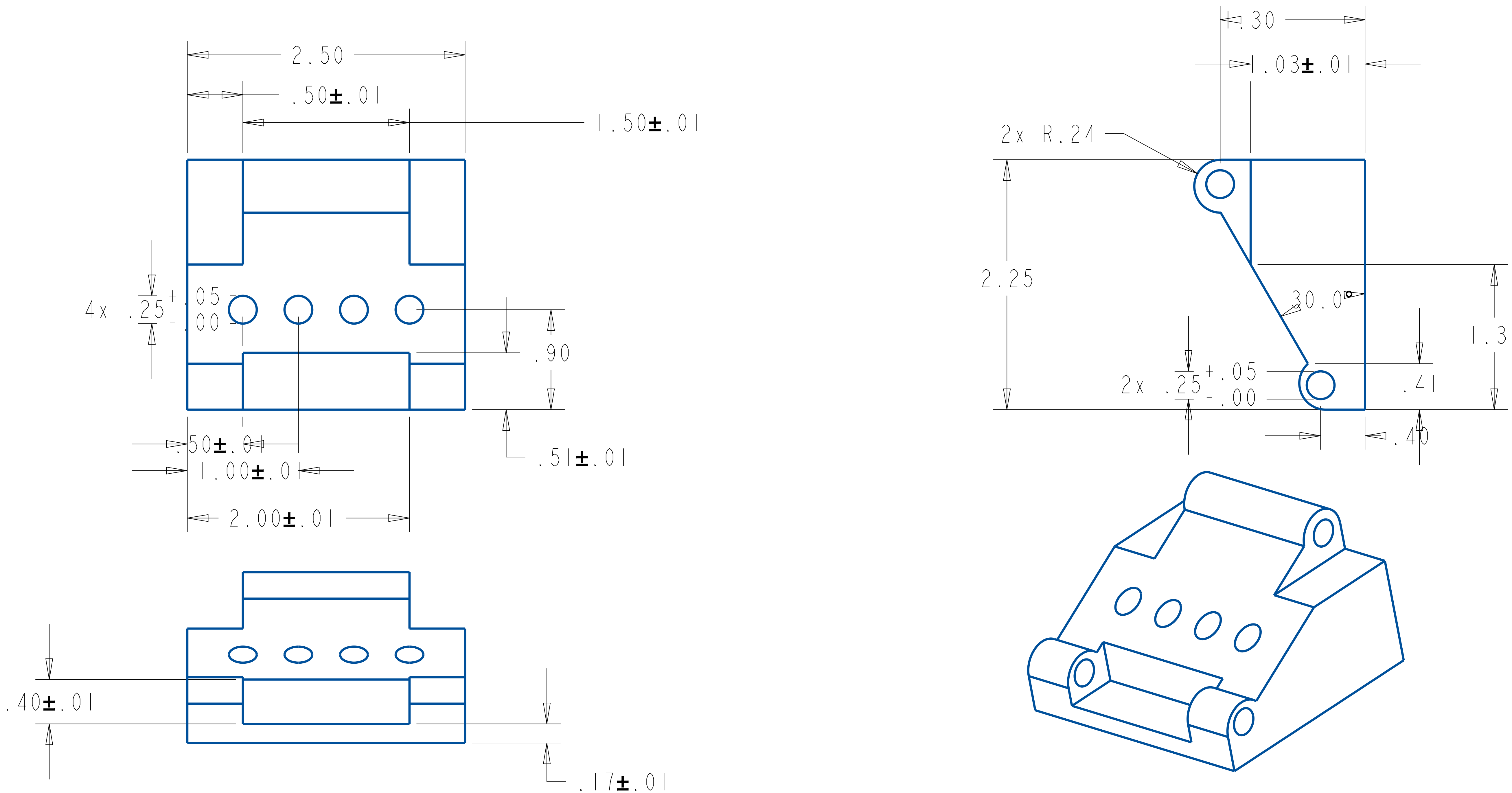






DETAIL A
SCALE 1.500

	Binghamton University Hyperloop		
Scale: 1.00	Part Name: Upper Base- Horizontal		
Material: 6061 AL.	Author:	Austin J Lallier	
All units are in inches	Date:	11/30/2018	



Binghamton University Hyperloop

Part Name:
Base 1 Horizontal

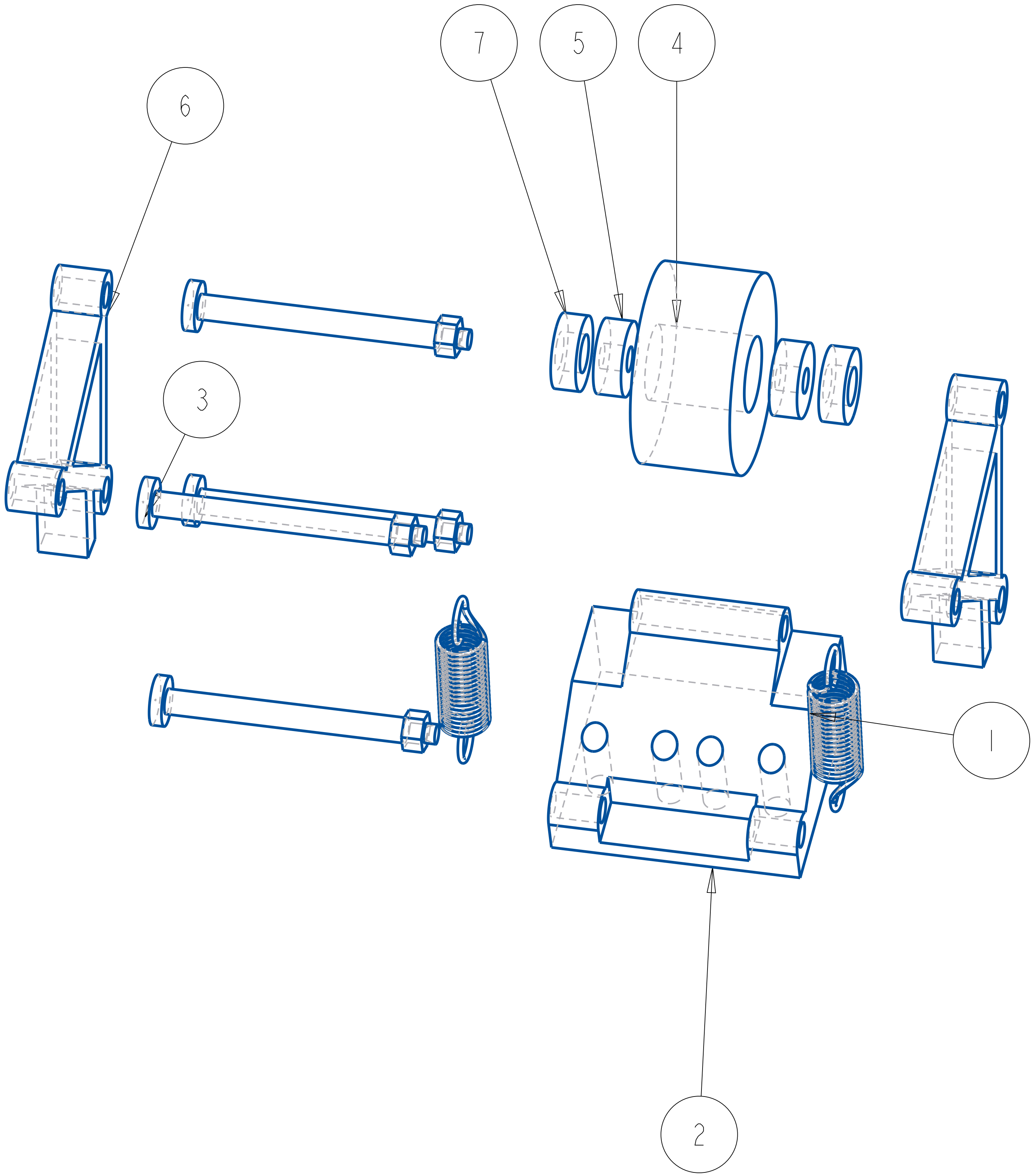
Scale: 1.000

Material: 6061 AL.

All units are in inches

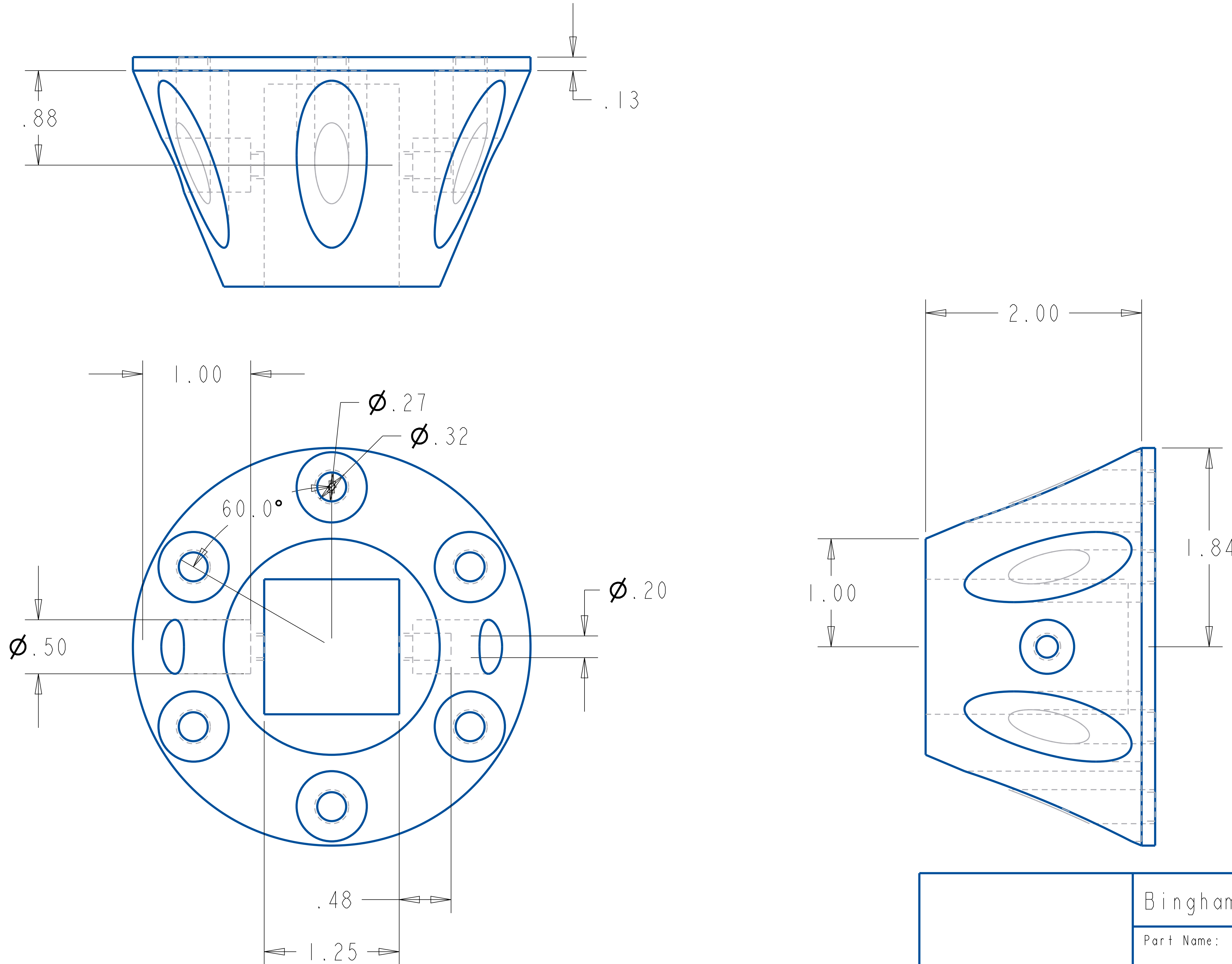
Author: Austin J Lallier

Date: 11/30/2018

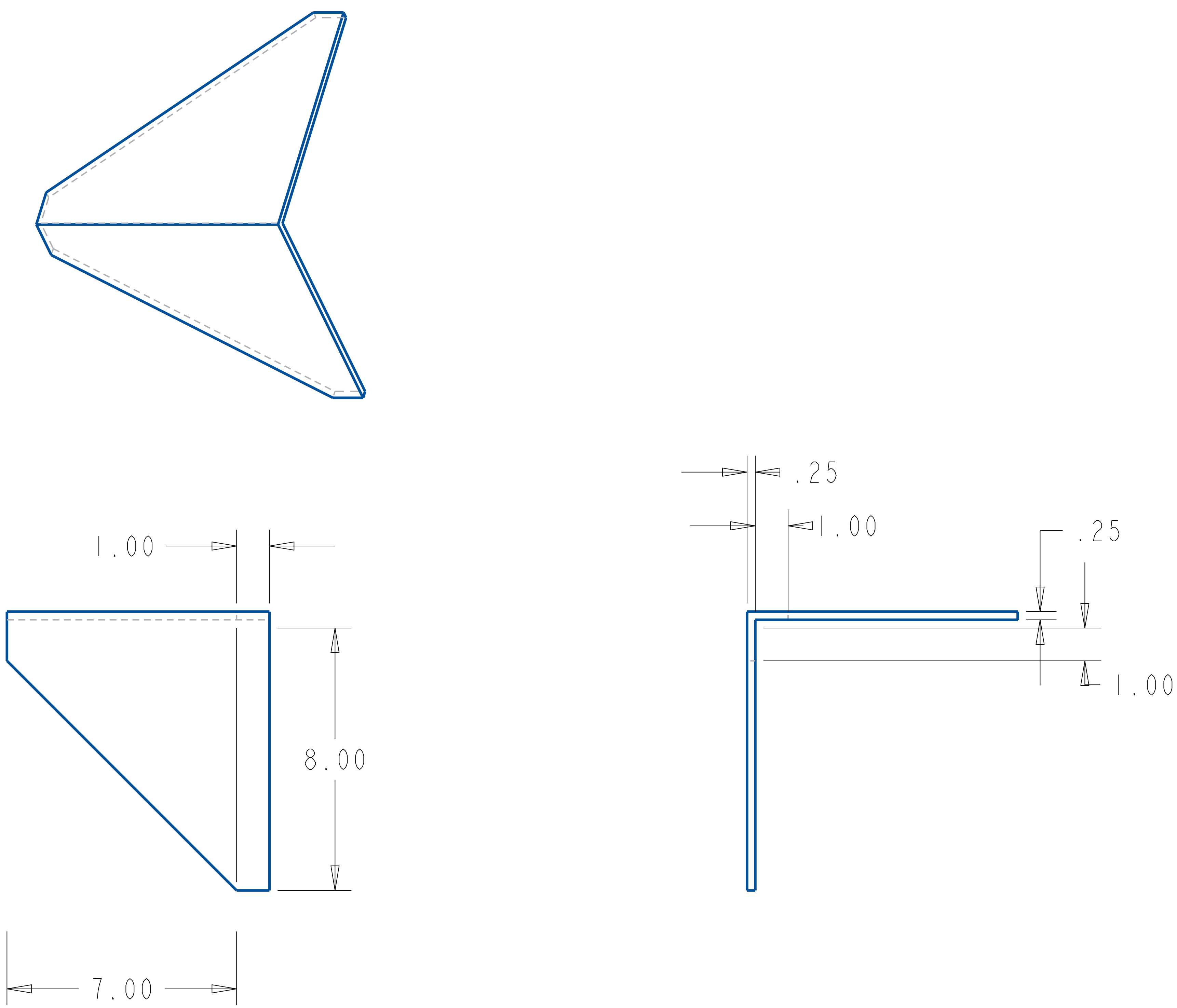


ITEM NO	PART NUMBER	QTY	TYPE
1	1920N470_SPRING	2	Vendor
2	BASE	1	Custom
3	DOWEL1	4	Vendor
4	EXISTINGWHEEL	1	Custom
5	R4A-2Z_BALLBEARING	2	Vendor
6	UPPERBASE	2	Custom
7	WASHER	2	Vendor

	Binghamton University Hyperloop
	Part Name: Horizontal Stability
Scale: .75	
Material: 6061 AL.	Author: Austin J Lallier
All units are in inches	Date: 11/30/2018



	Binghamton University Hyperloop	
Scale: 1	Part Name: Axle Sleeve	
Material: AL 6061	Author:	Cameron Ringo
All units are in inches	Date:	



	Binghamton University Hyperloop		
	Part Name: Axle Braces		
Scale: 1			
Material: AL 6061	Author:	Cameron Ringo	
All units are in inches	Date:		