[The following slides were presented at the LoopTransPort-2018 Conference, July 23-24, 2018, by Prof. Vimal Viswanathan (San Jose State Univ). Copyright retained by the authors.]

SPARTAN
HYPERLOOP

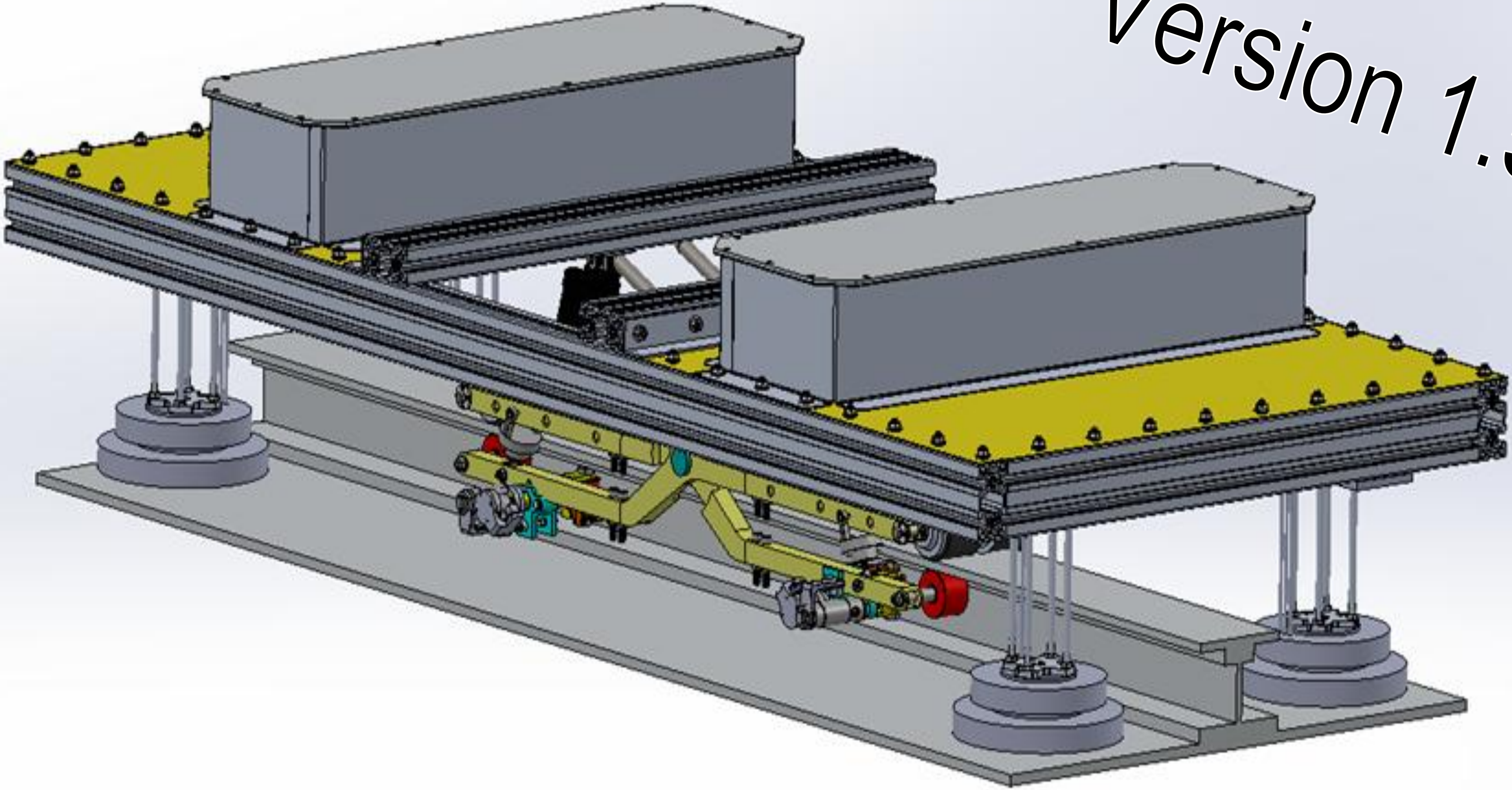
A Hallbach-array based Levitating Pod

July 23, 2018

ABOUT US

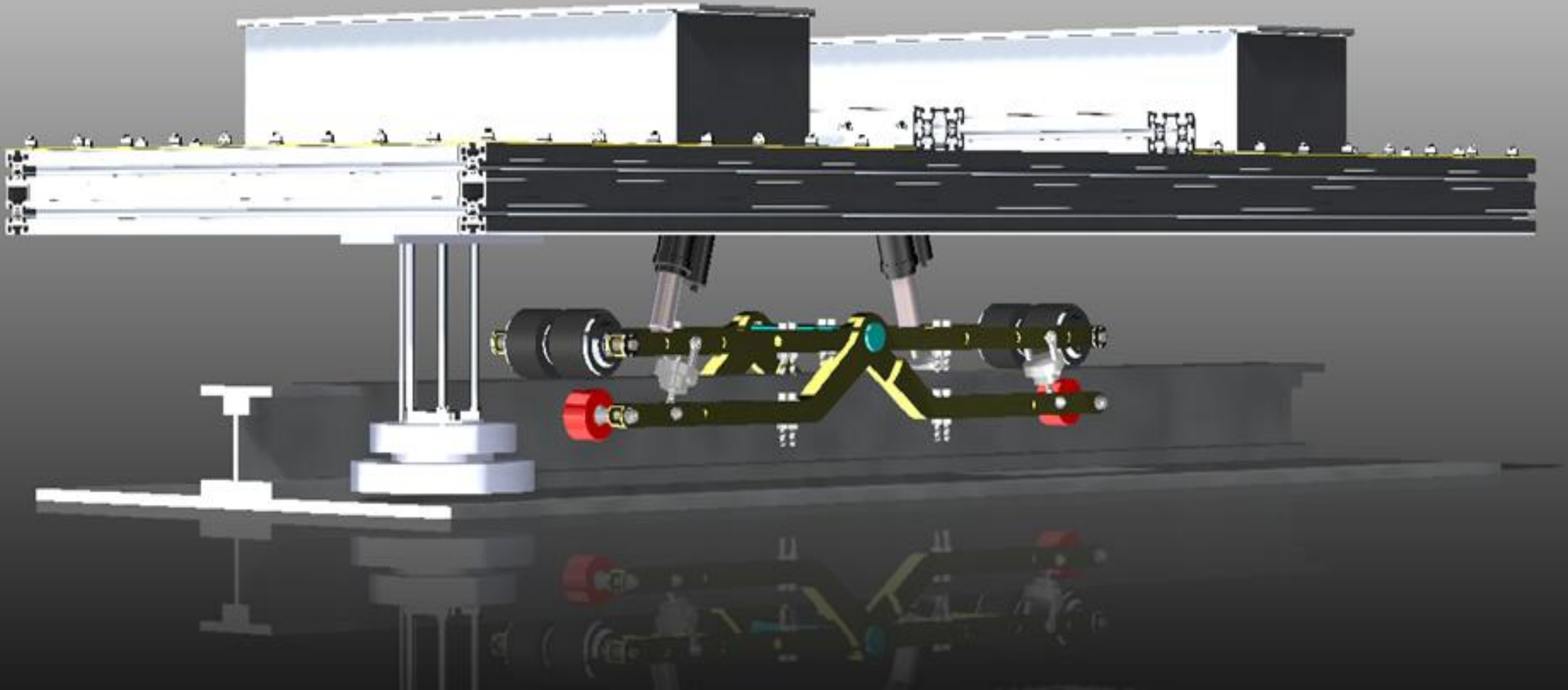
Multidisciplinary team from the Davidson College of Engineering at SJSU

- ❖ Participated in previous Hyperloop competitions and were inspired by the spirit of collaboration and innovation
  - ➢ Wanted to share this rewarding experience with a greater number of students to experience
- ❖ Research and develop various advancements in technologies giving our team practical knowledge and technical skills to bolster our education and career



Version 1.5

Current Model



TOP LEVEL DESIGN SUMMARY

LEVITATION: Magnetic Levitation with Arx Pax HE Compacts

POD FRAME: T-Rail Construction

PROPULSION: Clamping Scissor Mechanism with in-hub propulsion

NAVIGATION/STABILITY: Spring-loaded Yaw Stability Mechanism

POWER: 33.4V Venom LiPo, 67.2V Energus LiPo

CONTROLS:

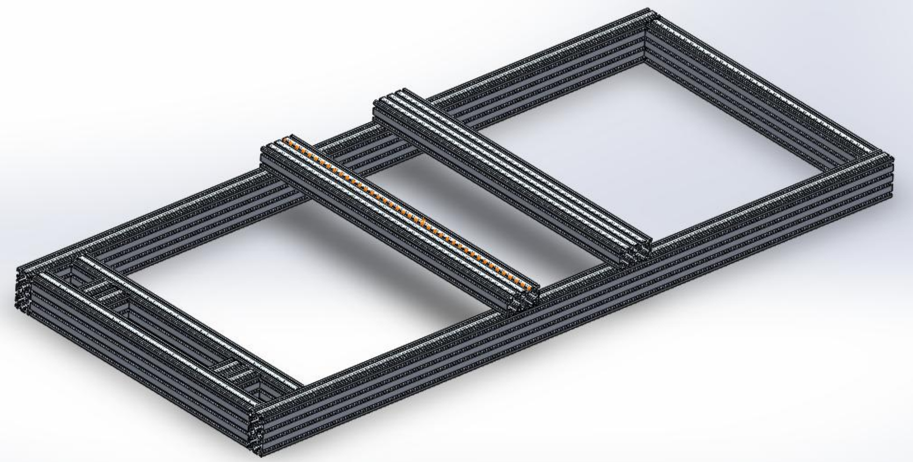
Spartan Hyperloop Pod Overview

Weight: 325 lbs
Length: 78 in x 34 in x 24 in (L x W x H) Frame Outer Dimensions
Drive Type Method: Motorized Rotary Halbach Arrays
Propulsion Method: 4x Venom LiPo powered BLDC Hub motors on top flange of guide rail
Primary Braking: Hub Motor Back-EMF using TMCM-1630 *position mode* (Top of I-beam)
Secondary Braking: Pneumatic Friction Brakes on Lateral Stability Mechanism (webbing of I-beam)

Maximum speed at which Pod can maintain control while levitating 60+ mph
Maximum speed at which Pod can maintain control while not levitating (e.g. on wheels; if no wheels are on the Pod, then the answer should be zero mph) 25 mph
Maximum acceleration at which Pod has been structurally designed 1.63g
Maximum acceleration for which Pod can maintain control 0.6g

FRAME

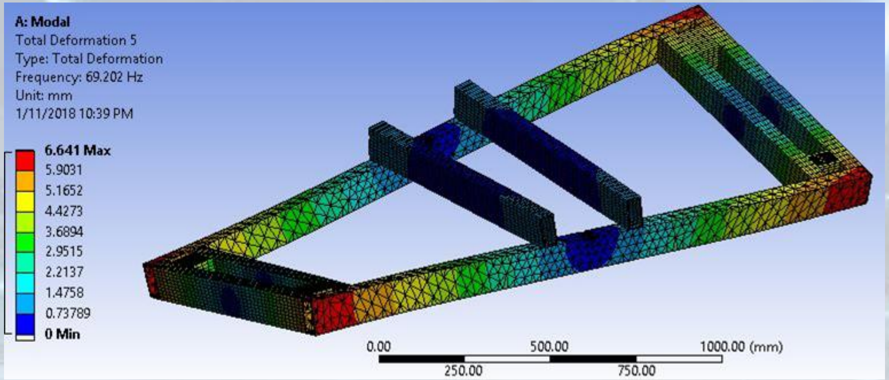
- Weight
  - Aiming to keep overall pod under 180 kg (Distributes 45 kg to each Hover Engine)
- Manufacturing and Assembly
  - T-Rails are a readily available cross section that come in various sizes
  - They are easily configurable to mount to each other for frame construction
- Ease of Mounting
  - Universal mounting hardware allows easy mounting of components
- Material
  - Aluminum is light, strong and is commonly used for structural components



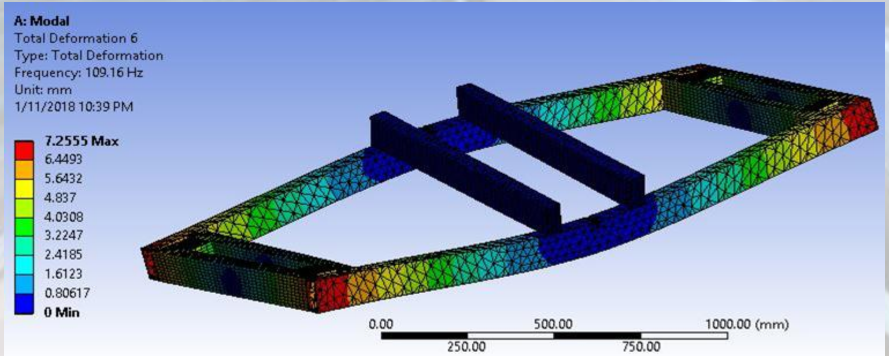
DIMENSIONS:
- 6.5 ft Long
- 2.5 ft Wide
- 1 ft Height

MODAL ANALYSIS

- We found 2 natural frequencies of bending for our frame, 69.2 and 109.1 hz
- Our operating frequency is 100 hz
- Therefore, we will be operating safely outside of the natural frequencies



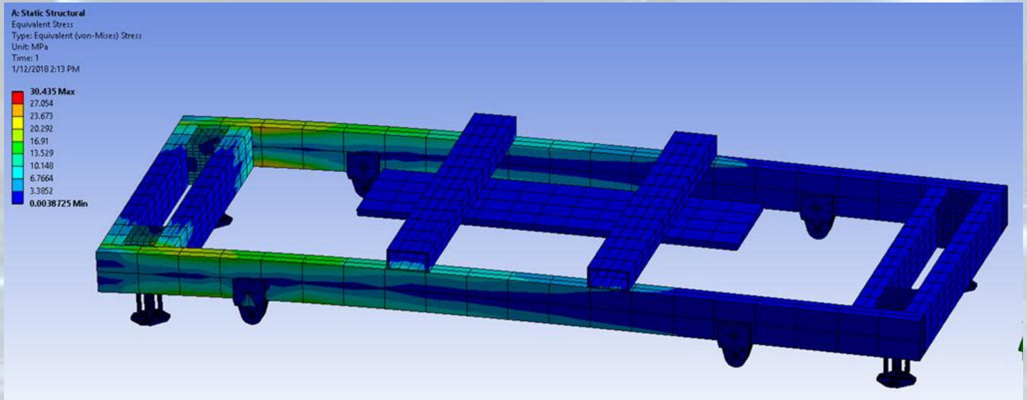
A: Modal
Total Deformation 5
Type: Total Deformation
Frequency: 69.202 Hz
Unit: mm
1/11/2018 10:39 PM

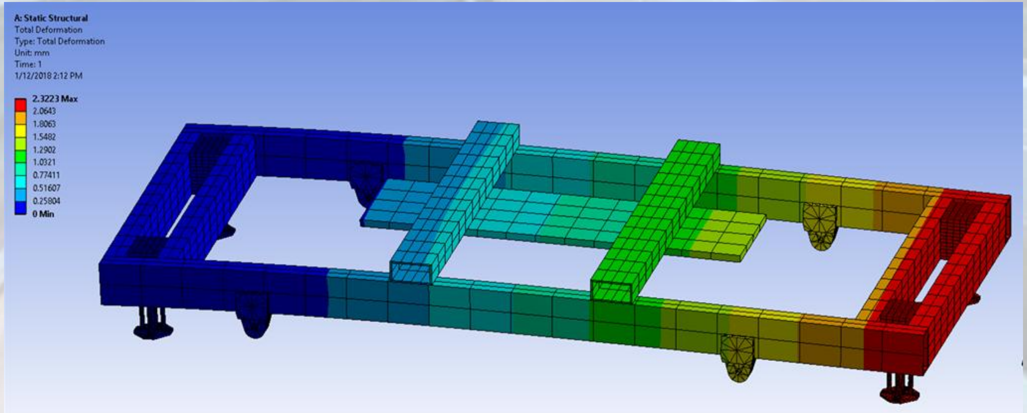


A: Modal
Total Deformation 6
Type: Total Deformation
Frequency: 109.16 Hz
Unit: mm
1/11/2018 10:39 PM

ACCELERATION TEST

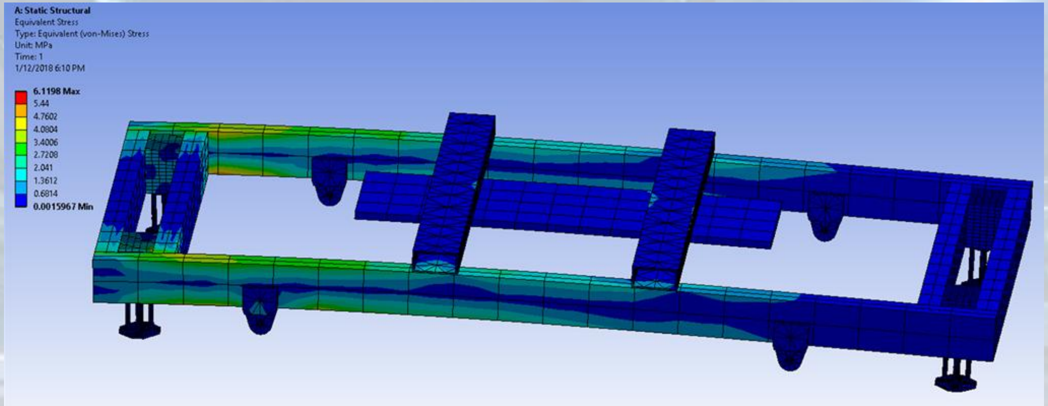
- Fixed support on one end of the frame
- Acceleration force of 272 newtons applied to other end
- Minimum factor of safety of 8.2
- Maximum deformation during acceleration was 2.3 mm

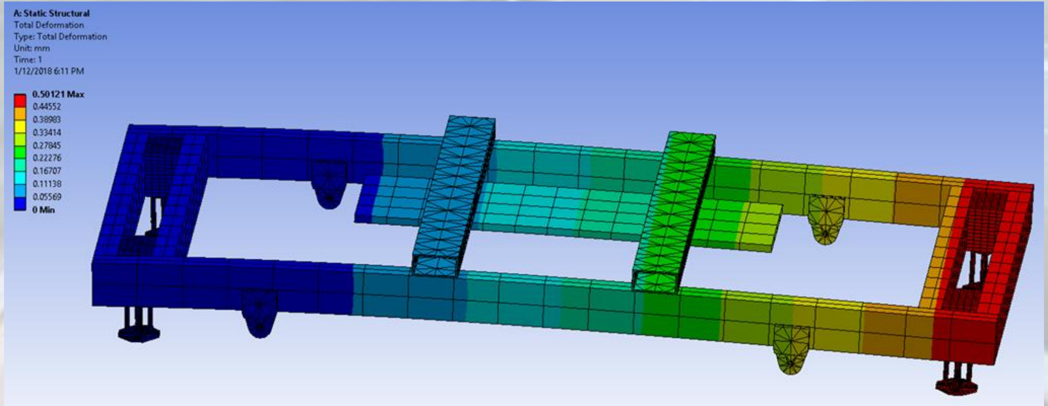




BRAKING TEST

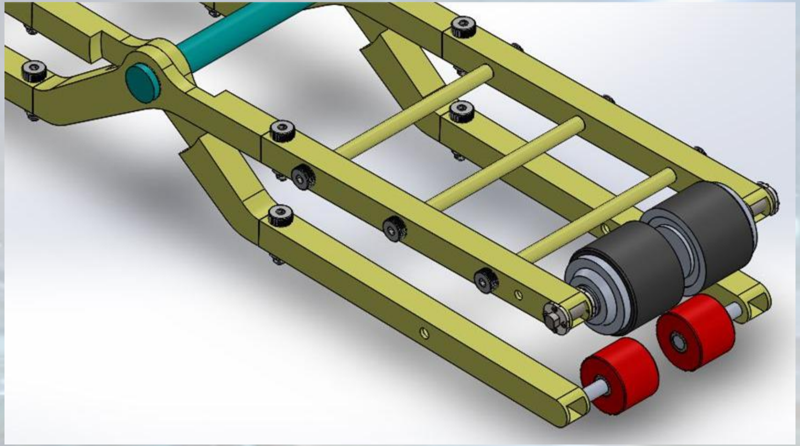
- Fixed support on one end of the frame
- Braking force of 420 newtons applied to middle cross members
- Minimum factor of safety of 15
- Maximum deformation during braking was 0.5 mm

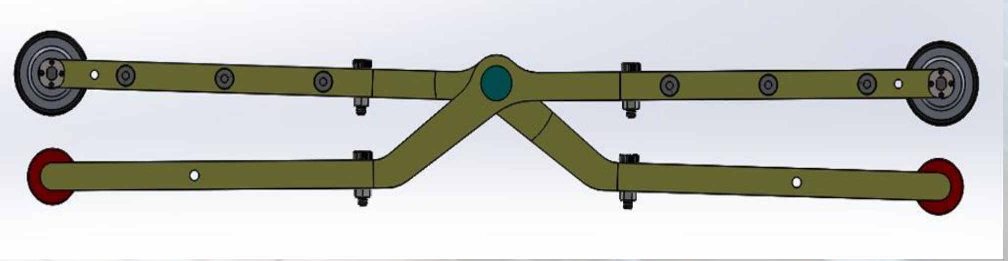




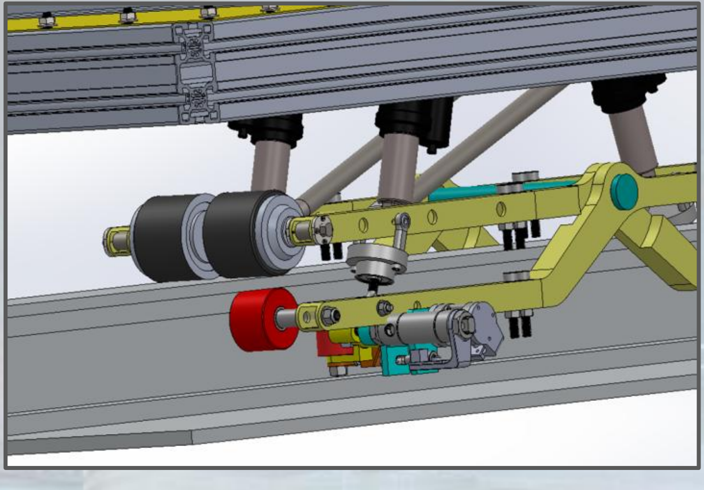
SCISSOR MECHANISM

- Due to Levitation there is no Normal Force for Traction
  - Pneumatics cylinders will actuate arms into place to clamp onto I-Beam
  - ~200lbs of total Normal Force can be applied
- Scissor mechanism is used for propulsion and braking by actuating the hub motors to make contact with the flange of I-beam

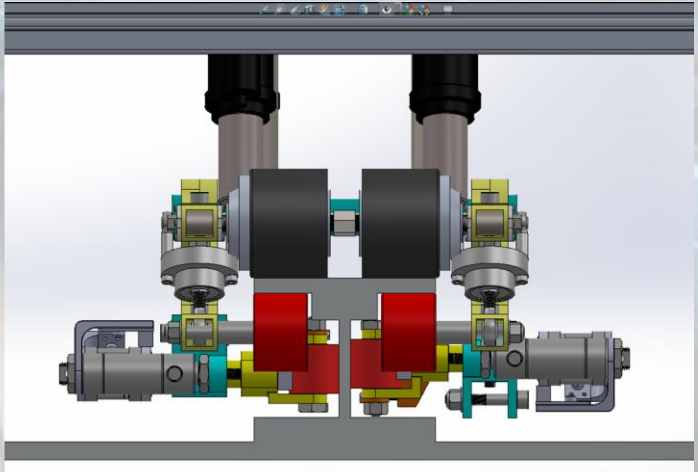




STABILITY

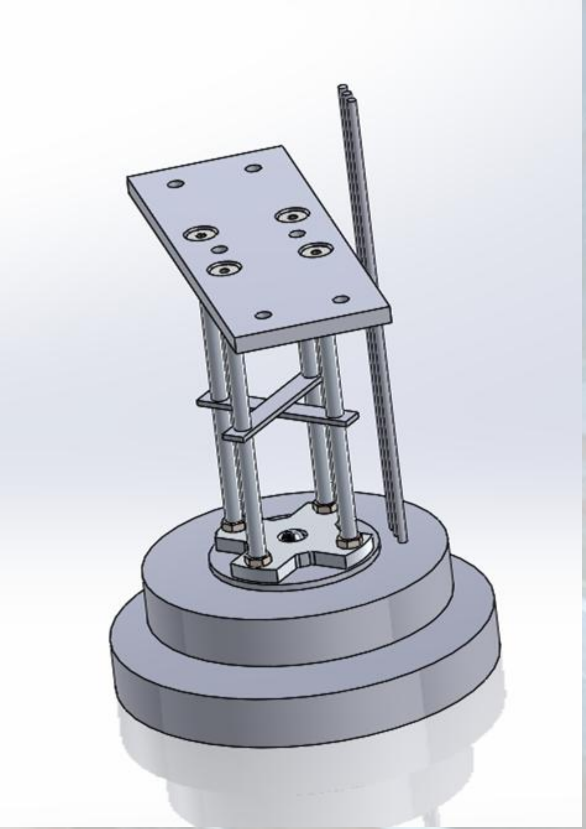


- Vertical, Roll and Pitch Stability
  - Proper Dispersal of Hover Engines across Pod body make the pod inherently stable during Levitation
  - Any mismatch in height across the pod will be rectified by a change in lift force generated and thus stabilize pod
- Lateral and Yaw Stability
  - The pod has a chance of turning in the yaw direction thus a stability mechanism is required.
  - A clamping mechanism interfacing with the I-beam web should provide sufficient stabilization
  - Vertical, actuated, clamping rollers will allow the pod to engage and disengage from the I-Beam and provide clamping

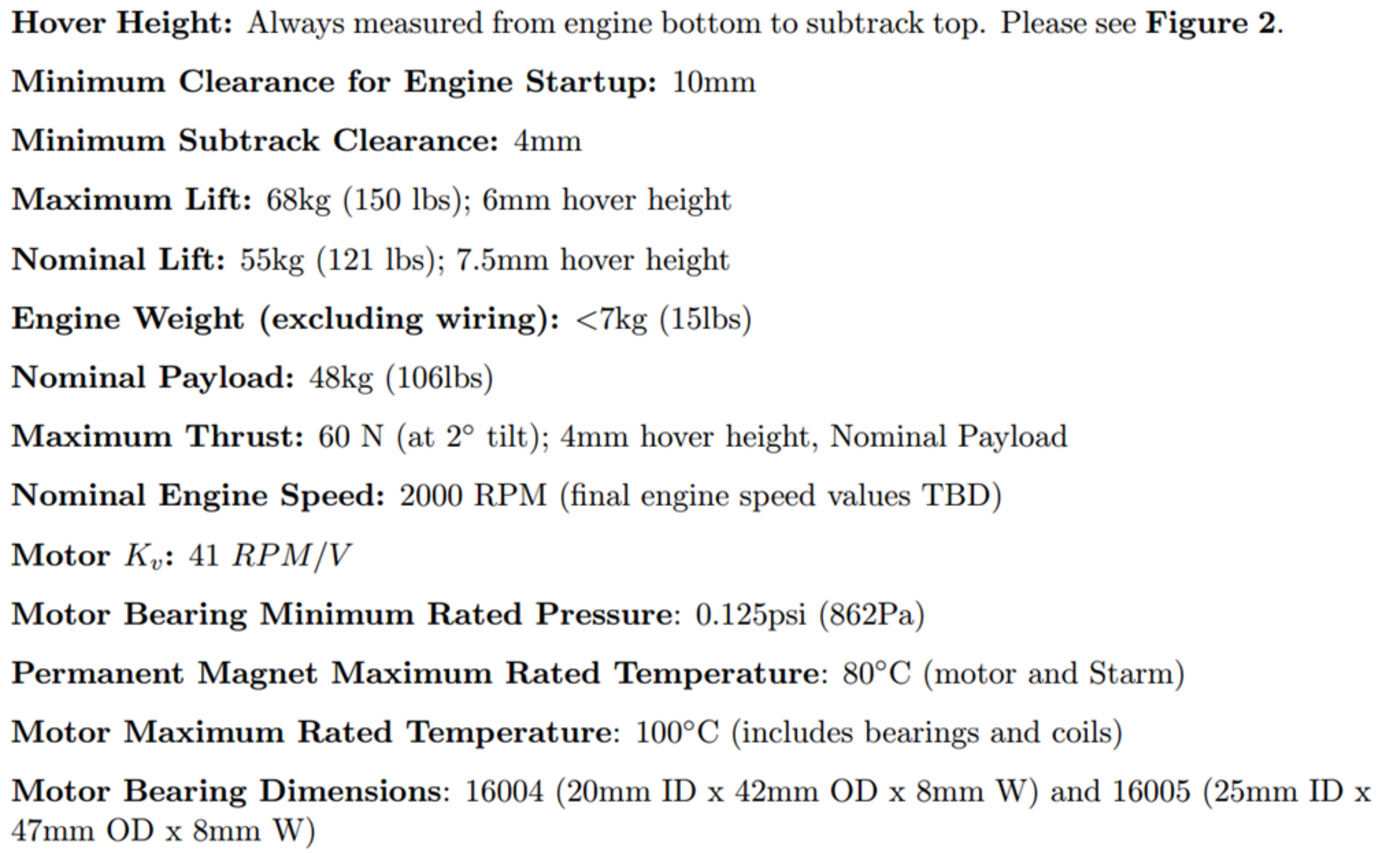


LEVITATION

- Magnetically Induced Eddy Currents
  - Circular Halbach Arrays spun at high speeds will induce currents in conductive sub-track allowing for stationary levitation instead of requiring translation
  - The magnetic field generated by the currents will oppose the primary field of the Halbach Array
- 4x Arx Pax Hover Engine 3.0
  - Contain Magnetic Array in the Lower Starm
  - High speed, 3-Phase motor provides rotation
  - With a distributed weight of 45 kg per engine, we get an estimated hover height of ~10 mm



Single Hover Engine Specifications



Hover Height: Always measured from engine bottom to subtrack top. Please see **Figure 2**.

Minimum Clearance for Engine Startup: 10mm

Minimum Subtrack Clearance: 4mm

Maximum Lift: 68kg (150 lbs); 6mm hover height

Nominal Lift: 55kg (121 lbs); 7.5mm hover height

Engine Weight (excluding wiring): <7kg (15lbs)

Nominal Payload: 48kg (106lbs)

Maximum Thrust: 60 N (at 2° tilt); 4mm hover height, Nominal Payload

Nominal Engine Speed: 2000 RPM (final engine speed values TBD)

Motor K_v: 41 RPM/V

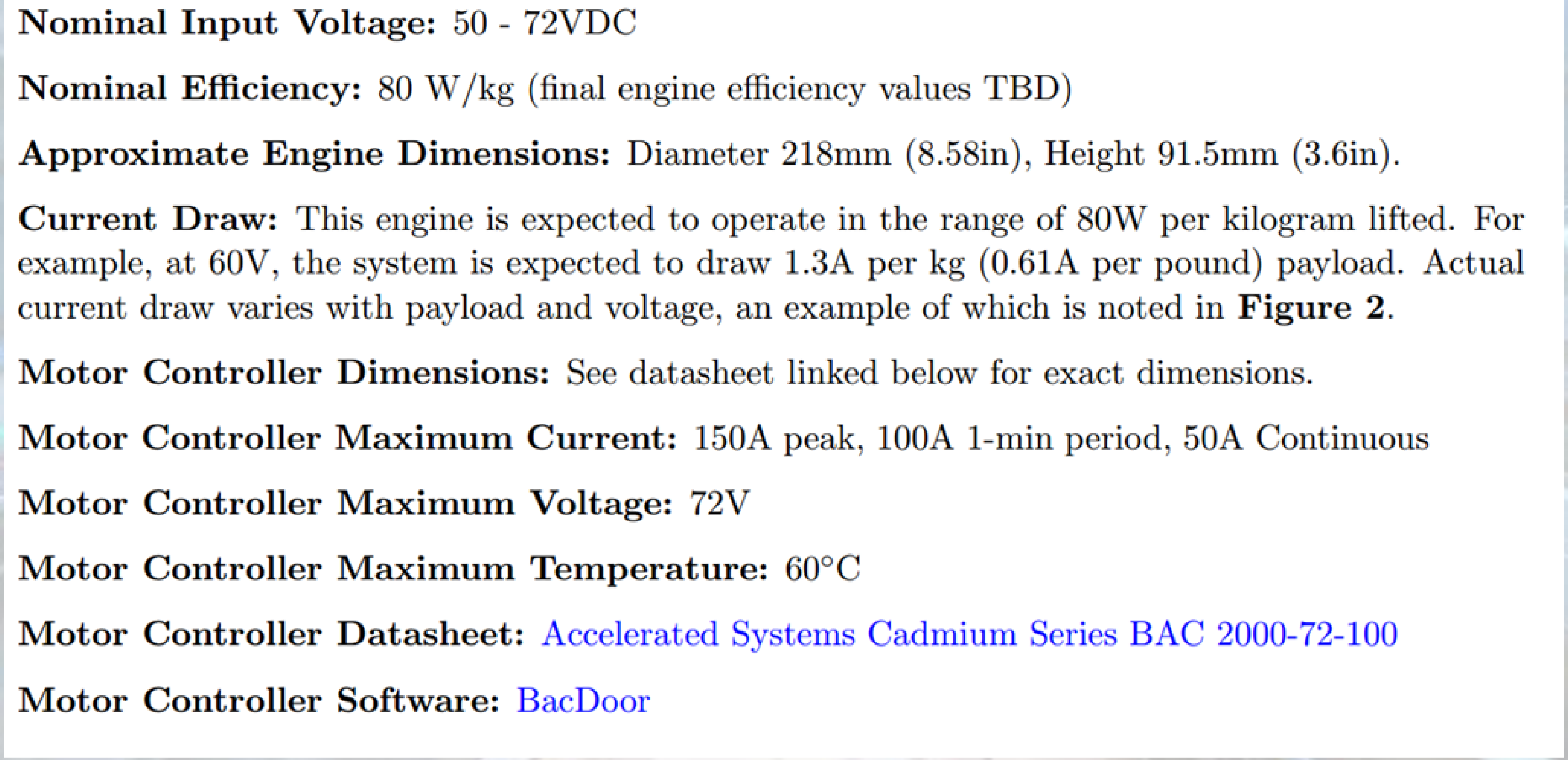
Motor Bearing Minimum Rated Pressure: 0.125psi (862Pa)

Permanent Magnet Maximum Rated Temperature: 80°C (motor and Starm)

Motor Maximum Rated Temperature: 100°C (includes bearings and coils)

Motor Bearing Dimensions: 16004 (20mm ID x 42mm OD x 8mm W) and 16005 (25mm ID x 47mm OD x 8mm W)

Single Hover Engine Specifications



Nominal Input Voltage: 50 - 72VDC

Nominal Efficiency: 80 W/kg (final engine efficiency values TBD)

Approximate Engine Dimensions: Diameter 218mm (8.58in), Height 91.5mm (3.6in).

Current Draw: This engine is expected to operate in the range of 80W per kilogram lifted. For example, at 60V, the system is expected to draw 1.3A per kg (0.61A per pound) payload. Actual current draw varies with payload and voltage, an example of which is noted in **Figure 2**.

Motor Controller Dimensions: See datasheet linked below for exact dimensions.

Motor Controller Maximum Current: 150A peak, 100A 1-min period, 50A Continuous

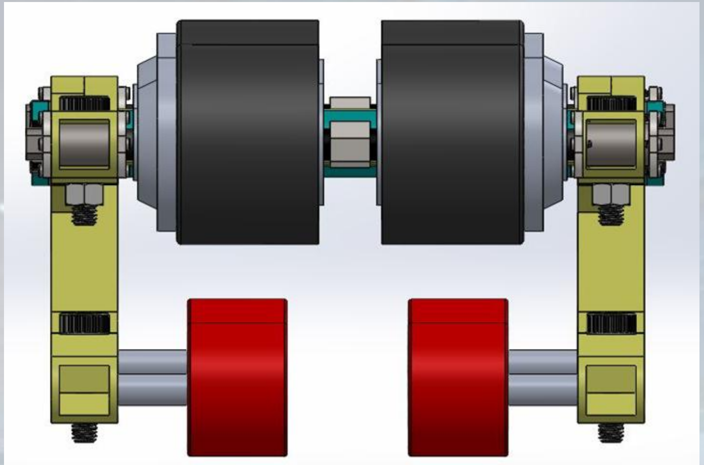
Motor Controller Maximum Voltage: 72V

Motor Controller Maximum Temperature: 60°C

Motor Controller Datasheet: Accelerated Systems Cadmium Series BAC 2000-72-100

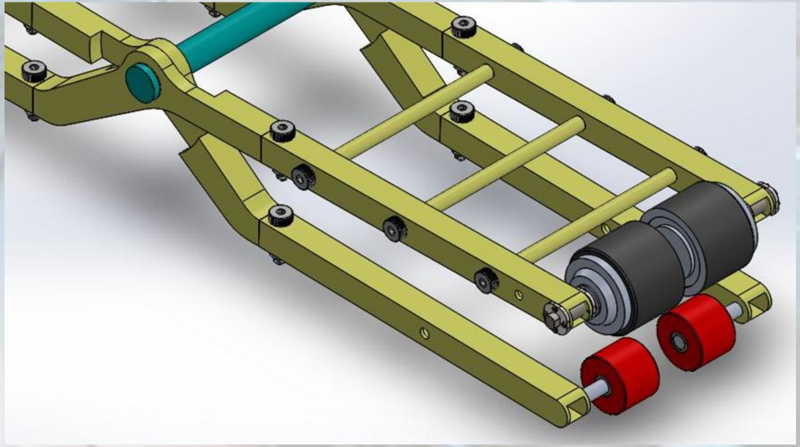
Motor Controller Software: BacDoor

PROPULSION



Single Stage Propulsion:

- Delrin Rollers on I-Beam
  - Because the pod will be levitating, an artificial normal force is needed in order to provide traction.
  - A scissor mechanism will allow the rollers to clamp to the I-Beam in a symmetric manner.



PROPULSION

- BLDC Wheel-hub motors (x4)
  - 70mm low noise E-WHEELIN skate hub motor
    - Weight: 1kg (2.2 lbs) (x4)
    - Input Voltage: 24-48V (3-phase)
    - Nominal Rated Power: 150W
    - Efficiency: 95%
    - Integrated Hall-effect sensors
    - Double-shafted

Supplied by Hongjun Science and Technology Co.

Total Weight of Hub Motors: 8.8025lb

Motor Controller Specs for Propulsion and Braking

- Trinamic TMCM-1630-4U BLDC Motor Controller
    - Single Brushless Driver 10A-per-phase 12-48V load
    - ARM Cortex-M3
    - Interface: RS485 / USB Type B
    - *(Chosen over the TMCM-1630-2C model with RS232/CAN interface)*
    - Velocity or Position modes
    - Current Sensing
    - Slope Control
    - *TMCL IDE* Software and *Direct Mode* via binary cmds

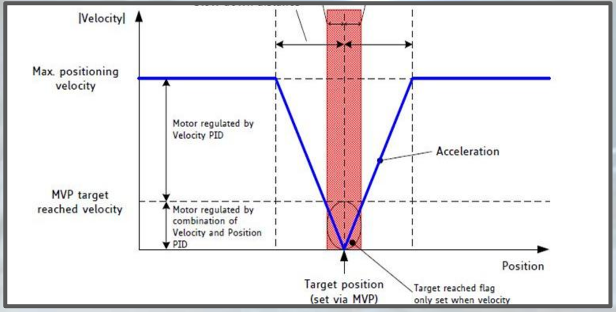
- Trinamic BB-1630 BaseBoard
    - Stand-alone (EEPROM) or remote operation via the interface types mentioned above (USB)
    - Hall-sensor based position control
    - Velocity and torque control (via current)
    - Supports 12-55V motor supply

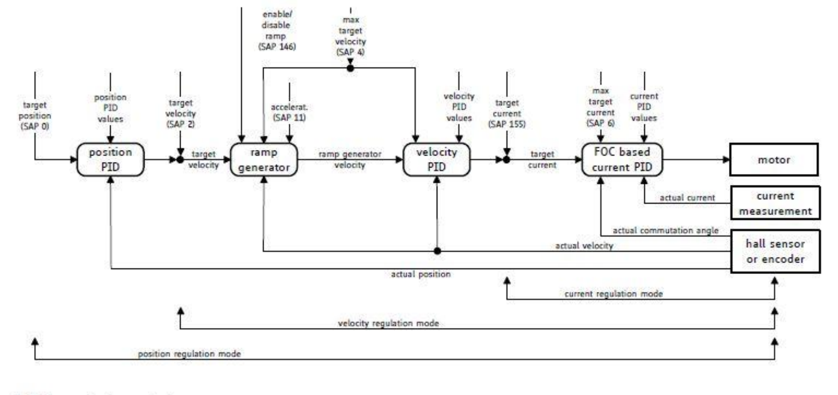
TMCM-1630-4U

BB-1630

BRAKING

- Electrical Braking - Primary
  - <u>Plugging:</u> The TMCM-1630’s *position mode* uses a closed-loop PI control system. A constant acceleration and maximum velocity are set, and the system will compare the actual position measured from the hub motor hall-effect sensors with the set target position. A slowdown time is calculated preventing any overshoot to the destination while creating a symmetrical acceleration profile. Reversing the applied supply voltage (H-bridge) will assist the back emf forcing the armature current in reverse direction and producing deceleration.





7.1 Cascaded regulation

STRUCTURE OF THE POSITION REGULATOR

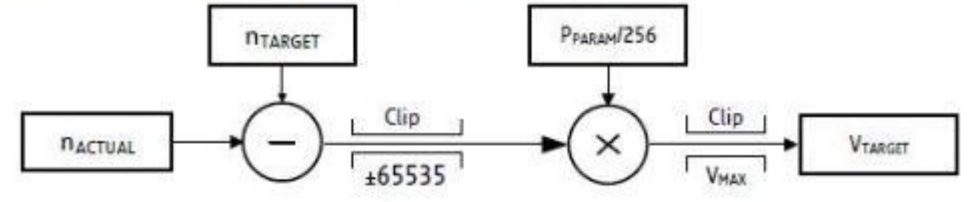
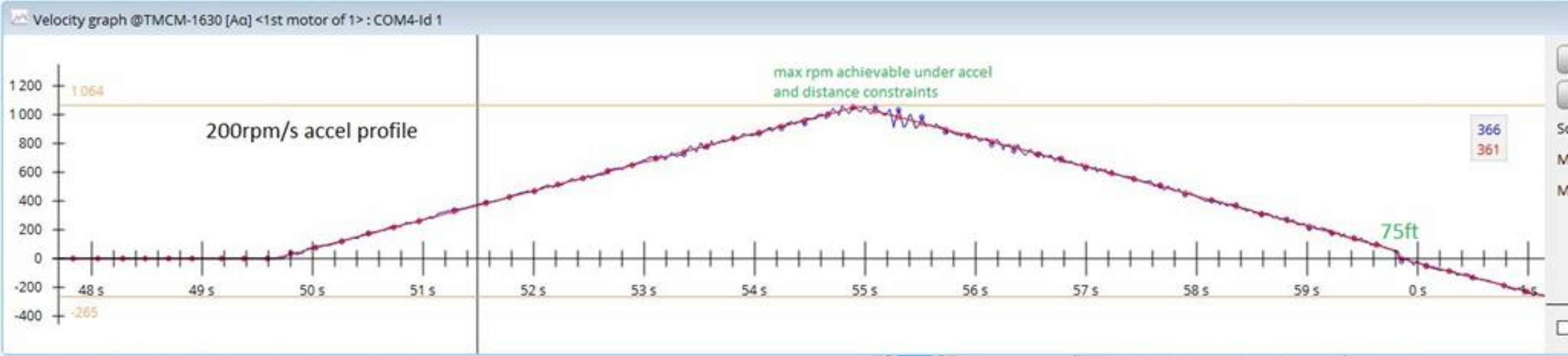


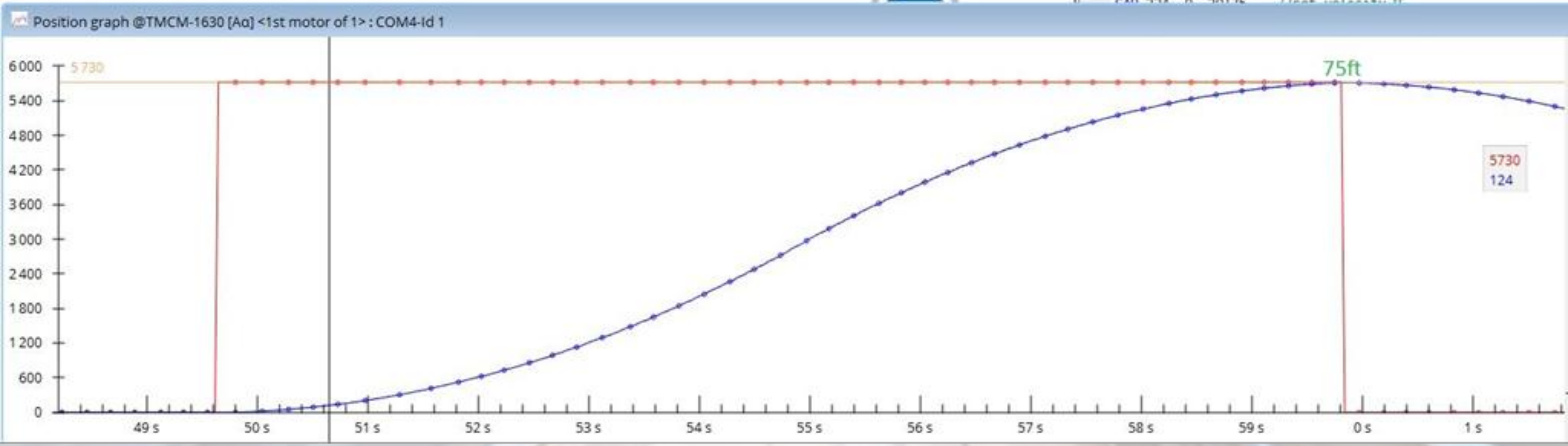
Figure 7.4 Positioning regulation



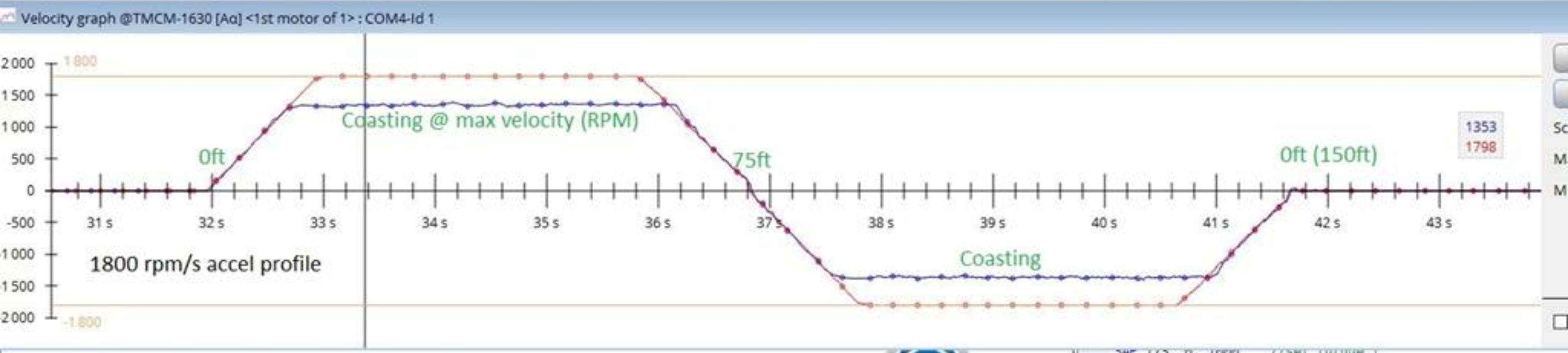
200rpm/s accel profile

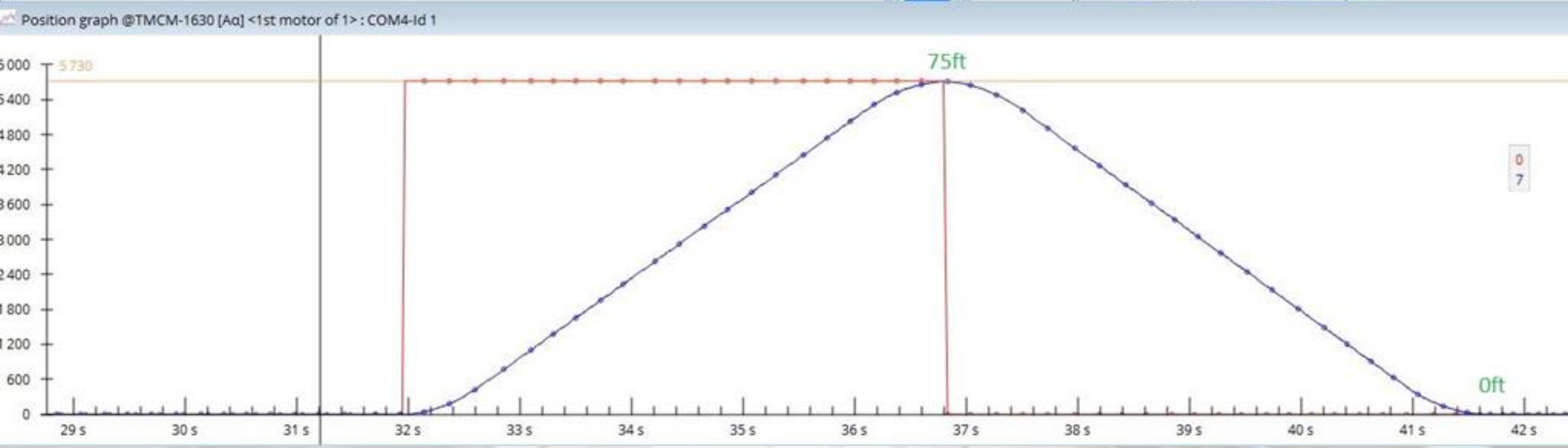
max rpm achievable under accel
and distance constraints

75ft



75ft


Velocity graph @TMCM-1630 [Aα] <1st motor of 1> : COM4-Id 1
2 000
1 500
1 000
500
0
-500
-1 000
-1 500
-2 000
1 800
-1 800
31 s
32 s
33 s
34 s
35 s
36 s
37 s
38 s
39 s
40 s
41 s
42 s
43 s
0ft
Coasting @ max velocity (RPM)
75ft
0ft (150ft)
Coasting
1800 rpm/s accel profile
1353
1798


Position graph @TMCM-1630 [Aα] <1st motor of 1> : COM4-Id 1
6 000
5 400
4 800
4 200
3 600
3 000
2 400
1 800
1 200
600
0
5 730
29 s
30 s
31 s
32 s
33 s
34 s
35 s
36 s
37 s
38 s
39 s
40 s
41 s
42 s
75ft
0ft
0
7

Velocity/Accel Profile Calculations

Hub Motor diameter (mm): 76.2 mm

Pod Weight: 148 kg

1 Revolution (ft): 0.785 ft

1675 RPM -> 21.92 (ft/s) or 6.68 (m/s)**

75ft / 0.785 (ft/rev) = 95.49 revolutions for 75 ft

75ft / 21.92 (ft/s) = 3.42s for 75 ft (velocity step function)

<u>Velocity Ramp Duration (seconds until max velocity is reached):</u>

3 sec -> 0.22g

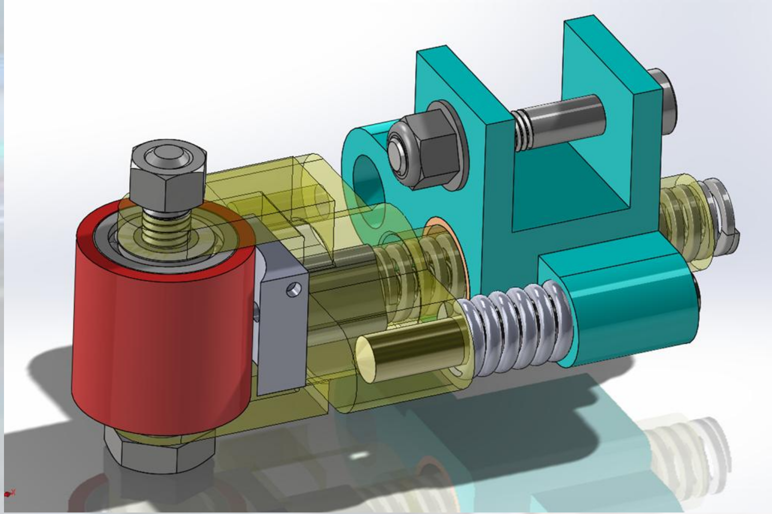
2 sec -> 0.34g

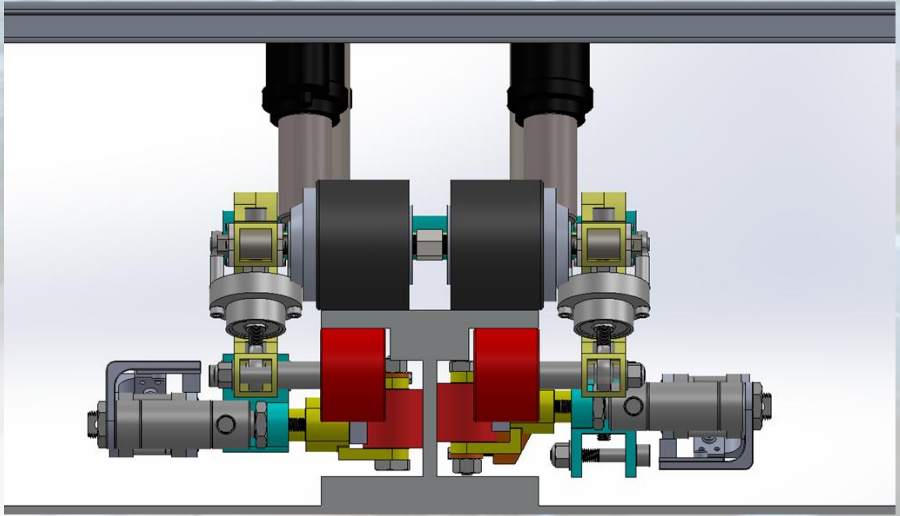
1 sec -> 0.68g

**Final RPM value is subject to change after final load test

BRAKING

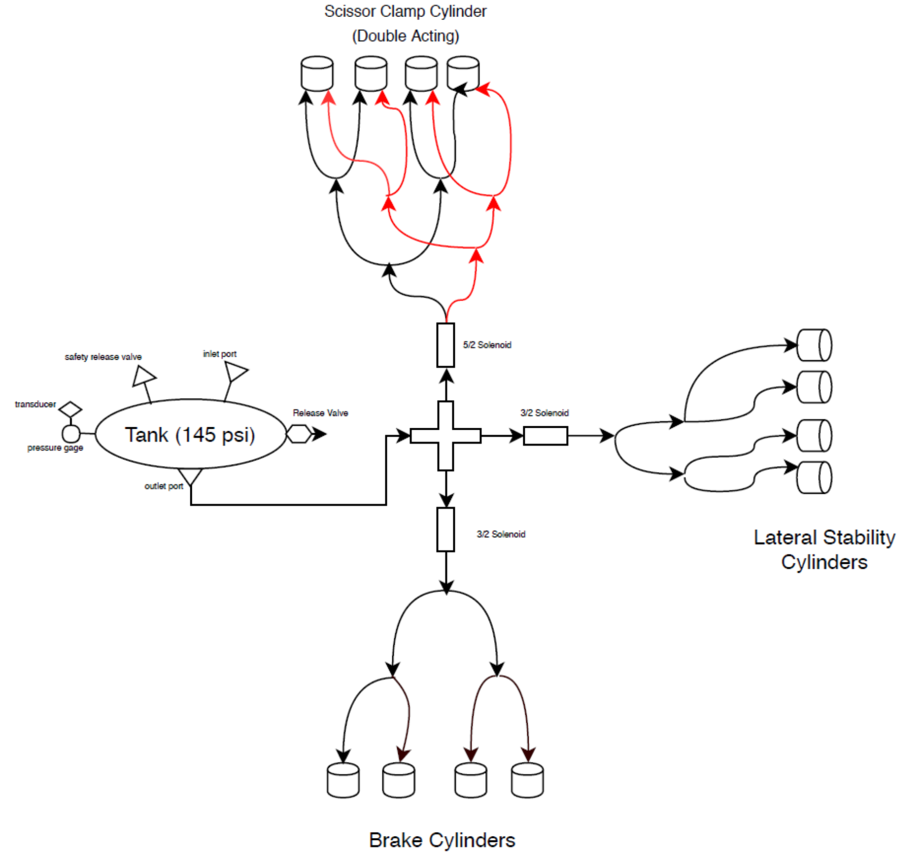
- Contact Braking - Emergency
  - Lateral stability wheels will be braked with a brake pad to lock them up and act as friction brakes against the web of the I-Beam (~96N of brake force anticipated)
  - Spring loaded brake pad is pulled back with an actuator when ready for run, upon pressure/electrical failure brakes engage





Pneumatic Diagram

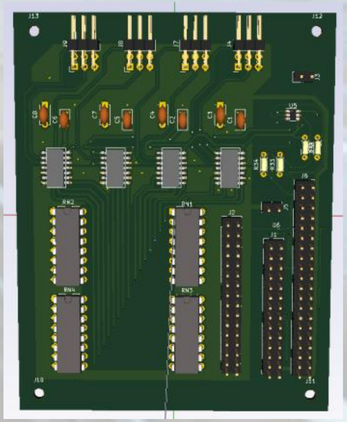
- McMaster Tank:
    - https://www.mcmaster.com/#9888K42
    - ASME Rated for 200 PSI
- 145 psi working pressure
- Safety Release Valve - 150 psi



MICROCONTROLLER

- **Raspberry Pi 3 Model B**
  - Processor: Quad Core 1.2GHz Broadcom BCM2837
  - Address Bus Width: 64 bit
  - Core Clock: 1.2 GHz
  - RAM: 1 GB LPDDR2 (@900MHz)
  - GPIO: 40
  - Busses: 1xSPI, 2xI2C
  - 10/100 Ethernet connectivity
  - ADC: 0 built-in, 16 w/ expansion board
- **Number of units on pod: 5**

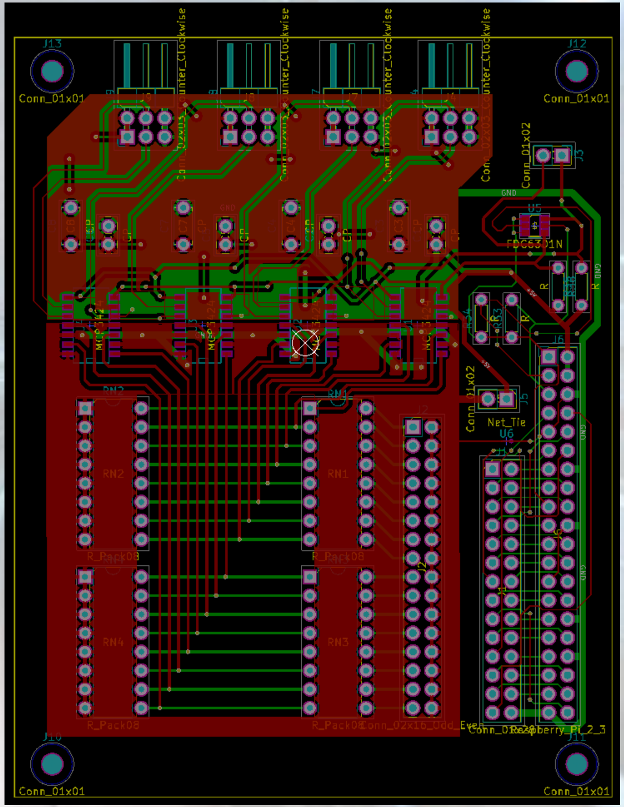
Raspberry Pi 3 Model B



16 Channel ADC Expansion Board

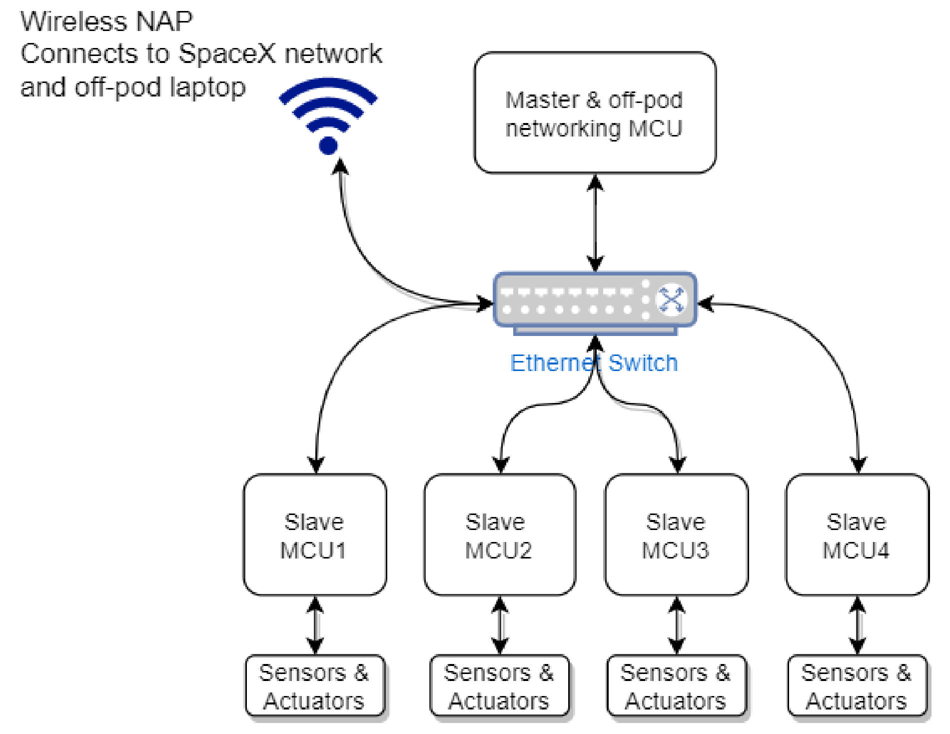
ADC Input/Output (I/O) Expansion Board

- Utilizes four MCP3424 ΔΣ Analog to Digital Converters (ADC)
  - Each chip features four analog to digital (AD) inputs, giving 16 total AD inputs per board
  - The chip will be ran in 12 bit mode at the 240 SPS listed in the datasheet
  - A resistor network will divide 5V sensor input to a maximum voltage below the 2.048V internal reference voltage of each ADC
- Also provides breakouts for Raspberry Pi general Inputs/outputs (GPIOs)

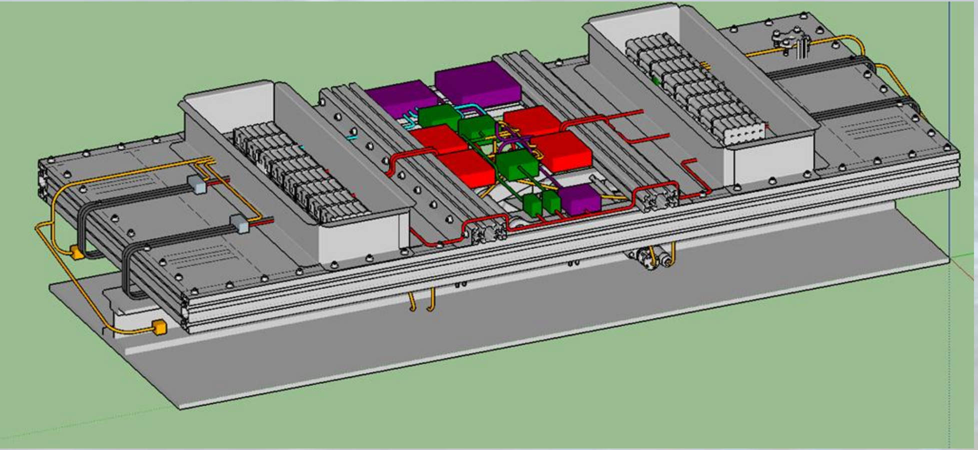


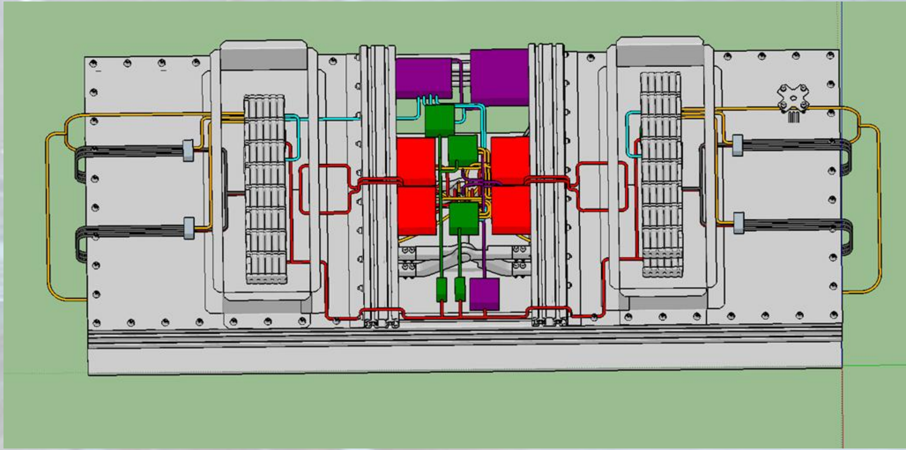
NETWORK ARCHITECTURE

- MCUs communicate with each other over a switched ethernet network
- UDP packets are sent to the concerned MCUs
- Exploring ZCM library as it allows to specify datagrams in a C-struct-like syntax
- Netgear GS108T Managed Switch
  - Supports Multicasting (if needed at a later stage) and IGMP snooping for debugging



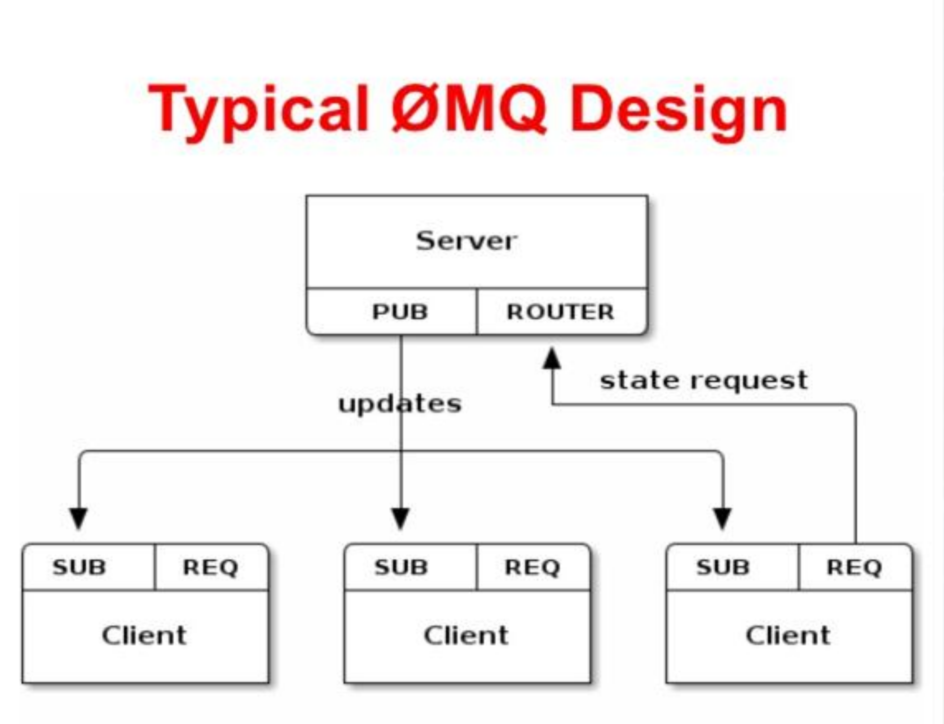
Wiring Harness





ZCM Library

- Intelligent socket library for messaging between devices.
- Allows for queuing at receiving side and sending side.
- Simple and efficient to implement for network design.
- Large open community
- High Speed - 30usec latency
- Based on ZeroMQ.
- Enforces in-order delivery
- Underlying technology - UDP broadcast

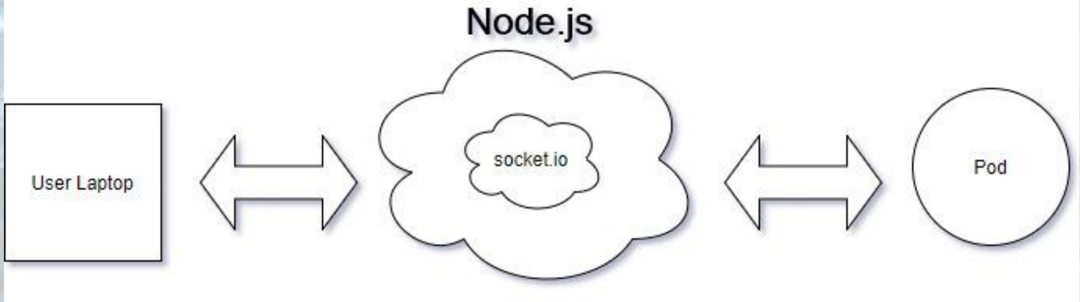


NETWORK PROTOCOL

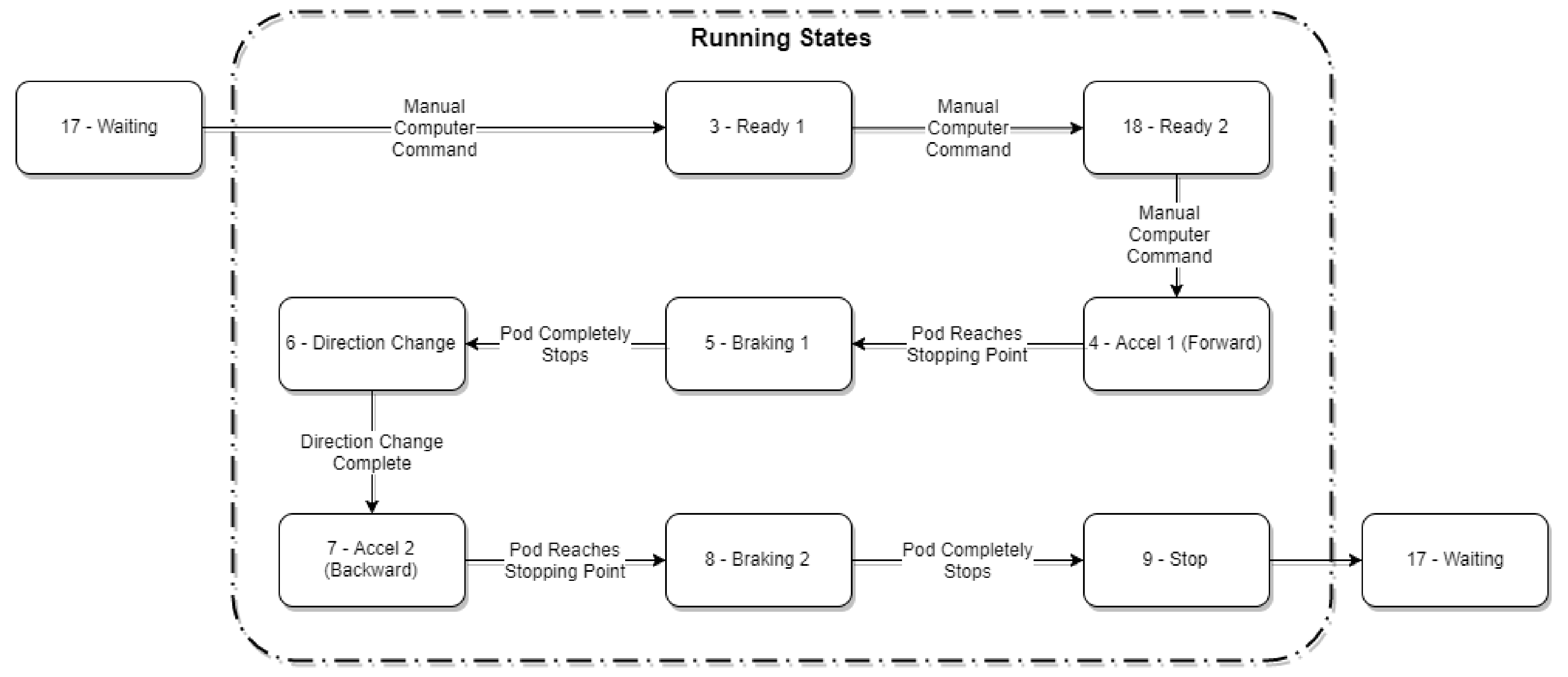
- Slave MCUs send flags and summary data to the Master MCU
- MCUs and the off-pod laptop communicate with each other at regular intervals. This is monitored by watchdog timers
    - If data packets aren't received within the minimal time requirements, then emergency states are initiated
- To makeup for the “non-reliability” of UDP, the master MCU periodically sends state-data to the slave MCUs. The slave MCUs send sensor data packets on a regular basis
- Data is sent to the pilot laptop wirelessly using the NAP

OFF-POD COMMUNICATION

- Established through the usage of Node.JS and Socket.io
- Laptop will communicate to pod and pod will give real-time updates back through Node.JS
- Socket.io will be established within Node.JS allowing bidirectional communication and real-time updates between the pod and the laptop



STATE MACHINE



Running States

17 - Waiting

Manual Computer Command

3 - Ready 1

Manual Computer Command

18 - Ready 2

Manual Computer Command

4 - Accel 1 (Forward)

Pod Reaches Stopping Point

5 - Braking 1

Pod Completely Stops

6 - Direction Change

Direction Change Complete

7 - Accel 2 (Backward)

Pod Reaches Stopping Point

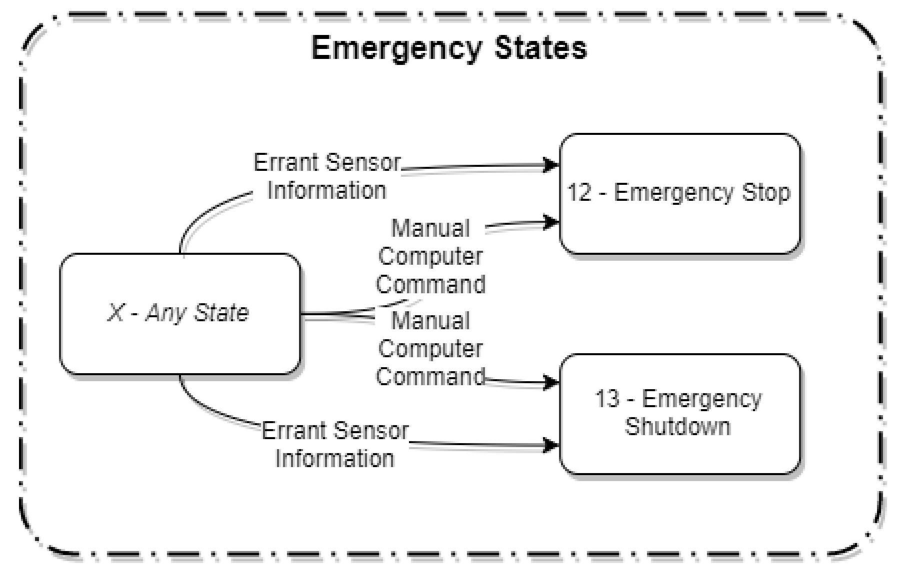
8 - Braking 2

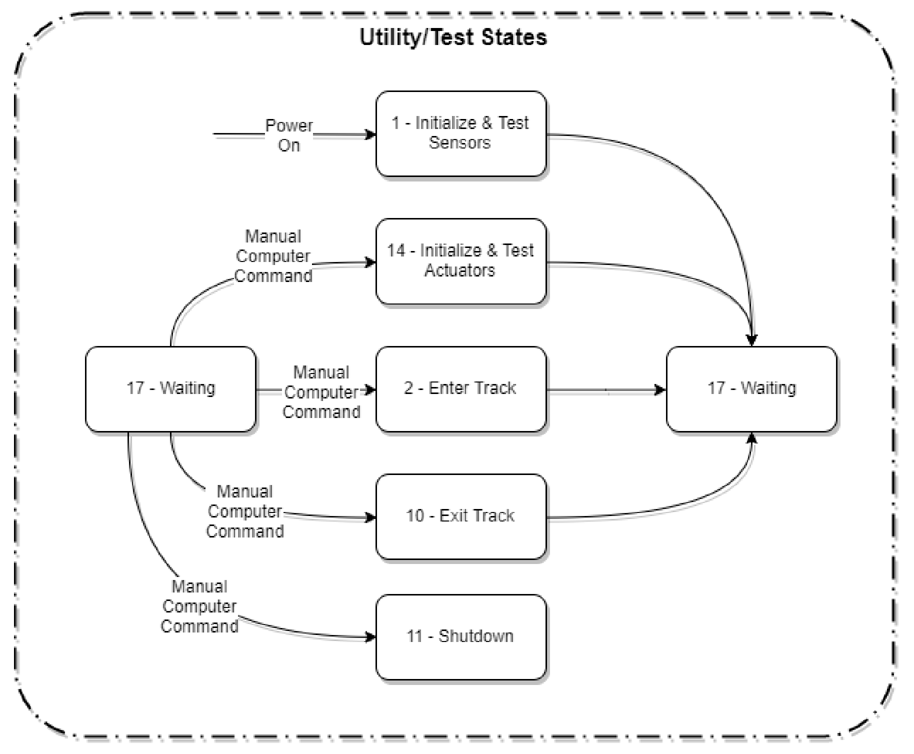
Pod Completely Stops

9 - Stop

17 - Waiting

STATE MACHINE

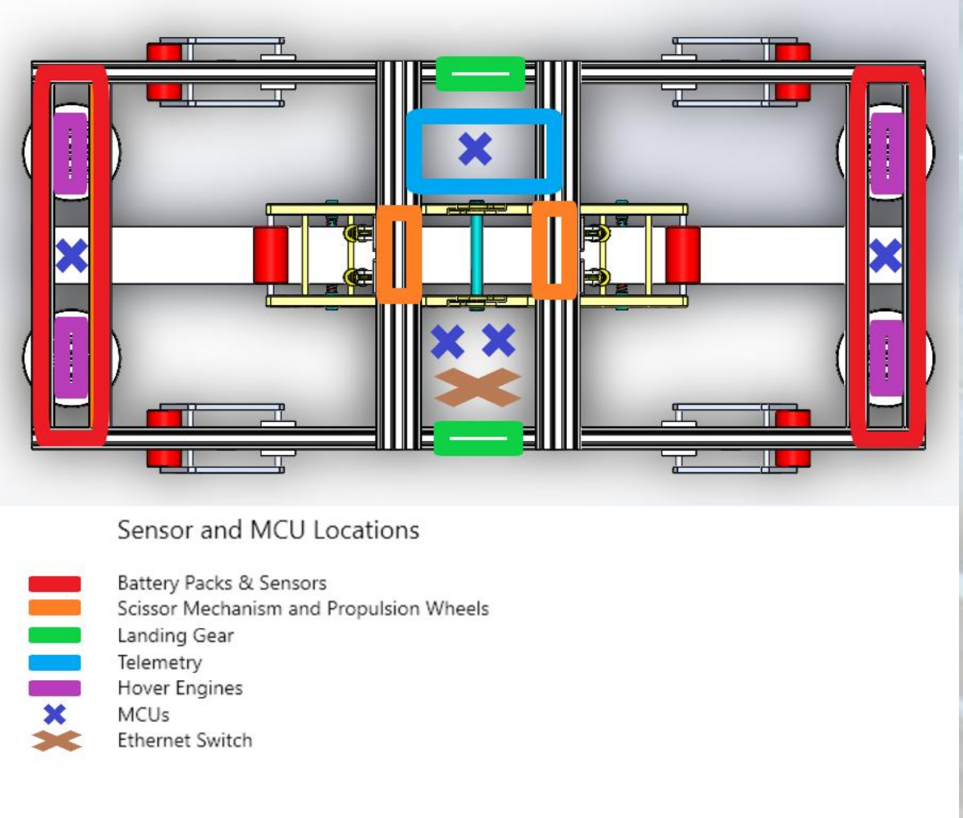




STATE MACHINE DETAILS

- Initialize & Test Sensors
  - MCUs boot up and read in sensor information and confirm expected values
- Initialize & Test Actuators
  - Test actuator movements and confirm expected sensor readings
- Enter Track & Exit Track
  - Pod enters a state that makes it easy and safe to manually enter or exit the track. (scissor mechanism open, brakes off, landing gear engaged, all motors stopped and electrically disconnected)
- Ready
  - Pod attaches to track (scissor mechanism clamps to track) and performs pre-flight tests (ensures sensor readings are normal) then hovers in place (levitation motors spin up and sensors read normal)
- Braking & Stop
  - Pod brakes as strongly as is safe until it comes to stop. (using in hub motors to slow wheels and brake pad if necessary) Engages landing gear and slowly ceases levitation.

SENSOR PACKS



SENSOR PACKS

- <u>Front Hover Engine & Battery</u>
  - Hover Engines
    - accelerometer (2)
    - IR Proximity (2)
    - force (2)
    - current (2)
    - voltage (2)
  - Battery
    - contact temp (1)
    - Pressure (1)
    - current (1)
    - voltage (1)

- <u>Scissor Mechanism</u>
  - accelerometer (2)
  - proximity (arms) (2)

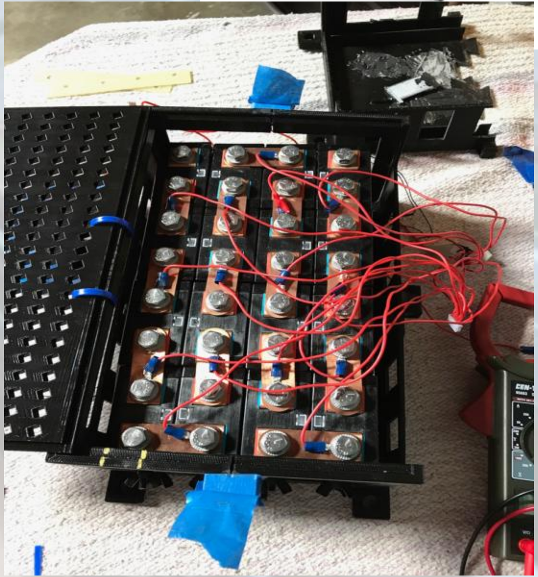
  - proximity (brake pads) (2)
  - pressure (4)
  - non-contact temp for engines (4)

- <u>Telemetry/Stability Arm/Battery</u>
  - Telemetry
    - proximity (2)
    - accelerometer (2)
  - Lateral Stability Arm
    - proximity (2)
    - pressure regulator (4)
  - Battery
    - contact temp (1)
    - current (1)
    - voltage (1)

- <u>Rear Hover Engine & Battery</u>
  - Hover Engines
    - accelerometer (2)
    - IR Proximity (2)
    - force (2)
    - current (2)
    - voltage (2)
  - Battery
    - contact temp (1)
    - pressure (1)
    - current (1)
    - voltage (1)

POWER SYSTEMS

- Separate batteries for Arx Pax and Control Systems
  - 2.96kWh Sony VTC5AT
  - 0.334kWh Venom 4S Flight Pack
- Power for Arx Pax engines:
  - Two Li-Ion Battery Box
    - Each pack has 10 cells in parallel and the pack is wired in series
  - Sony VTC5AT Lithium Ion Battery modules
  - 67.2 V delivered to hover engine
  - 9.6 min of hovering time
  - Estimated required time is 4.8 minutes (Safety factor of 2)
- Power for Controllers + Sensors + Propulsion:
  - Venom Fly 50C 4S 5000mAh 16.7V LiPo batteries (2P 2S)
  - Step down voltage to 12V (x1), 5V (x4) w/ Buck converters
- Battery safety
  - Temperature sensors (Heat fuse)
  - 3D printed PLA enclosure velcroed to the housing box
  - Short runtime minimizes the heating of the batteries.
  - Linear technology LT6802-2 Battery management IC



POWER MANAGEMENT

GOALS

- Provide power to the system reliably and efficiently
    - 3.6 kW/engine ⇒ 14.4kW total + 200W for auxiliary systems
- Ability to step-down the voltage and deliver high amount of current
- Implement fail-safe mechanisms in case of battery shorts and overvoltage.
- Redundant Systems - with separate power supplies for each hover engine. Independent front and rear controls for power loss safety

IMPLEMENTATION

- Single phase buck converters, 33V - 12V & four 33V- 5V
- The MOSFET gate drivers alternate the duty cycle for more efficiency
- The batteries are stored in a PLA printed box velcroed to the bigger box
- Short circuit switches, and current surge protection for the motors

THERMAL MANAGEMENT

❖ Engine Heating

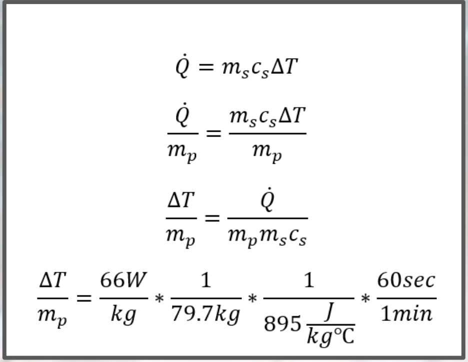
- ➢ Heat generated by a single engine is 14W/kg
- ➢ Since no vacuum environment forced convection during run should provide enough cooling

❖ Battery Packs

- ➢ Heat generated is very low when discharging
- ➢ Two fans in each infinity box dissipate heat via forced convection

❖ Sub-track Heating

- ➢ must be < 30^o C
- ➢ Estimated heating from Arx Pax Data sheet
- ➢ 10.1^o C per min which is ⅓ the allowable
- ➢ Maximum stationary hover time 2.5 min

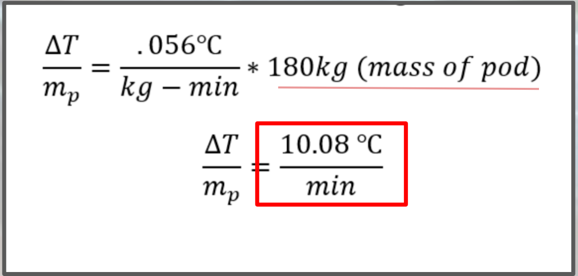


$$\dot{Q} = m_s c_s \Delta T$$

$$\frac{\dot{Q}}{m_p} = \frac{m_s c_s \Delta T}{m_p}$$

$$\frac{\Delta T}{m_p} = \frac{\dot{Q}}{m_p m_s c_s}$$

$$\frac{\Delta T}{m_p} = \frac{66W}{kg} * \frac{1}{79.7kg} * \frac{1}{895\frac{J}{kg°C}} * \frac{60sec}{1min}$$



$$\frac{\Delta T}{m_p} = \frac{.056°C}{kg-min} * 180kg\ (mass\ of\ pod)$$

$$\frac{\Delta T}{m_p} = \boxed{\frac{10.08\ °C}{min}}$$

SAFETY CONCERNS

- Energy Storage Systems
    - Lithium Ion Batteries
    - Spring/Suspension system when compressed
    - Fiberglass air tanks

SAFETY PRECAUTIONS

- High Priority Safety Considerations
  - All energy storage systems will only contain energy as rated by container with appropriate numerical safety factor (2) and further contained in safety capsules.
  - Low speed support and brake pads will be spring loaded for automatic actuation during power loss
  - All forces are applied in as symmetric and balanced a manner as possible
  - Various monitoring sensors for all subsystems (temperature, pressure, proximity, voltage, current)
  - Central emergency shut-off system
  - Multi-stage braking systems

SCALABILITY

Structures

- Frame
  - Readily available beam cross sections can be ordered quickly
  - Additional cross bracing will be required if lengthened
- Propulsion and Braking (Competition Specific Design)
  - These mechanisms are specific to the I-Beam monorail configuration and are not scalable
- Lateral Stability(Competition Specific Design)
  - These mechanisms are specific to the I-Beam monorail configuration and are not scalable

THANK YOU