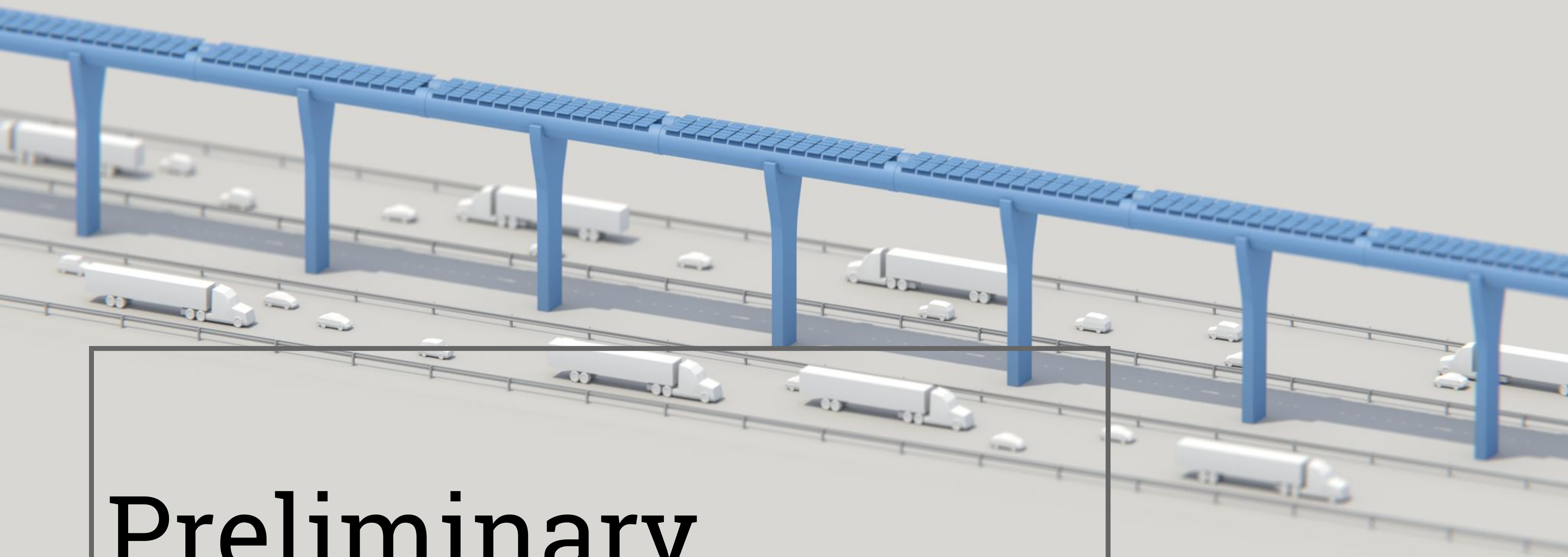

Preliminary Design Briefing

for SpaceX Hyperloop Competition submitted by rLoop, Inc.

The rLoop Team

The rLoop team is comprised of 91 members coming from over 14 countries, originally born on Reddit. The span of expertise ranges from Engineering to Law and Finances.

Team Leads

- Brent Lessard [*Project Manager*]
- Thomas Lambot [*Engineering Lead*]
- Daniel Hunter [*Assistant Project Manager]*
- Richard Behiel [*Public Relations*]
- Scott Leonard [*Aero/Structures Lead*]
- Andy Woerpel [*Electrical/Software Lead*]
- Amir Hasan Khan [*Simulation Lead*]
- Paul Kazmierski [*Battery Lead*]
- Joey Sharette [*Compressor Lead*]
- Kyle Zienin [*Engineering Systems Lead*]
- Ari Porad [*IT Lead*]
- Kalab Wood [*Rendering Lead*]
- Michael Cook [*Mechanical Lead*]
- Jonathan Ward [*HR Lead*]
- Kevin Burville [*Social Media Lead*]

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- Jim D'Souza
- Rick Simpson
- Mitch Rodriguez
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- Mark Duane
- Corey Stein
- Ian Whitney
- Gregory Georgianna
- Eoghan Kidney
- Brett Haines
- Ervin Romo
- AJ Peck
- Micah Gerald Taulbee
- Malachi Allison
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- Ilyas Vali
- Joseph Marc Stephen Ribbons
- Joseph Cutler
- Kane L S Smith
- Mark Sakowski
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- Philippe Carpentier-Savard
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- Darren Midkiff
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- Nathaniel Thompson
- Dominykas Doacenko
- Stephen Metzger
- Mitch Pascoe
- Erik Brizzee

The rPod Overview

For the purpose of the competition we've named our sub-scale pod "rPod" to differentiate from development on our full scale pod, "HPod".

rLoop intends to present rPod at the design weekend, as well as to build rPod for the competition weekend.

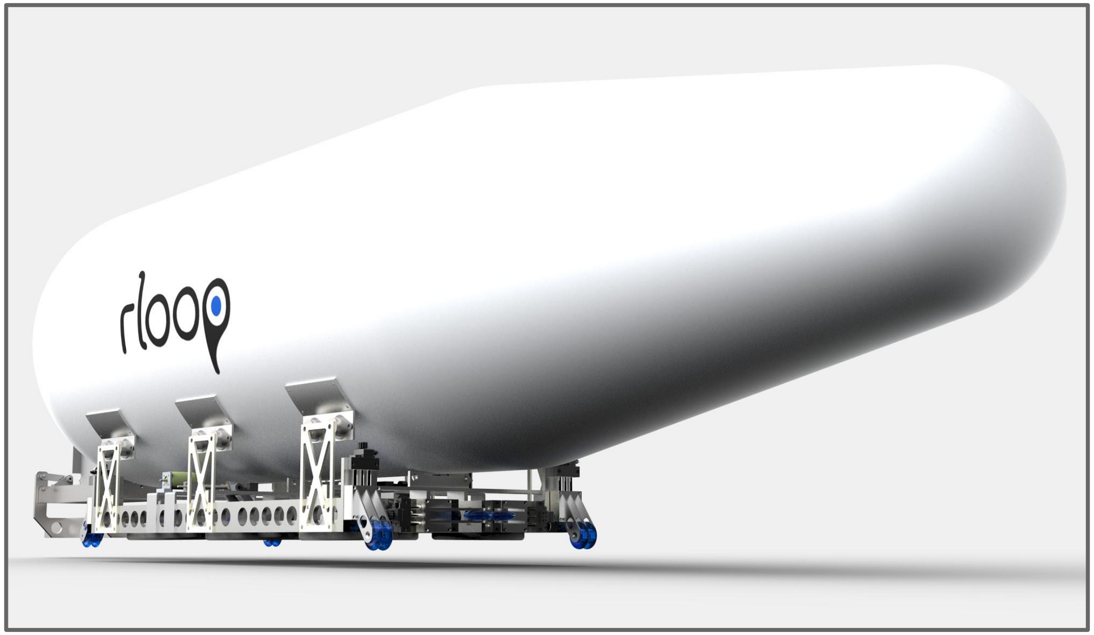
The rPod design philosophy is to have a simple yet efficient design to minimize R&D, primarily using previously-demonstrated technologies.

The dimensions would be a little over 3m long for a radius of around 1m and weight under 300 kg.

The primary rPod structure contains a pressure vessel of a semi-monocoque construction. It will host the non-vacuum rated components and the SpaceX "passenger". No life support would be implemented. A simple aeroshell (more aesthetic than aerodynamically useful for these conditions) would be made of a vacuum-compliant lightweight simple material.

The rPod would use 8 Arx Pax hover engines for levitation. The engines will be gimballed in order to be able to provide some thrust and braking. The main braking system will use magnetic eddy brakes. The alignment system takes advantage of the central I-beam to avoid lateral jerks.

All dimensions, systems, and numbers are our current best estimate with available information and are subject to changes.



Artist rendering of the rPod. The pressure vessel, mounted above the lower aluminum structure, is hidden inside the aerodynamic fairing. The wheels visible at the bottom serves as a backup in case of levitation system failure.

Estimated Pod Dimensions

The structure of the pod will be constructed in the proven method of high-altitude passenger aircraft, such as business jets, which operate in similar pressure and speed regimes. The structure will be built in a semi-monocoque design, with stringers and frames attached to a main pressure skin. This pressure vessel, manufactured out of 2024-T3 Aluminum, will be capped at both ends by dome-style pressure bulkheads.

The sizing of the pressure vessel was chosen to accommodate the SpaceX dummy as well as the larger components, such as the batteries. It was decided to make the majority of the primary structure consist of the pressure vessel in order to save weight and volume.

The pressure vessel will be mounted above an external support structure that houses the levitation, braking, and propulsion for the rPod. Aerodynamic fairings for the primary structure and levitation substructure will be manufactured from lightweight materials and mounted on the fore and aft sides of the pressure vessel, as well as around the substructure.

Overall Pod Dimensions	
Max Length	3.5 m
Max Height	1.14 m
Max Width	1 m
Pressure Vessel	
Constant Diameter	1 m
Constant Diameter Section Length	2 m
Frame Spacing	0.33 m
Stringer Spacing	45°
Spherical Pressure Bulkhead Domes Diameter	2 m
Spherical Pressure Bulkhead Domes Curvature Height	0.13 m
Pressure Vessel Bottom Relative to Track	0.14 m
Aerodynamic Fairings to Max Length	3.5 m

Estimated Pod Mass by Subsystem

C.1 - Command and Control Subsystem

This subsystem is comprised of the following components:

- C.1.1 Primary Communication Node
- C.1.2 Backup Communication Node
- C.1.3 Power Distribution Node
- C.1.4 Pod Status Node
- C.1.5 Pod Control Node
- C.1.6 Emergency Node
- C.1.7 Non-Realtime Network (Ethernet Switch)
- C.1.8 Realtime Network (CAN Bus)
- C.1.9 Network Access Port

A physical block diagram for the Command and Control Subsystem can be found in the Systems Architecture on slide 27.

C.1 - Command and Control Subsystem	Mass (kg)	Qty
C.1.0.1 - Node Microcontroller	0.02	6
C.1.0.2 - Node Computer	0.05	6
C.1.0.3 - Node Data Logger	0.00	6
C.1.0.4 - Node Power Distribution	1.00	6
C.1.3.6 - Power Measurement Sensors	0.23	1
C.1.3.7 - Power Temperature Sensors	0.23	1
C.1.4.6 - Temperature Sensors	0.23	1
C.1.4.7 - Attitude Sensors	0.23	1
C.1.4.8 - Pressure Sensors	0.23	1
C.1.4.9 - Position Sensor	2.27	1
C.1.5.6 - Hover Height Sensor	0.23	1
C.1.7 - Non-Realtime Network	2.27	1
C.1.8 - Realtime Network	2.27	1
C.1.9 - Network Access Port	2.99	1
C.1 - Command and Control Total	**17.56**	

Estimated Pod Mass by Subsystem

C.2 - Electrical Power Subsystem

This subsystem is comprised of the following components:

- C.2.1 Active Cooling System
- C.2.2 Batteries
- C.2.3 Power Supply
- C.2.4 Standard Outlet
- C.2.5 Umbilical Connector

A physical block diagram for the Electrical Power Subsystem can be found in the Systems Architecture on slide 28.

C.2 - Electrical Power Subsystem	Mass (kg)	Qty
C.2.1 - Active Cooling System	9.98	1
C.2.2 - Batteries	33.00	1
C.2.3 - Power Supply	9.07	1
C.2.4 - Standard Outlet	2.27	1
C.2.5 - Umbilical Connector	2.27	1
C.2 - Electrical Power Subsystem Total	**56.59**	

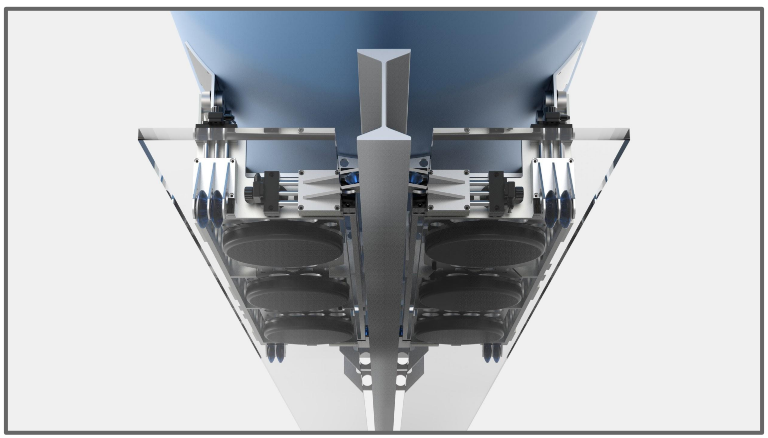
Estimated Pod Mass by Subsystem

C.3 - Propulsion Subsystem

This subsystem is comprised of the following components:

- ➢ C.3.1 Primary Braking
- ➢ C.3.2 Gimbal System
- ➢ C.3.3 Hover Controller
- ➢ C.3.4 Hover Engine
- ➢ C.3.5 Physical Fail Safe & Lateral Control
- ➢ C.3.6 Service Propulsion
- ➢ C.3.7 Braking Backup

A physical block diagram for the Propulsion Subsystem can be found in the Systems Architecture on slide 29.



Artist rendering from under the pod. Dimensions and design may not be representative of the final system

C.3 - Propulsion Subsystem	Mass (kg)	Qty
C.3.1 - Primary Braking	11.79	1
C.3.2 - Gimbal System	5.70	4
C.3.3 - Hover Controller	0.73	8
C.3.4 - Hover Engine	7.00	8
C.3.5 - Physical Fail Safe & Lateral Control	2.27	1
C.3.6 - Service Propulsion	16.58	1
C.3.7 - Braking Backup	21.00	1
C.3 - Propulsion System Total	**136.28**	

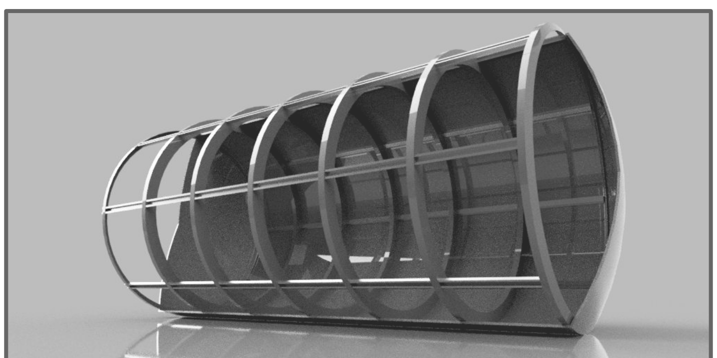
Estimated Pod Mass by Subsystem

C.4 - Structural Subsystem

This subsystem is comprised of the following components:

- ➢ C.4.1 Pusher Plate
- ➢ C.4.2 Access Panel
- ➢ C.4.3 Dummy Payload
- ➢ C.4.4 Primary Structure
- ➢ C.4.5 Hardpoints
- ➢ C.4.6 Gimbal Physical Interface
- ➢ C.4.7 SpaceX Data Recorder Physical Interface
- ➢ C.4.8 Pressure Bulkhead
- ➢ C.4.9 Pod Skin

A physical block diagram for the Structural Subsystem can be found in the Systems Architecture on slide 30.



Artist rendering of the pressure vessel showing the structure design

C.4 - Structural Subsystem	Mass (kg)	Qty
C.4.1 - Pusher Plate	0.25	1
C.4.2 - Access Panel	2.27	1
C.4.3 - Dummy Payload	15.88	1
C.4.4 - Primary Structure	12.19	1
C.4.5 - Hardpoints	0.45	4
C.4.6 - Gimbal Physical Interface	2.77	4
C.4.7 - SpaceX Data Recorder Physical Interface	0.91	1
C.4.8 - Pressure Bulkhead	4.49	2
C.4.9 - Pod Skin	13.49	1
C.4 - Structural Subsystem Total	**66.83**	

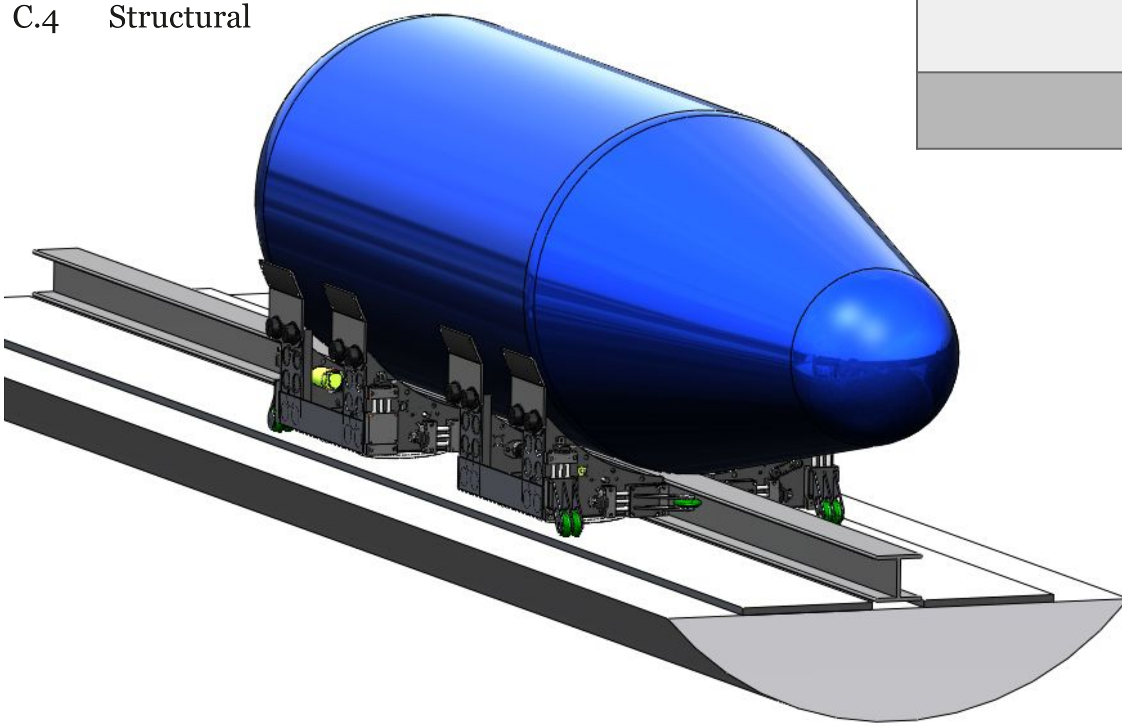
Estimated Total Pod Mass

C - rPod

The total rPod is comprised of the following subsystems:

- C.1 Command and Control
- C.2 Electrical Power
- C.3 Propulsion
- C.4 Structural

C - rPod	Mass (kg)
C.1 - Command and Control	17.56
C.2 - Electrical Power	56.59
C.3 - Propulsion	136.28
C.4 - Structural	66.83
C - rPod Total	**277.25**



Artist rendering of the pod. Dimensions and design may not be representative of the final system

Estimated Pod Power Consumption

C.1 - Command and Control Subsystem

This subsystem is comprised of the following components:

- ➢ C.1.1 Primary Communication Node
- ➢ C.1.2 Backup Communication Node
- ➢ C.1.3 Power Distribution Node
- ➢ C.1.4 Pod Status Node
- ➢ C.1.5 Pod Control Node
- ➢ C.1.6 Emergency Node
- ➢ C.1.7 Non-Realtime Network (Ethernet Switch)
- ➢ C.1.8 Realtime Network (CAN Bus)
- ➢ C.1.9 Network Access Port

A physical block diagram for the Command and Control Subsystem can be found in the Systems Architecture on slide 27.

C.1 - Command and Control Subsystem	Power (W)	Qty
C.1.0.1 - Node Microcontroller	1.00	6
C.1.0.2 - Node Computer	1.00	6
C.1.0.3 - Node Data Logger	0.00	6
C.1.0.4 - Node Power Distribution	0.00	6
C.1.3.6 - Power Measurement Sensors	0.25	1
C.1.3.7 - Power Temperature Sensors	0.25	1
C.1.4.6 - Temperature Sensors	0.25	1
C.1.4.7 - Attitude Sensors	0.25	1
C.1.4.8 - Pressure Sensors	0.25	1
C.1.4.9 - Position Sensor	0.25	1
C.1.5.6 - Hover Height Sensor	0.25	1
C.1.7 - Non-Realtime Network	10.00	1
C.1.8 - Realtime Network	0.00	1
C.1.9 - Network Access Port	20.00	1
C.1 - Command and Control Total	**43.75**	

Estimated Pod Power Consumption

C.2 - Electrical Power Subsystem

This subsystem is comprised of the following components:

- ➢ C.2.1 Active Cooling System
- ➢ C.2.2 Batteries
- ➢ C.2.3 Power Supply
- ➢ C.2.4 Standard Outlet
- ➢ C.2.5 Umbilical Connector

A physical block diagram for the Electrical Power Subsystem can be found in the Systems Architecture on slide 28.

C.2 - Electrical Power Subsystem	Power (W)	Qty
C.2.1 - Active Cooling System	43.20	1
C.2.2 - Batteries	0.00	1
C.2.3 - Power Supply	0.00	1
C.2.4 - Standard Outlet	0.00	1
C.2.5 - Umbilical Connector	0.00	1
C.2 - Electrical Power Subsystem Total	**43.20**	

Estimated Pod Power Consumption

C.3 - Propulsion Subsystem

This subsystem is comprised of the following components:

- C.3.1 Primary Braking
- C.3.2 Gimbal System
- C.3.3 Hover Controller
- C.3.4 Hover Engine
- C.3.5 Physical Fail Safe & Lateral Control
- C.3.6 Service Propulsion
- C.3.7 Braking Backup

A physical block diagram for the Propulsion Subsystem can be found in the Systems Architecture on slide 30.

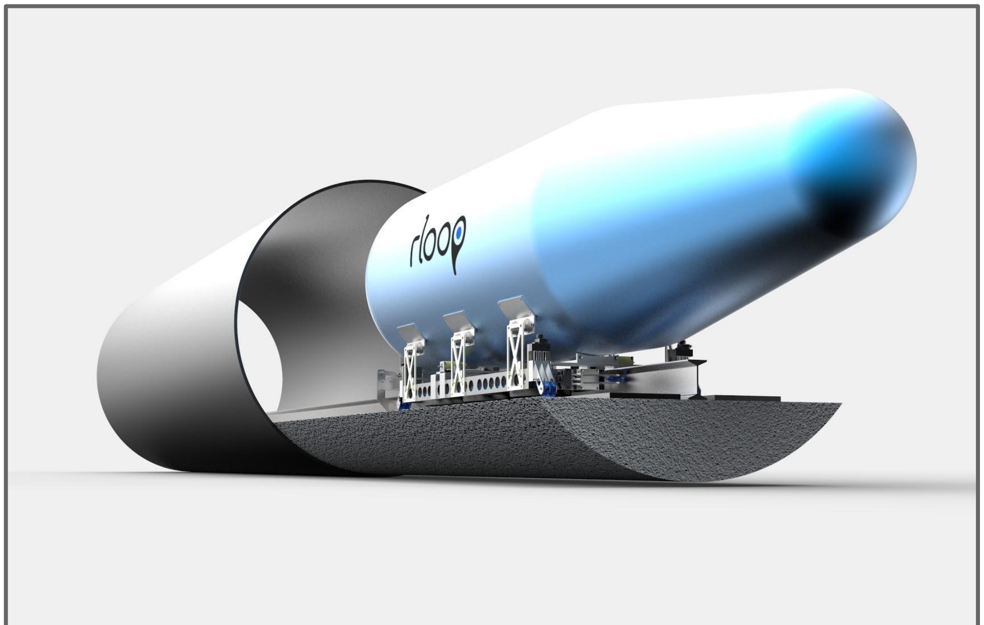
C.3 - Propulsion Subsystem	Power (W)	Qty
C.3.1 - Primary Braking	500.00	1
C.3.2 - Gimbal System	72.00	4
C.3.3 - Hover Controller	10.00	8
C.3.4 - Hover Engine	1 750.00	8
C.3.5 - Physical Fail Safe & Lateral Control	0.00	4
C.3.6 - Service Propulsion	500.00	1
C.3.7 - Braking Backup	0.00	1
C.3 - Propulsion System Total	**15 368.00**	

Estimated Total Pod Power Consumption

C - rPod

The total rPod is comprised of the following subsystems:

- C.1 Command and Control
- C.2 Electrical Power
- C.3 Propulsion
- C.4 Structural



Artist rendering of the pod. Dimensions and design may not be representative of the final system

C - rPod	Power (W)
C.1 - Command and Control	43.75
C.2 - Electrical Power	43.20
C.3 - Propulsion	15 368.00
C.4 - Structural	0.00
C - rPod Total	**15 454.95**

Pod Navigation System

In order to optimize rPod navigation, we've taken a dual pronged approach. Utilizing the reflective strips placed at even intervals by SpaceX in the Hyperloop Test-Track, rPod will be able to make accurate absolute position measurements by employing retroreflective photodetection sensors with a fast (<1ms) response time and a 4 meter detection range. By using redundant detectors spaced at a known distance, rPod is also able to calculate its velocity.

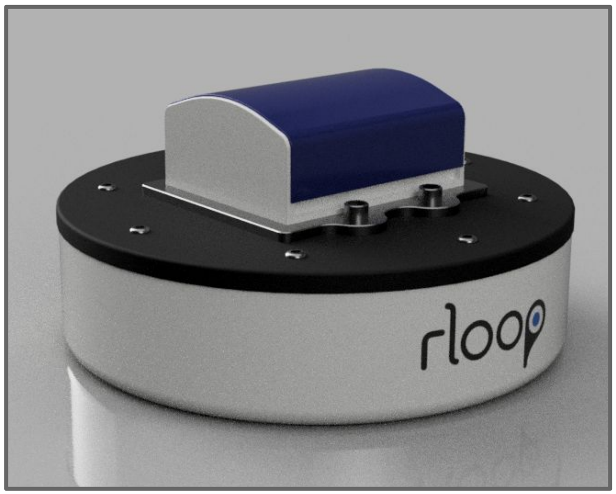
As an additional measurement method, rPod includes several inertial measurement units (IMUs) which will enable complete characterization of pod dynamics. In addition to measuring lateral and angular acceleration, rPod will improve positional accuracy by interpolating inertial measurement data between detection of reflective strips.

The rPod control system will act according to a predetermined flight profile which will command rPod during the various phases of flight (acceleration, coast, deceleration). The constant positional data provided by the rPod navigation system will enable the rPod control system to precisely traverse through each phase of flight. Additionally, the rPod control system will continuously monitor all subsystems for fault condition, and act accordingly, should such a situation occur.

Sensor	Measurement Function
3 Axis Accelerometers	Acceleration, Velocity
3 Axis Gyroscopes	Attitude
Retroreflective Photodetectors	Position, Velocity

Pod Levitation Mechanism

When the Test Track Tube Specifications were released on October 20th, 2015, our concerns regarding the flatness profile of the sub-track were confirmed and air bearings were deemed a suboptimal candidate for levitating rPod. A form of magnetic levitation was decided to be pursued, and rLoop opted to employ those made by Arx Pax.



Arx Pax HE3.0 Hover Engine	
Estimated Quantity	8
Rated Lift @ 5mm Hover Height	41 kg
Total Lift Capacity	328 kg
C - rPod Estimated Total Mass	277.25 kg

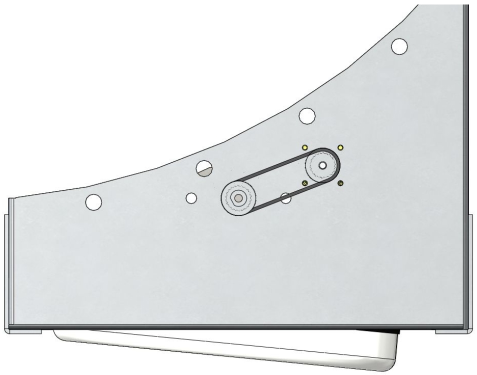
In order to better characterize performance of the Arx Pax HE3.0 Hover Engines, there is a need for more quantitative data, including the evolution of lift and power requirements versus speed, as well as the change in levitation height or power requirement at non-normal angle of incidence.

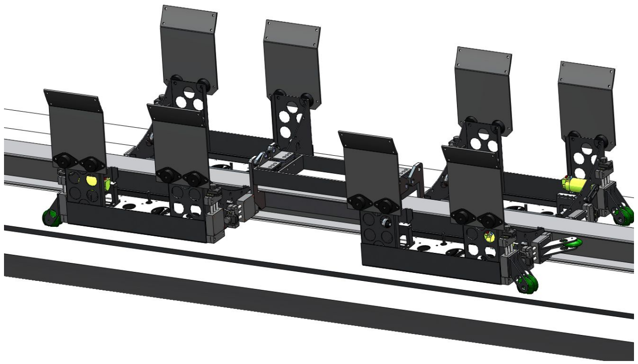
rLoop intends to secure several HE3.0 Hover Engines as soon as available from Arx Pax in order to conduct our own testing.

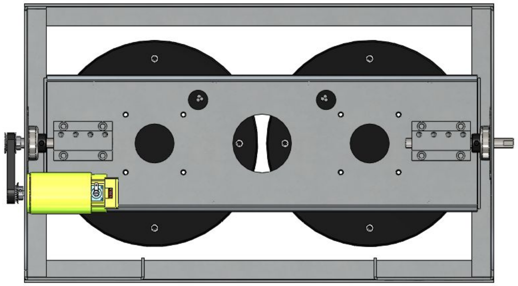
Pod Propulsion Mechanism

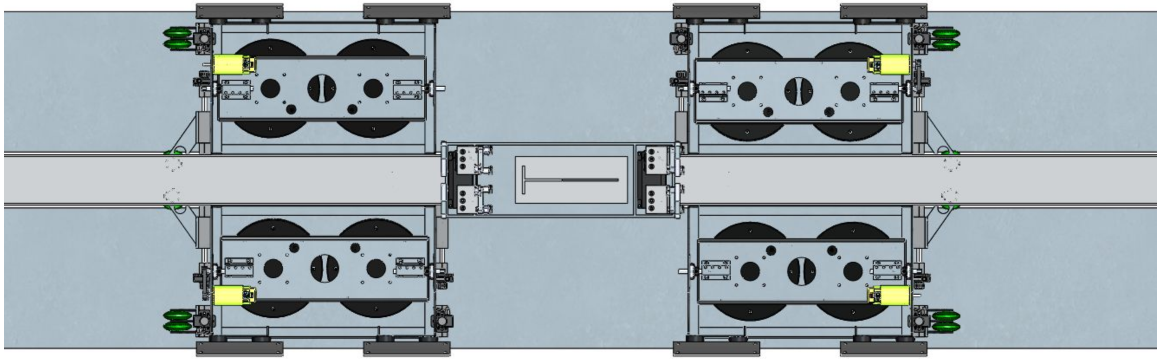
A custom gimbal has been designed to actuate the hover engines in order to convert lift vector into propulsion, directional control, and braking. The gimbal can be turned 5° in each direction in order to serve as both an additional propulsion and braking system.

In the case of complete hover engine failure, the possibility of an emergency propulsion system is being designed in the form of an electrical motor to drive a planetary linked to the emergency landing wheels.







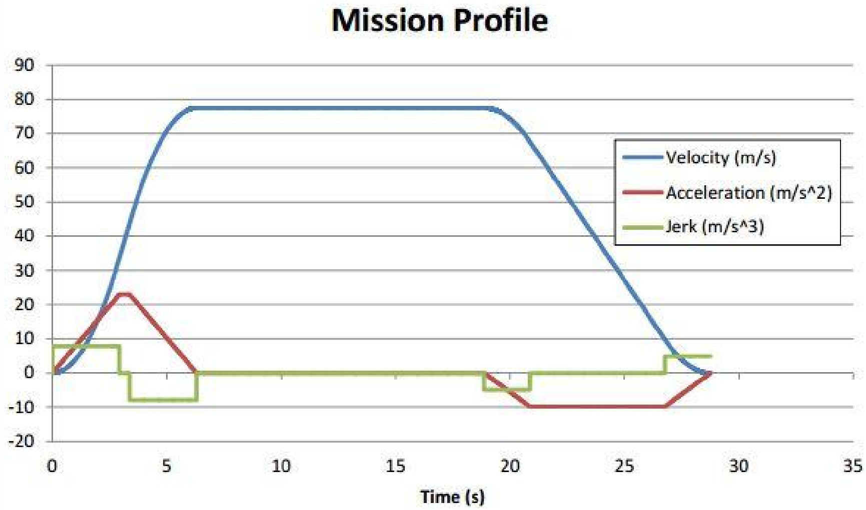


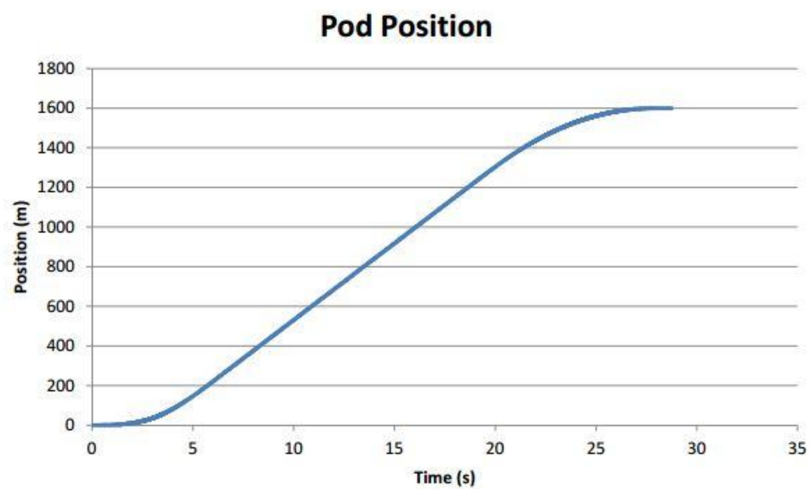
Artist rendering of the gimbal. Dimensions and design may not be representative of the final system

Mission profile

To ensure the comfort of the passenger (SpaceX Dummy/Data Recorder) during normal operation, our system architecture requirement REQ.1.3 has mandated a maximum acceleration of 1g and maximum jerk of 0.5g/s. These levels were chosen comparable to 0-60 mph times for best-in-class luxury sports cars as there is no authoritative source on acceleration comfort for a Hyperloop. Taking the maximum pusher displacement and REQ.1.3 into account, the maximum pod speed provided by the pusher would need be 60 m/s (134 mph). If the pusher is used to its maximum potential on rPod, a velocity of 77 m/s (172 mph) could be reached, providing a mission profile and pod position profile such as can be seen below.

The amount of thrust able to be produced by the hover engines is unknown at this point, but it is assumed they will contribute some small amount of force. This, in conjunction with the SpaceX pusher, will be the primary method of propulsion for rPod.



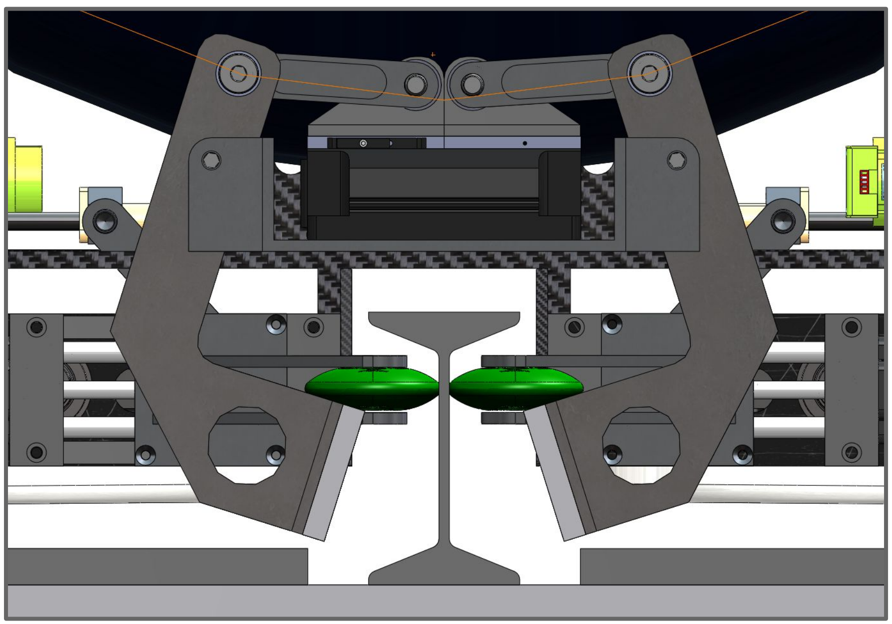


Pod Braking Mechanism

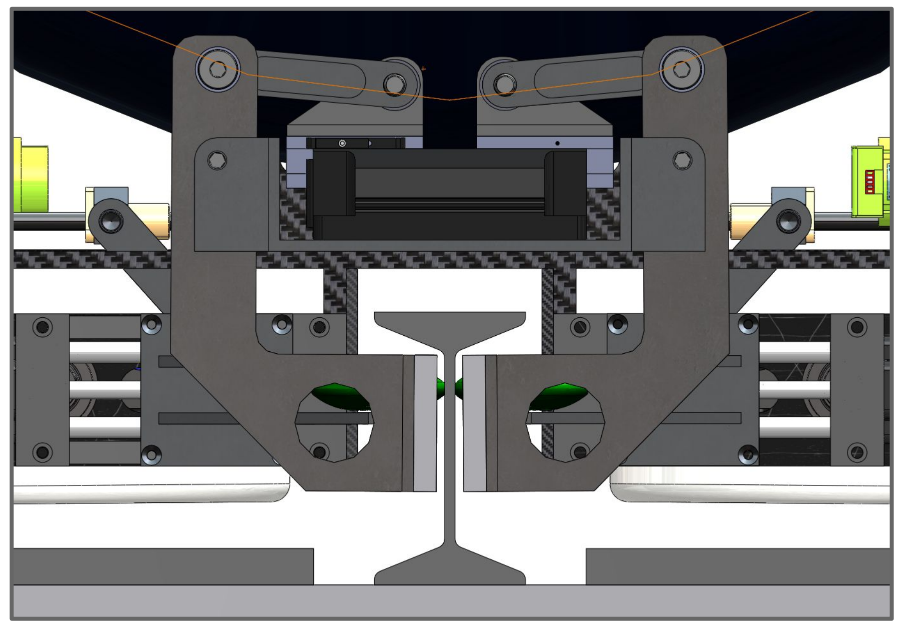
A passive eddy brake system is planned as the primary braking mechanism for rPod. Based on a two neodymium N52 magnet array sized 3"x2"x0 .5", a deceleration profile of approximately 1g is achieved, with the brake force achieving 600N at 100mph and gradually increasing to a peak of 2400N at approximately 6m/s.

The amount of brake force achievable by the HE3.0 Hover Engines is unknown at this point, but it is assumed they will contribute some small amount of force. This, in conjunction with the passive eddy brake system, will be the primary method of braking for rPod.

Brake disengaged



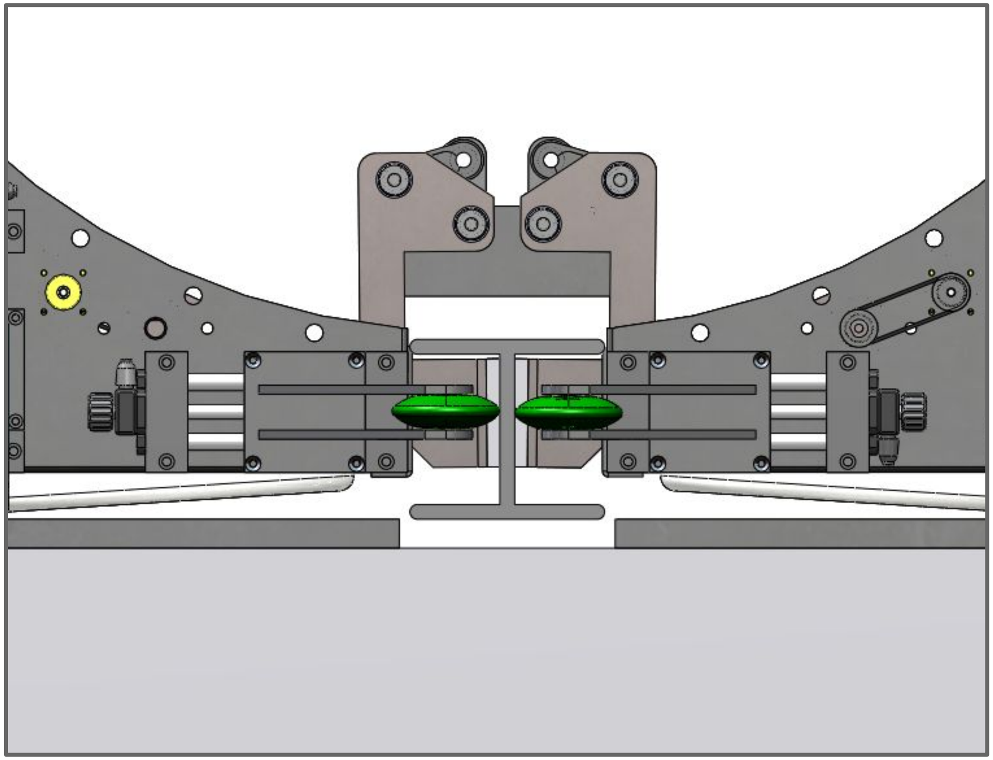
Brake engaged

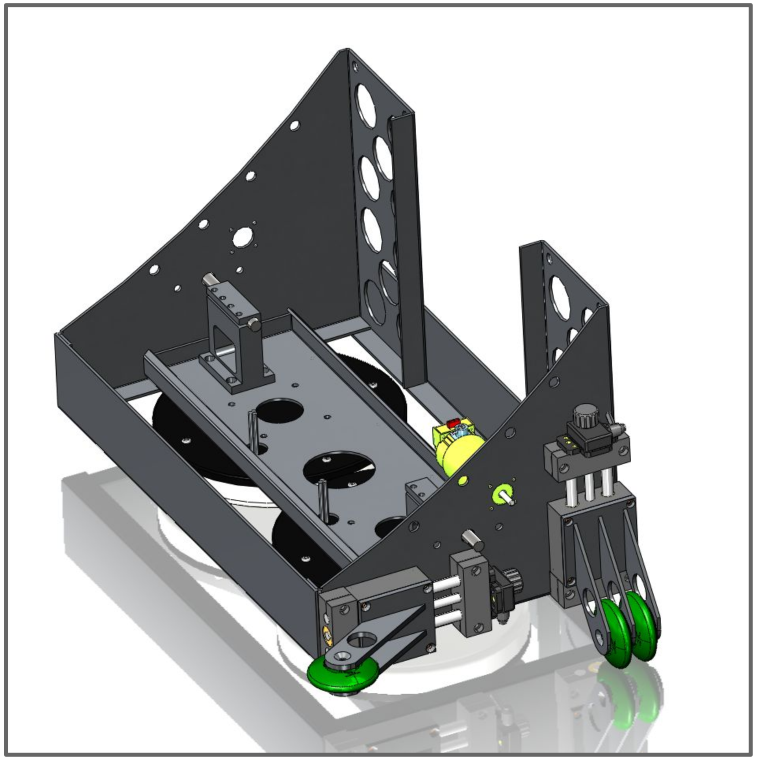


Artist rendering, the dimensions and clearance distances are not representative of the final system

Pod Stability Mechanism

The custom alignment support for the rPod incorporates several wheel pairs mounted horizontally that will utilize the center rail to assist with control and stability. Care has been given to ensure proper vertical positioning and horizontal engagement of the wheels with the center rail while the rPod is hovering, as well as to avoid the “KEEP OUT” zone. This is achieved by incorporating adjustment capability for the horizontal wheel pairs (one pair fore and one pair aft).





Artist rendering, the clearance distances from the subtrack shown on the illustrations are not representative of the final system.

Stored Energy on Pod

Batteries

In order to achieve the power requirements for rPod, a bank of 18650 battery cells will be used. Various battery types were investigated but the 18650 series had a near 100% higher energy density than all other types that were compared. Specifically, the LG Chem 18650 Hg2 cell was selected as our battery cell due to availability, price, and rated continuous power output. The stored electrical energy required by our pod will be in the area of 3.5kWh with an expected power draw of up to 14.2kW during peak power usage. This will be made possible by using 340 cells. The voltage, current, and temperature of the battery pack will be monitored to ensure safe operation of the battery pack.

Compressed air

The rPod pressure vessel is 1.68m^3 of air at a maximum pressure difference of 101,225 Pa (assuming an exterior pressure of 100 Pa). This assumes a 1 atm internal pressure upon sealing of the rPod for launch.

CO2 tank for the cooling system would contain around 1.5L of CO2 at 51 bar.

System	Energy Stored (kJ)
Batteries	12 600
Pod pressure vessel	1 178
Cooling Co2 vessel	0.5
Total	**~ 13 778.5**

Diagram of the battery bank cooling system

Cooling

To maintain ideal operating temperatures for the battery bank during the anticipated rPod test-track travel time, a custom cooling system has been designed using liquid CO2. A preliminary schematic of the design can be seen below. Note that in the current configuration the CO2 (no more than 4 L) is vented in the tube.

Eventually the cooling system will be expanded to extract the heat from electronics and hover engines (if required). More analysis and testing are required before being able to commit to a final design.

An effort will be made to come up with a design not venting CO2 into the tube in the future developments.

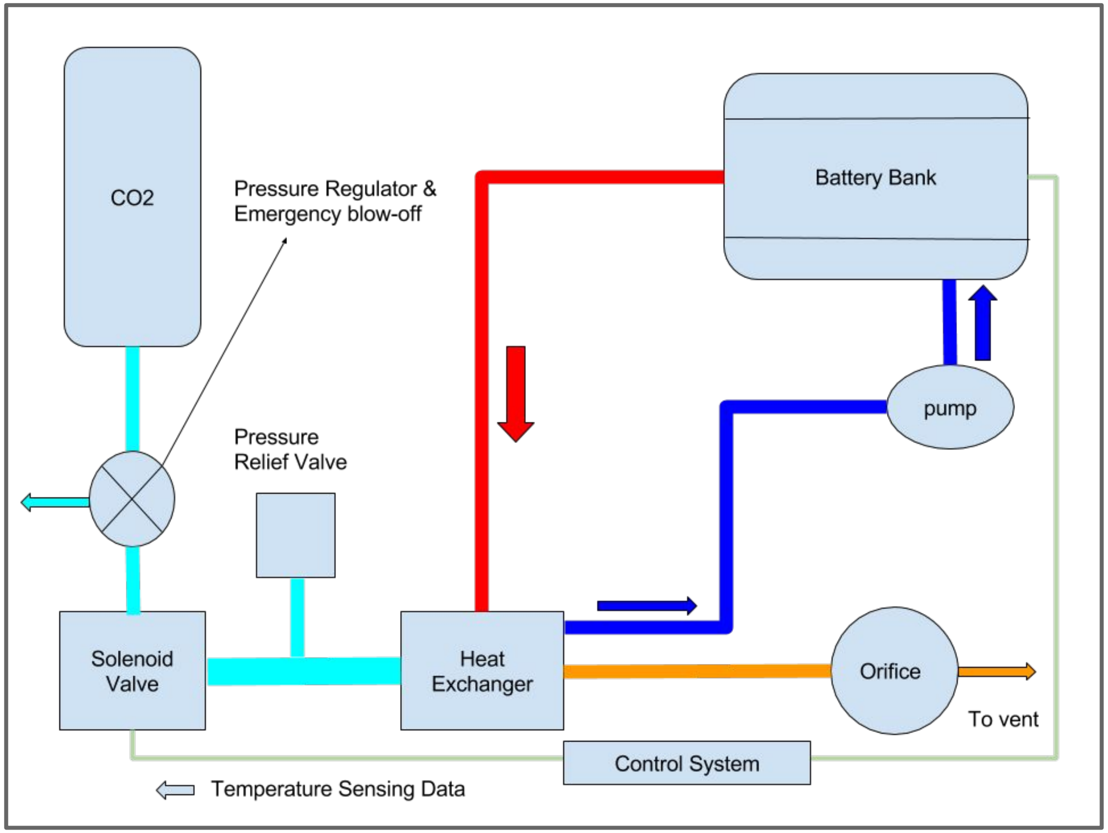


Diagram of the battery bank cooling system

Pod Safety Features

Structural Loads standards

The rPod structure will be evaluated to conservative loads as defined by [14 CFR Part 25 Airworthiness Standards for Transport Category Airplanes](). Summaries of particular CFR's of note:

- 25.303: Factor of Safety minimum of 1.5.
- 25.365(d): 1.67 pressurization factor for "aircraft above 45,000 feet", total analyzed capable pressure load of 257,000 Pa.
- 25.561(b)(3): Inertial forces, which are conservative due to the constrained nature of the rPod.

Stress analysis will be conducted using industry-standard finite element programs, as well as classical hand calculations to determine ultimate loadings and margins of safety.

Emergency Brakes

In the event of catastrophic power failure, the eddy brakes will be constructed with a normally closed system such that they will be released and engage the central rail when not energized.

Emergency Wheels

In the event of hover engine failure, the gimbal system for rPod has a set of emergency wheels set below the maximum 5° tilt of the HE3.0 engine actuation to allow the pod to land safely. An emergency propulsion system is being designed in the form of an electrical motor to drive a planetary linked to the emergency landing wheels to allow rPod to reach the egress of the Test Track.

Risk analysis

A comprehensive failure mode and risk analysis has been developed with detection method, prevention, and mitigation. This document is too long to include in the preliminary review, but is available on request.

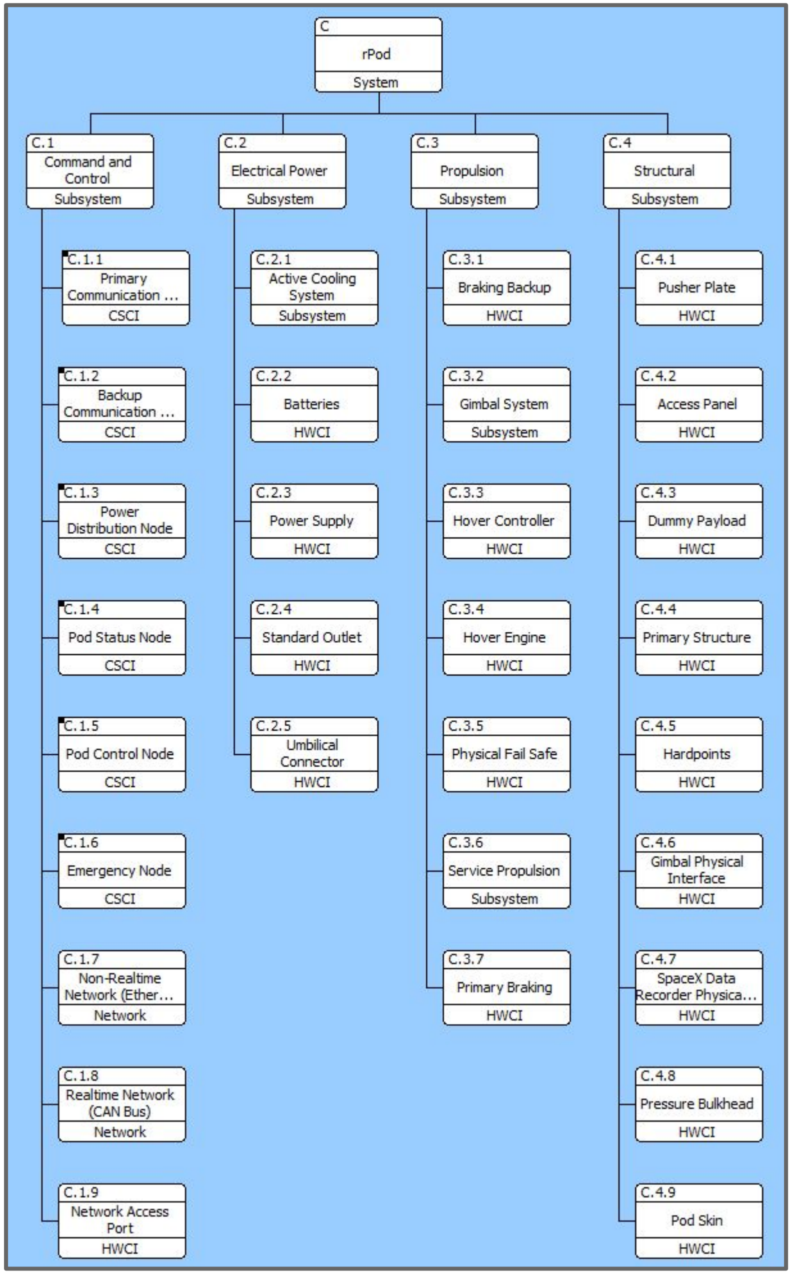
System Architecture

A comprehensive Systems Architecture was drafted for the rPod, the physical hierarchy for which can be seen to the right. To take a disciplined approach to our overall system design, a detailed Requirements Traceability Matrix has been created as well, based on the following Mission Needs Statement:

> *The rPod needs to perform the mission of safe, cost-effective, and efficient high speed transit over the length of the Hyperloop test track while providing a "comfortable" cabin for a self-contained flight data recorder and passenger dummy, in order to win the SpaceX competition.*

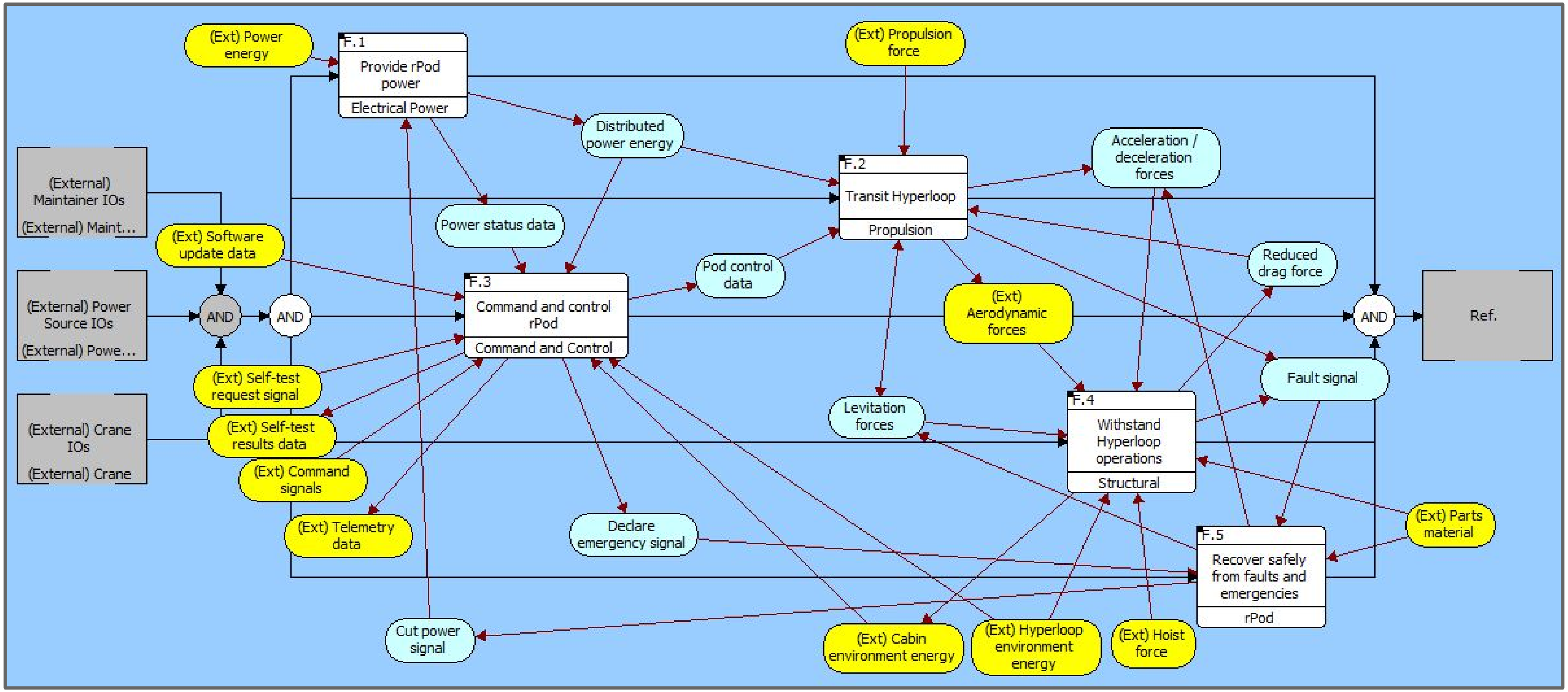
<u>Mission Objectives:</u>

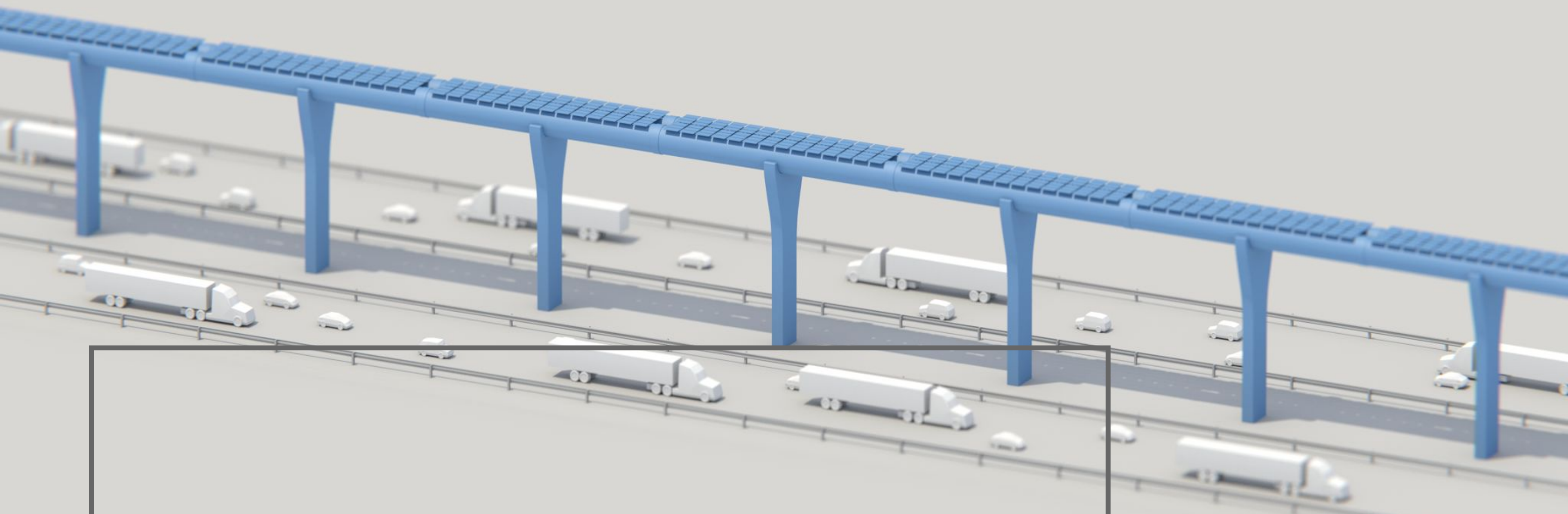
- ➢ To transit at high speeds over the length of the Hyperloop test track.
- ➢ To provide a "comfortable" cabin for the self-contained flight data recorder.
- ➢ To be compatible with the functional capabilities of the Hyperloop.
- ➢ To function within the low-pressure environment of the Hyperloop.
- ➢ To provide a safe design for the competition.
- ➢ To provide an energy efficient means of transportation.
- ➢ To ensure high system maintainability during competition operations.
- ➢ To minimize system cost.
- ➢ To win the SpaceX competition.



System Architecture

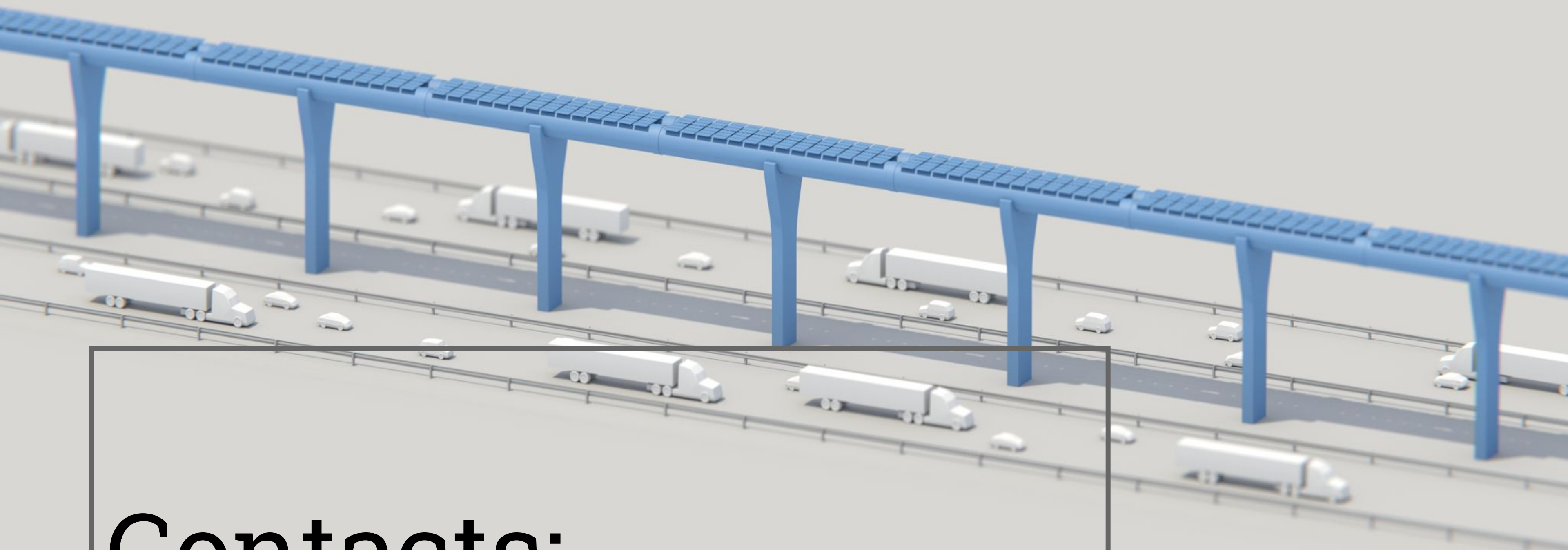
The top-level functions of the rPod are mapped to their associated subsystem and displayed within the Functional Flow Block Diagram presented below. Each function is further decomposed into lower level block diagrams to provide high-level definition of system functionality to scope detailed engineering design.





The rLoop Team

is on track to complete a detailed design for the rPod system on schedule for the Design Weekend in January at Texas A&M. Plans are in place to design, test, build, and field a competitive rPod system to race on the test track next summer. With the rLoop Team’s vast array of resources from all over the world, we are confident that we will win the SpaceX competition.



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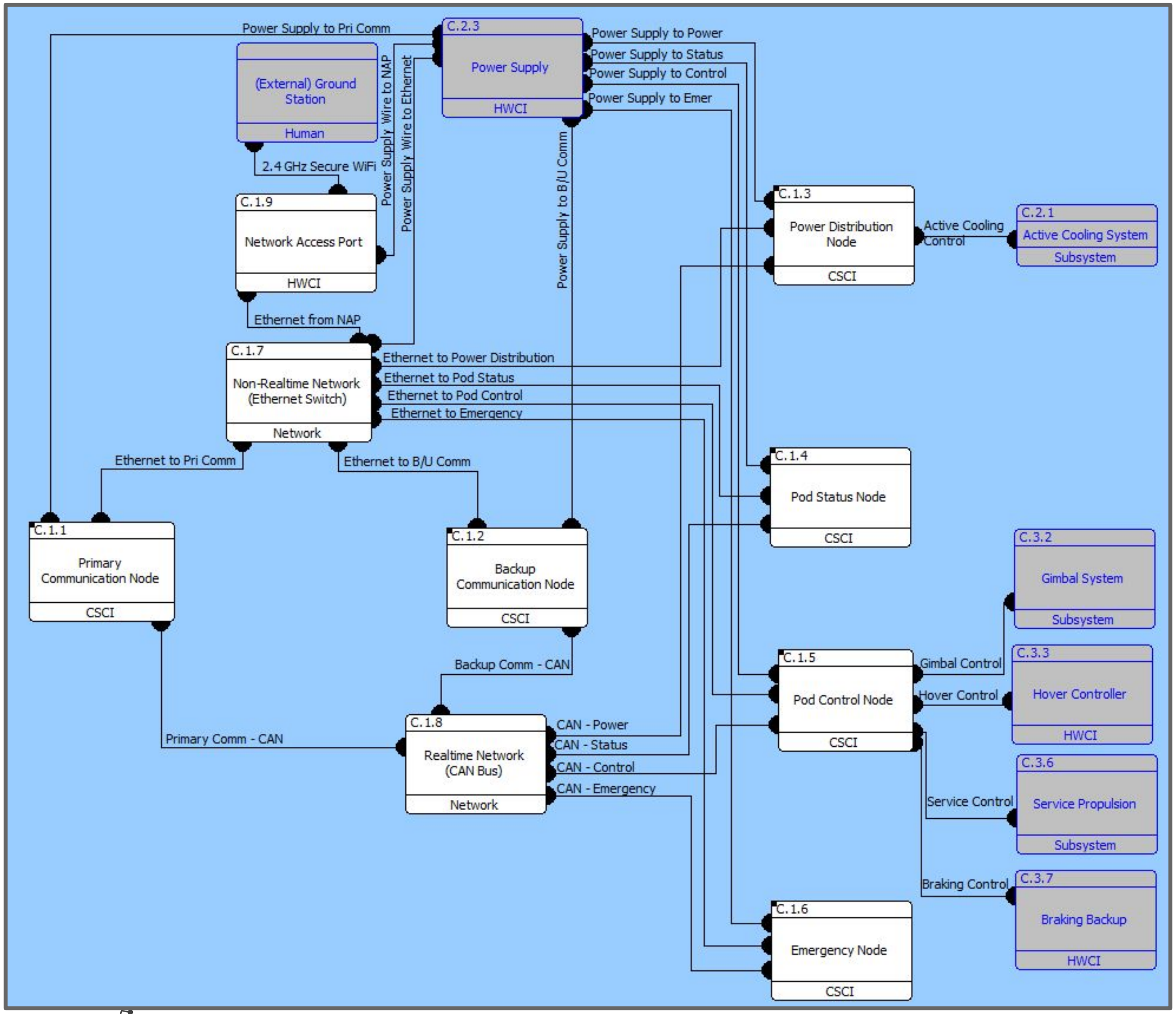
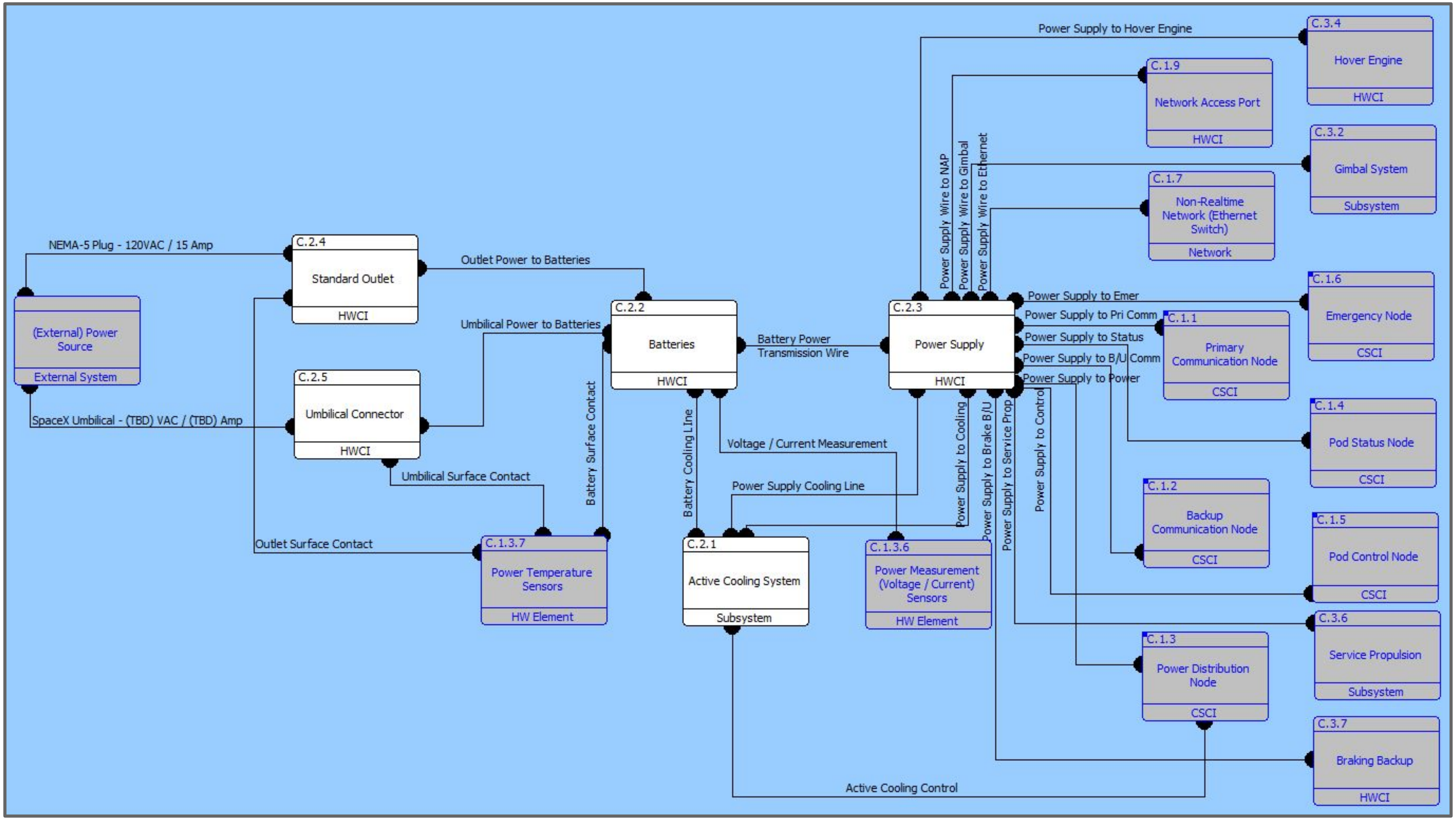
System Architecture

C.1 - Command and Control Physical Block Diagram



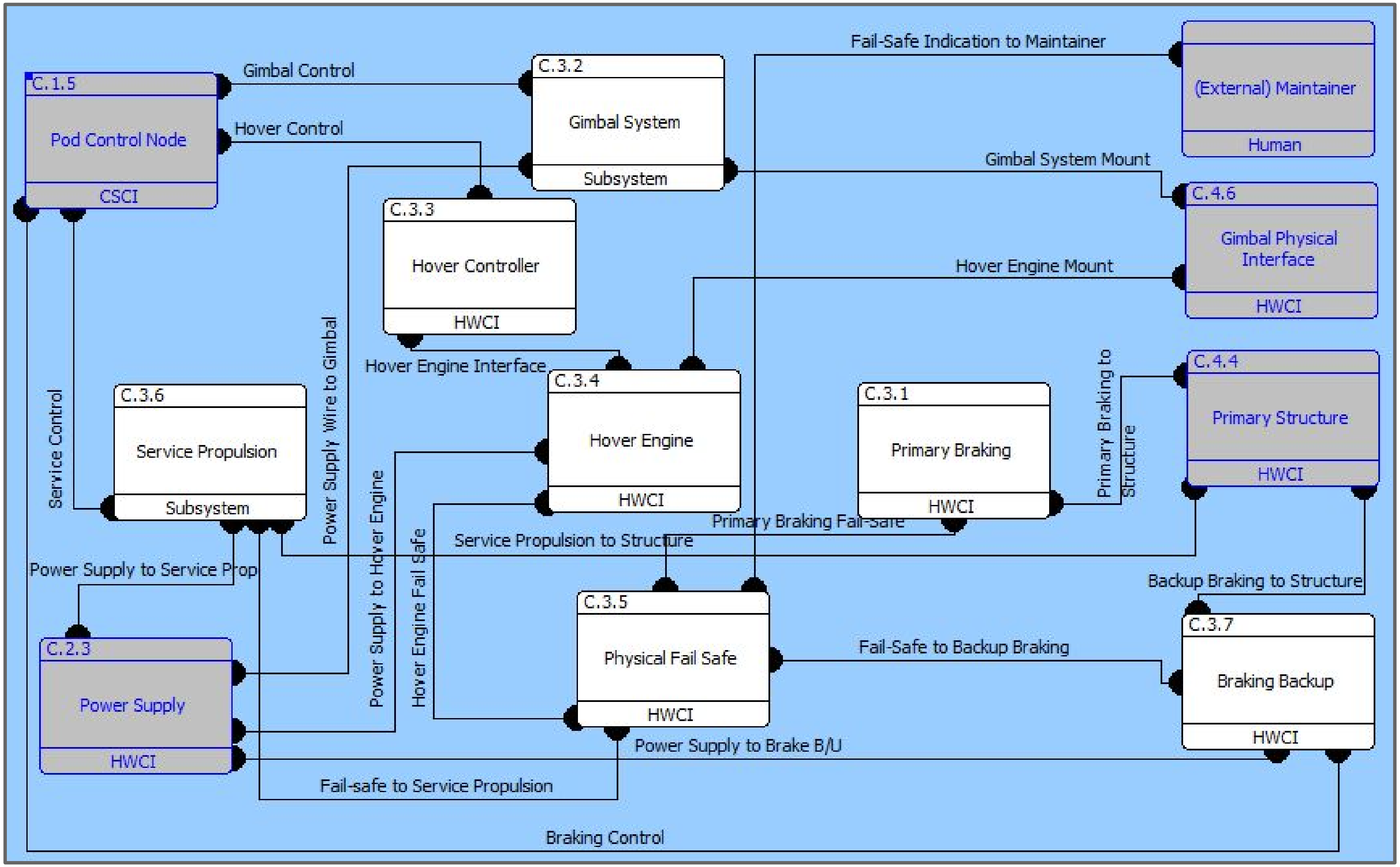
System Architecture

C.2 -Electrical Power Physical Block Diagram



System Architecture

C.3 - Propulsion Physical Block Diagram



System Architecture

C.4 - Structural Physical Block Diagram