LunaSim

Critical Design Review

University of Colorado Boulder
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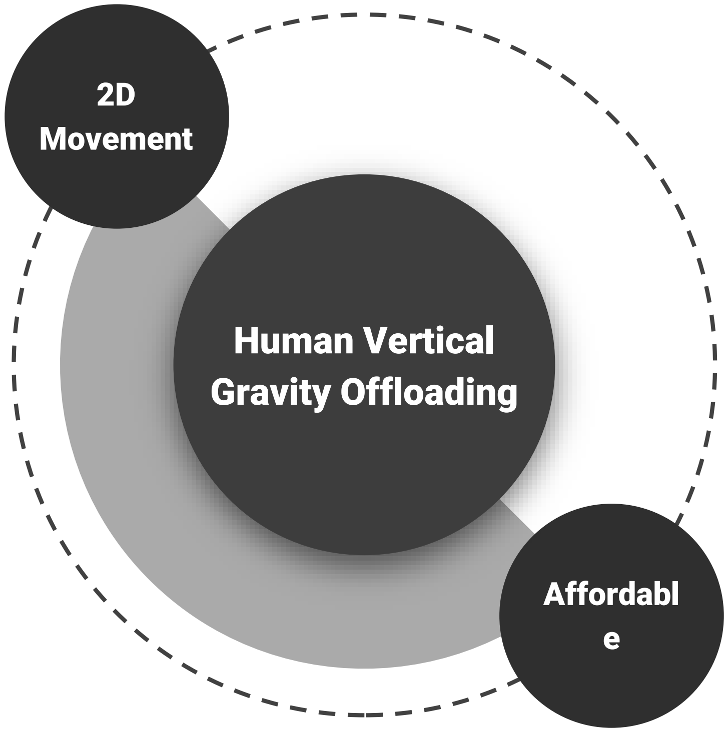
Academic Advisor: Dr. Anderson
Sponsor: EchoStar

Overview

- Project Purpose & Objectives
- Design Solution
- Critical Project Elements & Risks
- Design Requirements & Satisfaction
- Verification & Validation
- Project Planning

Project Purpose & Objectives

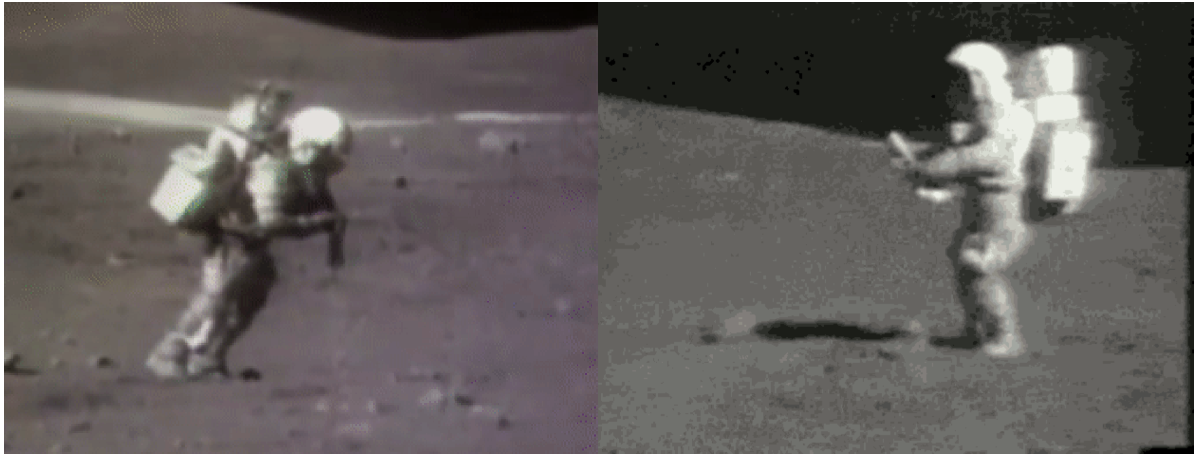
Project Definition & Objectives



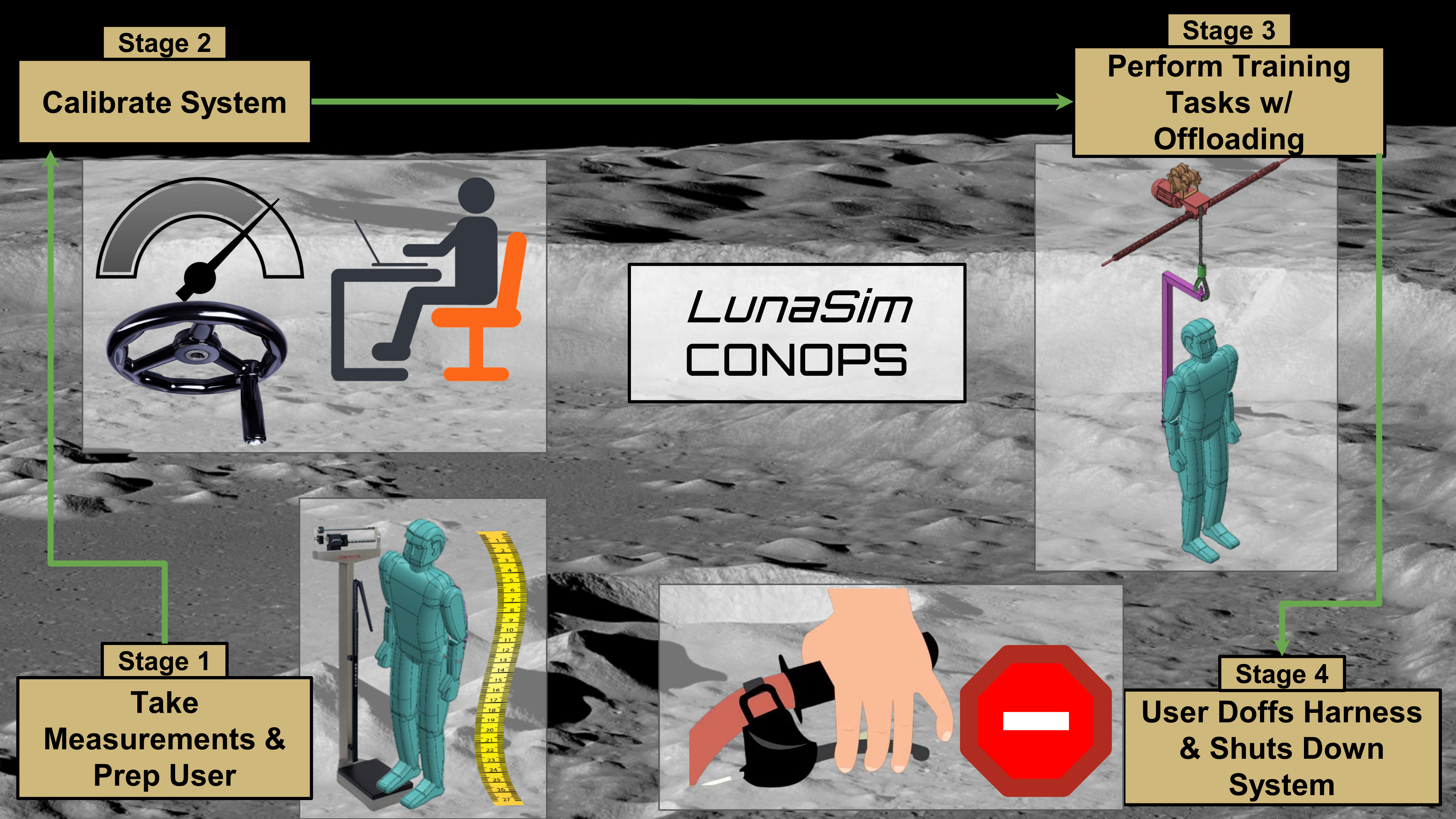
Background

- Artemis 1 has launched, meaning humanity's return to the moon is fast approaching
- New generation of untrained astronauts
- Gravity in particular is difficult to train for, and can cause serious safety concerns

ARTEMIS



Apollo astronauts experienced difficulties maneuvering in lunar gravity.


Stage 2
Calibrate System
Stage 3
Perform Training Tasks w/ Offloading
LunaSim
CONOPS
Stage 1
Take Measurements & Prep User
Stage 4
User Doffs Harness & Shuts Down System

Design Solution

Scope Adjustments

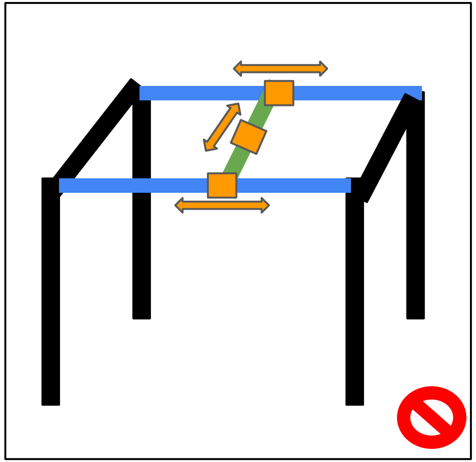
Reasoning

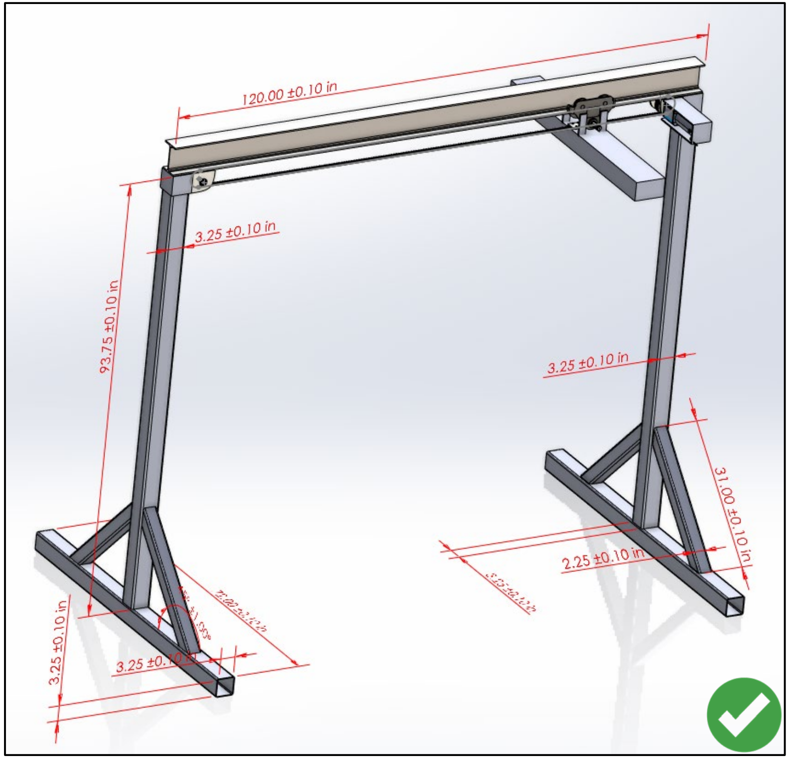
- Timeline Constraints
- Budget Constraints
- Anticipated Integration Challenges
- Design Space Constraints

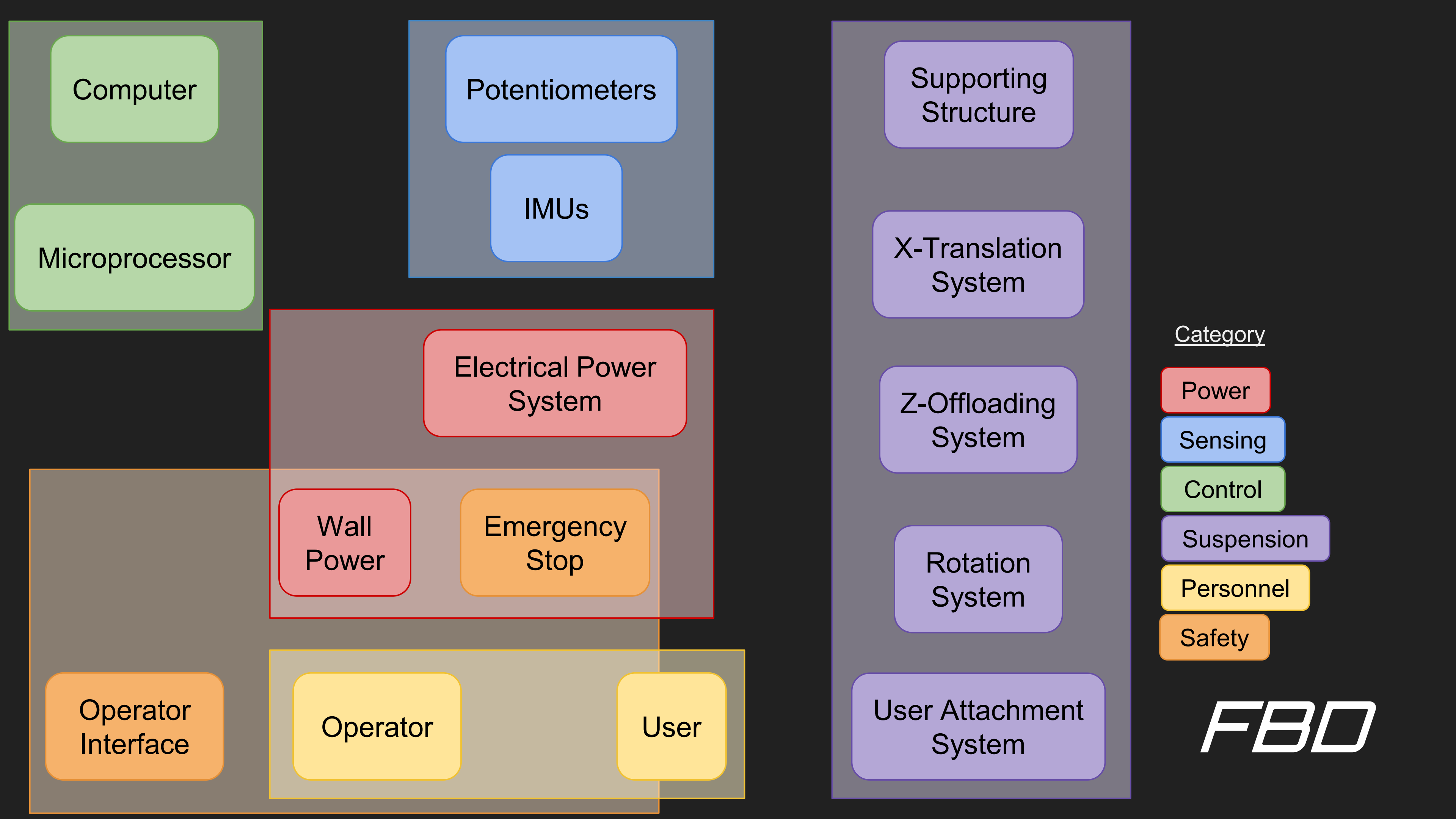
Requirements Modified

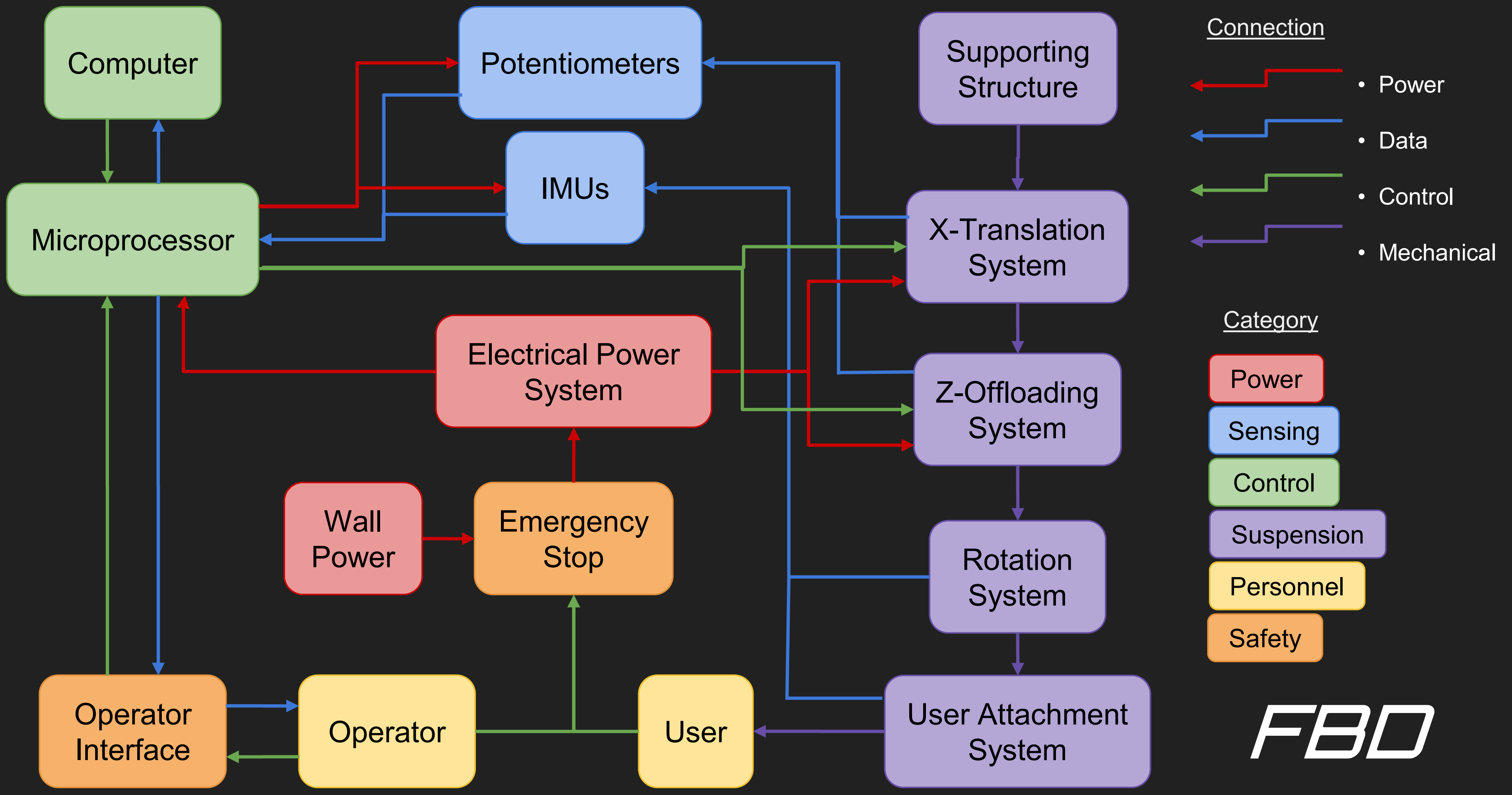
- Preserved vast majority of requirements
- Maintained > ~90% per level
- Approved by customer

X-Axis Gantry Design






Computer
Microprocessor
Potentiometers
IMUs
Electrical Power System
Wall Power
Emergency Stop
Operator Interface
Operator
User
Supporting Structure
X-Translation System
Z-Offloading System
Rotation System
User Attachment System
Category
Power
Sensing
Control
Suspension
Personnel
Safety
FBD



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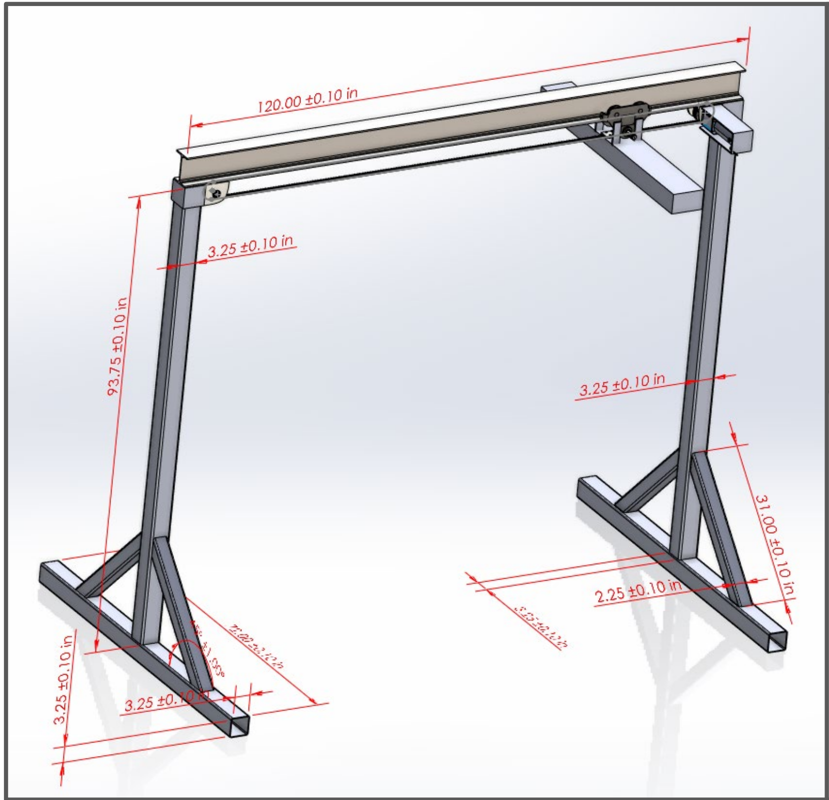
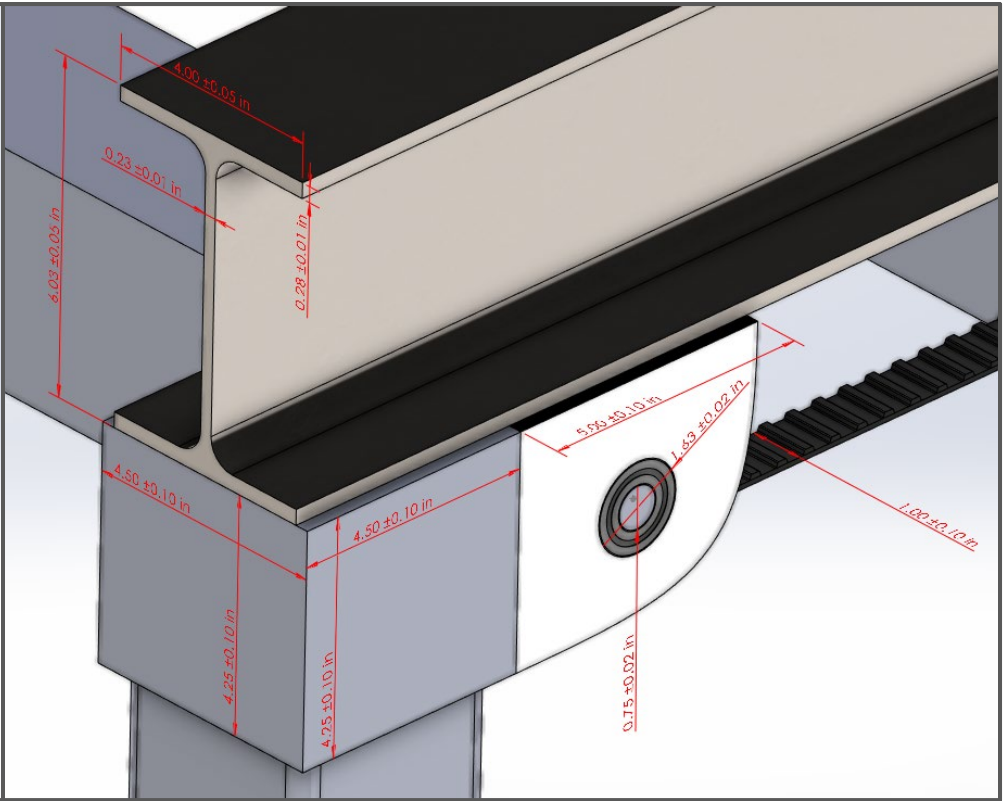
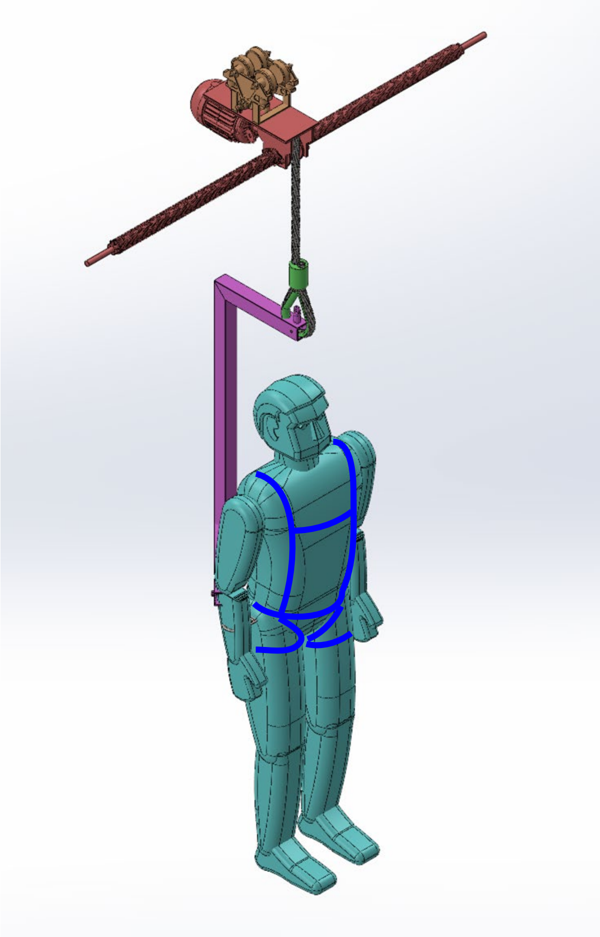
Structures CAD and Specs





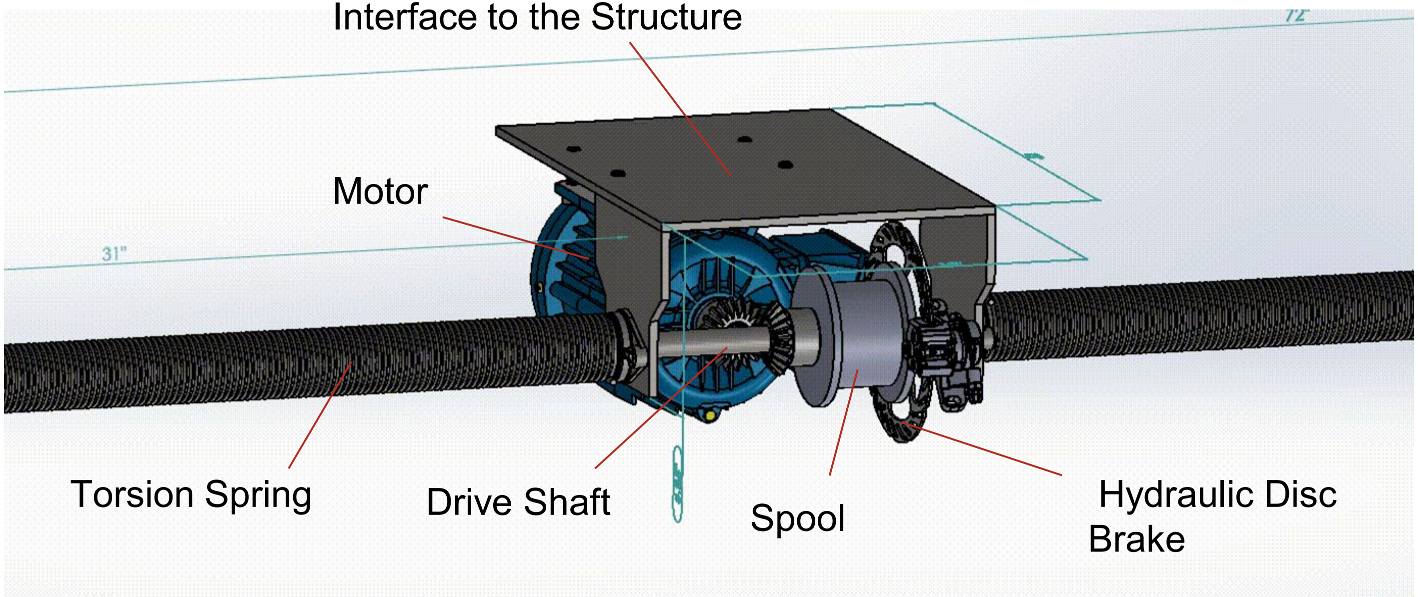
Suspension Breakdown

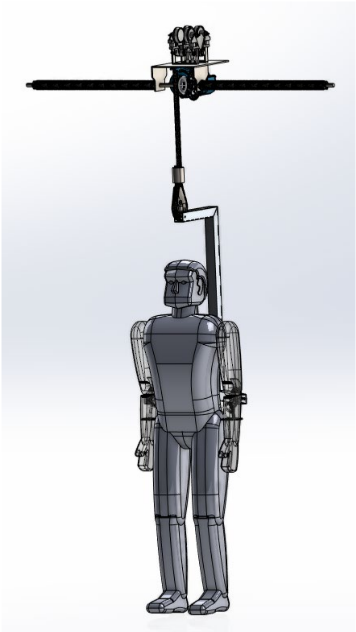
- Z-Offloading System
- Rotation System
- User-Attachment System
- User



Structure Interface
Z-Offloading System
Cable
Rotation System
User
Harness

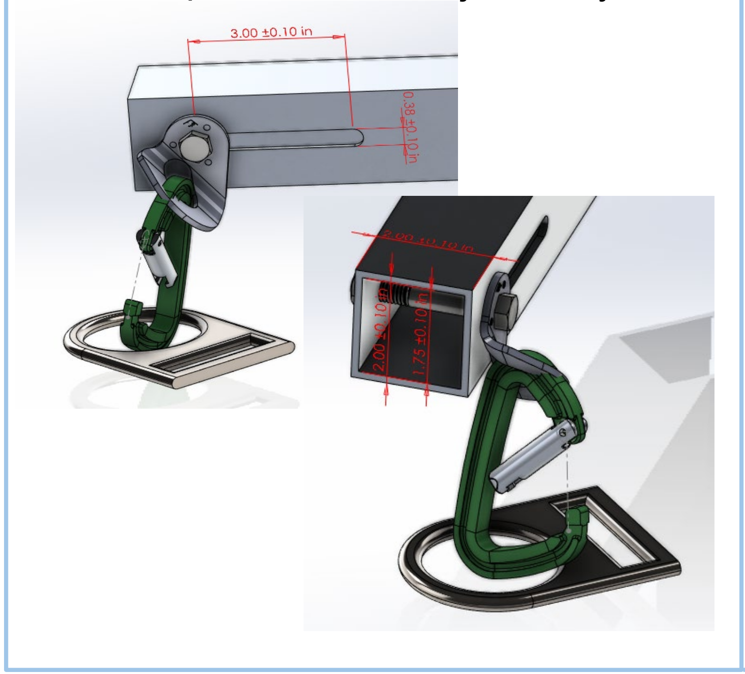
Z-Offloading System: Functional Overview

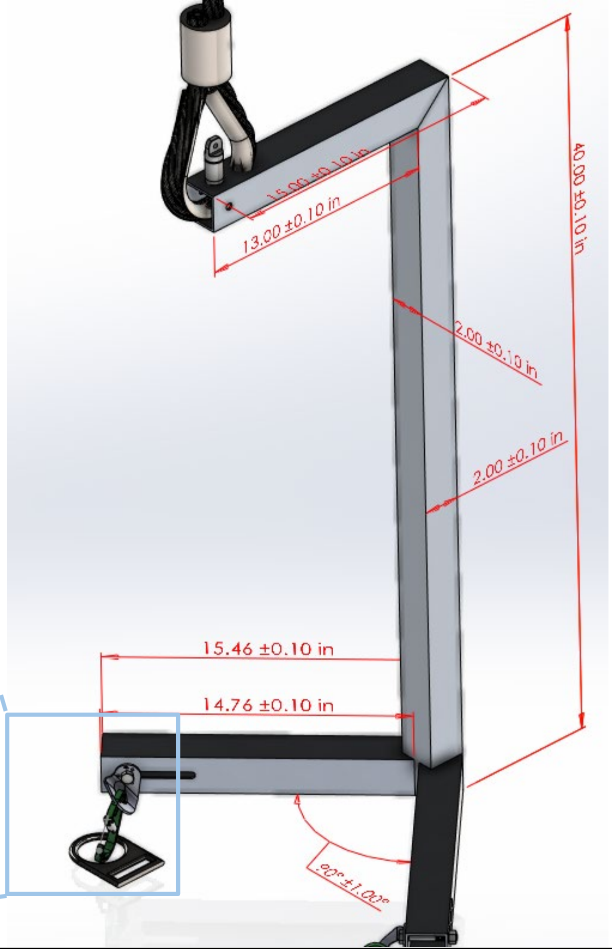




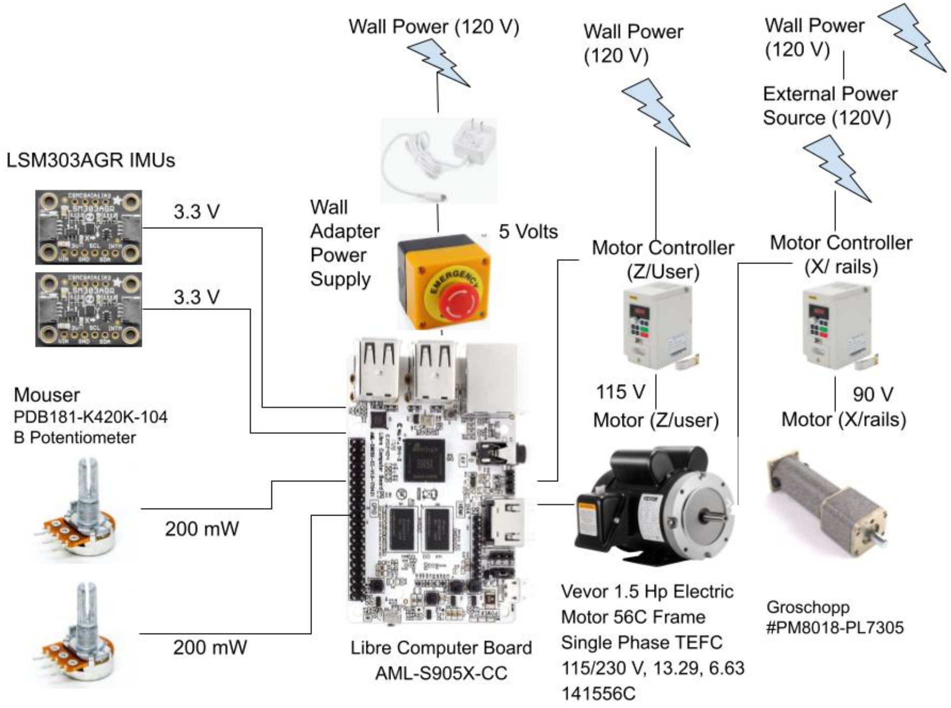
User Attachment System: Functional Overview

Hip Attachment Adjustability





Electronics System: Design Overview

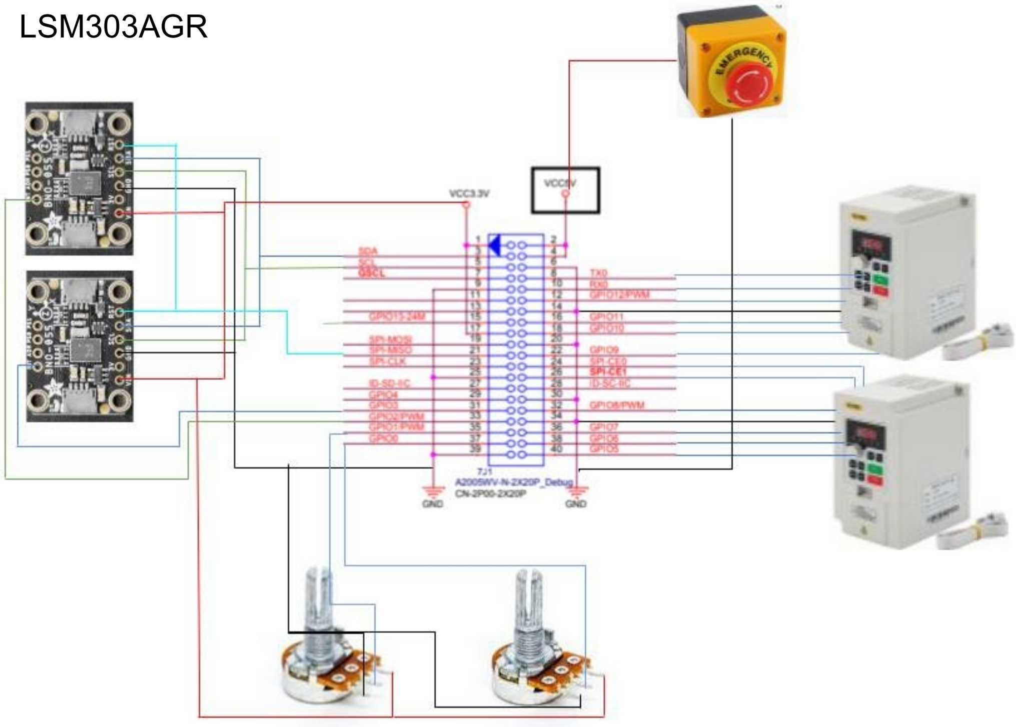


Pin Out Diagram

Legend

- Power
- Ground
- Data

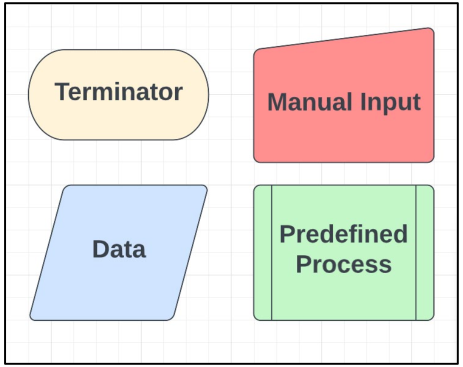
LSM303AGR

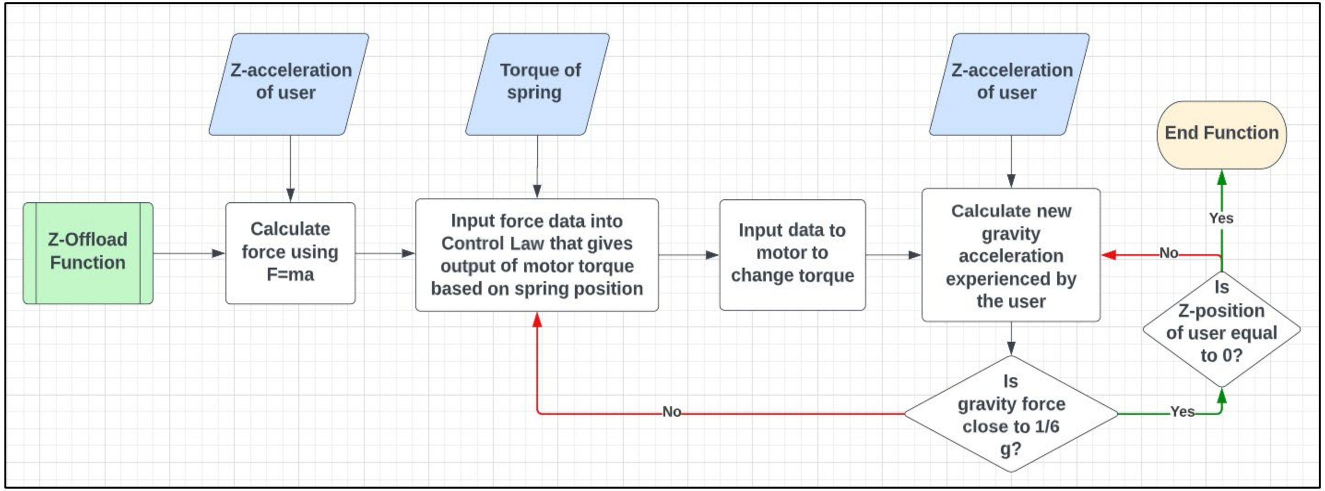


VEVOR
VFD 2.2KW
110V 3HP

Software FBD

Legend





Critical Project Elements & Risks

Functional Requirements

RQMT #	Requirement Statement
Objectives	
LO-01	The system shall simulate the gravity of the lunar environment.
LO-02	The system shall allow sufficiently free user motion to accomplish simulated tasks expected during a mission on the lunar surface.
LO-03	The system shall provide an environment suitable for operational training.
LO-04	The system shall enable continuous use for one hour.
Constraints	
LO-05	The system shall be constructed in a manner that allows for future integration with a hybrid reality (HR) system.
LO-06	The system shall obey all relevant rules and regulations surrounding its operation, including those responsible for ensuring user safety.
LO-07	The system shall remain at or below the total project budget of $4,000.

Critical Project Elements

Critical Element	Rationale	Related FRs
Gravity Offloading	Most important baseline functionality of the system desired by customer	L0-01
Training Viability	Broad-view utility of the final system, justification to build in the first place	L0-02, L0-03
User Safety	Essential for ethical and program viability reasons	L0-06
Cost	Inflexible constraint critical to project success	L0-07

Risk Measurement

Severity	Definitions	Examples
Catastrophic	Total program failure or massive reduction in scope	Shutdown from supervising organization, depletion of budget without viable prototype
Critical	Major delays, significant reductions in scope, fundamental engineering issues requiring redesign	Unexpectedly constrained budget, significant schedule shift, unviable late-stage prototypes
Moderate	Delays, minor reductions in scope, very challenging engineering problems	Significant missed work, lacking necessary manufacturing capability
Negligible	Minor delays, moderately difficult engineering problems	Shipping delays, interfacing challenges

Probability	Definitions
Highly Probable	Very likely to occur once, several occurences likely
Very Probable	Likely to occur, several occurences possible
Probable	Moderate probability to occur, several occurences less likely
Somewhat Improbable	Unlikely to occur, several occurences very unlikely
Improbable	Very unlikely to occur even once, multiple occurences nigh impossible

Risks

Risk	Mitigation Strategy	Relevant CPEs
Insufficient budget	Scope reduction results in vastly decreased material costs, particularly for the structure	Cost
Insufficient time	Scope reduction results in reduced development and testing time in all areas	Gravity Offloading, Training Viability
User injury	Implementation of a user- and operator-controlled E-stop as well as software stops mitigates injury risk	User Safety

Other risks addressed:

- Sensor unviability
- Inaccurate offloading
- Manufacturing issues
- Procurement issues

Risk Matrix - Before Mitigation

Severity \ Probability	Highly Probable	Very Probable	Probable	Somewhat Probable	Improbable
Catastrophic				User injury	
Critical	Insufficient budget	Insufficient time	Sensor unviablility		
Moderate	Inaccurate offloading			Manufacturing issues	
Negligible			Procurement issues		

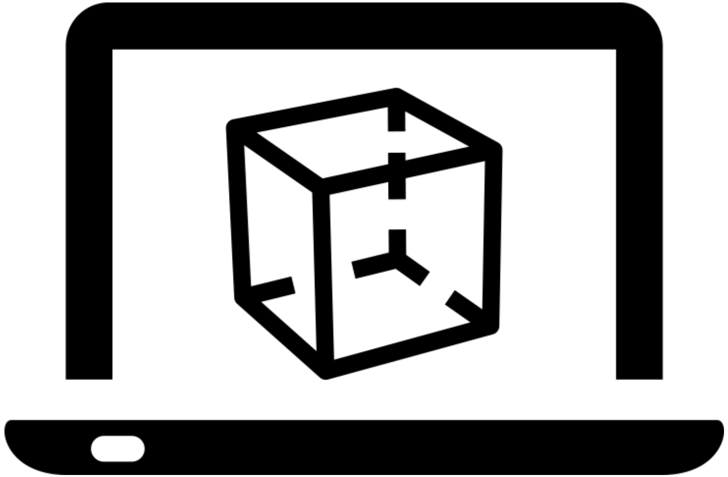
Risk Matrix - After Mitigation

Severity \ Probability	Highly Probable	Very Probable	Probable	Somewhat Probable	Improbable
Catastrophic				User injury	
Critical	Insufficient budget	Insufficient time	Sensor unviability	Scope reduction (materials)	E-Stop Implementation
Moderate	Inaccurate offloading		Scope reduction (dev. time)	Less demanding sensing needs Manufacturing issues	Simplified design
Negligible		Simplified control needs	Procurement issues	Alternative suppliers	

Design Requirements & Satisfaction

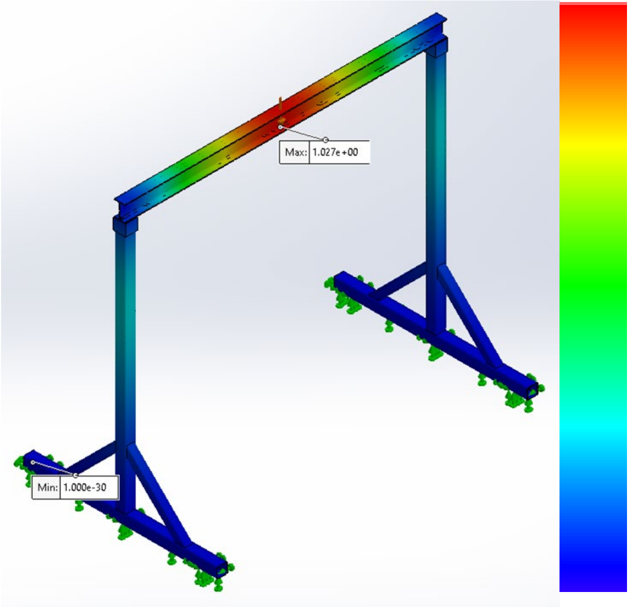
Detailed Requirements and Models

- Structural Modeling
  - Static Loading
  - Dynamic Loading
  - Column Buckling
- X-Axis Belt System Model
- Z-Axis Offloading Model
- IMU Combination Testing
- User Interface Model



Static Load Modeling

Deflection Modeling at 1200 lbs



Red - largest deflections <= 4 in

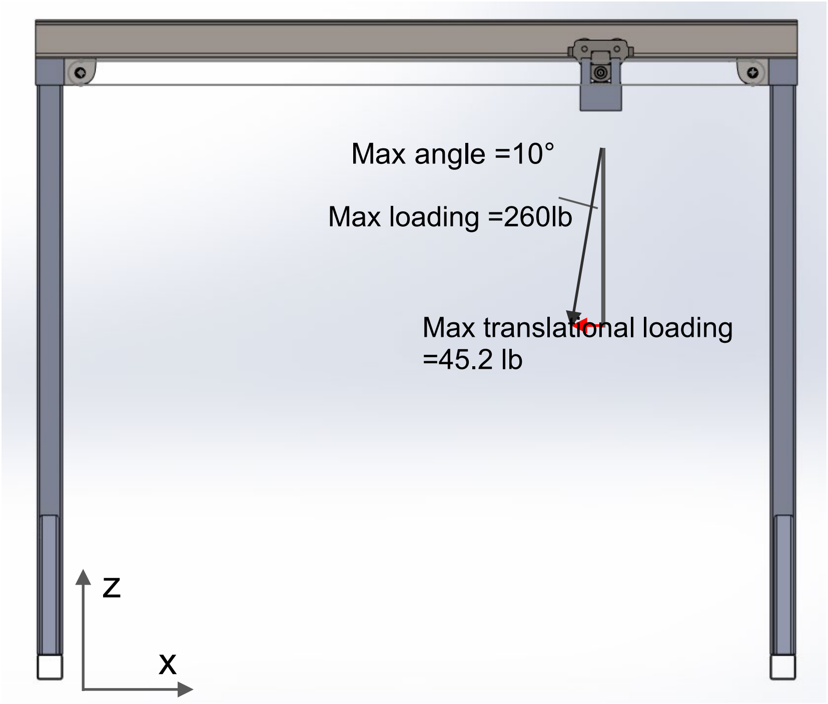
Blue - smallest deflections ~6e-9 in

Material: A500 B steel

1200 lbs Central Load Analysis

- Max stress on beam: 36.9x10^3 ksi
  - Concentrated at support points
- Max deflection at center: 0.04 in
- FOS: 23
- Requirements Met
  - L2-26: Support the weight of user/attachment system/movement system
  - L3-74: Withstand 350 lbs of static force with a maximum deflection of 0.05 inches

Dynamic Load Modeling



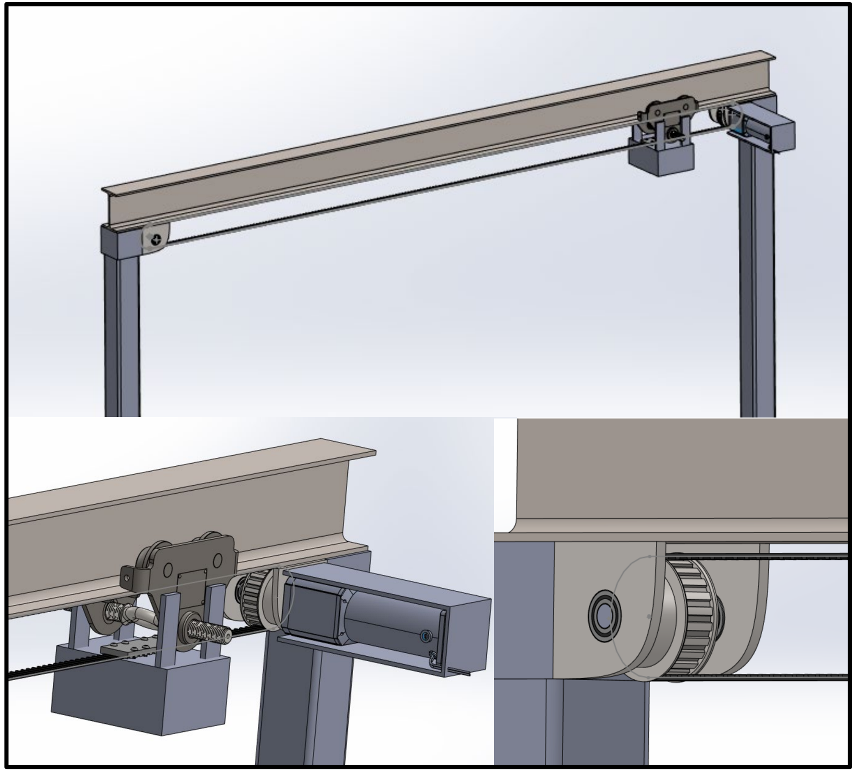
Lateral loading conditions

- Forces in translational x-direction
  - Moment & horizontal forces
- Max 45.2lb in x-direction with max weight and angle
- Max stress concentration: 378 psi

Requirements

- L2-27: Support reactive forces of user
- L3-75: Withstand dynamic loading

Belt System and Proofs



Belt System Structure

- Timing belt w gears
  - Attached to blackbox on trolley

Justification

- Max predicted tension: 124.5 N
- Max allowable tension in 1” belt: 1100 N

Requirements

- L2-29: Sufficiently free user motion
- L2-37: Interface w/ movement system

Z-Offloading: Design Path

Max Load
260 lbs
(L3-21)

Cable Diameter
5/32”
Rated for 2,023 lbs
F.S. = 7.8 (L3-17)

Stay Within Power Budget

Minimize Torque

Increases radius

Decreases radius

Fall Speed
5.67 ft/s
(L3-19)

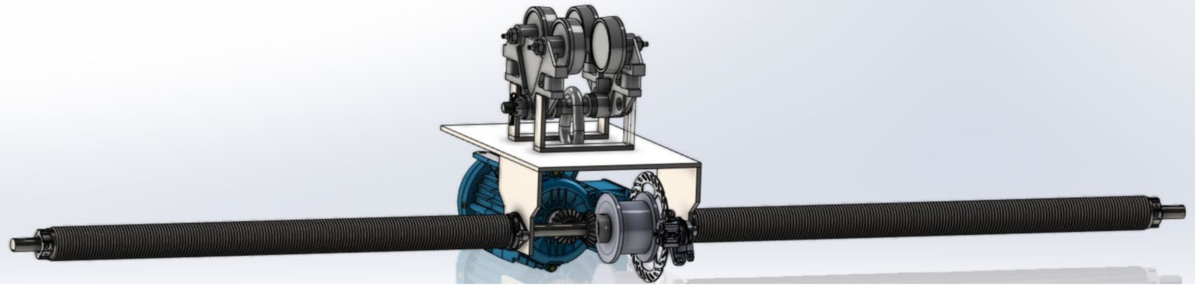
Spool Radius
1.875”

Motor RPM

Motor Torque

Spring Torque

Legend
- Driving Requirements
- Requirement driven choice
- Choice driven outcome



Z-Offloading Dynamics Model

Spool Size: R = 1.875 [in]

Spring Constant: 5.6 [in*lbf/rad]

Motor Size: ~1 HP* (~746 W)

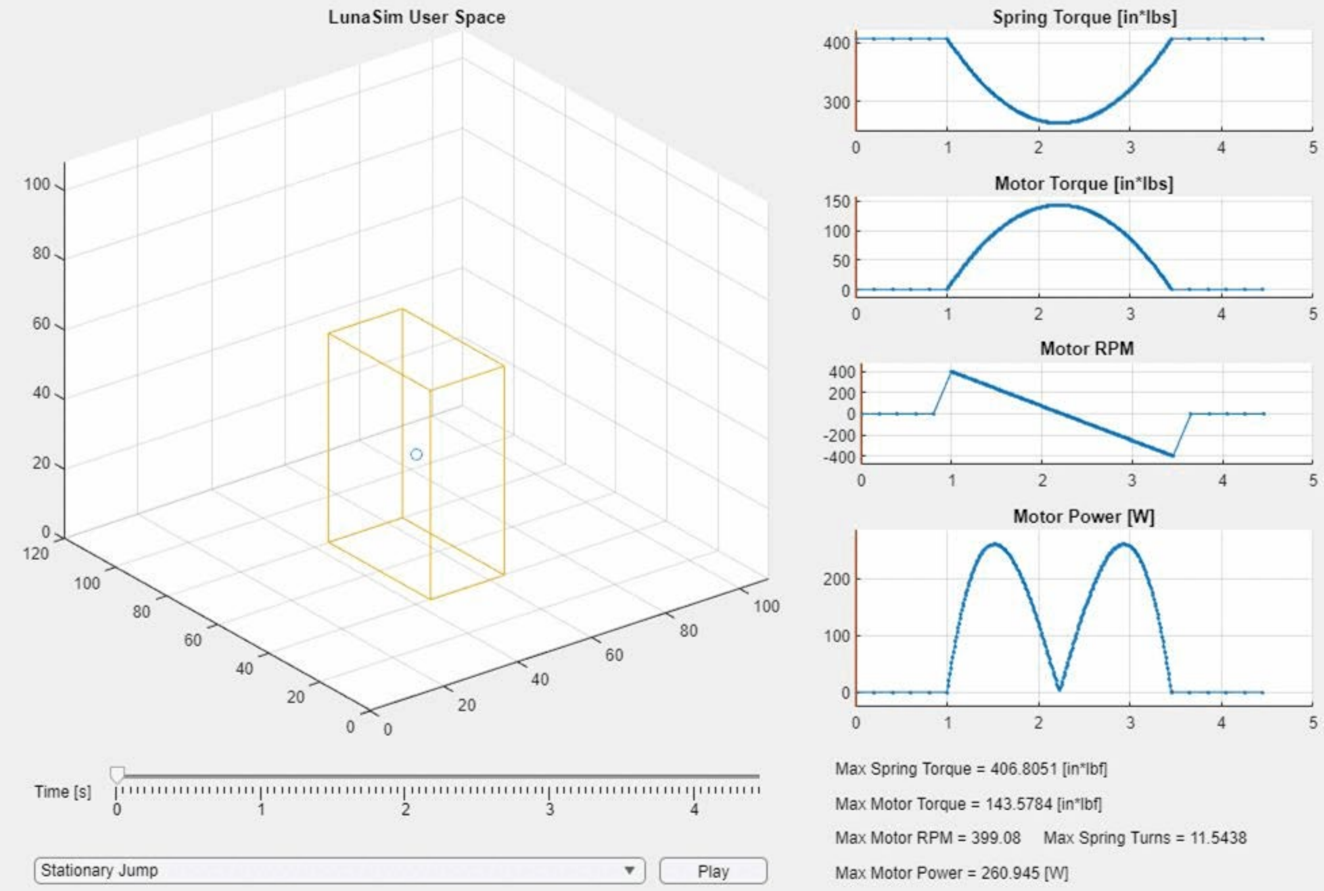
Requirements:

L2-17 (offload weight)

L2-18 (simulate Lunar gravity)

L3-18 (simulate g=1.62 m/s^2)

L3-19 (max speed = 5.67 ft/s)



* to meet torque and RPM requirement, a 4:1 gear reduction is required

Electronics - IMU Combination Testing

Accelerometer Chosen: LSM303AGR

Data acquired from previous Colorado Space Grant experiment using same sensor.

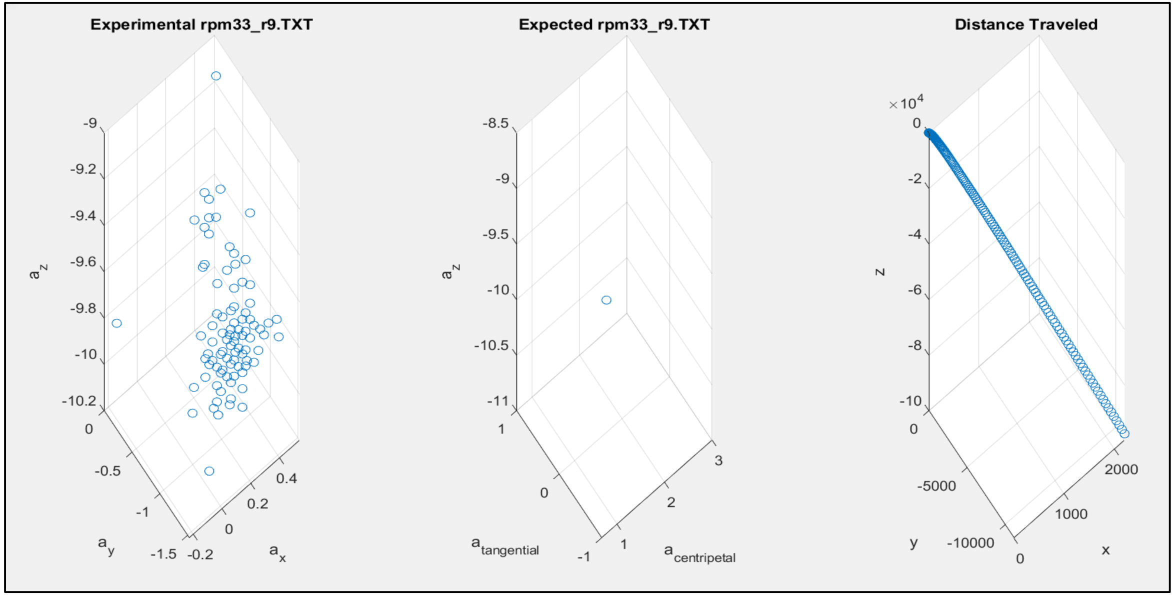
Individual Accuracy: ~0.5 m/s^2

Combined accuracy will increase: however, for our testing we only had one IMU to test, which limits the ability to test combined data.

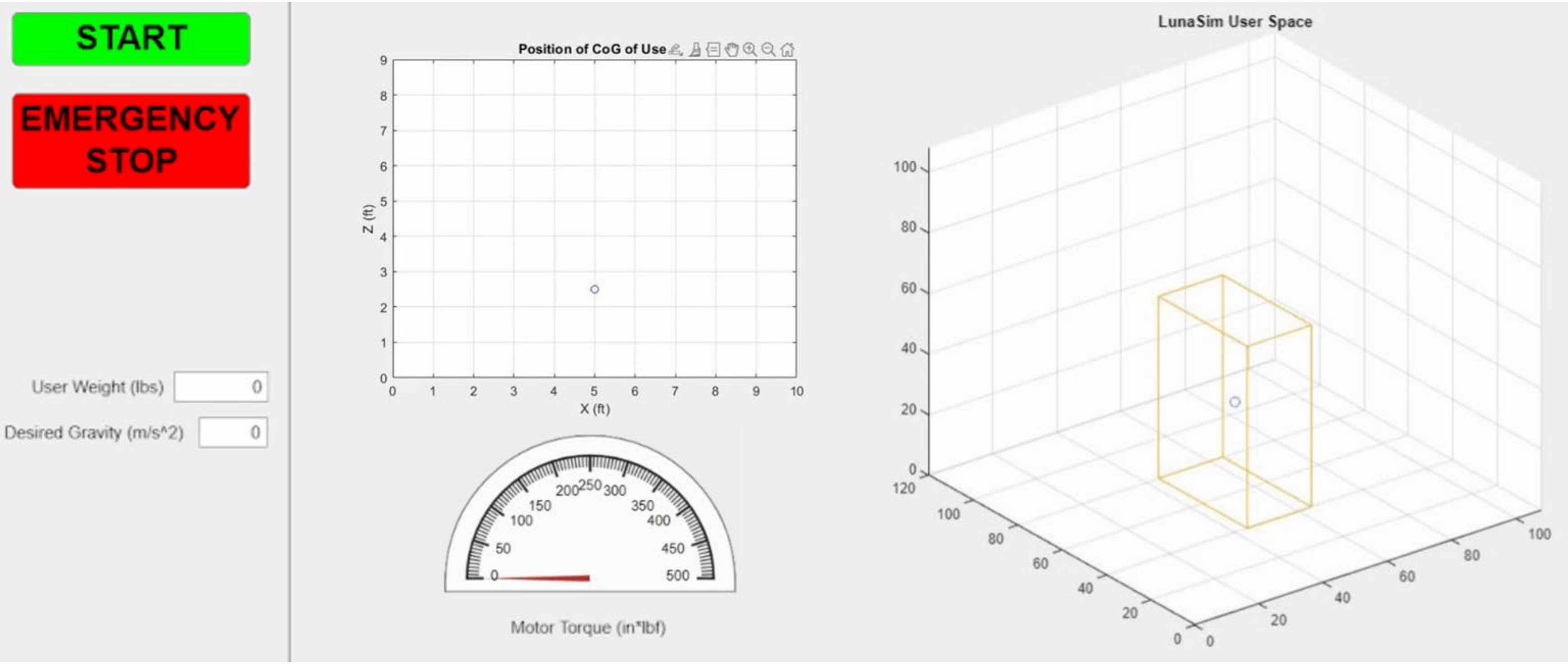
Requirements:

L2-50: The sensors shall collect data to characterize user position.

L2-51: The sensors shall collect data to characterize user motion.



Software - UI and Animation



Verification & Validation

Overall Test Plan

Design Area	Tests and Summary	Driving Requirement
Structure	Stability & structural integrity testing	L2-26, L2-27
Suspension	Gravity simulation accuracy test	L3-18
Electronics	Motor characterization, sensor testing	L1-01, L1-03, L2-50, L2-51
Software	Hard and soft stop testing	L3-96

Structures System Verification

Purpose

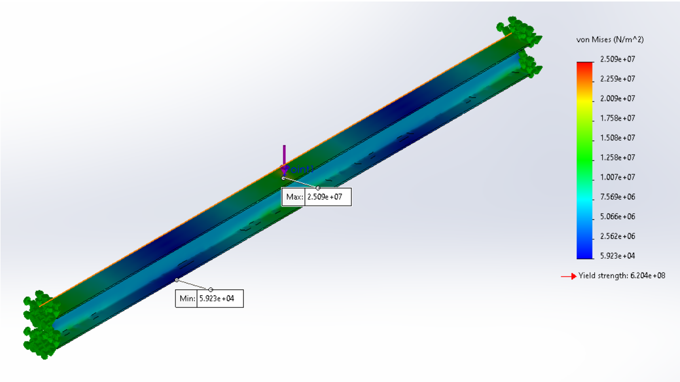
- Verify structural integrity of overhead structure
- Verify Stability of entire structure

Plan

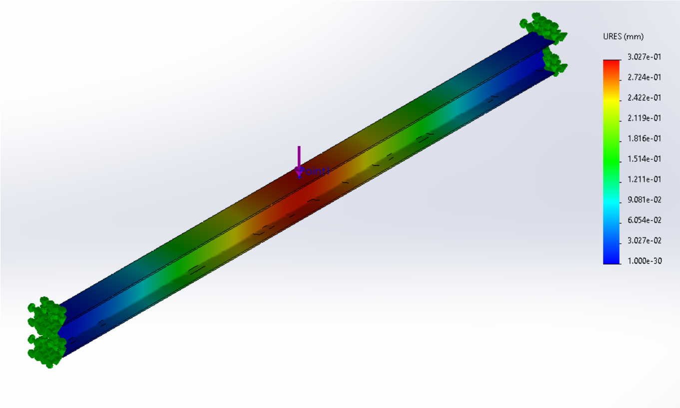
- Statically load structural components
- Dynamically load structure at key stress points
- Safety lead on-site

Driving Requirements

- L2-26: The supporting structure shall be able to support the weight of the combined user, user attachment system, and movement system.
- L2-27: The supporting structure shall be able to support the reactive forces due to the actions of the user and response from the movement system.



Stress



Deflection

Suspension System Verification

Purpose

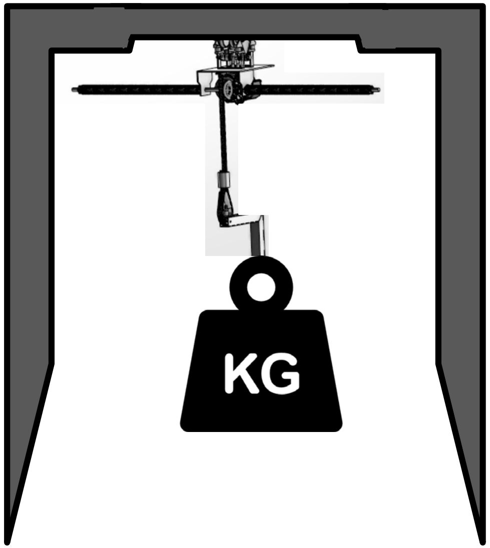
- Prove accurate gravity simulation

Plan

- Attach test weight onto cable
- Drop from max height to ground
- Slow motion video to determine fall time

Driving Requirements

- L3-18: The z-offloading system shall be able to simulate an acceleration due to gravity of 1.62 [m/s/s] ±10%.



Electrical Tests - Motor Characterization

Objective: Determine the relationship between torque, rpm, and current to ensure motors can perform well at the predicted speed and current.

Requirements Met:

L1-01: The system shall dynamically offload the user's weight to simulate lunar gravity.

L1-03: The system shall allow the user to maintain free translational movement within its spatial bounds.

Steps:

- Measure coefficient of friction between floor and mass
- Use motor to move mass across floor
- Measure speed of the mass
- Calculate torque

Facilities Required:

- Classroom space, wall power

Safety Risks:

- Personnel safety risks associated with moving parts
- Potential damage to motor if proper precautions are not taken

Electrical Tests - IMUs and Potentiometers

Objective: Determine the accuracy of the IMUs and Potentiometers

Requirements Met:

L2-50: The sensors shall collect data to characterize user position.
L2-51: The sensors shall collect data to characterize user motion.

Steps:

- Attach sensors and microprocessor to ASEN 3200 Inertial Wheel.
- Start recording data with the microprocessor and the Inertial Wheel Odometer.
- Spin the wheel.
- After 10 seconds, stop recording data.
- Compare sensor measurements to predicted values based on speed and radius of wheel.

Facilities Required:

- ASEN 3200 Inertial Wheel

Safety Risks:

- Personnel safety risks associated with moving parts
- Potential damage to sensors if they are not properly attached to the wheel.

Software System Verification

Objective

- Determining if the hard and soft stops are activated and run correctly if the user were to jump too high.

Safety Risks:

- Potential damage to the structure and equipment

Plan

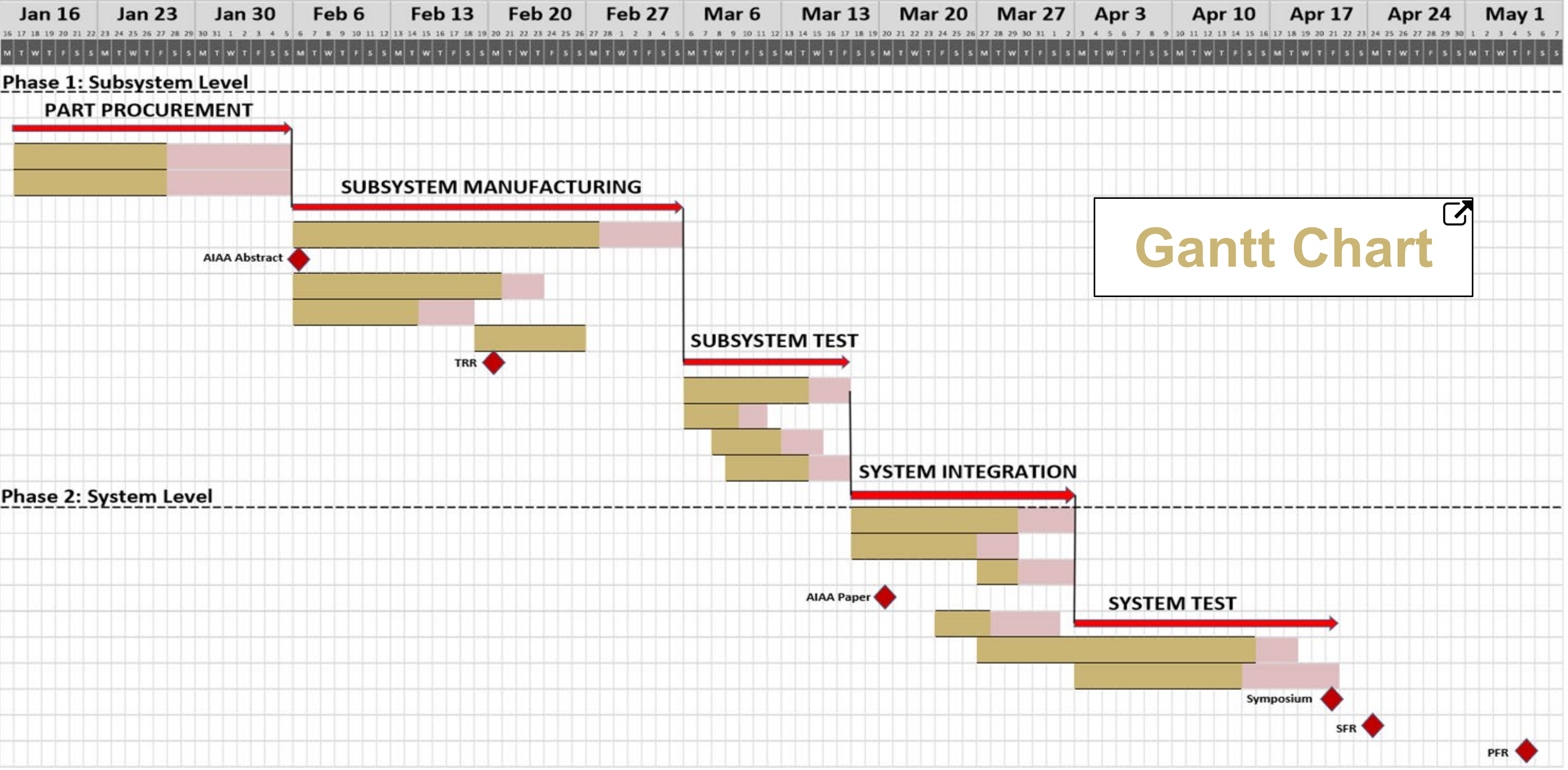
- Attach test weight onto cable
- Throw the weight up with enough force to initiate the soft stop and not the hard stop
- Throw the weight up with enough force to initiate the hard stop

Driving Requirements

- L3-96: The software shall command the actuators to slow the user's movement in the z-direction to prevent the user from moving outside of the system space.

Project Planning

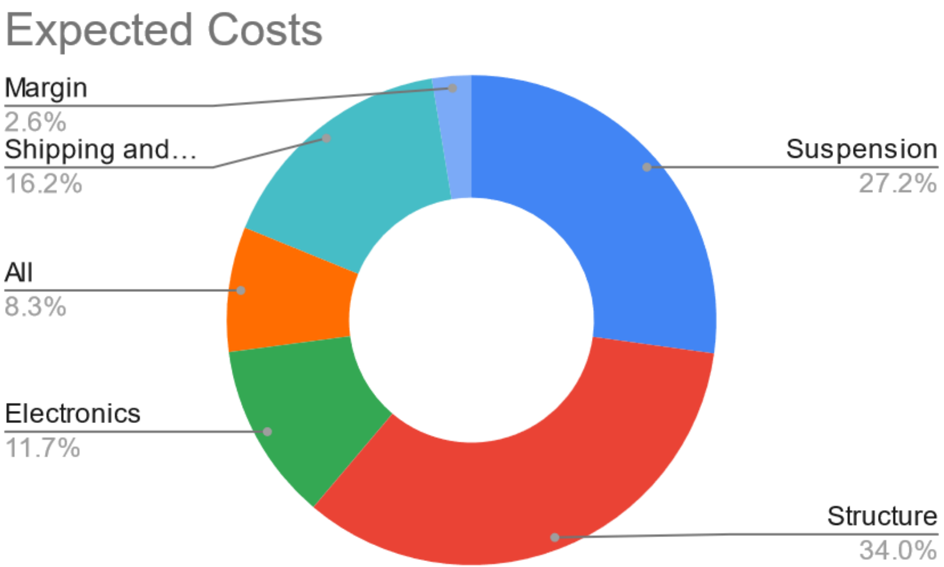
Gantt Chart



Jan 16
Jan 23
Jan 30
Feb 6
Feb 13
Feb 20
Feb 27
Mar 6
Mar 13
Mar 20
Mar 27
Apr 3
Apr 10
Apr 17
Apr 24
May 1
Phase 1: Subsystem Level
PART PROCUREMENT
SUBSYSTEM MANUFACTURING
AIAA Abstract
TRR
SUBSYSTEM TEST
SYSTEM INTEGRATION
Phase 2: System Level
AIAA Paper
SYSTEM TEST
Symposium
SFR
PFR

Cost Plan

	Actual Budget	Minimum Budget	Maximum Budget
Suspension	1086.95	1079.19	2548.45
Structure	1360.00	1360.00	2920.00
Software	0.00	150.00	150.00
Electronics	469.50	395.29	1773.00
All	330.00	280.00	810.00
20% Buffer (Shipping, etc)	649.29	652.90	1640.29
Margin	104.26	82.63	-5841.74



Testing

Test Phase	Expected Date	Facility	Access
Component Testing	Early March ‘23	AERO 140	✓
Electronics/Software Testing	March ‘23	AERO 140	✓
Structure/Suspension Testing	March ‘23	TBA	•••
Full System Integration Test	Late March ‘23	TBA	•••
Safety Testing	Early April ‘23	TBA	•••
Human Testing	April ‘23	TBA	•••

Acknowledgements

Dr. Anderson - Advisor and Customer, CU Assistant Professor

Sandor Nemethy - VP, Mission Management at EchoStar

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Bobby Hodgkinson - Assistant Teaching Professor

Dr. Wingate & Dr. Muldrow - CU Boulder Professor’s

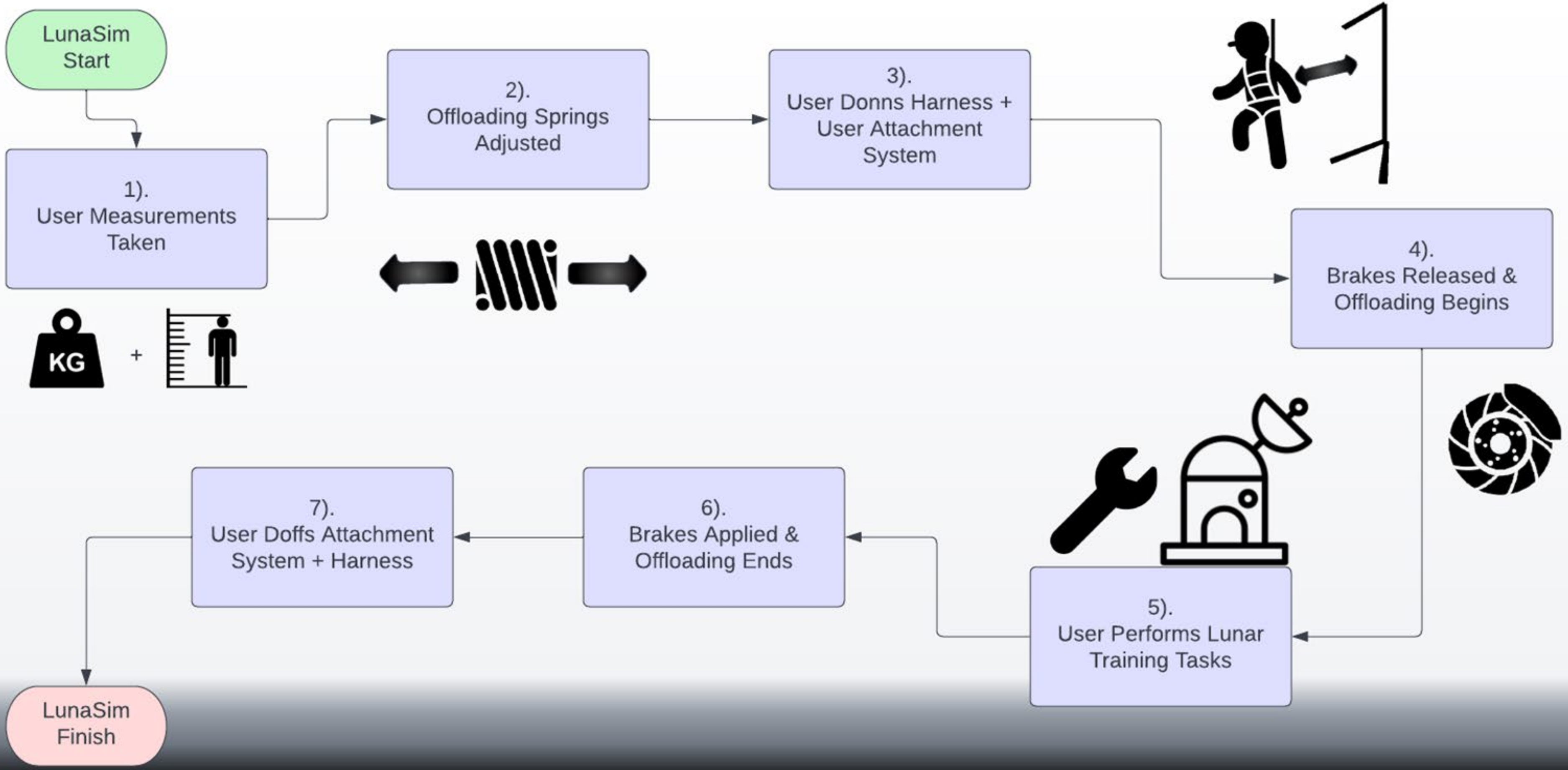
Jasmin Chadha - CU Boulder Masters Student & TF

TF Team - CU Boulder Senior Design

Thank you.

Questions?

Additional Slides


LunaSim Start
1). User Measurements Taken
KG
+
2). Offloading Springs Adjusted
3). User Donns Harness + User Attachment System
4). Brakes Released & Offloading Begins
5). User Performs Lunar Training Tasks
6). Brakes Applied & Offloading Ends
7). User Doffs Attachment System + Harness
LunaSim Finish

Backup:
Z-Translation System Trade Matrix

Z-Offloading: Design Change - Trade Matrix

Static Load

Spring Offload

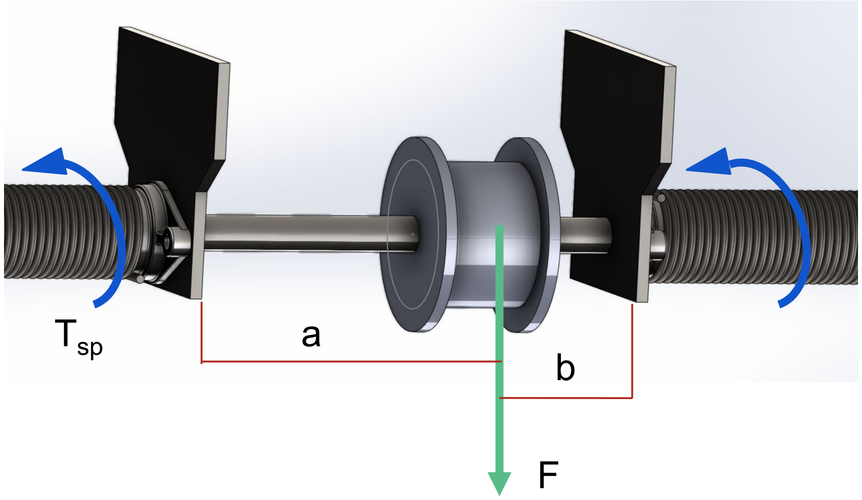
Metric	Weight	Static Load	Spring Offload
Cable Management	0.25	2	5
Size of Offloading System	0.20	3	4
Reliability	0.20	4	3
Manufacturing Simplicity	0.15	4	3
Mass	0.10	1	4
Structural Modification	0.10	3	5
Weighted Total	**1.00**	**2.90**	**4.00**

Z-Translation System - Trade Matrix Scale Definitions

Metric	1	2	3	4	5
Cable Management	The cable required exceeds 20 ft between maximum and minimum range	The cabld required exceeds 15 ft between maximum and minimum lengths	The Cable required exceeds 12 ft between maxmimum and minimum lengths	The cable required exceeds 10 ft between maximum and minimum length	The cable required exceeds 6 ft between maximum and minimum length
Size	The system extends 2 ft outside of or into the footprint of the structure	The system extends 1 ft outside of or into the footprint of the structure	The system extends 1/2 ft outside of or into the footprint of the structure	The system extends 1/2 ft outside of or into the structure, but does so in unused space	The system can lie entirely within the structure and not require extra space
Reliability	≥9 points of failure	7-8 potential points of failure	5-6 potential points of failure	3-4 potential points of failure	1-2 potential points of failure
Design/ Manufacturing Simplicity	The system requires specialized manufacturing from an external company	The system can be manufactured entirely within Smead AES capability, but requires significant research, training, or time	The system requires little assistance from manufacturing experts, and requires special equipment training	The system requires little assistance from manufacturing experts, and requires basic equipment training	The system can be constructed entirely by the team using Smead AES workshops
Mass	The offloader adds >=400 lbs to the structure	The offloader adds >=300 lbs to the structure	The offloader adds >=200 lbs to the structure	The offloader adds >=100 lbs to the structure	The offloader adds <100 lbs to the structure
Structural Modification	Requires 5 or more modifications to function with a simple gantry with a mobile crossbar	Requires 4 or more modifications to function with a simple gantry with a mobile crossbar	Requires 3 or more modifications to function with a simple gantry with a mobile crossbar	Requires 2 or more modifications to function with a simple gantry with a mobile crossbar	Requires 1 or more modifications to function with a simple gantry with a mobile crossbar

Backup: Z-Translation System Drive Shaft Model

Z-Translation System - Drive Shaft Stress and Strain Modeling Inputs



Input	Value
Spool Radius, r	1.875 [in]
Drive Shaft Radius, c	0.375 [in]
Drive Shaft Length, L	48 [in]
Torque from each Spring, T_{sp}	-203 [in-lb]
Weight of the User and Attachment, F	260 [lb]
Distance from Center of Spool to Left Support, a	6.53 [in]
Distance from Center of Spool to Right Support, b	2.97 [in]

Z-Translation System - Drive Shaft Stress and Strain Modeling Intermediate Outputs and Equations

Applied Torque from User and V-Clamp: $T_{ua} = Fr \;\Rightarrow\; T_{ua} = 487.5\;[in\;lb]$

Net Torque on Shaft: $T_{net} = 2 * T_{sp} + T_{ua} \;\Rightarrow\; T_{net} = 81.5\;[in\;lb]$

Polar Moment of Inertia: $J = \frac{\pi}{2}c^4 \;\Rightarrow\; J = 0.497\;[in^4]$

Angle of Rotation Between Ends: $\phi = \frac{T_{net}L}{GJ} \;\Rightarrow\; \phi = 0.622^o$

Bending Moment: $M = \frac{Fab}{a+b} \;\Rightarrow\; M = 530.8\;[in\;lb]$

Z-Translation System - Drive Shaft Stress and Strain Modeling Results

Selected Material: *Nitride-Coated 1045 Carbon Steel*	
Material Property	**Value [ksi]**
Yield Strength, Y	45
Elastic Modulus, E	29,900
Shear Modulus, G	11,600

Calculated Variable	**Value**	**Safety Factor, SF**
Maximum Shear Stress, τ_{max}	0.9839 [ksi]	45.74
Maximum Shear Strain, γ_{max}	0.0049°	-
Maximum Bending Stress, σ_{max}	12.82 [ksi]	3.51
Maximum Bending Strain, ε_{max}	0.00043 [in/in]	-
Maximum Deflection, δL_{max}	0.00016 [in]	-

$$\tau_{max} = \frac{T_{net}c}{J}$$

$$\gamma_{max} = \frac{\tau_{max}}{G}$$

$$\sigma_{max} = \frac{32M}{\pi(2c)^3}$$

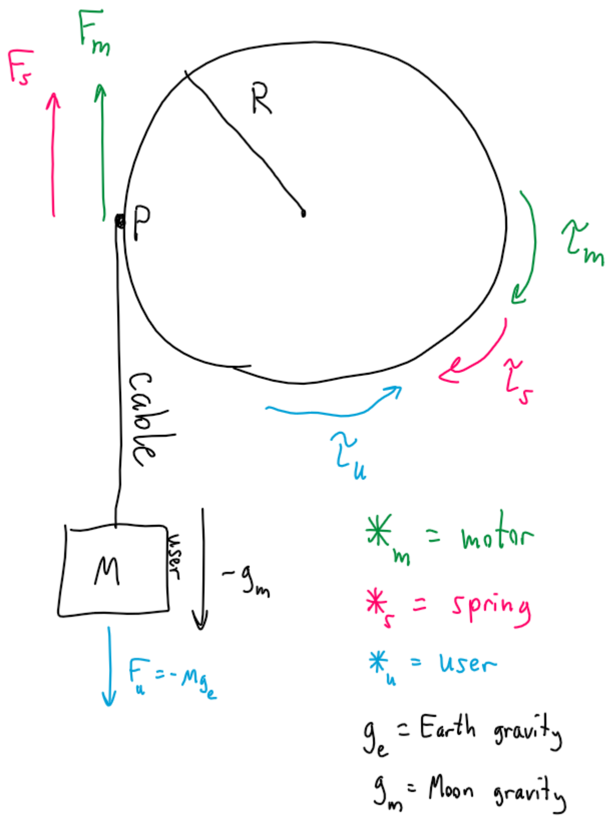
$$\varepsilon_{max} = \frac{\sigma_{max}}{E}$$

$$\delta L_{max} = c\,\varepsilon_{max}$$

$$SF = \frac{Y}{value}$$

Backup: Z-Translation Dynamics Model Equations

Z-Translation Dynamics Equations Derivation



$$\tau = F \times R \quad | \quad F = \frac{\tau}{R}$$

$$W = Mg_e \quad | \quad M = \frac{W}{g_e}$$

$$\tau_s = k\theta \quad | \quad [k] = [\frac{in*lbf}{rad}]$$

$$P_{HP} = \frac{\tau_{in*lbf} * RPM}{63025}$$

$$1\ HP = 745.7\ W$$

$$\Sigma F = Ma = -Mg_m$$

$$F_m + F_s - F_u = -Mg_m$$

$$(F_m + F_s = Mg_e - Mg_m) \times R$$

$$\tau_m + \tau_s = MR(g_e - g_m)$$

$$\tau_m = \frac{WR}{g_e}(g_e - g_m) - \tau_s$$

$$\tau_m = WR(1 - \frac{g_m}{g_e}) - \tau_s$$

Backup: Motor Gearbox

Motor Gearbox

1 = driver
2 = driven

gear diameter, # of teeth

$$\frac{d_2}{d_1} = \frac{\omega_1}{\omega_2} = \frac{N_2}{N_1} = \frac{RPM_1}{RPM_2} = \frac{\tau_2}{\tau_1}$$

$$\begin{bmatrix} RPM_1 = 1750 & RPM_2 \geq 400 \\ \tau_1 = ? & \tau_2 = 143.53\ in*lbf \end{bmatrix}$$

$$\tau_1 = \frac{P_{HP}*63025}{RPM} = \frac{(1\ HP*63025)}{1750\ RPM} = 36\ in*lbf$$

Stats from real motor

$$\frac{RPM_1}{RPM_2} = \frac{\tau_2}{\tau_1}$$

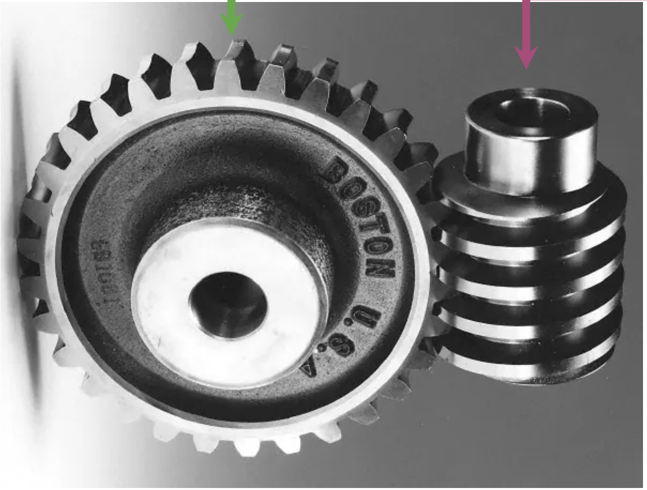
$$RPM_2 = \frac{RPM_1*\tau_1}{\tau_2}$$

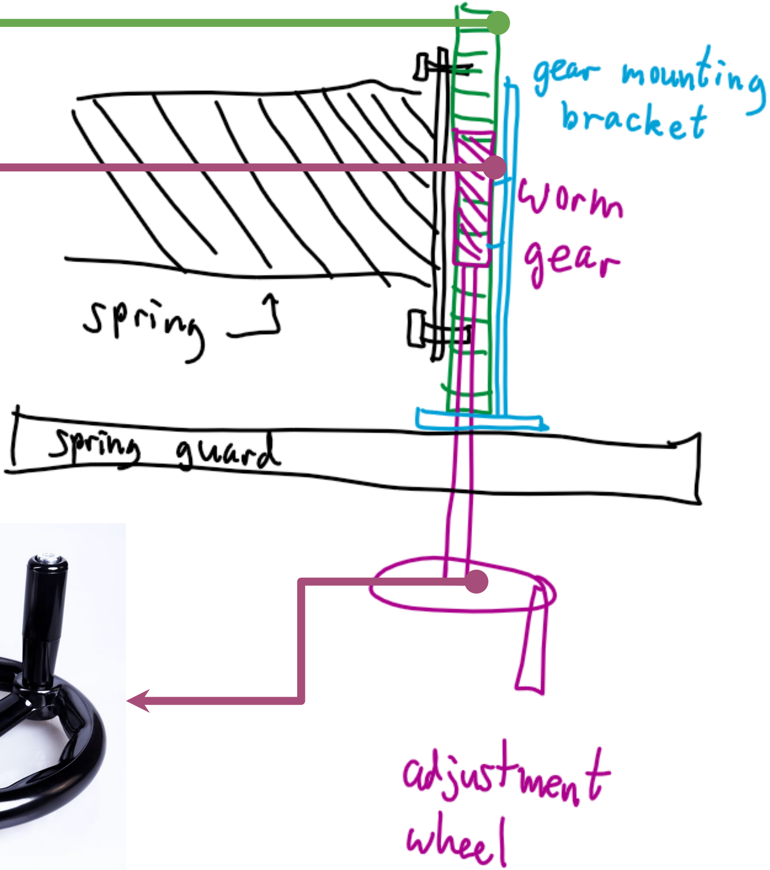
$$RPM_2 = \frac{1750*36}{143.53} = 431\ RPM$$

$$\frac{N_2}{N_1} = \frac{\tau_2}{\tau_1} = \frac{143.53}{36} = 4.05$$

Backup: Spring Adjustment Mechanism

Spring Adjustment Mechanism





Backup: Cable and Spool Selection

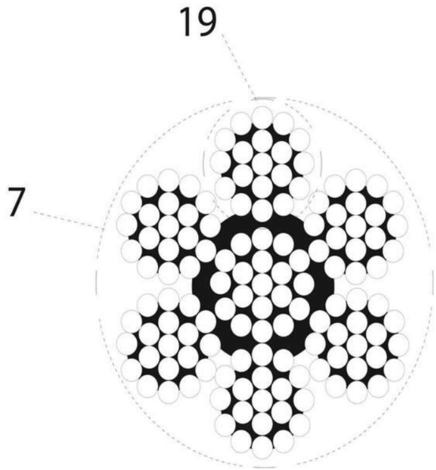
Suspension Cable and Spool Selection

Cable:

Material: Professional marine grade-316 exterior stainless steel
Rated Load: 2,023 lbs
Diameter: 5/32 inch
Wire Configuration: 7x19

Spool:

Radius: 1.875 inch



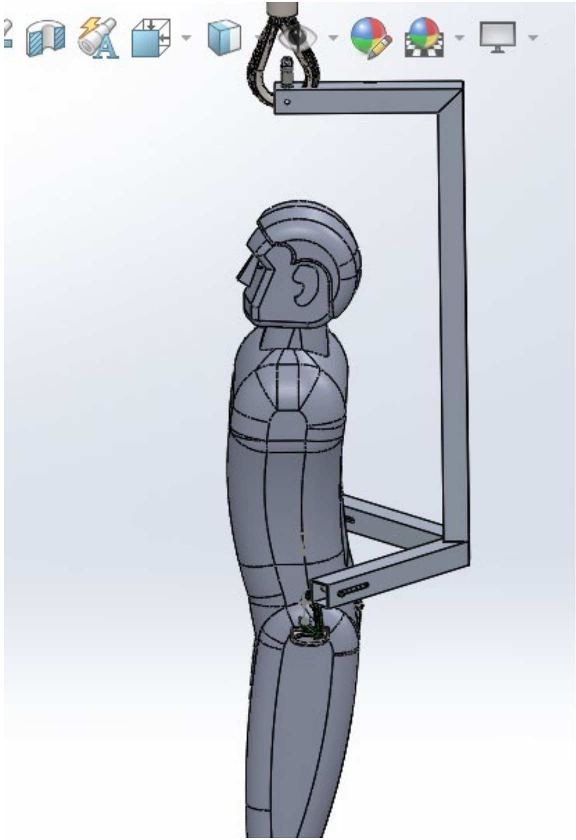
Backup:
Rotation System

Rotation System: Interfacing User and Offloader

Rated Load: 2,200 lbs
Opening Wd: 15/16”
Usable Lg: 5 ⅜”
Eye ID: 1 ½”
Eye Thickness: ½”

Requirements Met:
L3-35: The rotation system shall allow the user full 360 degree yaw rotation

User Attachment



Design Heritage

Backup:
User Attachment System (Harness)

Harness - Trade Options

Points for consideration when narrowing down harness options:

- Certified to industry standards
- Company credibility
- Durability
- Ratings and reviews
- Size options
- Modifications needed
- Loading direction on body
- Cost

	TORNADO	THUNDER	HURRICANE	SCORPION
ANSI TESTED?	✓	✓	✓	✓
DORSAL D-RING?	✓	✓	✓	✓
SIDE D-RING?		✓	✓	
CHEST D-RING?				
BACK SUPPORT?			✓	
BUCKLE TYPE:	PASS-THROUGH BUCKLE	PASS-THROUGH BUCKLE	PASS-THROUGH BUCKLE	PASS-THROUGH BUCKLE

Harness - Trade Matrix

Metric	Weight	KwikSafety HURRICANE Safety Harness	KwikSafety THUNDER Safety Harness	KwikSafety SCORPION Safety Harness	KwikSafety TORNADO Safety Harness
Level of Modification Needed	0.40	3	3	3	1
Options for attachment points or level of support	0.30	4	5	3	3
Cost	0.20	3	4	3	4
User Comfort (Level of Padding)	0.10	3	1	1	1
Weighted Total	**1.00**	**3.30**	**3.60**	**2.80**	**2.20**

Key Requirements:
- **L0-2:** Free user motion
- **L0-4:** 1-hour continuous use
- **L0-6:** Safety

Key Constraints:
- Interfacing complexity

Key Interfaces:
- Rotation system
- User

Harness - Trade Matrix Scale Definitions

Metric	1	2	3	4	5
Level of modification needed	Additional modifications must be made to add and remove components without the need of sewing		Additional modifications must be made to add components without the need of sewing		No modifications needed.
Options for attachment points or level of support	The harness does not have hip attachments on the sides or a back attachment	The harness does not have hip attachments on the sides, but there is an attachment point on the back	The harness has hip attachments on the sides but no attachment on the back	The harness has three or more attachment points but not in the desired location	The harness has three or more attachment points in the desired locations
Cost	The cost is more than $100	The cost is between $75-100	The cost is between $50-75	The cost is between $25-50	The cost is between $0-$25
User Comfort	The harness has exposed webbing everywhere it contacts the user.		Some parts of the harness offer padded webbing while other sections are just webbing.		All points of contact with the body are padded.

User Attachment: Harnessing

- ANSI/ASSE Z359.11-2014 standards
- OSHA compliant
- Meets human adjustability requirements - one size fits all
- May need to add additional waist belt to distribute loads

KwikSafety Thunder Safety Harness

Backup: Suspension Tests

Suspension/User Attachment Test(s)

Suspension

- Weight drop test

Rotation System

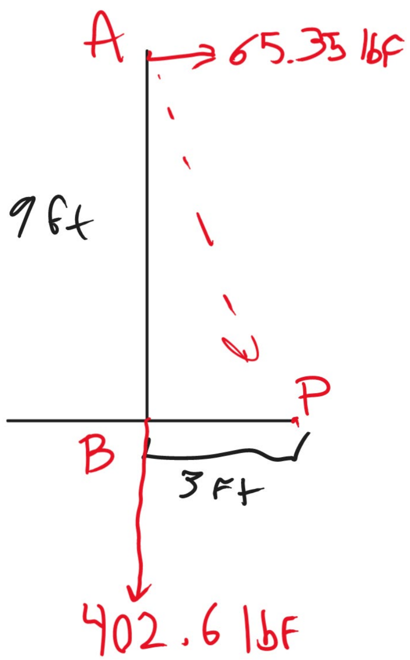
- Weld strength test
- Load bearing test
- Joints strength/freedom of movement

Harness

- Comfort test
- Forced sitting test

Backup:
Structure Material Selection and Moment Analysis

Backup:
Lateral Moment Test



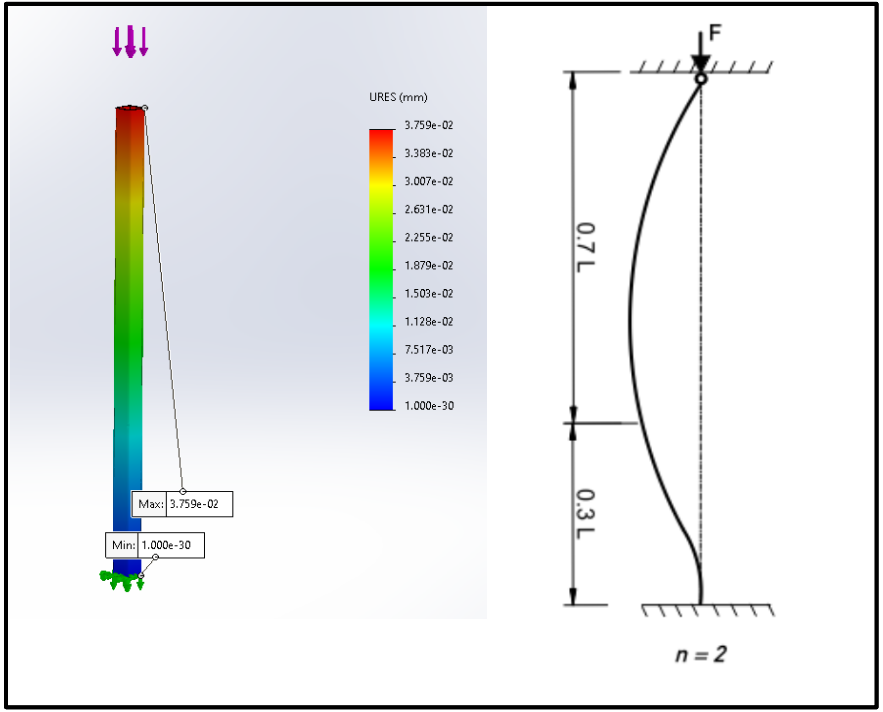
$M_{P,A}$= Fd = 65.35(9) = 588.14 lb-ft

$M_{P,B}$= Fd = 402.6(3) = 1207.68 lb-ft

$M_{P,tot}$= M_A+M_B = 1207.68 - 588.14 = 805.08 lb-ft

Conclusion: Structure is laterally stable

Column Buckling and Tipping Moment Model



Buckling Calculations:

$$F_{buckle} = n\pi^2 EI / L^2$$

- One end fixed: n = 0.7
- E = 27.5x10^3 ksi
- I = 6.94 in^4

Max static buckling load: 113000 lbs

Moment Calculations:

- A lateral force of 400 lbs would be required to cause the structure to tip over

Material Selection

A500 B Steel:

- Young's Mod: 27.5×10^3 ksi
- YS: 46 ksi
- TS: 58 ksi
- Does not warp to TS over time

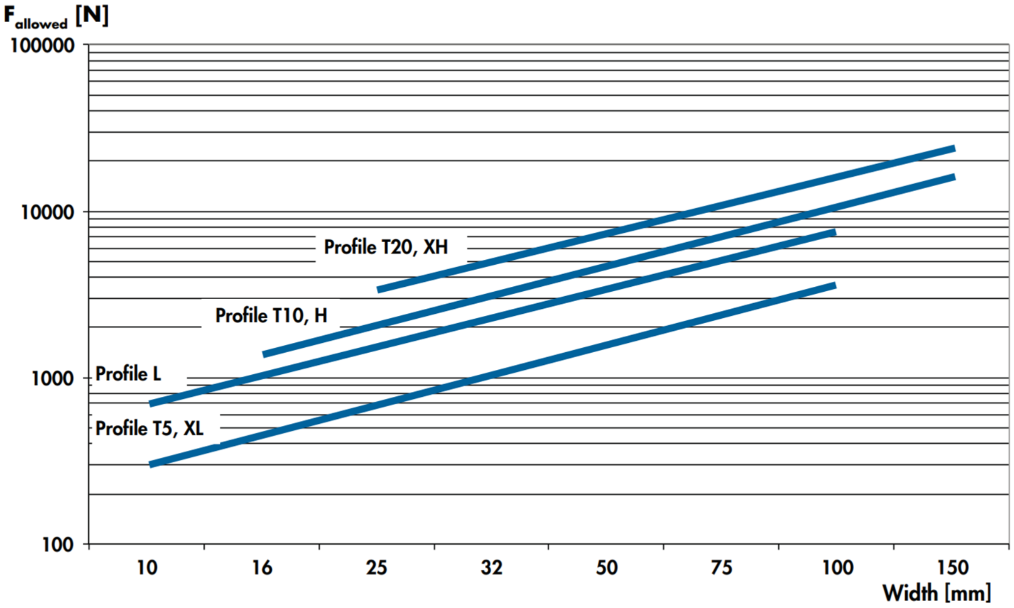
Wood

- Flexural Mod: 8.56 ksi
- YS: 6000 psi
- TS: 305 psi
- Warps over time and repeated usage

Backup:
Belt Selection and Tensile data

Belt Empirical Data

Diagram 4.3.1: T and imperial profile, permitted tensile forces $F_{allowed}$ depending on profile and width in a simplified representation



1 in width = 25.4 mm

Max tension: 1100 N

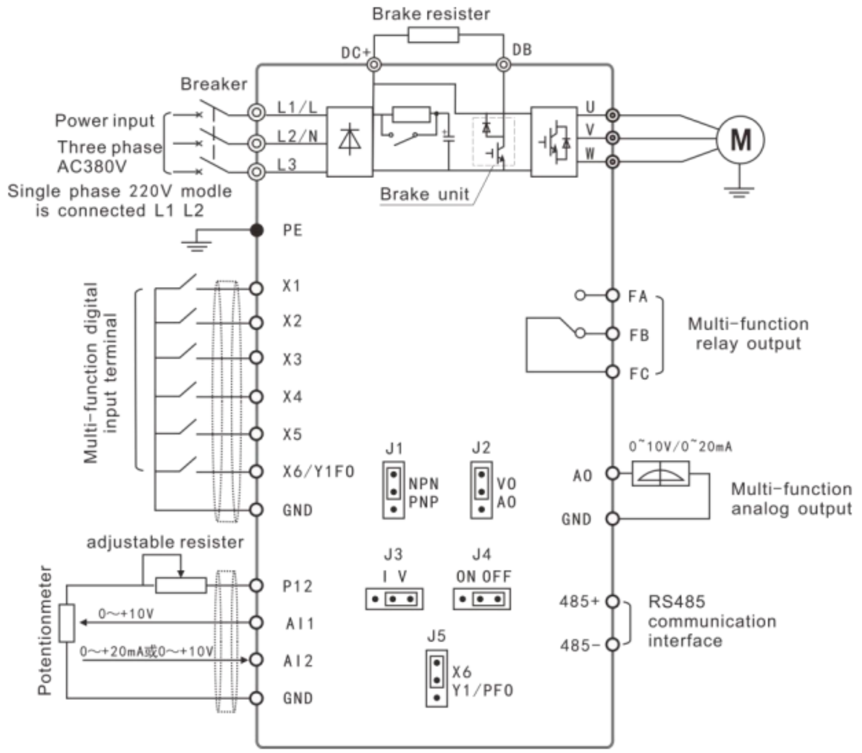
Max predicted tension: 124.5 N

Backup: Electronics

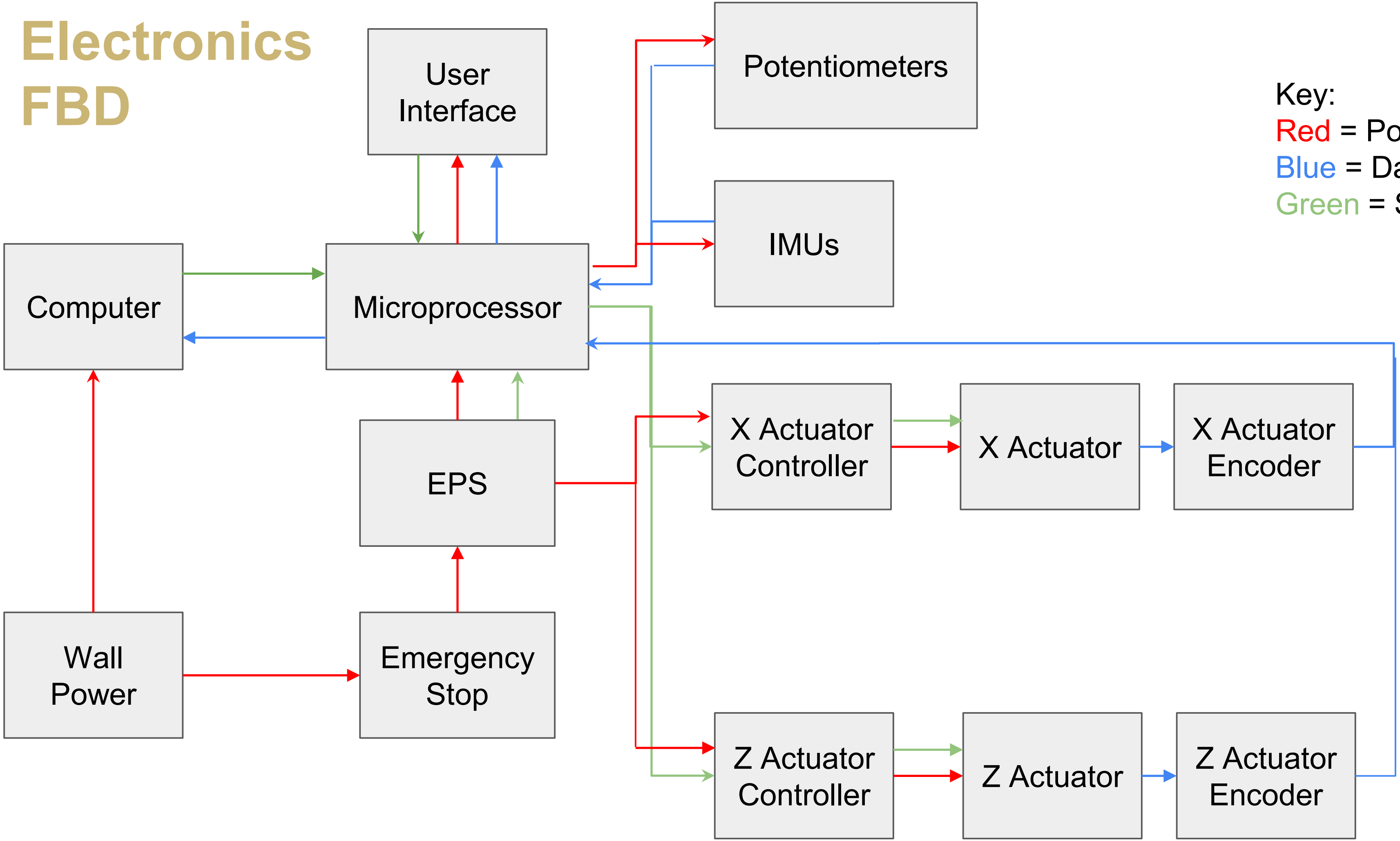
Power Budget

Part	Quantity	Continuous Current (A)	Peak Current (A)	Voltage (V)	Power (W)	Peak Power (W)
Microprocessor	1	0.4	0.82	5	2	4.1
Motor (x)	1	0.98		90 VDC	88.25	
Motor (z)	1	9.73	15.2	115 V	1118.55	1748
VFD	2	0.150	0.150	12	1.8	1.8
Potentiometers	2	.000625	.001	3.3	0.125	.2
IMUs	2	0.00123	0.00123	5	0.00615	0.00615

VFD Controller Pinout



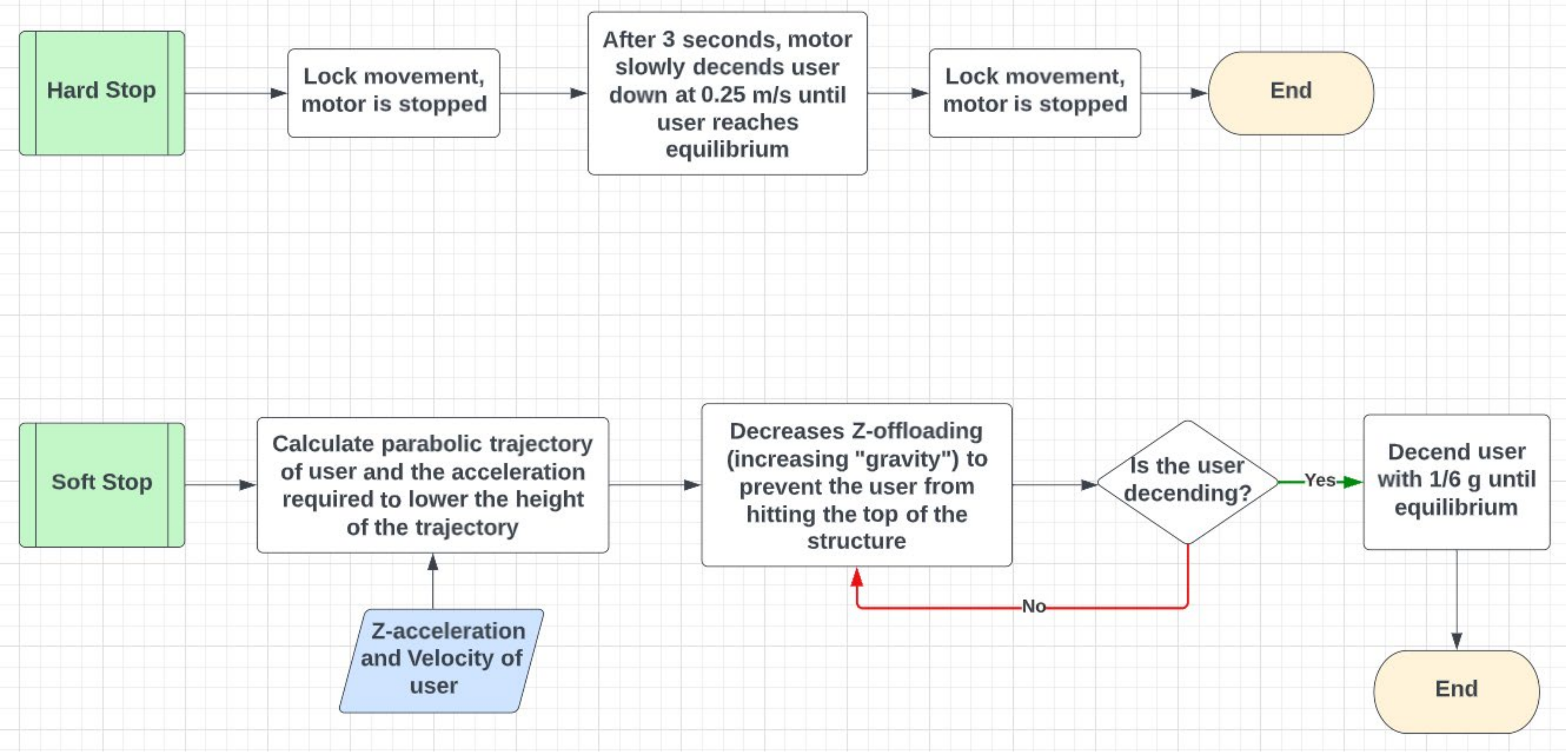
Electronics FBD



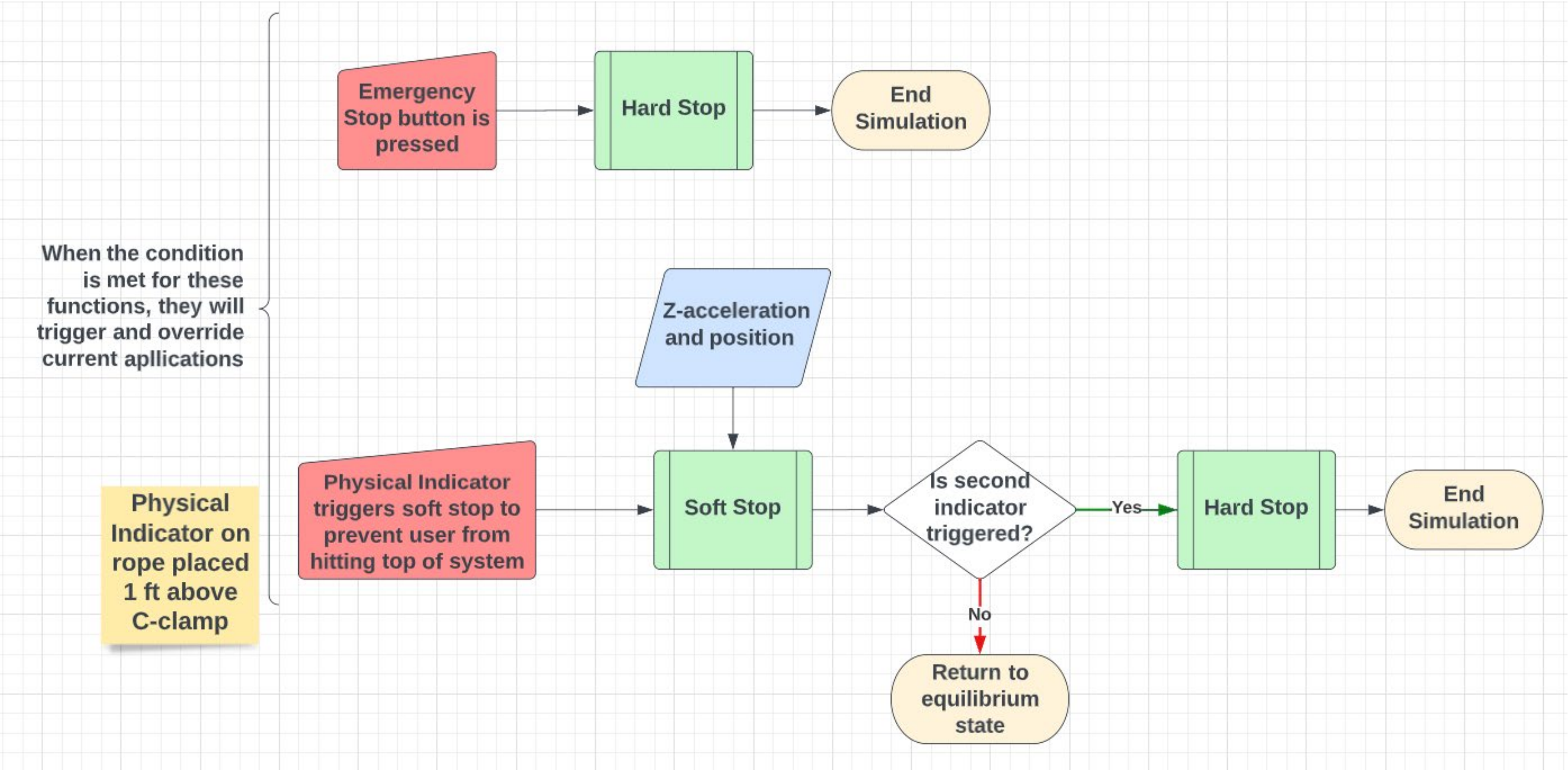
Key:
Red = Power
Blue = Data
Green = Signals

Backup:
Software Slides

Software FBD



Software FBD



Software - X-Translation, the “Joystick”

- Small angle sensor detects when the user begins to move in the x-direction
- Activates motor to move along with user
- Angle sensor detects once the user comes to a halt, then slows down the motor to a halt

Requirements: L3-92 The software shall command the movement system to move to the x-position of the user.

Software - Soft and Hard Stops

- Physical indicators placed along to prevent the user from hitting the top of the system
- First indicator is placed 1 ft above the V-clamp. When this passes through the joystick, it activates the soft stop
- Second indicator is placed directly above the V-clamp. This cannot pass through and when it hits the joystick, it activates the hard stop

Requirements: L3-96 The software shall command the actuators to slow the user's movement in the z-direction to prevent the user from moving outside of the system space