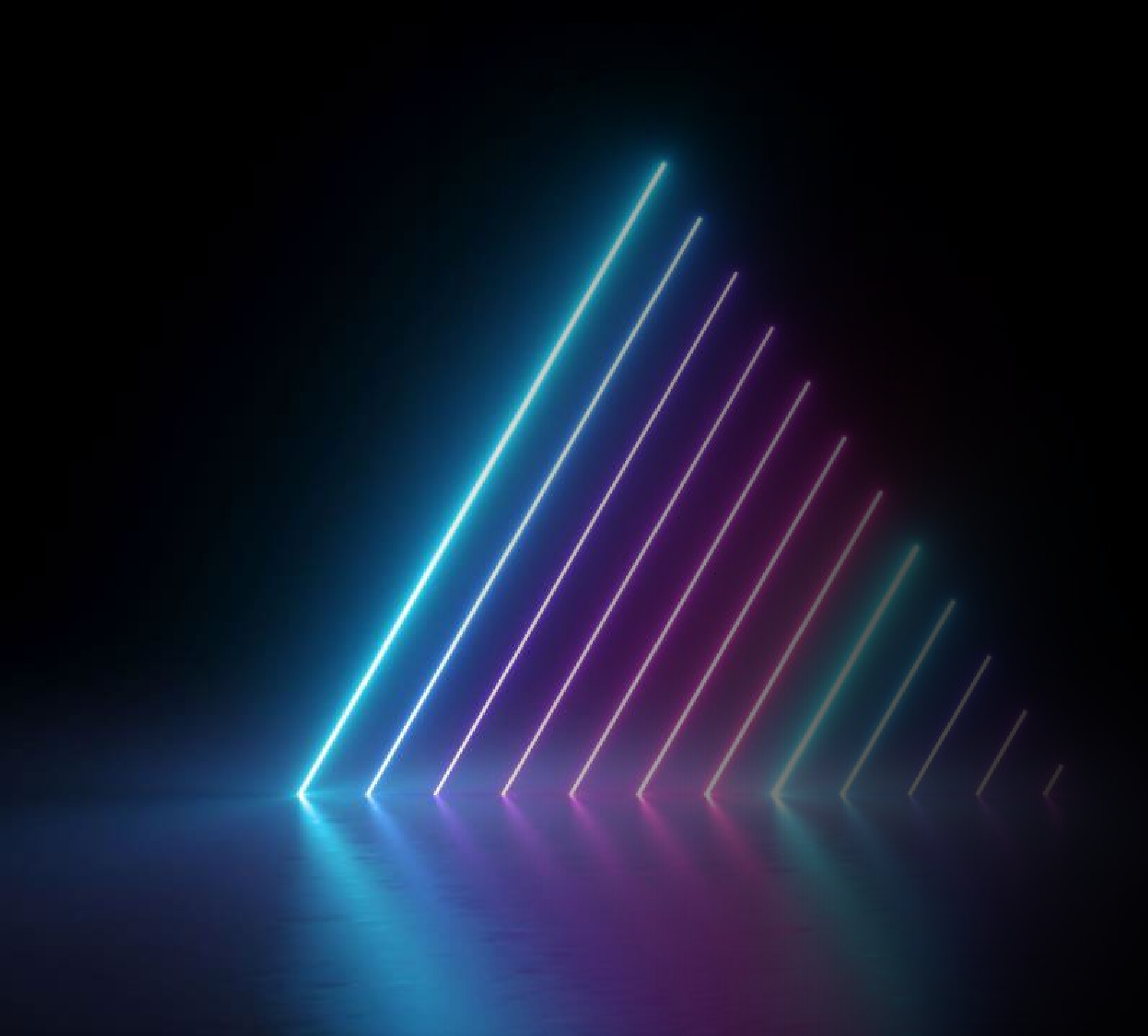


HEIST

Test Readiness Review

ASEN 4028 - Team 5

ANN & HJ SMEAD AEROSPACE
ENGINEERING SCIENCES

HEIST

HYBRID ENVIRONMENTAL IMMERSIVE
SIMULATION TRAINING

INTAKE NUMBER:
4018/4028

DATE:
2022/2023

Agenda

- Overview
- Schedule
- Test Readiness
- Budget

Main Acronyms and Definitions

VR - *Virtual Reality*	• Computer-generated environment
PR - *Physical Reality*	• The world we live in
HR - *Hybrid Reality*	• VR and PR combined. Interaction with PR has consequences in VR
EVA - *Extravehicular Activity*	• Astronaut activity outside of a spacecraft/habitat
ORU - *Orbital Replacement Unit*	• Block of electrical components for easy replacement/fixes
MSSQ - Motion Sickness Susceptibility Questionnaire	• Form given to test subjects to predict likelihood of motion sickness
BS - Base Station	• Device used to obtain the location of object trackers

Overview

Mission Statement

The HEIST system will develop the capability to train humans for lunar EVA habitat maintenance and repair operations using HR.

Project’s Goals

Develop a hybrid reality (HR) training system (VR + PR)

- Track the user’s interaction with PR hardware
- Track the user’s motion (head and hands) in PR
- Display the outcomes of the user’s actions in VR

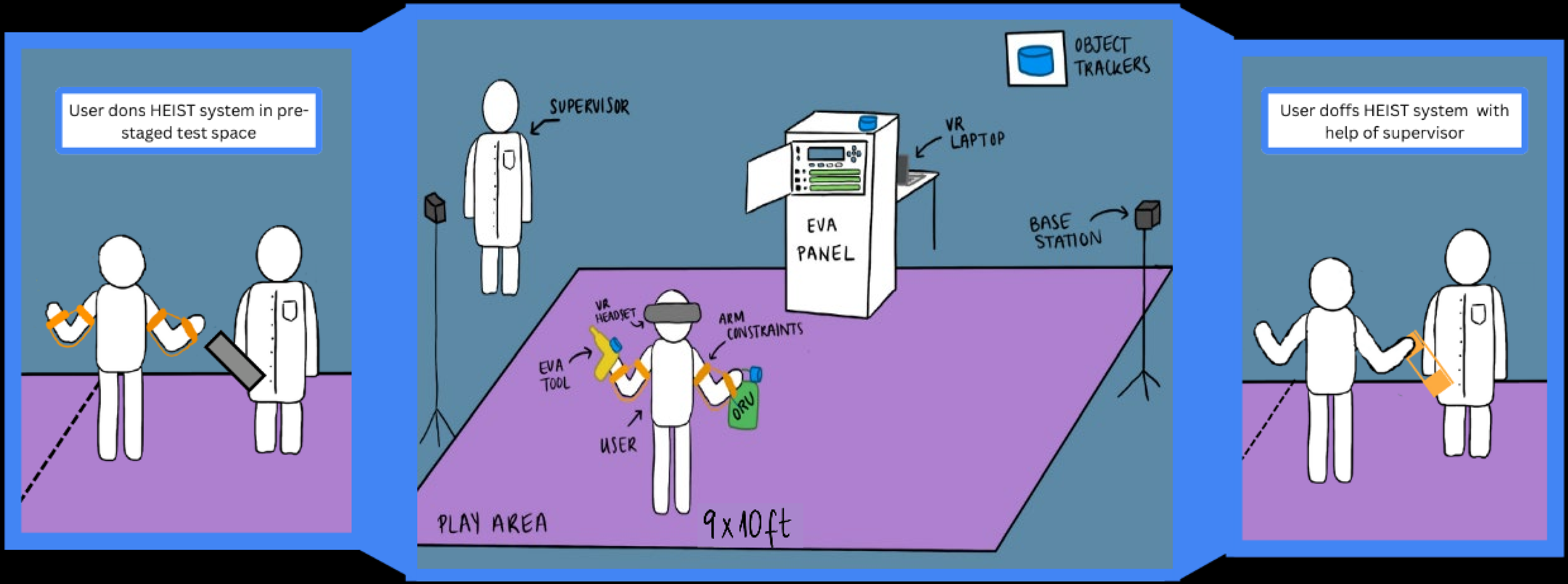
Increase training immersion

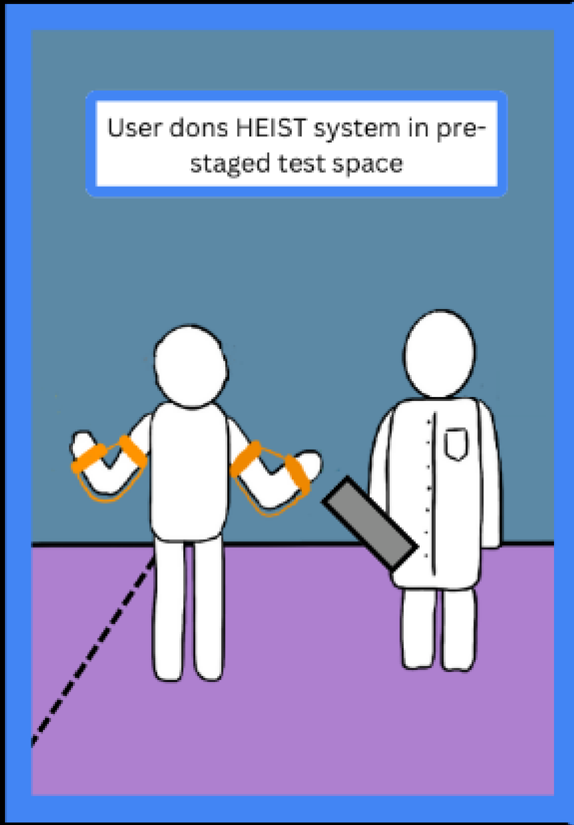
- Constrain user’s arm and shoulder motion
- Display environmental constraints (in VR)

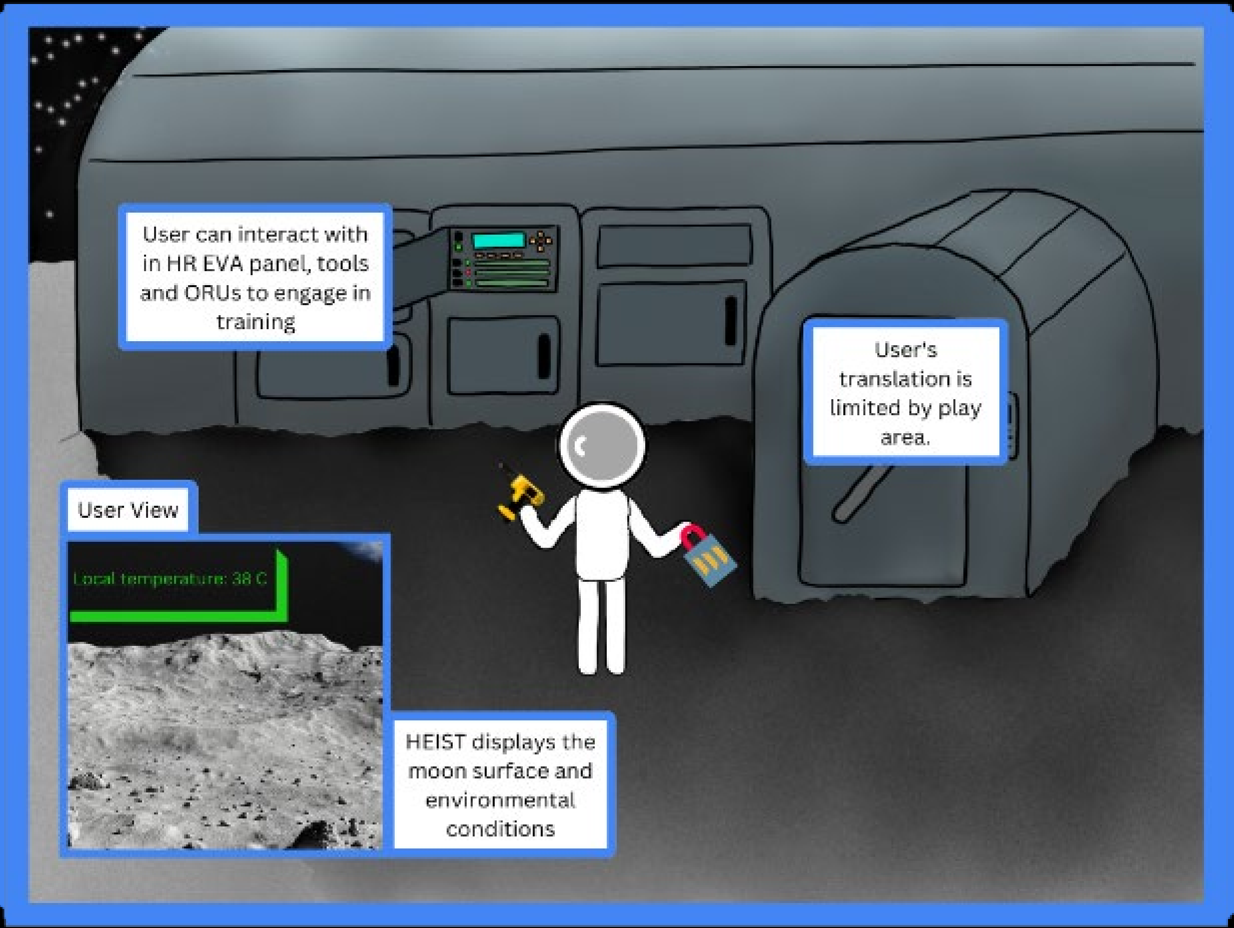
Create a safe and versatile training environment

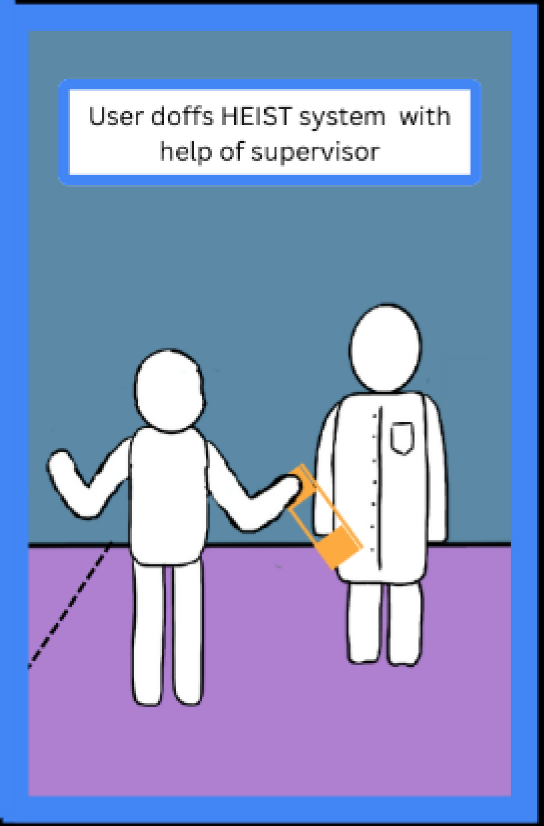
Objectives & Levels of Mission Success

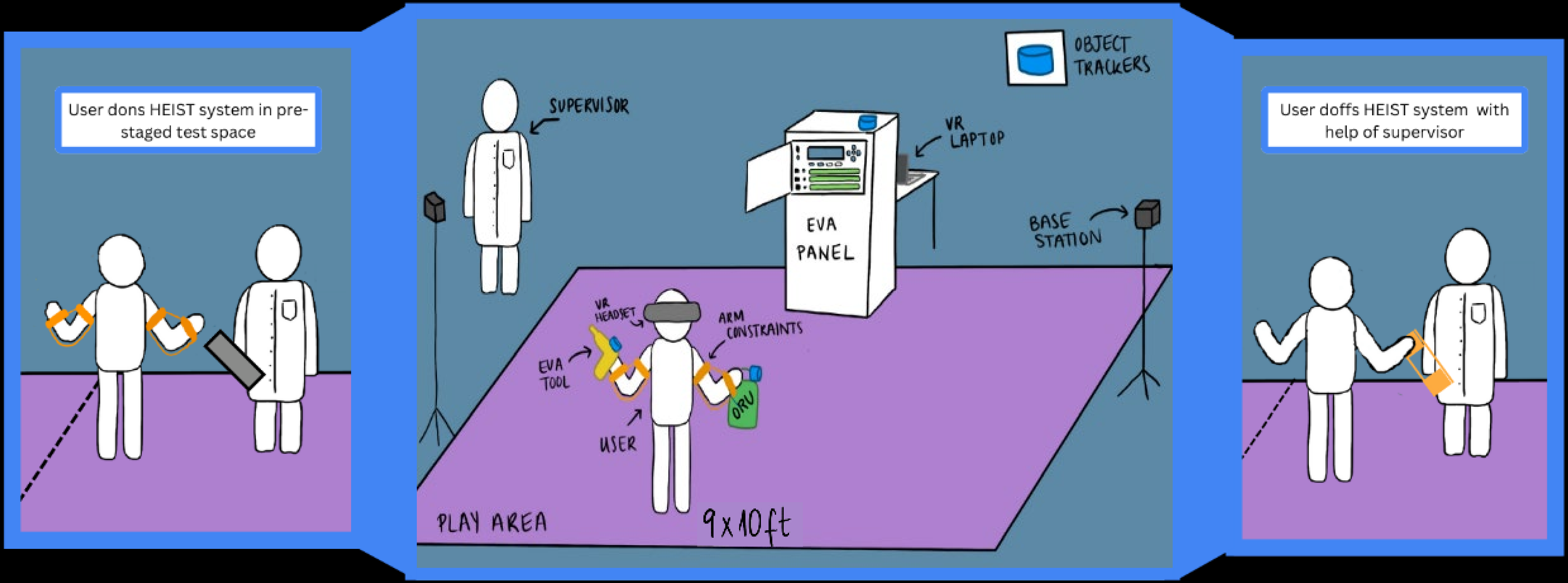
Objectives	Level 1 Success	Level 2 Success
VR Environment	The project must include a VR environment that allows for some user interaction and resembles a lunar environment	The project must include a fully interactive and visually accurate VR lunar environment that includes shadows, lighting, and lunar textures
Integrate with Real-World Elements	The project must allow for **one** tool and/or panel to integrate from PR to the VR environment, resulting in an HR environment	The project must allow for the integration of **multiple** tools and/or panels in the HR environment
Lunar Environment Conditions	The project will represent lunar lighting, temperature, **or** auditory inputs	The project will simulate lunar lighting, temperature, **and** auditory inputs
Movement Constraints	The project will incorporate range-of-motion constraints that limit arm and shoulder mobility more than regular clothes	The project will incorporate range-of-motion constraints that limit arm, upper-body, and hand mobility


User dons HEIST system in pre-staged test space
OBJECT TRACKERS
SUPERVISOR
VR LAPTOP
EVA PANEL
BASE STATION
VR HEADSET
ARM CONSTRAINTS
EVA TOOL
ORU
USER
PLAY AREA
9x10ft
User doffs HEIST system with help of supervisor


User dons HEIST system in pre-staged test space


User can interact with in HR EVA panel, tools and ORUs to engage in training
User's translation is limited by play area.
User View
Local temperature: 38 C
HEIST displays the moon surface and environmental conditions


User doffs HEIST system with help of supervisor



User dons HEIST system in pre-staged test space
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EVA PANEL
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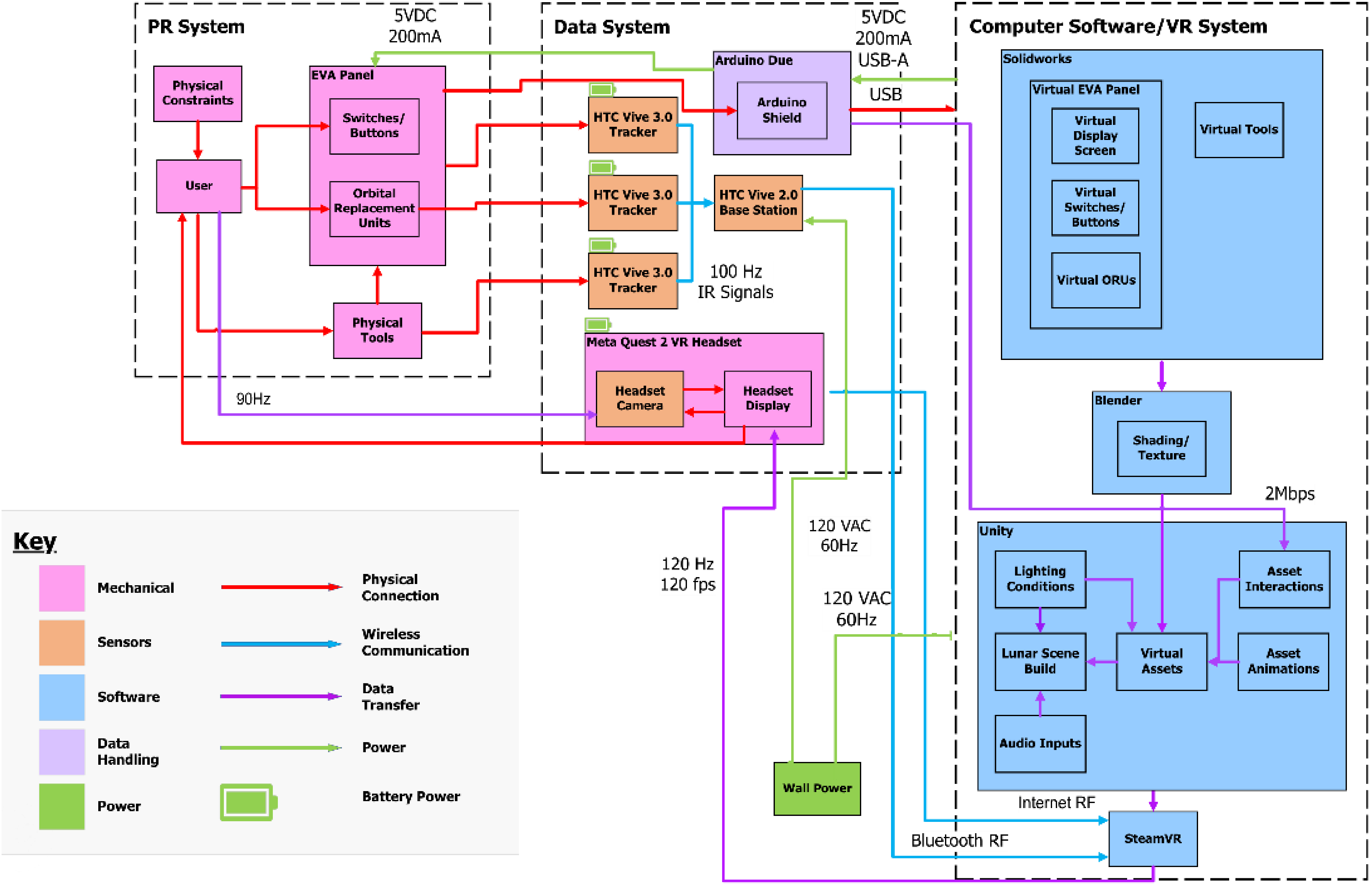
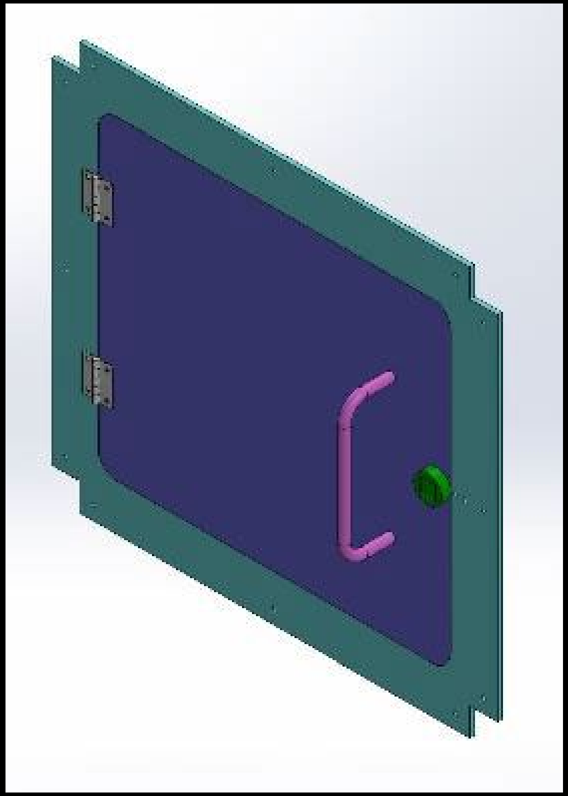
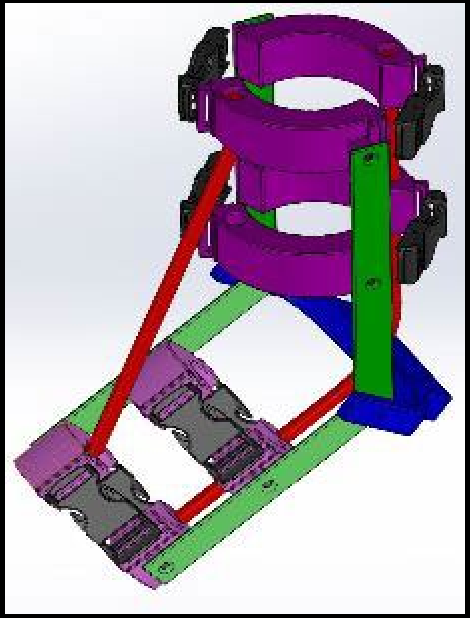

PR System
5VDC
200mA
Physical Constraints
EVA Panel
Switches/ Buttons
User
Orbital Replacement Units
Physical Tools
90Hz
Data System
5VDC
200mA
USB-A
Arduino Due
Arduino Shield
USB
HTC Vive 3.0 Tracker
HTC Vive 3.0 Tracker
HTC Vive 2.0 Base Station
HTC Vive 3.0 Tracker
100 Hz
IR Signals
Meta Quest 2 VR Headset
Headset Camera
Headset Display
120 Hz
120 fps
120 VAC
60Hz
120 VAC
60Hz
Wall Power
Computer Software/VR System
Solidworks
Virtual EVA Panel
Virtual Display Screen
Virtual Switches/ Buttons
Virtual ORUs
Virtual Tools
Blender
Shading/ Texture
2Mbps
Unity
Lighting Conditions
Asset Interactions
Lunar Scene Build
Virtual Assets
Asset Animations
Audio Inputs
Internet RF
Bluetooth RF
SteamVR
Key
Mechanical
Sensors
Software
Data Handling
Power
Physical Connection
Wireless Communication
Data Transfer
Power
Battery Power

Major Design Changes

- Arm Harness Design
  - Resistance Bands
  - 3D Printed Straps
  - Elbow Joint Hinge Method
- ORUs will be made from MDF wood instead of 3D-printed
- Panels will be made from MDF wood instead of foamed PVC
- Obtained Valve Index BS 2.0





Schedule

HEIST Tests

Test Name	Location	Equipment	HITL?
Arm Harness Elastic Bands	MTS Room	MTS Machine	No
Switch/Button Bouncing Time	AERO 150	Oscilloscope	No
EVA Panel Tipping	AERO 140	Safety foam, fish scale, weights	No
Headset Battery Discharge		-	No
Computer Processing Workload			
Hand Tracking Accuracy		Ruler, 1 tracker	Yes
Object Tracking Accuracy			
Arm Harness Counter-Torque		Fish scale, camera, tripod, test rig (HEIST design)	No
Arm Harness Comfort		-	Yes
HR Latency		Arduino DUE, button	Yes
HEIST Day-In-The-Life	AERO 140	-	Yes

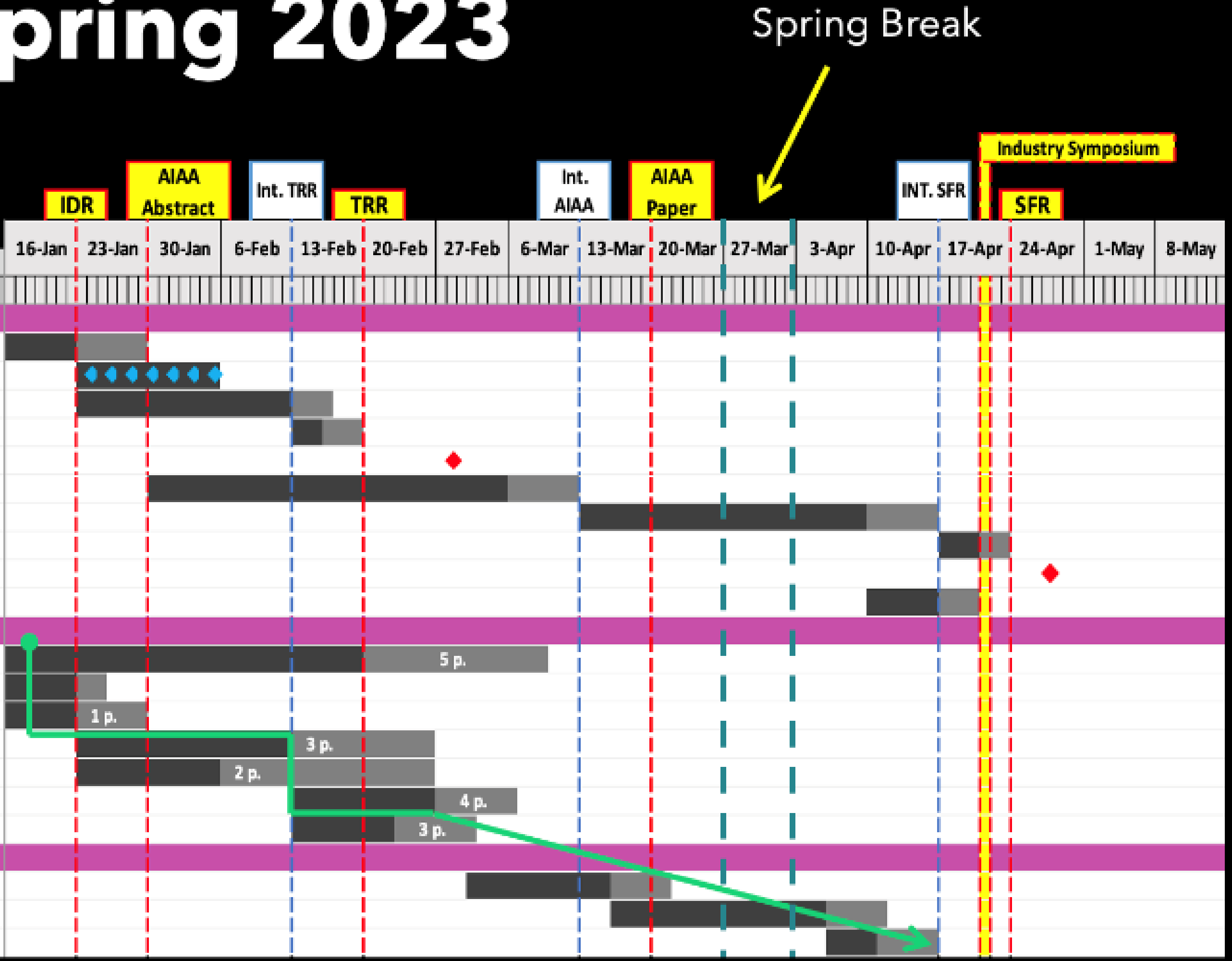
CDR Gantt Chart
Spring 2023

WBS & GANTT CHART

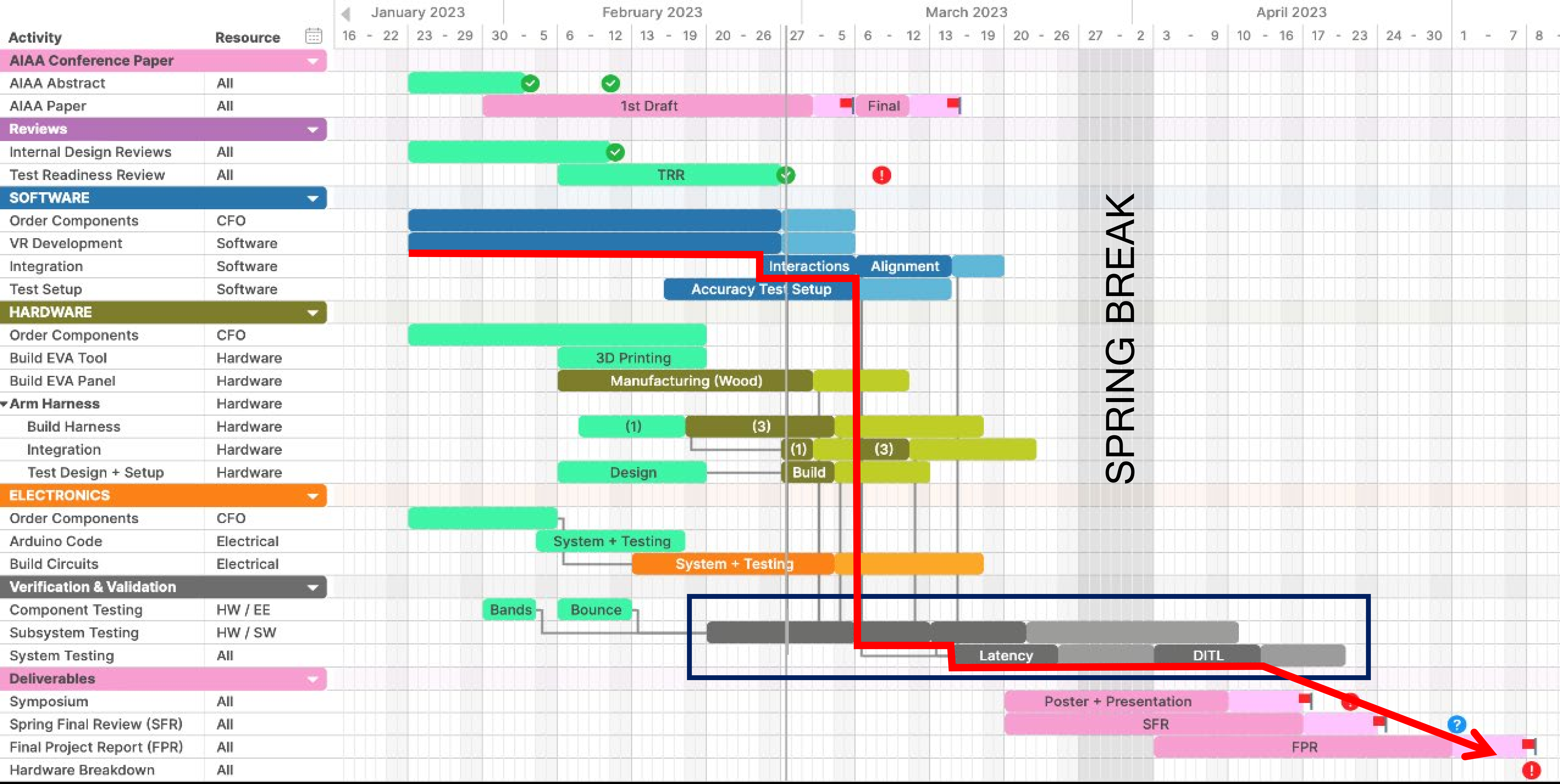
SEMESTER START DATE	16-Jan-23
SEMESTER END DATE	10-May-23

LEGEND	
ES	EARLY START
EF	EARLY FINISH
LS	LATE START
LF	LATE FINISH

TASK	DAYS DURATION	DATE ES	DATE EF	DATE LS	DATE LF	DAYS FLOAT
DELIVERABLES						
AIAA Abstract	7	16-Jan	22-Jan	23-Jan	29-Jan	7
Internal Design Review	14	23-Jan	5-Feb	23-Jan	5-Feb	0
Test Readiness Review - SLIDES	21	23-Jan	12-Feb	27-Jan	16-Feb	4
Test Readiness Review - SLIDE REVIEW	3	13-Feb	15-Feb	17-Feb	19-Feb	4
Test Readiness Review - PRESENTATION	1	27-Feb	27-Feb	27-Feb	27-Feb	0
AIAA Paper	35	30-Jan	5-Mar	6-Feb	12-Mar	7
Spring Final Review - SLIDES	28	13-Mar	9-Apr	20-Mar	16-Apr	7
Spring Final Review - SLIDES REVIEW	4	17-Apr	20-Apr	20-Apr	23-Apr	3
Spring Final Review - PRESENTAION	1	26-Apr	26-Apr	26-Apr	26-Apr	0
Prepare Symposium	7	10-Apr	16-Apr	14-Apr	20-Apr	4
BUILD & DEVELOPMENT						
Develop VR Environment	35	16-Jan	19-Feb	3-Feb	9-Mar	18
Order Components	7	16-Jan	22-Jan	19-Jan	25-Jan	3
Build EVA Tool	7	16-Jan	22-Jan	23-Jan	29-Jan	7
Build Arm Constraints	21	23-Jan	12-Feb	6-Feb	26-Feb	14
Build EVA Panel + Electronics	14	23-Jan	5-Feb	13-Feb	26-Feb	21
Integration	14	13-Feb	26-Feb	21-Feb	6-Mar	8
Testing Setup: Hardware & Software	10	13-Feb	22-Feb	21-Feb	2-Mar	8
VERIFICATION & VALIDATION						
Phase T1: Component Testing	14	2-Mar	15-Mar	8-Mar	21-Mar	6
Phase T2: Subsystem Testing	21	16-Mar	5-Apr	22-Mar	11-Apr	6
Phase T3: Day-in-the-life testing	5	6-Apr	10-Apr	12-Apr	16-Apr	6



Intro | Overview | Schedule | Test Readiness | Budget

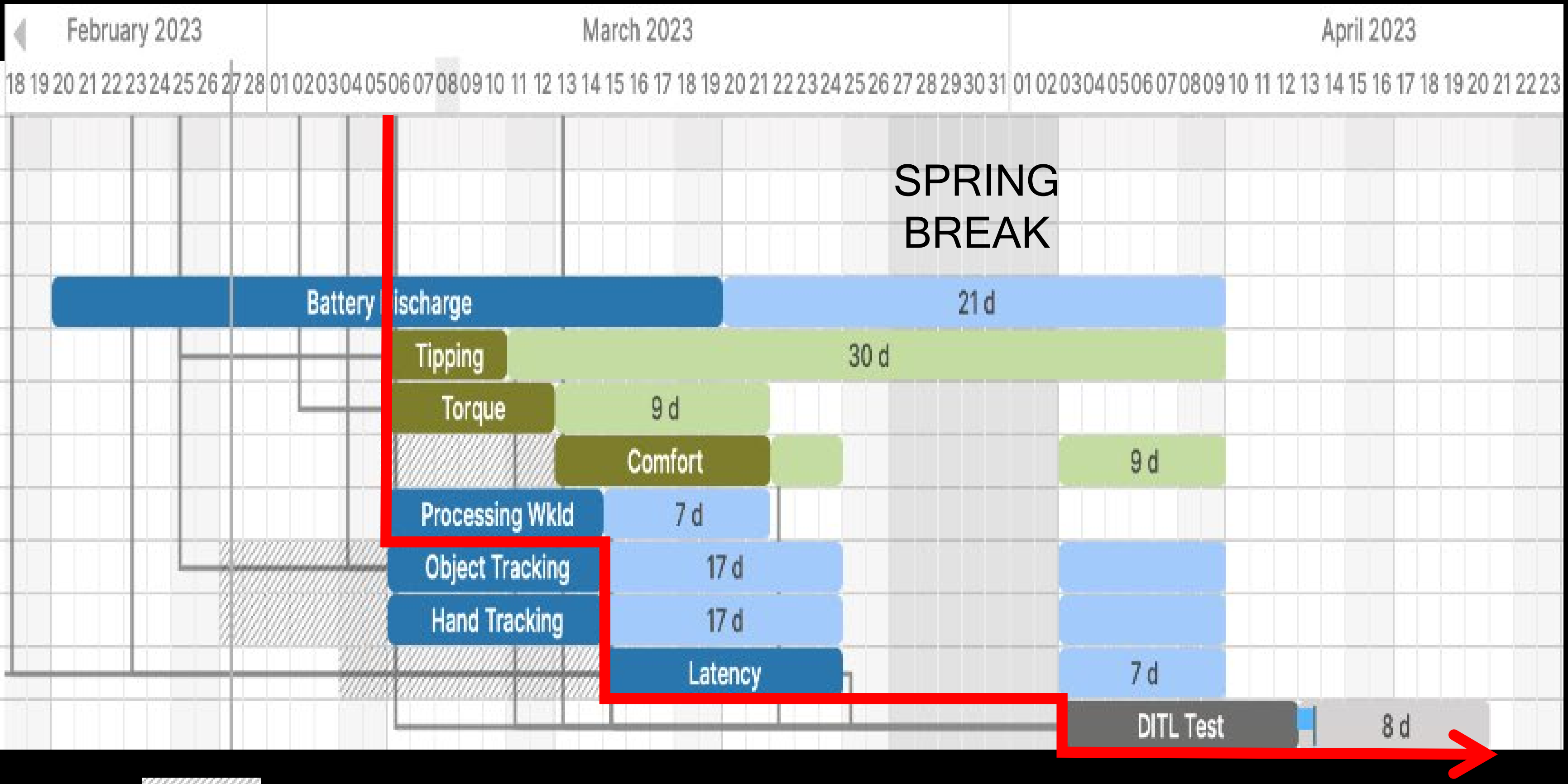

January 2023
February 2023
March 2023
April 2023
16 - 22
23 - 29
30 - 5
6 - 12
13 - 19
20 - 26
27 - 5
6 - 12
13 - 19
20 - 26
27 - 2
3 - 9
10 - 16
17 - 23
24 - 30
1 - 7
8
Activity
Resource
AIAA Conference Paper
AIAA Abstract
All
AIAA Paper
All
1st Draft
Final
Reviews
Internal Design Reviews
All
Test Readiness Review
All
TRR
SOFTWARE
Order Components
CFO
VR Development
Software
Integration
Software
Interactions
Alignment
Test Setup
Software
Accuracy Test Setup
HARDWARE
Order Components
CFO
Build EVA Tool
Hardware
3D Printing
Build EVA Panel
Hardware
Manufacturing (Wood)
Arm Harness
Hardware
Build Harness
Hardware
(1)
(3)
Integration
Hardware
(1)
(3)
Test Design + Setup
Hardware
Design
Build
ELECTRONICS
Order Components
CFO
Arduino Code
Electrical
System + Testing
Build Circuits
Electrical
System + Testing
Verification & Validation
Component Testing
HW / EE
Bands
Bounce
Subsystem Testing
HW / SW
System Testing
All
Latency
DITL
Deliverables
Symposium
All
Poster + Presentation
Spring Final Review (SFR)
All
SFR
Final Project Report (FPR)
All
FPR
Hardware Breakdown
All
SPRING BREAK

Testing Schedule

- Software
- Software Margin
- Hardware
- Hardware Margin

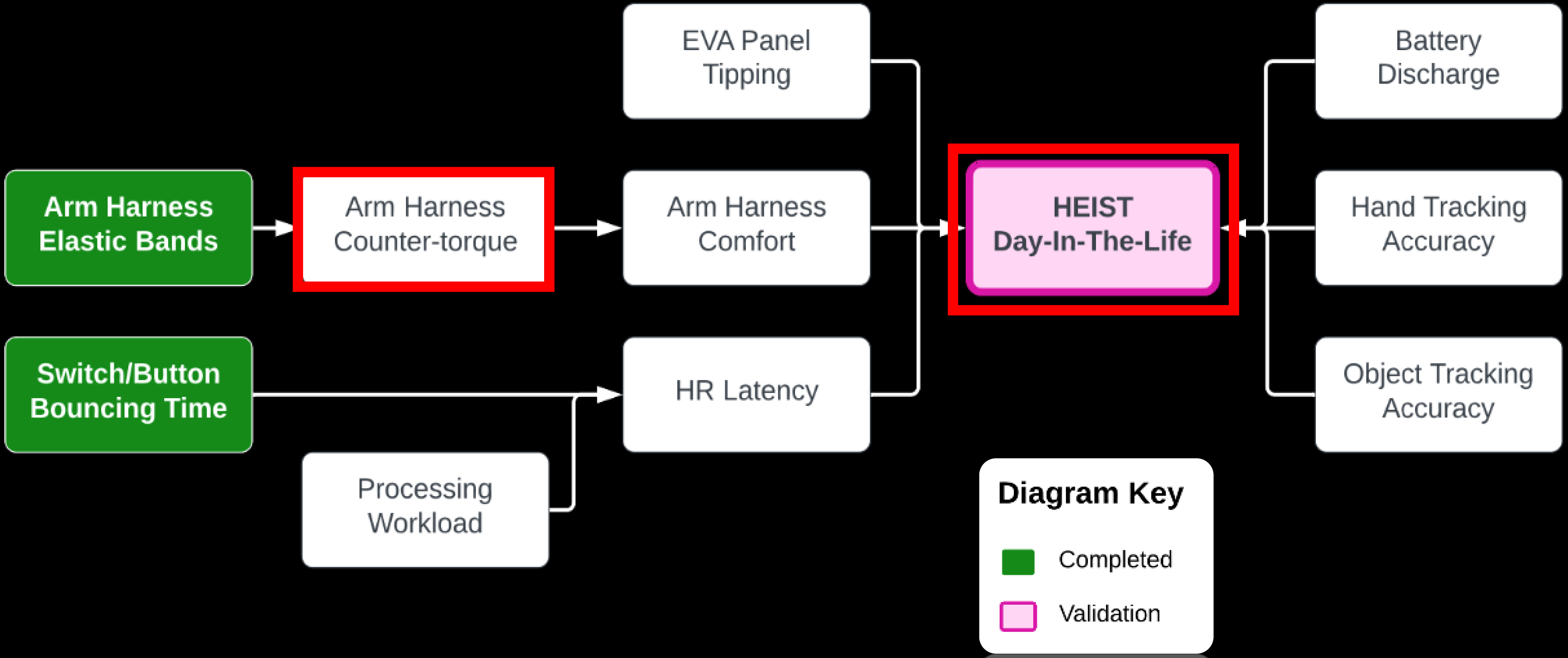
- External Deadline
- Internal Deadline
- Critical Path

Task #	Activity	Resource	S
7	Verification & Validation		→
7.1	Test Resistance Bands	Hardware	✓
7.2	Switch/Button Bouncing	Electrical	✓
7.3	Battery Discharge	Software	→
7.4	EVA Panel Tipping	Hardware	
7.5	Counter-torque	Hardware	
7.6	Arm Harness Comfort	Hardware	
7.7	Processing Workload	Software	
7.8	Object Tracking Accuracy	Software	
7.9	Hand Tracking Accuracy	Software	
7.10	HR Latency	Software	
7.11	Day-in-the-life	All	



Test Subject Search

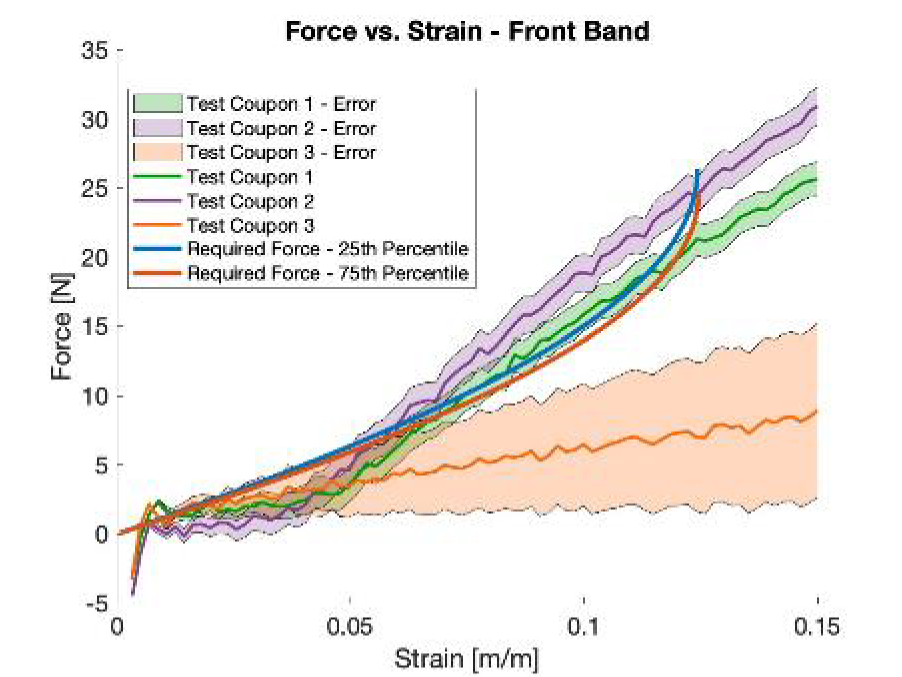
Test Readiness

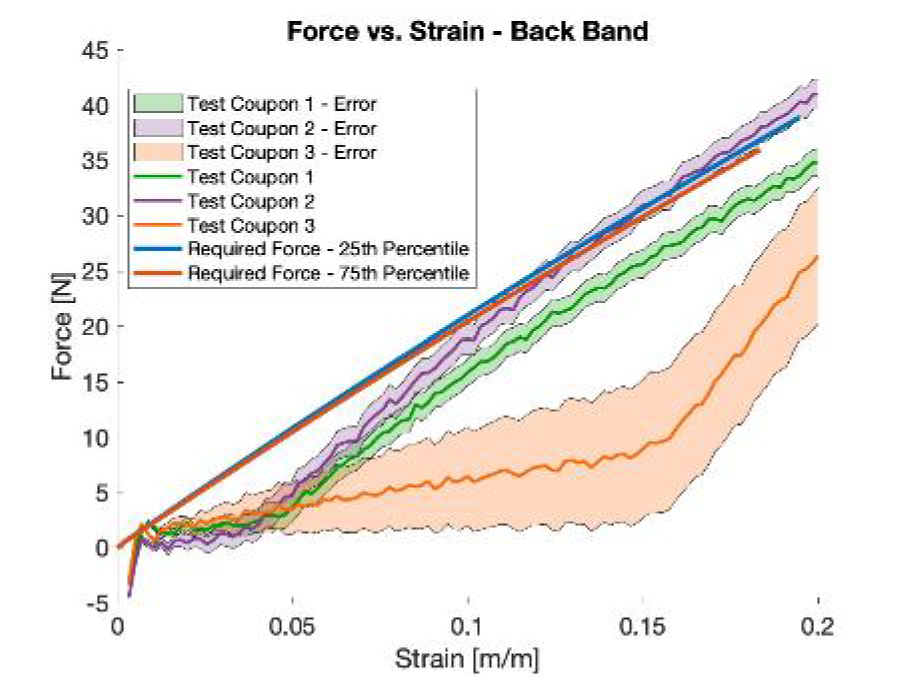

Arm Harness Elastic Bands
Arm Harness Counter-torque
EVA Panel Tipping
Arm Harness Comfort
Switch/Button Bouncing Time
HR Latency
Processing Workload
HEIST Day-In-The-Life
Battery Discharge
Hand Tracking Accuracy
Object Tracking Accuracy
Diagram Key
Completed
Validation

COMPLETED Arm Harness Elastic Bands

DR 2.1.2.1 - The PCs shall provide counter-torque to the elbow within a range of **-6 to 7 ± 10%** Nm.

- Used MTS Machine to obtain the Force vs. Displacement values for each Test Coupon (TC)
- Determined that the front band will be TC1 and back band will be TC2

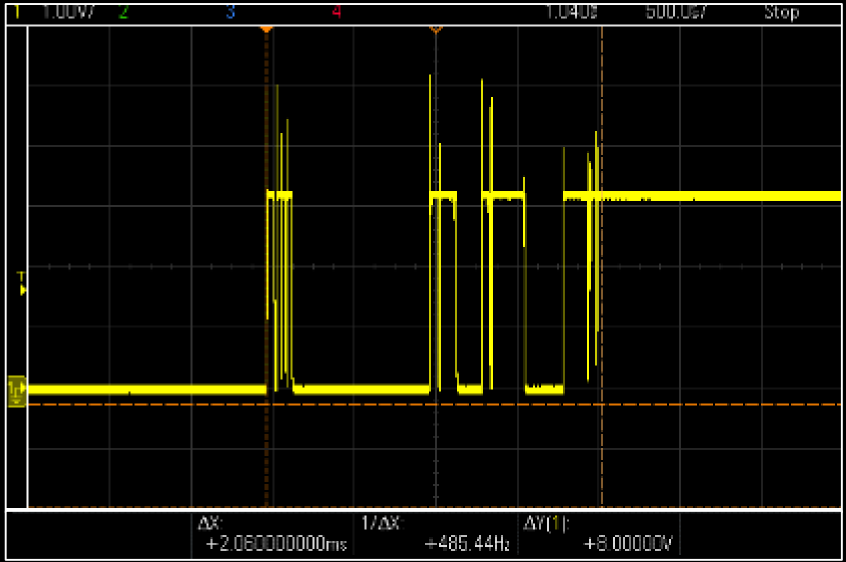


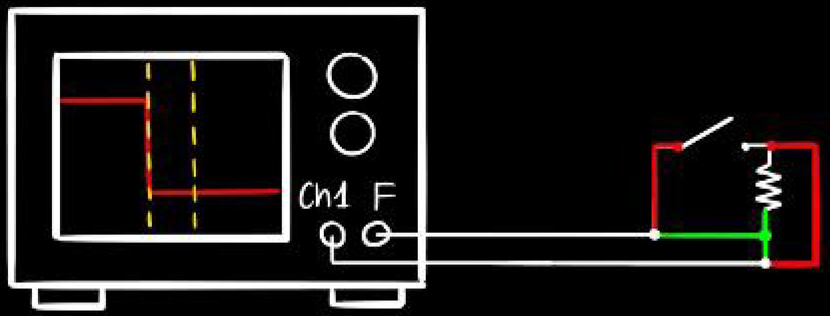


COMPLETED Switch/Button Bouncing Time

DR 1.2.2 – The state of PR input devices shall be sampled at a rate of at least **90 Hz**.

- Clicked buttons / flipped switches to find settling time to determine maximum sampling rate.
- Determined that all buttons and switches work in accordance with specifications and HEIST can sample at **300Hz** (FS = 1.5) if needed.





Settling Time	Buttons	Switches
Average (AVG) [ms]	1.62	0.69
Absolute error (STD) [ms]	0.47	0.11
Relative error (STD/AVG)	29%	16%

Arm Harness Counter-Torque Test

COUNTER TORQUE - Purpose

- **Purpose**: to address concerns during CDR that arm harness would provide either too much or too little counter torque.
  - Too little = not as immersive, doesn't realistically simulate a space suit
  - Too much = might harm the user, be uncomfortable
  - Verify torque profile is within 10% of the EVA suit torque linear fit
- **Past Tests**:
  - Completed the Arm Harness Elastic Band test to find the necessary elastic bands to use in the Arm Harness system
    - Guided prediction of the counter-torque values based on angle

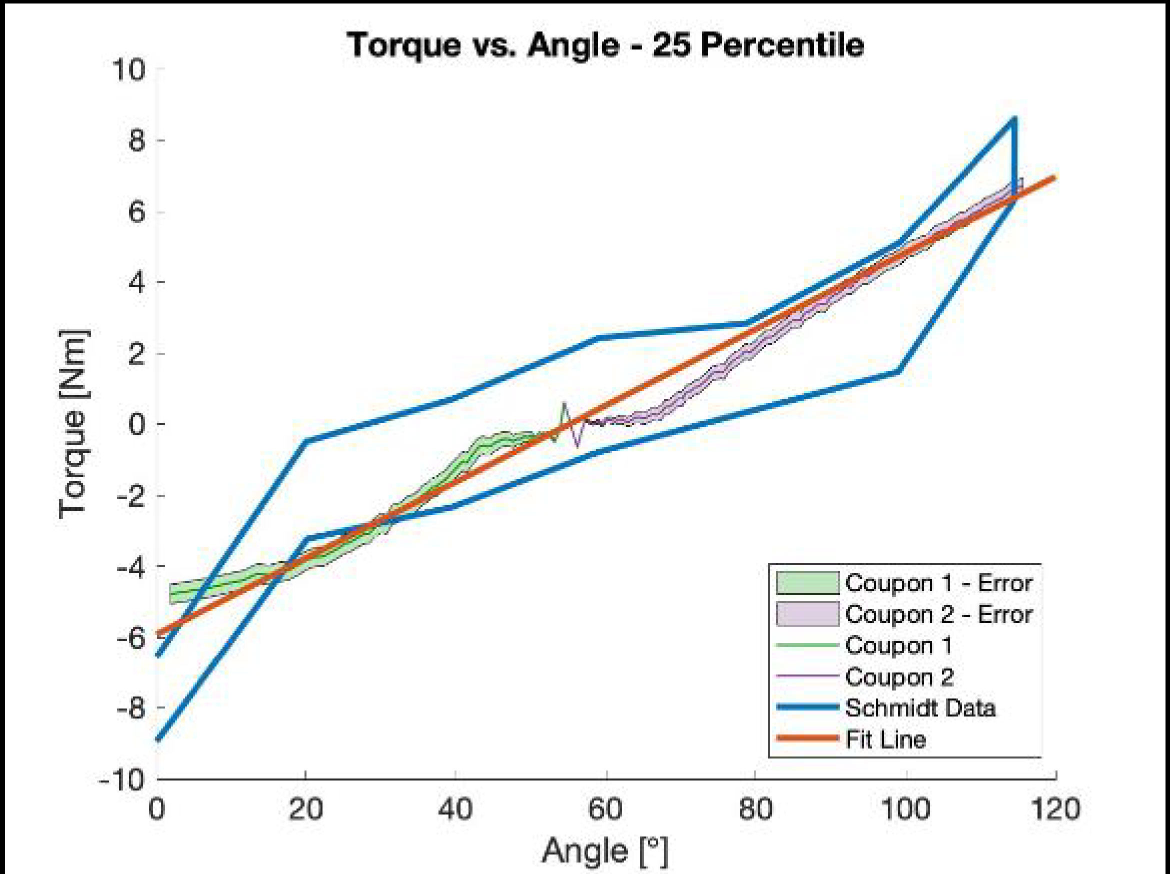
COUNTER TORQUE - Test Summary

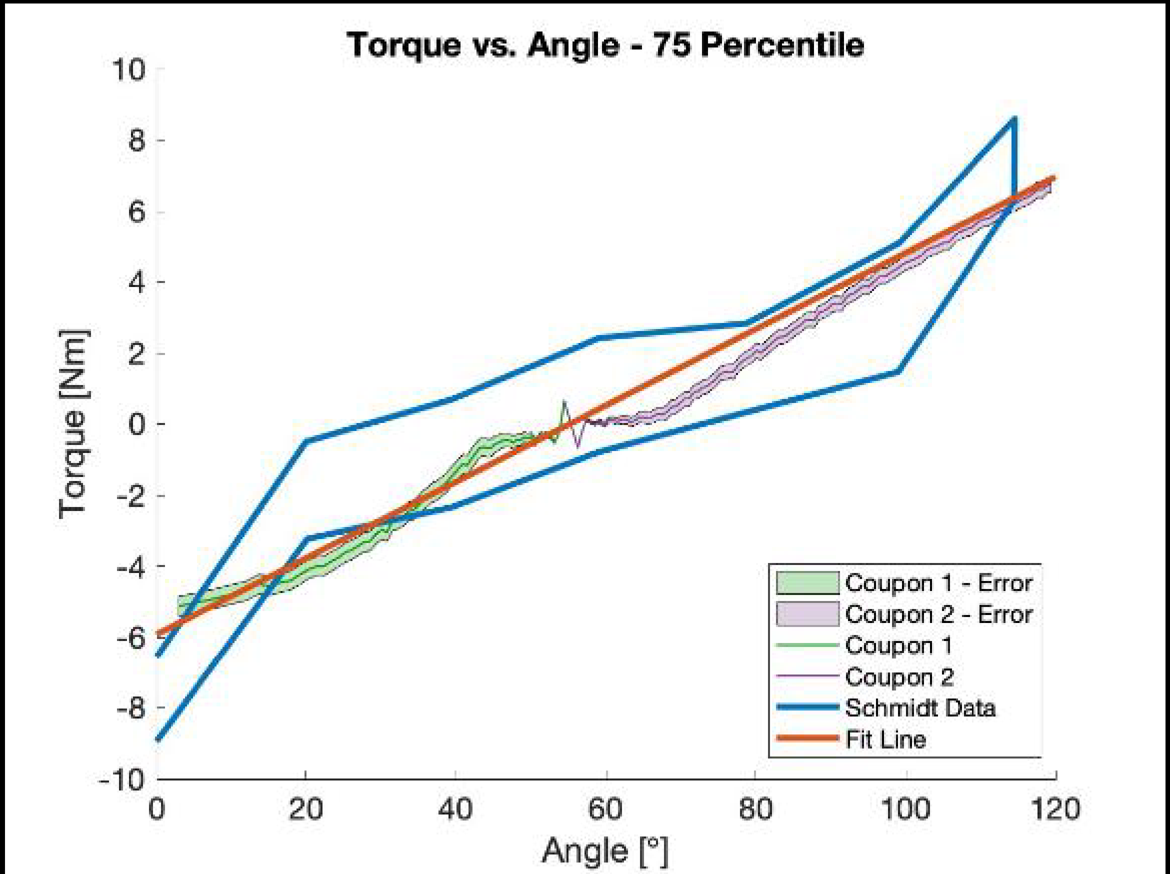
DR 2.1.2 – The PCs shall constrain the user's elbow extension movement within a range of **0 - 115** deg.

DR 2.1.2.1 – The PCs shall provide counter-torque to the elbow within a range of **-6 to 7 ± 10%** Nm.

- The arm harness will be flexed/extended at 5° intervals and the normal force required to keep it there will be measured.
- Torque will be calculated from T = Fr, where F is the measured force, r is the moment arm and T is the torque that the arm harness applies.

COUNTER TORQUE - Expected Data Outputs





COUNTER TORQUE - Pass/Fail Criteria

DR 2.1.2 - The PCs shall constrain the user's elbow extension movement within a range of **0 - 115** deg.

DR 2.1.2.1 - The PCs shall provide counter-torque to the elbow within a range of **-6 to 7 ± 10%** Nm.

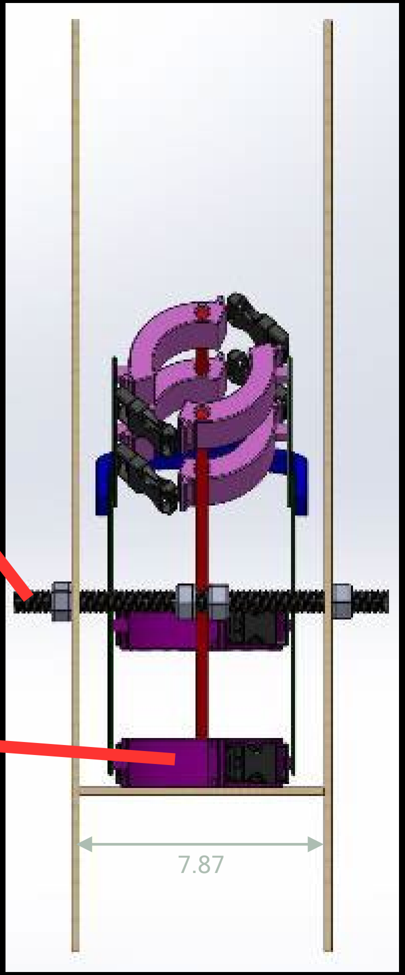
Pass = Counter-Torque profile is within 10% of EVA suit torque linear fit profile of all measured locations.

Fail = 1 or more torque values is outside 10% of EVA suit torque linear fit profile. If this is the case, iterate on current design to adjust torque.

COUNTER TORQUE - Procedure

1. Clamp the arm harness (AH) 3D printed straps (purple) to the table
2. Slide metal rod through fish scale loop to the center and tighten nuts to hold it in place

Front View

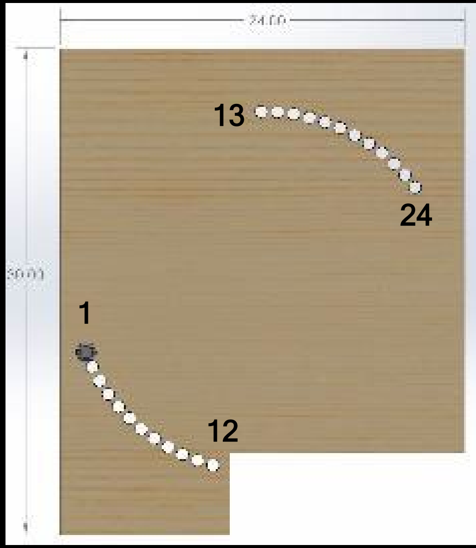


Measurements in inches

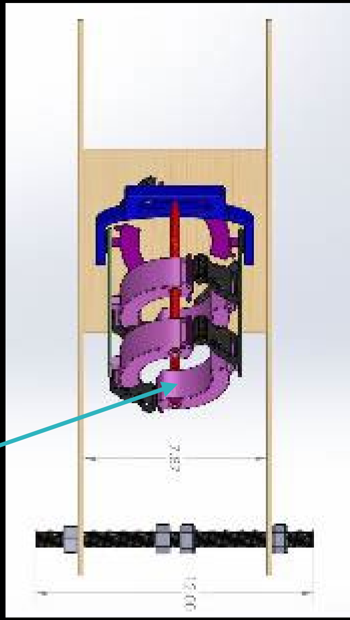
COUNTER TORQUE - Procedure

Measurements in inches

3. Place the metal rod through the holes pre-set at 5-degree increments starting with hole 1
4. Attach the fish scale to the top straps of the AH with a zip tie
5. Allow the fish scale to settle, record the value on the fish scale



Side View

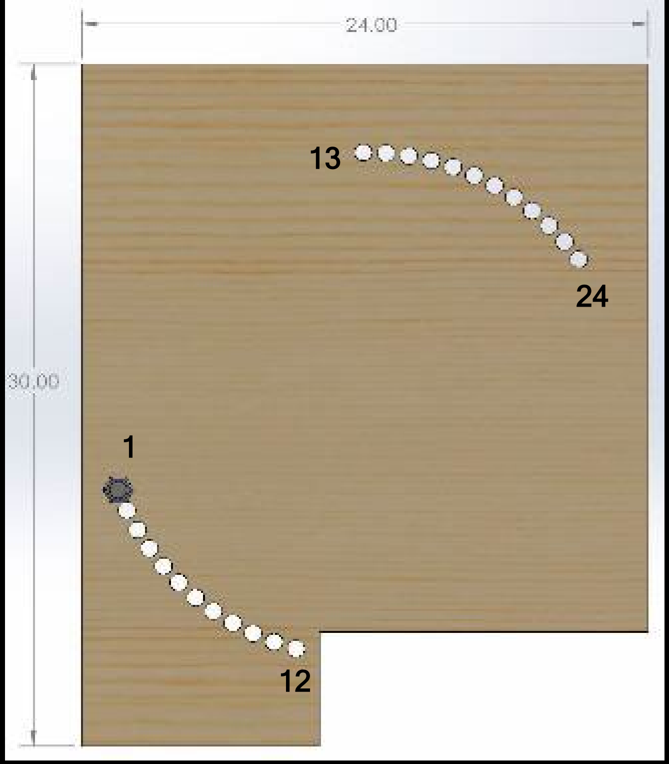


Top View

COUNTER TORQUE - Procedure

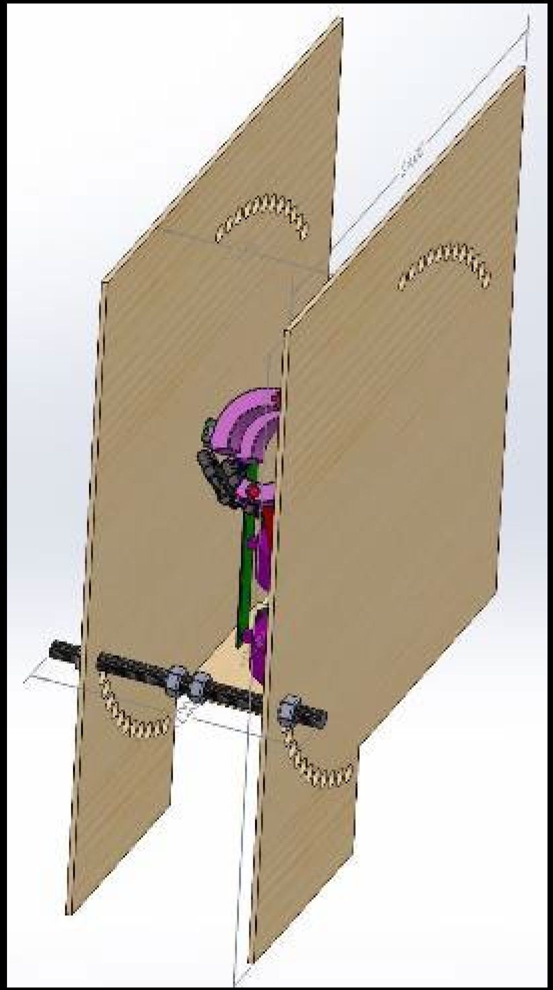
6. Continue through all angle positions for the arm harness (1-24)
7. Repeat 9 more times steps 1-6 for a total of 10 cycles
8. Send data to both the Test Lead and Hardware Lead for analysis

Side View



Measurements in inches

Isometric View



COUNTER TORQUE - Materials Needed

Material	Size	Quantity	Supplier
Wood	MDF 1/4in thick	1	Home Depot Laser Cut @AERO
Metal Threaded Bar	¼ - 16 x 12in	1	Home Depot
Nuts	¼ - 16	4	McGuckin's
Fish Scale	Maximum: 20 [kg] Precision: 0.01 [kg]	1	AES Electronics Shop
Clamps	N/A	2	AERO Machine Shop
Arm Harness	25^{th} Percentile Size	1	HEIST

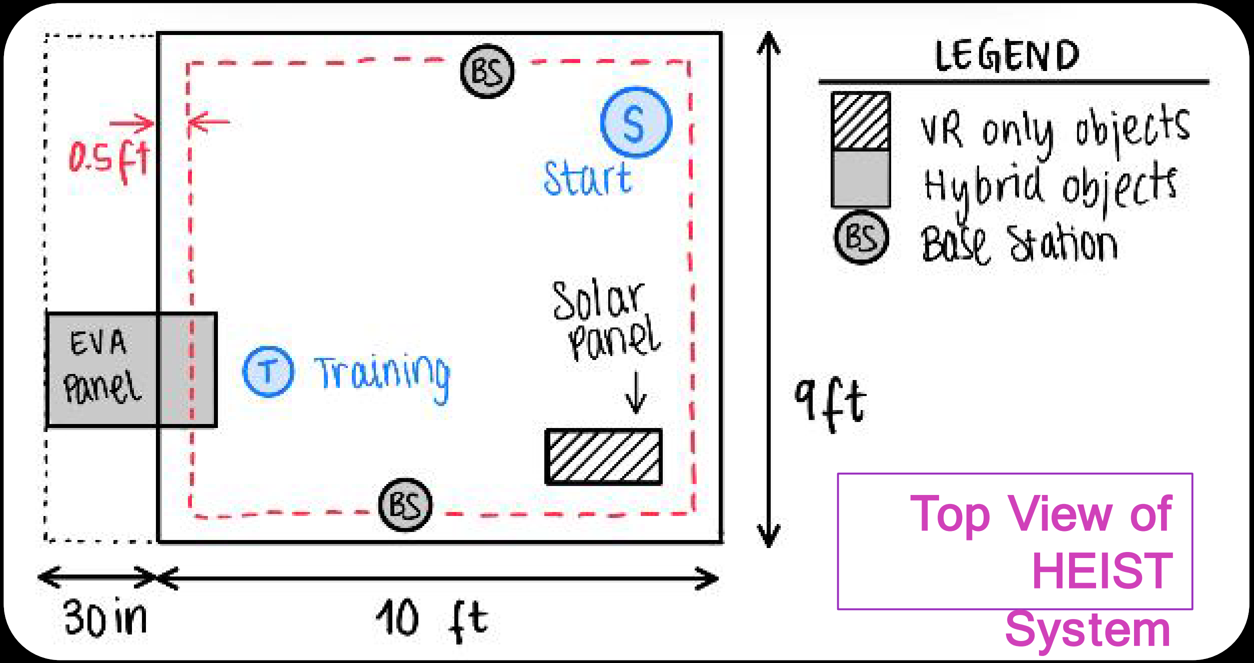
HEIST Day in the Life Test

DAY IN THE LIFE - Summary

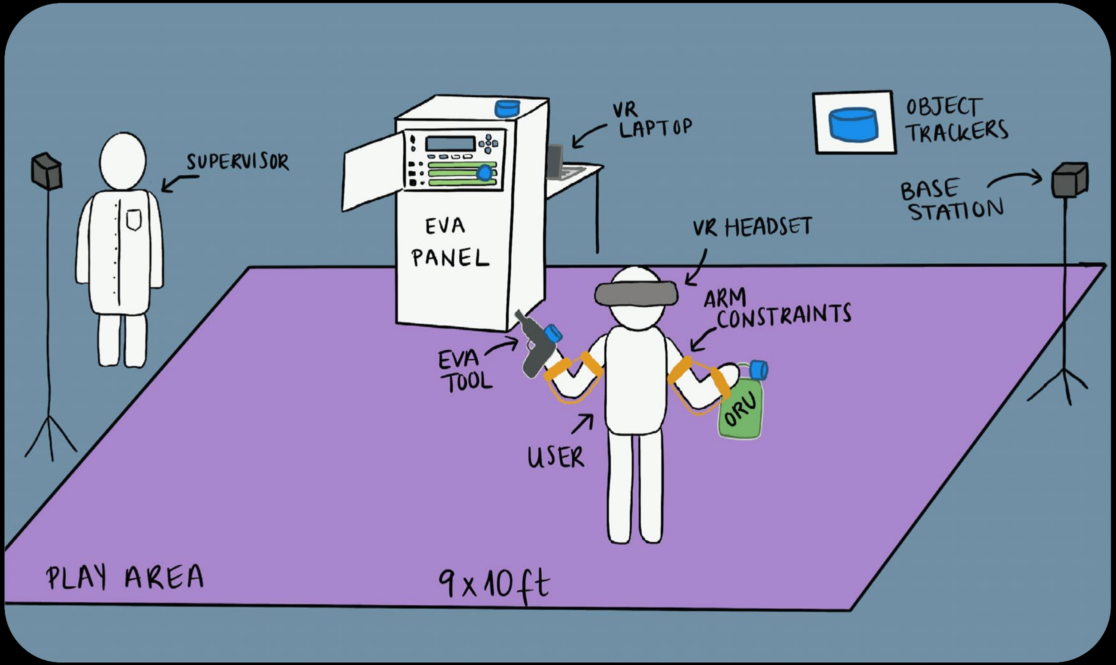
FR 1 - HEIST shall be an immersive HR system where the user can enter a VR environment and interact with it though PR elements.

FR 2 - The PCs shall inhibit movement of at least one part of the body.

FR 3 - The user shall be in no danger while operating in the HR environment.



Top View of HEIST System



DAY IN THE LIFE - Purpose

- This test will examine all components of the deliverable to verify that the project works as it is supposed to.
- To pass, the HEIST system must achieve all functional requirements and
  - Not cause motion sickness to the user
  - Allow the user to complete training tasks in HR
- To run this test, all other tests must be completed. If any one of them should fail, the system will have to be modified to pass this final test

DAY IN THE LIFE - Safety

- Pre-screening with MSSQ, arm mobility, and epilepsy questionnaire
- HEIST supervisor will be always watching the test
  - The supervisor will also be checking in with the user every 3 minutes to guarantee that they are not becoming motion sick
    - They will cancel the test if necessary if the subject becomes sick

	Not Applicable - Never Traveled	Never Felt Sick	Rarely Felt Sick	Sometimes Felt Sick	Frequently Felt Sick
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

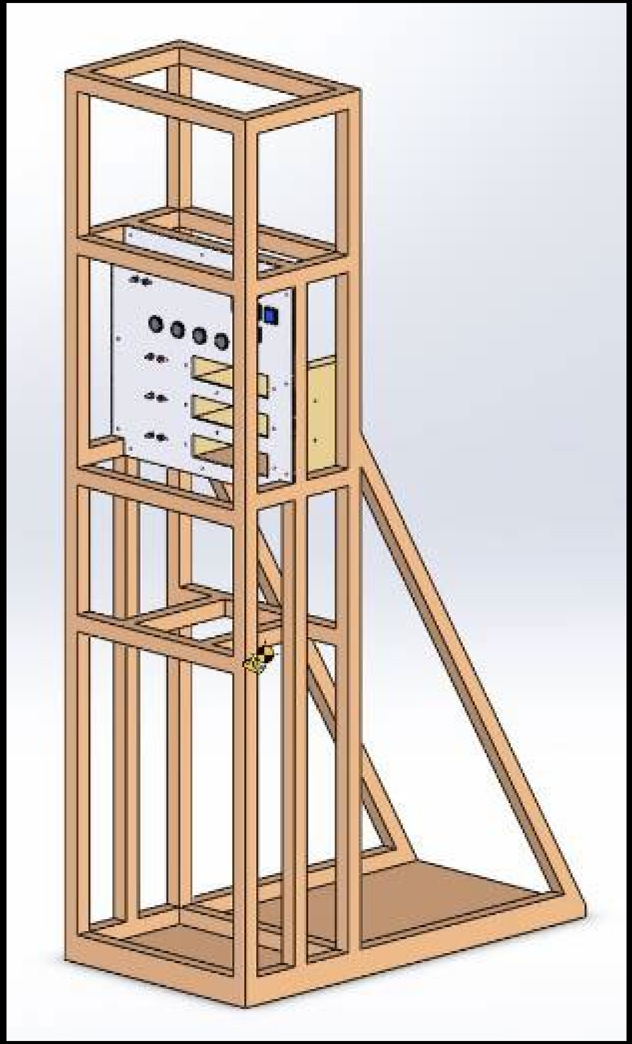
MSSQ

DAY IN THE LIFE - Test Procedure

- Screen the subject: MSSQ and health screening.
- Obtain verbal consent from subject
- Load the VR environment and start the headset and the panel
- With the individual already in the play area, have them put the arm harness and VR goggles on
- Start the tasks within VR and observe the user completing the objectives
- Once the individual has completed the tasks, help them remove the head set and arm harness and then have them fill out the accompanying survey.

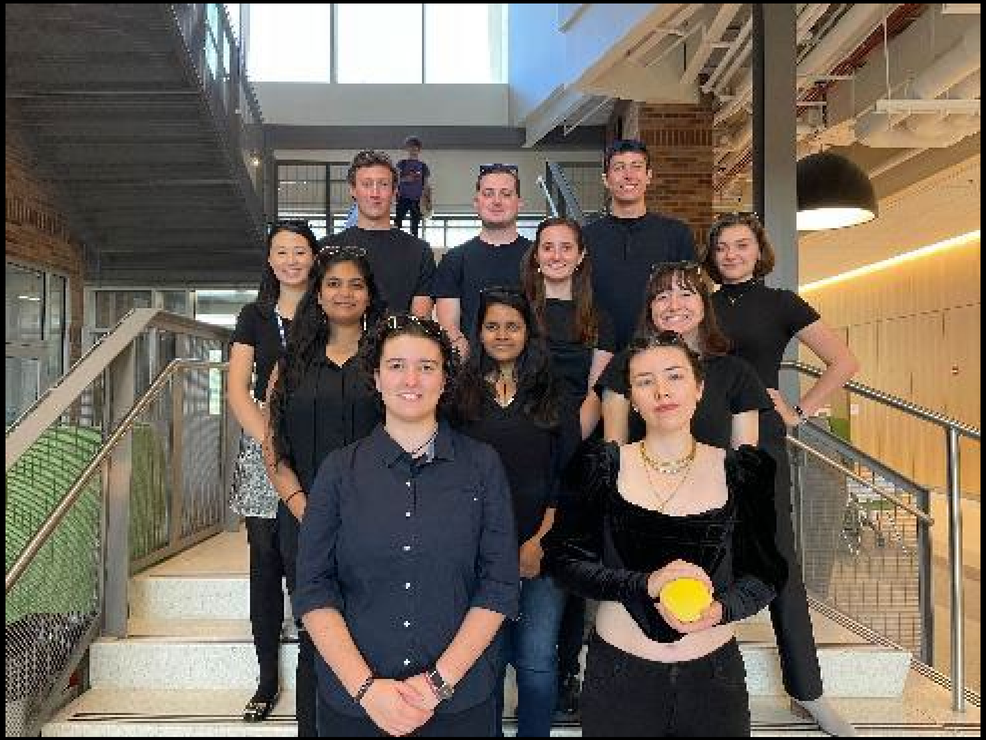
DAY IN THE LIFE - Materials Needed

- Completed Panel & ORUs
  - Including all electrical components hooked up and running
- Completed VR environment
- Completed arm harness (4x)
  - (1 right +1 left) per size
- Base Stations (2x)
- HTC Vive Trackers (4x)
- ORU Tool (1x)
- VR Laptop
- Personal Laptop
  - For the final survey



DAY IN THE LIFE - Samples

- A minimum of 10 individuals must be sampled
  - NASA-STD-3001: standard for testing with humans in the loop
- All individuals must pass the MSSQ and health questionnaires
- A variety of ages, genders, and experiences with VR will be tested
  - All subjects must be over 18 years old



DAY IN THE LIFE - Expected Data Outputs

- We will collect data with a Likert survey
- Binary answer of if the user was able to complete the test
- 1-5 rating on motion constraint of the arm harness
- 1-5 rating on immersive capabilities of the system
- 1-5 rating on perceived safety of the system

DAY IN THE LIFE - Pass/Fail Criteria

Pass = At least 80% of individuals rate the system as having met all functional requirements

- Consider that a subject thinks that we meet a functional requirement if they score above a 3.4 / 5 in the questions about such functional req.

Fail = Less than 80% of individuals rate the system as having met all functional requirements

- The team will evaluate the results to find the short comings and fix these before attempting the test again

Budget

Full Budget

Status of Items - Received

Hardware

Item	Purpose	Supplier	Quantity	Cost/Unit	Cost
Flat Aluminum Bar 96x1x1/8	Used for arm harness as the structure	HomeDepot	2	$22.93	$45.86
Pine Board 2x2x8'	Used for the EVA stand	HomeDepot	10	$15.20	$152.00
Pine Board 2x10x8'	Used for the EVA stand	HomeDepot	1	$16.57	$16.57
Resistance Loop Exercise Bands	Used to create resistance within the arm constraint mechanism	Amazon	1	$10.87	$10.87
Ball Bearing Roller	Used for locking and unlocking EVA panel door	McMaster	1	$7.05	$17.68
MDF Sheet	Used to construct EVA panel frame, ORUs	HomeDepot	1	$54.33	$54.33
Threaded Zinc Rod	Used for the EVA stand	HomeDepot	1	$1.97	$1.97
10-32-1 1/4 Machine Screw	Used for the EVA stand	HomeDepot	12	$1.38	$16.56
10-32-1 Machine Screw	Used for EVA stand and arm harness	HomeDepot	1	$1.38	$1.38
MDF Sheet 4x8' 1/4"	Used for EVA panel stand	HomeDepot	1	$54.33	$54.33

Software

HTC Vive 3.0 Tracker	Tracking pucks that allow for VR tracking of physical objects	Amazon	2/4	$129.98	$519.92
HTC Base Station 2.0	Base stations communicate with the Vive Trackers, send info to the headset	Amazon	2	$249.95	$516.89
Base Station Tripod (2 pack)	Allows the base stations to be held up for better communication to the trackers.	Amazon	1	$45.00	$45.00
Batteries (AA)	Used to power Oculus controllers	HomeDepot	1	$8.87	$8.87

Status of Items - Received

Electrical

Item	Purpose	Supplier	Quantity	Cost/Unit	Cost
Round Momentary Buttons (35 mm)	Buttons below the screen to control what the screen says/switch through tasks	Amazon	1	$15.49	$15.49
Rotary Potentiometer - 10k Ohm, Linear	used to track the motion of the hinge of the door	Amazon	1	$9.98	$9.98
Arduino Shield	Used to create the button panel on the EVA stand	Amazon	1	$17.90	$17.90
Square push buttons	Used for the buttons on the EVA panel	Amazon	1	$12.99	$12.99
Red and Black Wires	Used to connect electronics in EVA panel	Amazon	1	$9.98	$9.98

Status of Items - Pending

Software

Item	Purpose	Supplier	Quantity	Cost/Unit	Cost
Vive 3.0 Trackers	Used with base stations to track objects or body positions.	Amazon	2/4	$129.98	$519.92

Amazon sent the trackers back, then resent them to the aerospace building, which took about a month. On arrival, only 2 of the 4 trackers ordered were in the package, the packing slip says that there should be 4. Working with Jacqui to determine if there is a second package still to arrive, or if Amazon did not send enough.

Status of Items - Planned

Hardware

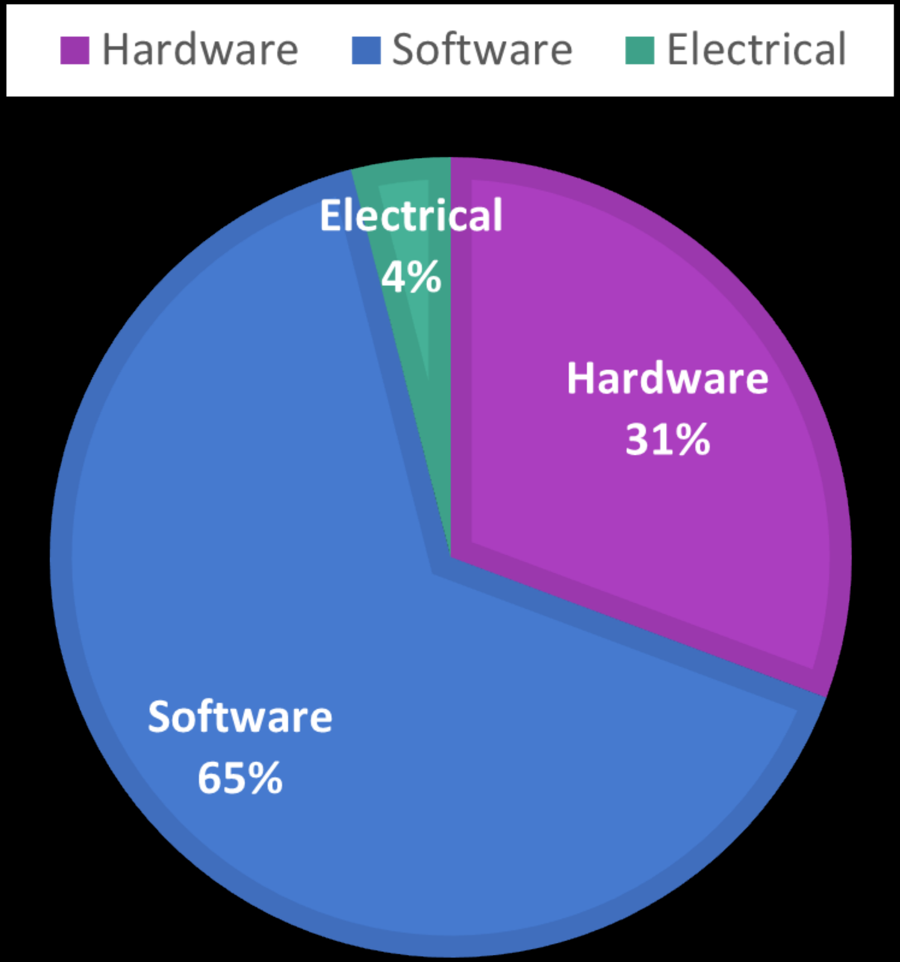
Item	Purpose	Supplier	Qty	Cost/Unit	Cost
3d Filament	Used for printing mock tools	AES Department	1	$50	$50
Belt for mock tools	Keep track of tools when not in use	Amazon	1	$15	$15

Software

DLink Air Bridge	Used to create a fast wireless connection to headset.	Meta	1	$100	$100
Quest 2 Strap	Alternate head strap option - more easily adjusted between people using headset.	Meta	1	$59.99	$59.99
3D Assets	Used to create immersion in the VR environment	Variable Locations	1	$100	$100

Other smaller items have also been planned for in the budget, such as fasteners, glue, etc.

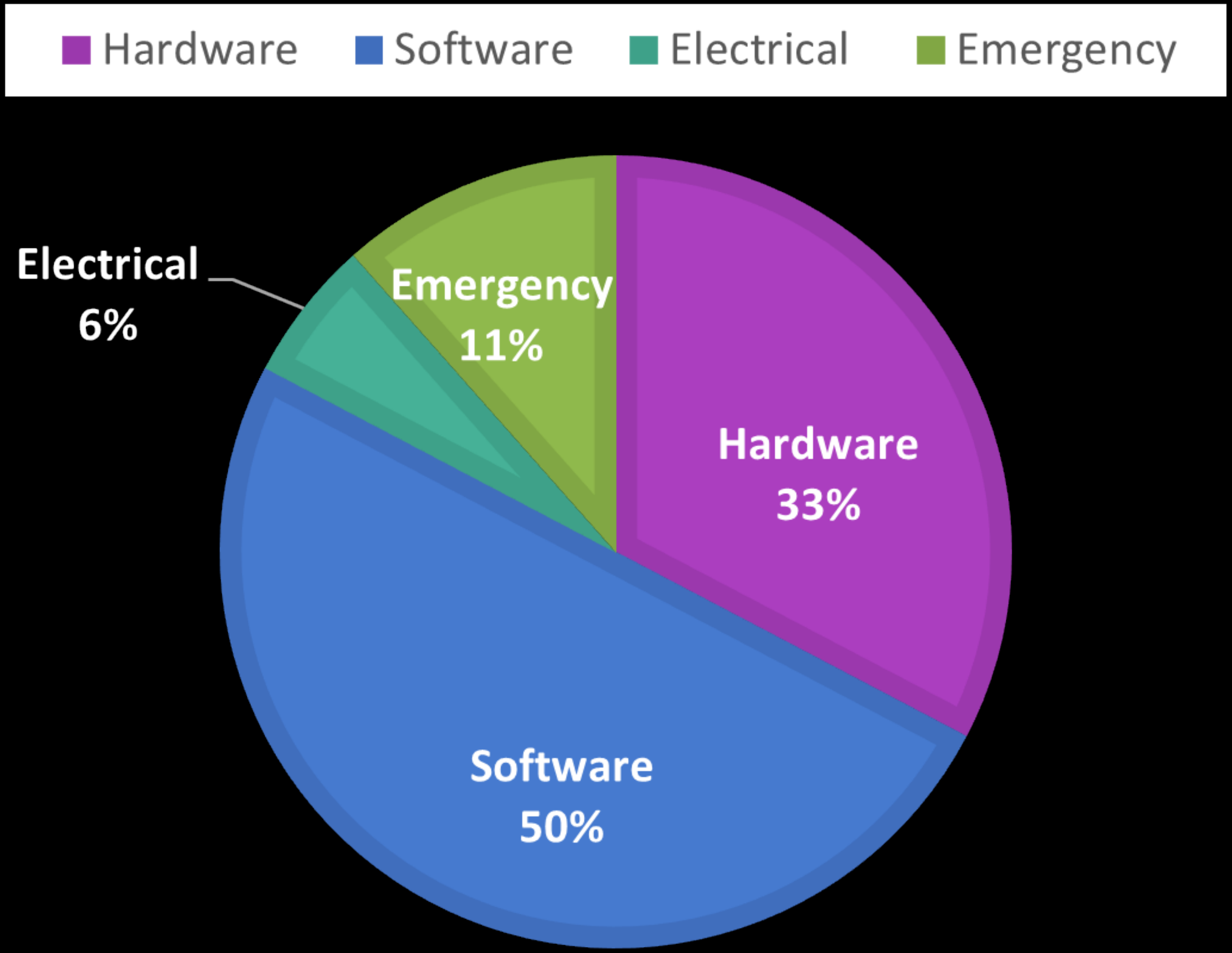
CURRENT SPENDING BY SUBTEAM



Hardware	512.75
Software	1090.68
Electrical	66.34
TOTAL	1669.77

Remaining Budget: $2330.23

PREDICTED SUBTEAM BUDGET BREAKDOWN



Hardware	850
Software	1400
Electrical	150
Emergency	300
TOTAL	**2700**

Credits

Presenters

Sruthi Bandla

Alicia Wu

Esther Revenga Villagra

Rachael Carreras

Matthew Grewe

Lucy Davis

Additional Team Members

Trayana Athannassova

Hattie Rice

Sebastian Boysen

Akanksha Nelacanti

Julia Claxton

Steven Young

Faculty Advisor

Dr. Allison Anderson

Mentor Company

Blue Origin

CDR Reviewers

Gina Staimer

Thank you!

Q&A Time (15 min)

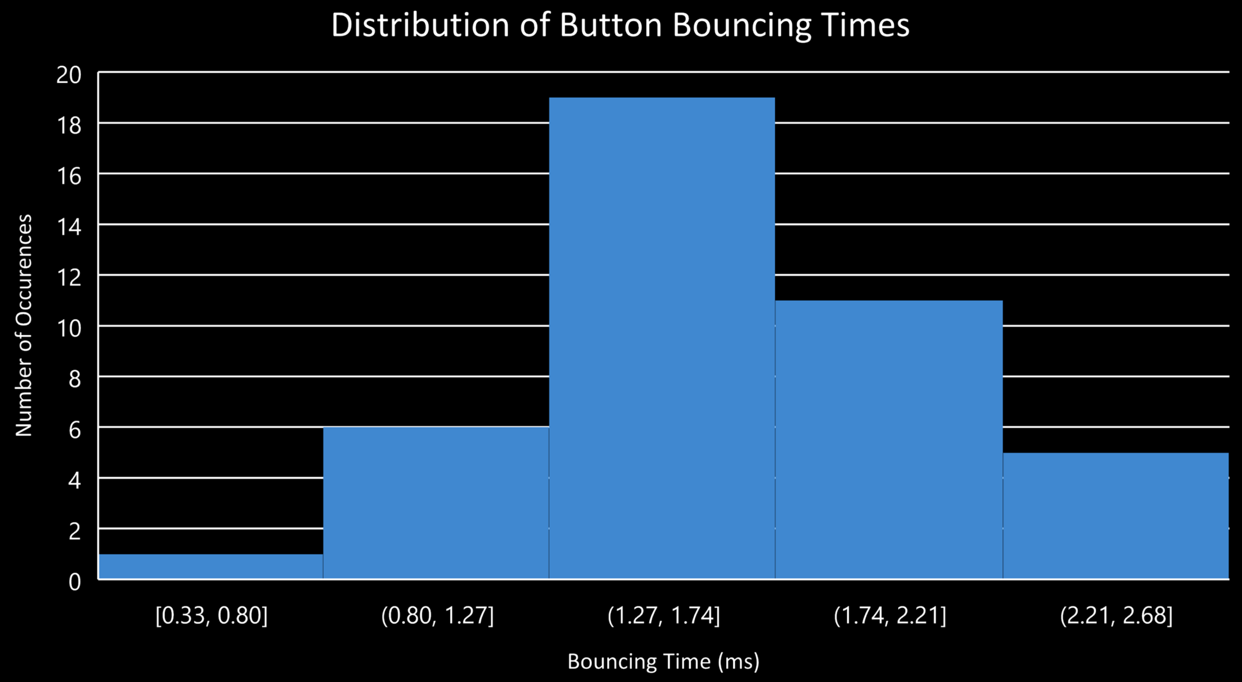
Appendix

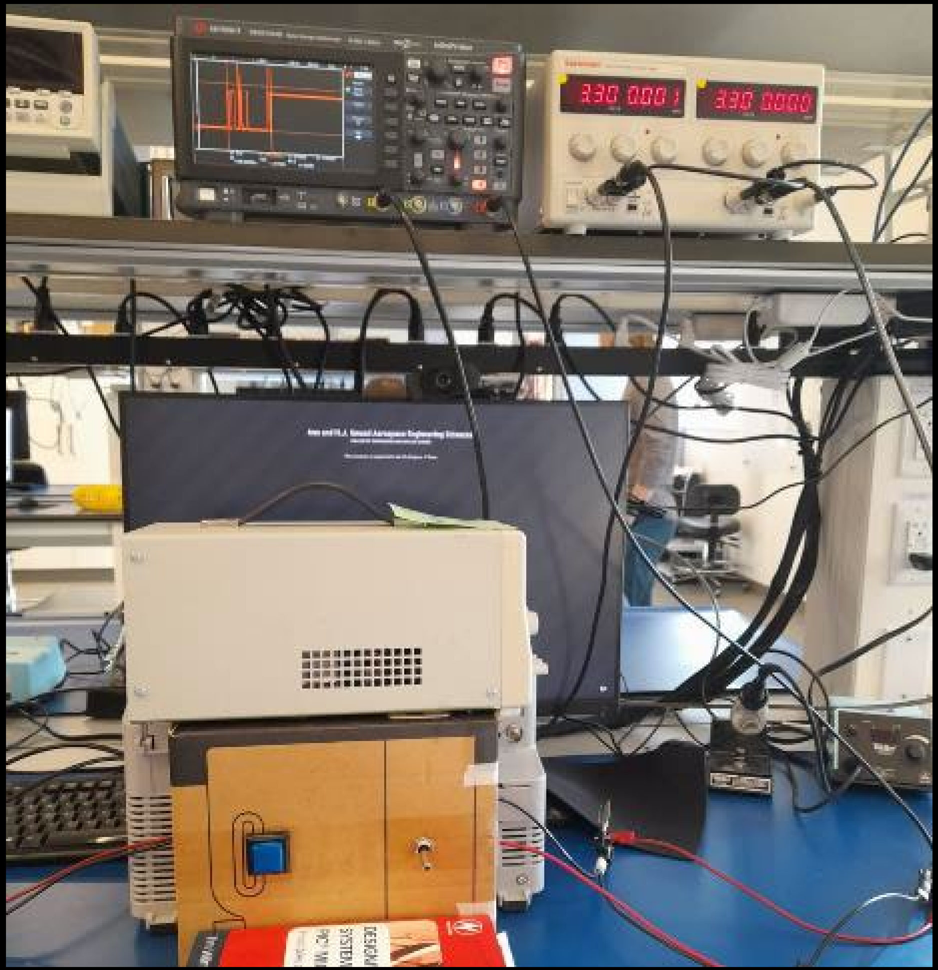
Backup Slides

Full List of Acronyms

A	=	Analysis (V&V)
AR	=	Augmented Reality
BS	=	Base Station
CDR	=	Critical Design Review
CFO	=	Chief Financial Officer
COTS	=	Commercial Off The Shelf
CPE	=	Critical Project Element
D	=	Demonstration (V&V)
DH	=	Data Handling
DoF	=	Degree of Freedom
DR	=	Design Requirement
Elect	=	Electrical
EVA	=	Extravehicular Activity
FBD	=	Functional Block Diagram
FFBD	=	Functional Flow Block Diagram
FOV	=	Field Of View
FR	=	Functional Requirement
HEIST	=	Hybrid Environmental Immersive Simulation Training
HT	=	Hand Tracking
HR	=	Hybrid Reality
I	=	Inspection (V&V)
LOS	=	Line Of Sight
Mech	=	Mechanical
Mgmt	=	Management
MS	=	Motion Sickness
ORU	=	Orbital Replacement Unit
PC	=	Physical Constraint
PDD	=	Preliminary Design Document
PDR	=	Preliminary Design Review
PM	=	Project Manager
PR	=	Physical Reality
SE	=	Systems Engineer
SME	=	Subject Matter Expert
SW	=	Software
T	=	Test (V&V)
TBD	=	To Be Determined
TBR	=	To Be Refined
TPM	=	Technical Performance Measure
UI	=	User Interface
UX	=	User Experience
VR	=	Virtual Reality

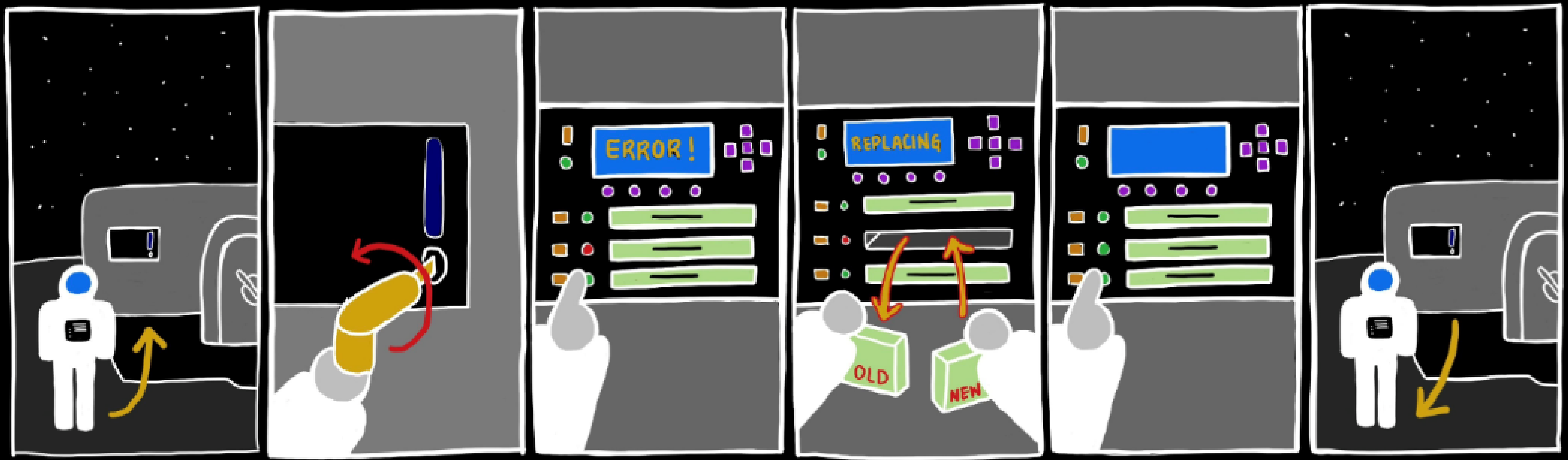
Switch/Button Bouncing Time Test





Scenario: Solar Panel Repair

The heaters have failed at a moon sensor station, and thermally sensitive equipment is at risk. The user's task is to identify a damaged solar panel control unit (ORU) and address the issue immediately.



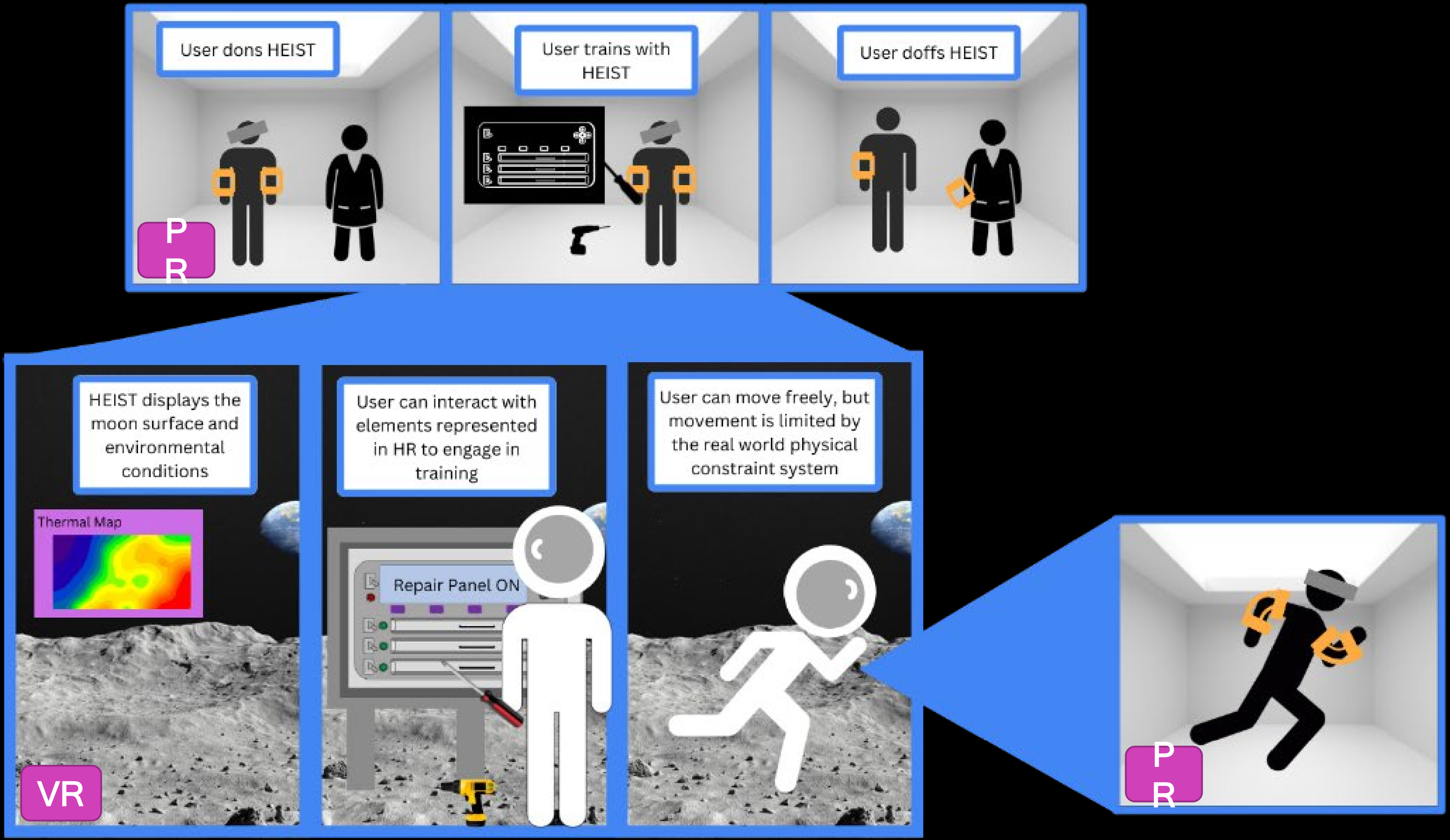
Approach panel | Open panel with tool | Find failure | Replace ORU | Ensure new ORU is working | Close panel and leave

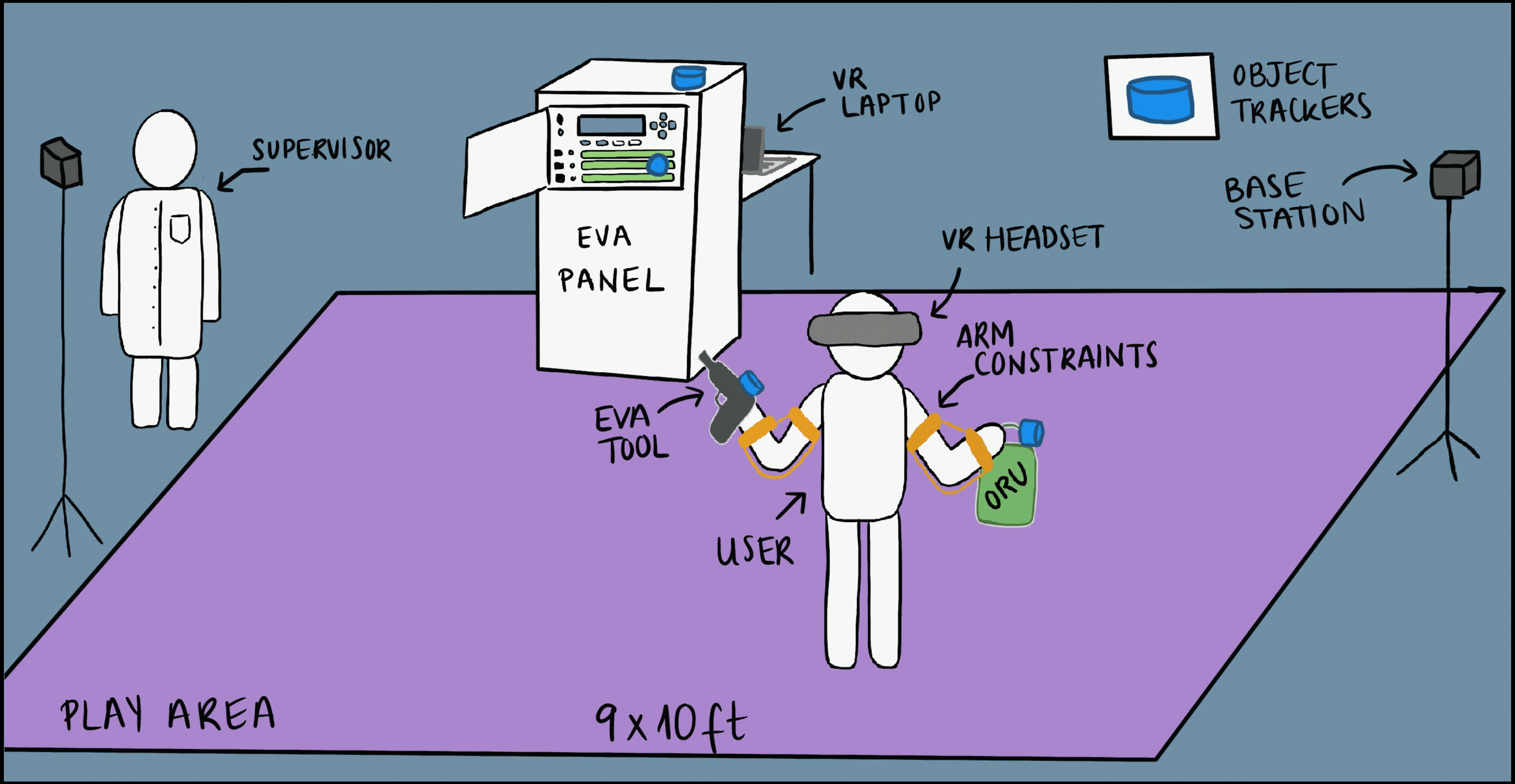
Training Scenario Details (1/2)

1. Exit the habitat and move to the remote sensor station
2. Inspect the sensor station for visible damage (should see broken solar panel)
3. Use the screwdriver to open the panel on side of the station
4. Use the display and keypad to check the system status tab
5. Read the system status tab to confirm solar panel error and recognize a failure of a resistor assembly (one of the three ORUs)
6. Use the keypad to navigate to the safe shutdown screen on the display and shut down safely
7. Use the switch on the panel to turn off the power to the panel
8. Use the button to unlock the ORUs
9. Uninstall the correct ORU for the resistor module

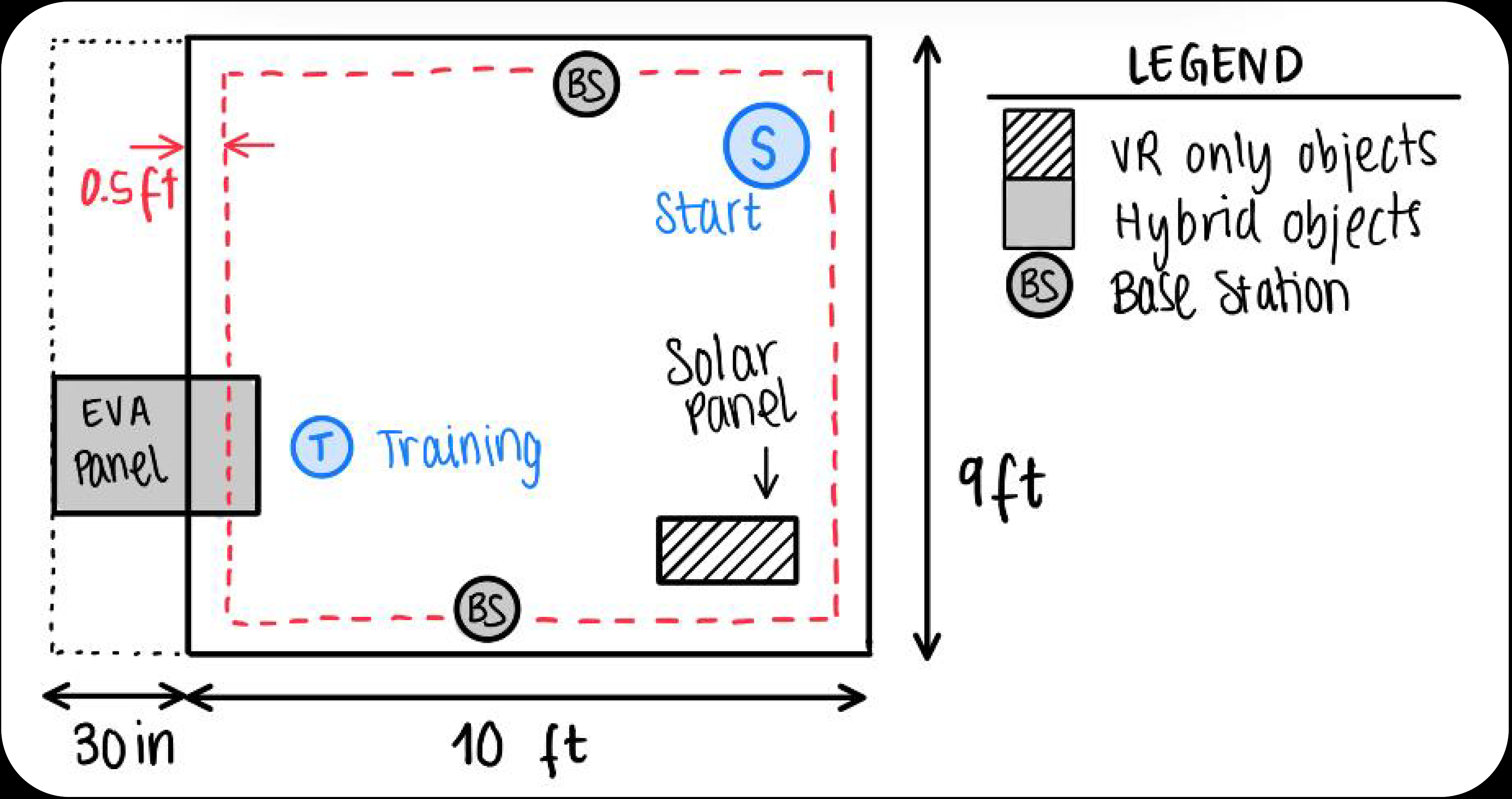
Training Scenario Details (2/2)

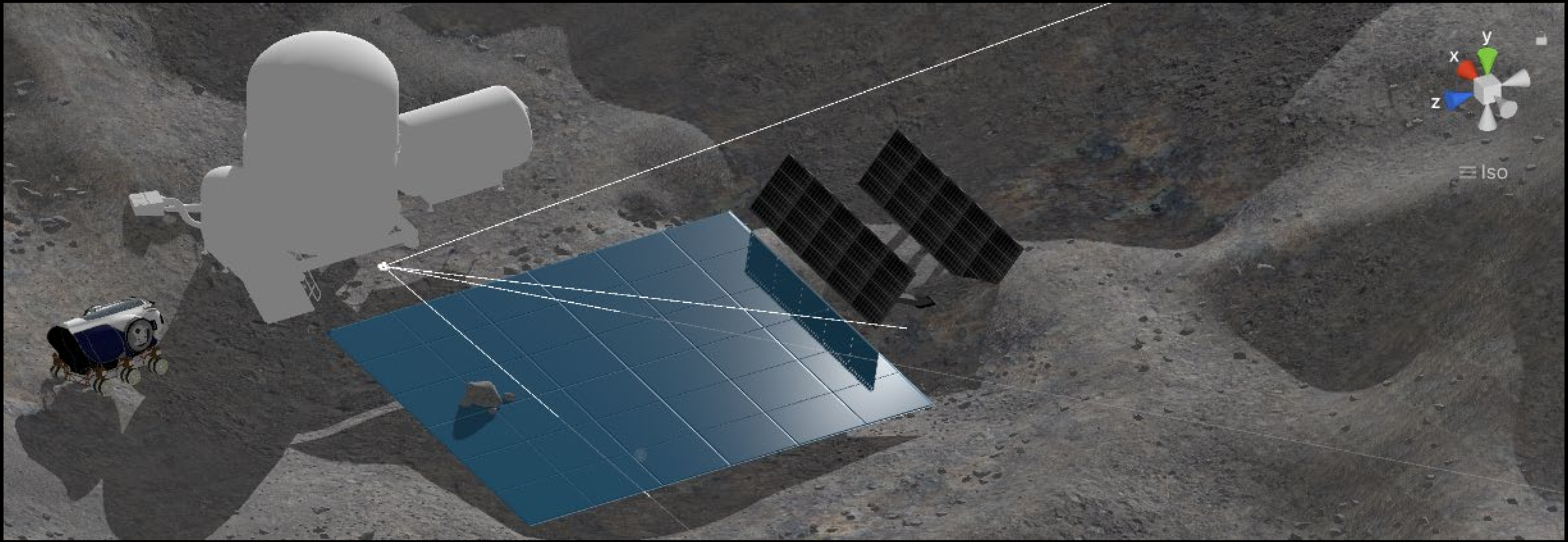
10. Reinstall the new module
11. Verify connection (did the right ORU end up in the right slot) using button and watching the button light up
12. Use button to re-engage locking of the ORUs
13. Navigate to the solar panel, recognize the damaged cell and release its latches
14. Remove solar panel, install new solar panel, and engage the latches
15. Navigate to the panel once again
16. Use the switch to turn on the panel power
17. Use the keypad and display to ensure proper installment of the ORU and solar panel replacement
18. Ensure the functionality of the heater and the rise of local temperature
19. Close the panel, lock it, and return to habitat


User dons HEIST
User trains with HEIST
User doffs HEIST
PR
HEIST displays the moon surface and environmental conditions
Thermal Map
VR
User can interact with elements represented in HR to engage in training
Repair Panel ON
User can move freely, but movement is limited by the real world physical constraint system
PR


SUPERVISOR
EVA
PANEL
VR
LAPTOP
OBJECT
TRACKERS
BASE
STATION
VR HEADSET
ARM
CONSTRAINTS
EVA
TOOL
ORU
USER
PLAY AREA
9 x 10 ft

HEIST System Layout




x
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Requirements

Requirements - FR1

Acronym	Verification	Description
I	Inspection	Use of human senses to verify requirement
A	Analysis	Modelling
T	Test	Requires data aquisition and use of special equipment
D	Demonstration	Run test w/o special equipment to collect data

Level 0	Level 1	Level 2	Level 3	Requirement	Predicted Compliance	SW	DH	Elect.	Mech.	Test
CONSTRAINTS										
C1				The cost of the project shall not exceed 4000 USD.						
C2				The system shall have a life span of no less than 3 years						
C3				Unity shall be used as the VR development engine.						
REQUIREMENTS FLOWDOWN										
FR 1	Immersiveness			**HEIST shall be an immersive HR system where the user can enter a VR environment and interact with it though PR elements.**						
				Physical Reality Environment (or PR) *is a tangible environment with real objects.*						
				Immersion *: deep mental involvment.*						
				Hybrid Reality (HR) *is an environment with combined real time interaction between Virtual Reality (VR) and Physical Reality (PR). It consists of a VR environment that receives ques from the PR when the user interacts with set PR elements.*						
				Virtual Reality Environment (or VR) *is a computer-generated environment.*						
	DR 1.1			**The user shall view a functional VR simulation of a lunar EVA.**						
	EVA CONDITIONS									
		1.1.1		The VR simulation shall display environmental conditions of the Moon.	Compliant	X				I
			1.1.1.1	The VR simulation shall visually display temperatures within the range of -200 ºC to 120 ºC.	Compliant	X				I
			1.1.1.2	The VR simulation shall visually display the high-contrast lighting properties of the Moon.	Compliant	X				I
		1.1.2		The VR simulation shall simulate the reduced field of vision (FoV) that the user would have wearing an EVA spacesuit helmet.	Compliant	X				I
			1.1.2.1	The VR simulation shall simulate a FoV of at least 90º horizontal by 90º vertical.	Compliant	X				I
	TRAINING FEEDBACK									
		1.1.3		The VR simulation shall provide mission-relevant task guidance to user.	Compliant	X				I
			1.1.3.1	The VR simulation shall provide training task sequence to the user, accessible at any time, in document form.	Compliant	X				I
		1.1.4		The VR simulation shall provide audio feedback to the user.	Compliant	X	X	X		I
			1.1.4.1	The VR simulation shall include ambient audio associated with an EVA.	Compliant	X		X		I
			1.1.4.2	The VR simulation shall include audio feedback in response to the user's input in PR.	Compliant	X	X	X		I

Requirements - FR1

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Level 0	Level 1	Level 2	Level 3	Requirement	Predicted Compliance	SW	DH	Elect.	Mech.	Test
	PR-VR INTERACTIONS									
	DR 1.2			**The user's actions in PR shall correlate to effects in VR.**						
				NOTE: finger tracking is a Lvl. 2 success criteria, so it is not essential but nice to have.						
	TRACKING									
	PR Elem.	1.2.1		The position and orientation of PR elements that the user can interact with shall be tracked.	Compliant			X	X	T/D
			1.2.1.1	The PR elements' user-relative orientation shall be tracked with an accuracy 10º about three orthogonal axes.	Compliant			X		T
			1.2.1.2	The PR elements' user-relative position shall be tracked with an accuracy of 0.025 m on three orthogonal axes.	Compliant			X		T
			1.2.1.3	PR elements' tracked positional and orientation data shall be collected at a rate of 90 Hz.	Compliant		X	X		A
	PR Input	1.2.2		The state of PR input devices shall be sampled at a rate of at least 90 Hz.	Compliant		X	X		D
			1.2.2.1	At least 4 input devices shall be sampled during the simulation	Compliant		X	X		I
	Hands	1.2.3		The motion of the user's hands shall be tracked.	Compliant			X		T/D
			1.2.3.1	The user's hand orientation shall be tracked with an accuracy 7º about three orthogonal axes.	Partially Compliant			X		T
			1.2.3.2	The user's hand position shall be tracked with an accuracy of 2.5 cm on three orthogonal axes.	Partially Compliant			X		T
	Fingers	1.2.4		The the motion of the user's fingers shall be tracked.	Partially Compliant			X		D
			1.2.4.1	The position of the user's fingers shall be tracked with an accuracy of 1.25 cm on three orthogonal axes.	Partially Compliant			X		T
			1.2.4.2	User's finger orientation shall be tracked with an accuracy of 7º about three orthogonal axes.	Partially Compliant			X		T
	Power	1.2.5		All electronic components, including tracking devices, shall be powered to their rated values.	Compliant			X		I
	COMMUNICATION TO VR									
	PR Input	1.2.6		The state of PR input devices shall be communicated to the VR simulation at a rate of at least 90 Hz.	Compliant		X			D
	PR Elem.	1.2.7		The dynamic PR elements' tracking data shall be communicated to the VR at a rate of 90 Hz	Compliant		X			D
			1.2.7.1	The data handling system shall send PR object positional data to the VR at a rate of 90 Hz.	Non Compliant		X			D
			1.2.7.2	The data handling system shall send PR object orientation data to the VR at a rate of 90 Hz.	Non Compliant		X			D
	Hands	1.2.8		The user's hands tracking data shall be communicated to the VR in real time.	Compliant		X			D
	Fingers	1.2.9		The user's finger tracking data shall be communicated to the VR in real time.	Compliant		X			D

Requirements - FR1

Acronym	Verification	Description
I	Inspection	Use of human senses to verify requirement
A	Analysis	Modelling
T	Test	Requires data aquisition and use of special equipment
D	Demonstration	Run test w/o special equipment to collect data

Level 0	Level 1	Level 2	Level 3	Requirement	Predicted Compliance	SW	DH	Elect.	Mech.	Test
	DISPLAY IN VR									
	PR Input	1.2.10		The VR simulation shall reflect user's interaction with PR input devices (e.g. switches, buttons, etc.) in real time.	Compliant	X				D
			1.2.10.1	The system shall display the state of PR input devices in the VR simulation in real time.	Compliant	X				D
			1.2.10.2	The VR simulation shall have indicators to show the current state of input PR devices.	Compliant	X				D
	PR Elem.	1.2.11		The VR simulation shall display the PR elements' motion to the user in real time.	Compliant	X				D
			1.2.11.1	The VR simulation shall display the orientation of PR elements relative to the user in real time.	Compliant	X				D
			1.2.11.2	The VR simulation shall display the location of PR elements relative to the user in real time.	Compliant	X				D
	Hands	1.2.12		The VR simulation shall display the user's hands motion in real time.	Compliant	X				D
			1.2.8.1	The VR simulation shall display the user's hands orientation in real time.	Compliant	X				D
			1.2.8.2	The VR simulation shall display the user's hands location in real time.	Compliant	X				D
	Fingers	1.2.13		The VR simulation shall display the user's finger motion in real time	Partially Compliant	X				D
			1.2.13.1	The VR simulation shall display the user's finger position in real time.	Partially Compliant	X				D
			1.2.13.2	The VR simulation shall display the user's finger orientation in real time.	Partially Compliant	X				D
	USER IMMERSION									
	DR 1.3			**The user shall only NEED TO interact with PR elements, not with the VR.**	Compliant	X			X	I
		1.3.1		The VR simulation shall only serve as an immersivity tool to provide visual and auditory ques to the user.	Compliant	X				I
		1.3.2		The user shall only interact with PR elements with their hands.	Compliant				X	I
		1.3.3		The user shall receive primary visual and auditory cues only from the VR simulation.	Compliant	X		X	X	I
	DR 1.4			**The user shall be spatially immersed in the VR simulation.**	Compliant	X			X	I
		1.4.1		The user shall be capable to turn 360º to view their surroundings in the VR simulation.	Compliant	X				I
		1.4.2		The user shall have the option to translate (walk) in the VR simulation.	Compliant	X			X	I
	PR-USER INTERACTIONS									
	DR 1.5			**The system shall have physical interactions with the PR that mimic Lunar habitat maintenance.**	Compliant				X	D
		1.5.1		The system shall have at least one (1) panel with a door that can be opened and closed.	Compliant				X	D
		1.5.2		The system shall have at least two (2) switches that can be flipped.	Compliant			X	X	D
		1.5.3		The system shall have at least two (2) buttons that can be pressed.	Compliant			X	X	D
		1.5.4		The system shall allow for the replacement of at least one (1) object in PR as part of the training scenario.	Compliant				X	D
		1.5.5		The system shall allow for the use of at least one (1) tool in PR as part of the training scenario.	Compliant				X	D
	DR 1.6			**The PR elements shall resemble the objects/tools that would be used during a lunar EVA mission.**	Compliant				X	I
		1.6.1		The PR elements shall have a similar volume as the objects/tools that would be used during a lunar EVA mission.	Partially Compliant				X	I
		1.6.2		The PR elements shall have a smilar weight as the objects/tools that would be used during a lunar EVA mission.	Compliant				X	I
			1.6.2.1	The PR elements shall weigh of 1/6 of the object's weight on Earth with an accuracy of 10%.	Compliant				X	T
		1.6.3		The PR elements shall have a similar shape as tools that would be used during a lunar EVA mission.	Partially Compliant				X	I

Requirements - FR2

Acronym	Verification	Description
I	Inspection	Use of human senses to verify requirement
A	Analysis	Modelling
T	Test	Requires data aquisition and use of special equipment
D	Demonstration	Run test w/o special equipment to collect data

Level 0	Level 1	Level 2	Level 3	Requirement	Predicted Compliance	SW	DH	Elect.	Mech.	Test
FR 2	Physical Constraints			**The PCs shall inhibit movement of at least one part of the body.**						
				Physical Constraint (or PC) *is a real body movement restriction used to simulate wearing an EVA spacesuit; therefore, it is part of the PR.*	-					
	ARM CONSTRAINTS			**LVL 1 SUCCESS CRITERIA: ESSENTIAL**						
	DR 2.1			**The PCs shall simulate the impacts of physical constraints of a lunar EVA spacesuit on shoulder and elbow movement.**	Compliant				X	T/D
		2.1.1		The PCs shall constrain the user's shoulder abduction and adduction within a range of 0 - 150 degrees.	Compliant				X	T
			2.1.1.1	The PC shall provide a range of counter-torque to the shoulder between -31 and 29 ± 10% Nm.	Partially Compliant				X	T
		2.1.2		The PCs shall constrain the user's elbow extension movement within a range of 0 - 115 degrees.	Compliant				X	T
			2.1.2.1	The PCs shall provide counter-torque to the elbow within a range between -9 and 9 ± 10% Nm.	Partially Compliant				X	T
		2.1.3		The user shall perform the motor motions of pulling, picking up, and setting down PR elements.	Compliant				X	D
	HAND / FINGER CONSTRAINTS			**LVL 2 SUCCESS CRITERIA: NOT ESSENTIAL**						
	DR 2.2			**The PCs shall simulate the impacts of physical constraints of a lunar EVA spacesuit on hand and finger motion.**	Partially Compliant				X	T/D
		2.2.1		The PCs shall constrain movement of the user's fingers flexion.	Partially Compliant				X	T
		2.2.2		The PCs shall constrain the user's hand flexion within a range of -14 to 50 degrees.	Non Compliant				X	T
		2.2.3		The PC shall constrain the user's hand extension withing a range of -20 to 55 degrees.	Non Compliant				X	T
		2.2.4		The user shall be able to perform fine motor skills to push, flip, and grasp PR elements.	Compliant				X	D

Requirements – FR3, FR4

Acronym	Verification	Description
I	Inspection	Use of human senses to verify requirement
A	Analysis	Modelling
T	Test	Requires data aquisition and use of special equipment
D	Demonstration	Run test w/o special equipment to collect data

Level 0	Level 1	Level 2	Level 3	Requirement	Predicted Compliance	SW	DH	Elect.	Mech.	Test
FR 3	Safety			**The user shall be in no danger while operating in the HR environment.**						
	DR 3.1			**The system shall be safe for humans to use.**	Compliant	X		X	X	T/D
		3.1.1		The user shall not receive audio input or feedback at a volume higher than 70 dB.	Compliant	X				T/D
		3.1.2		The user shall be capable of spending at least one (1) hour in the simulation.	Compliant	X				T/D
		3.1.3		The user shall be supervised during the entire training simulation.	Compliant					I
			3.1.3.1	The supervisor shall check in with the user every 10 minutes about their comfort and any motion sickness issues.	Compliant					I
		3.1.4		The VR headset shall display the VR simulation with a minimum frame rate of 90 fps (90 Hz).	Compliant	X		X		I
		3.1.5		The VR headset shall display the VR simulation with a minimum resolution of 3840 x 2160 pixels (4K).	Compliant	X		X		I
		3.1.6		The PR-VR data transfer shall have a latency smaller than 180 ms.	Compliant					T
	DR 3.2			**The system shall cause no physical harm to the user.**	Compliant	X	X	X	X	I
		3.2.1		The PR system shall have no sharp edges that the user could harm themselves with.	Compliant				X	I
		3.2.2		The PR system shall have no obstacles that the user can't see though VR.	Compliant	X	X	X	X	I
		3.2.3		There shall be no objects other than those required for training in the PR training area.	Compliant		X	X	X	I
	DR 3.3			**The VR simulation shall display a boundary such that the user will be warned if they approach the edge of the designated training area.**	Compliant	X			X	I
		3.3.1		The VR simulation shall have a bounded training area of 8.5' x 9.5'.	Compliant	X				D
		3.3.2		The PR shall encompass a training area no larger than 9' x 10'.	Compliant				X	T
FR 4	Adaptability			**The customer shall be able to implement their own training scenarios within the HR environment.y**						
	DR 4.1			**The system shall provide mission augmentation and customization for custom uses and scenarios.**	Partially Compliant	X	X	X	X	T/D
	DR 4.2			**The VR simulation shall run a specified mission scenario upon user selection in launch menu.**	Compliant	X				T/D

MS = Motion Sickness
LOS = Line Of Sight

Risk Identification

PROJECT ELEMENT	CAUSE	RISK	CONSEQUENCE	MITIGATION STRATEGY	Assessment P	I
SAFETY	User is prone to motion sickness	MS due to high sensitivity	Impeding further participation in the simulation	Screen users to decrease likelihood of motion sickness	4	5
EVA PANEL	Buttons/switches are too close together. Trackers are in the way	Hard to operate panel	Loss of immersion	Spacing buttons/switches (hand tracking accuracy). Place trackers where they don't impede operation	2	3
HARDWARE	Arm constraints don't allow needed arm rotations	Arm constraints harm the user	Loss of immersion Inability to continue the simulation	Human testing	3	5
SAFETY PR-VR INTERACTION	High latency. Low fps of display. Low resolution of display	MS due to latency/resolution	Impeding further participation in the simulation	Decrease resolution to aceptable range and complexity of environment	3	5
TRAINING VERSATILITY	Schedule delays	No time to design several scenarios	Decrease training versatility. Can't meet versatility 2nd level success criteria	Work in parallell. Have baseline for several scenarios ready to implement at any time	4	4
TRACKING	Loss of LOS between base station and tracker. Reflective surfaces	Delay/disconnect in tracking	The system would be hard or impossible to use	Redundant base stations. Reduce reflective surfaces by covering them with opaque materials	4	3
HAND TRACKING	Hands are outside the FOV of the headset's cameras	Inaccurate hand tracking	Increased chance of MS. Inability to operate hardware. Subsystem failure	Brief user in proper location of hands to ensure accurate tracking.	2	4
HARDWARE	Arm constraints provide too much counter-torque	Too much arm constraint	Inability to engage in the simulation Loss of immersion	Model and test	2	3
PR-VR DATA LINK	Arduino can't handle data rates due to amount of components	Lag in PR - VR connection	Increased latency in the simulation. Increased risk of motion sickness.	Prototyping and testing	3	3
VR SIMULATION	Not enough processing power	Simulation glitch / freeze	Loss of immersion Increased chance of motion sickness	Test more complex simulations than expected with available hardware to ensure it can handle it	3	3
MANUFACTURING	Too many teams using AES facilities for manufacturing	Manufacturing delay	Delay in schedule. Lack of access to the necessary components	Schedule access to required equipment ahead of time. Turn in part models as soon as possible	2	3

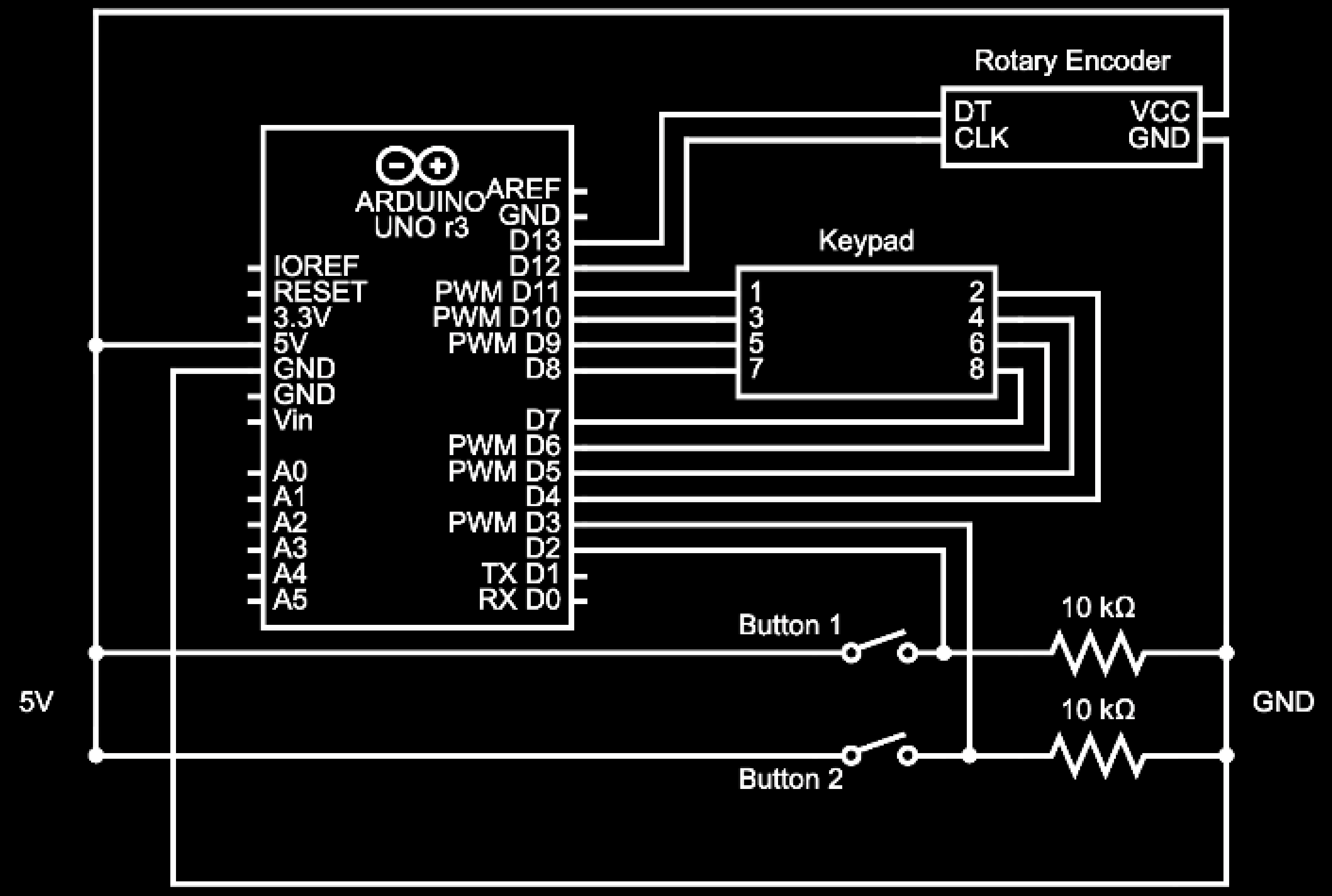
HR Data Transfer DEMO

HR Data Transfer Demo Goals

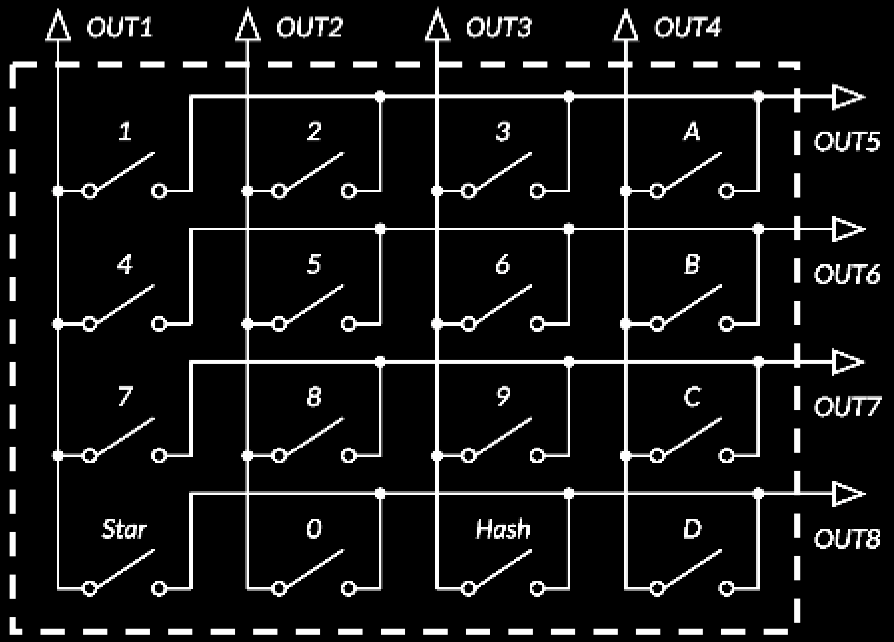
~ 1. Demonstrate capability to accurately determine the state of multiple RW assets per DR 5.1

✓ 2. Update state of RW assets at a rate of 90 Hz or greater per DR 6)

✓ 3. Communicate state of RW assets to Unity per DR ??



Full Demo Schematic



Keypad Internal Schematic

Demo Performance

- Demo accurately reads state of 19 inputs with two limitations
- Arduino communicates input devices' state to laptop at 2600 Hz – 2900 Hz
- Laptop can read and store state bitstring in Unity

Demo Limitations

1. Keypad 'Ghost' Presses
    - Due to the nature of the keypad's multiplexing array, certain key combinations being depressed simultaneously can create erroneous sensed presses on non-depressed keys
    - Only occurs when more than 3 keys are pressed simultaneously in certain combinations
2. Rotary Encoder Skips
    - Rotary encoder does not read high speed rotations accurately
    - Arduino loop speed is not fast enough to register each angle change pulse

Demo Limitations - Mitigation

1. Keypad 'Ghost' Presses
    - Do not require user to press more than 3 keys simultaneously
    - Reasonable limitation, as nearly all practical keypad use cases only require serial input and do not accept multiple simultaneous presses
2. Rotary Encoder Skips
    - Option 1: Do not employ a rotary encoder in situations with rapid rotations (screwdrivers, drills, etc.)
    - Option 2: Replace rotary encoder with potentiometer, which does not skip

HR Data Transfer - Feasibility Demo

DR 1.2.2.1 - At least 4 input devices shall be sampled during the simulation.

DR 1.2.6 - The state of PR input devices shall be communicated to the VR simulation at a rate of **90 Hz**.

PR - VR Data Transfer DEMO

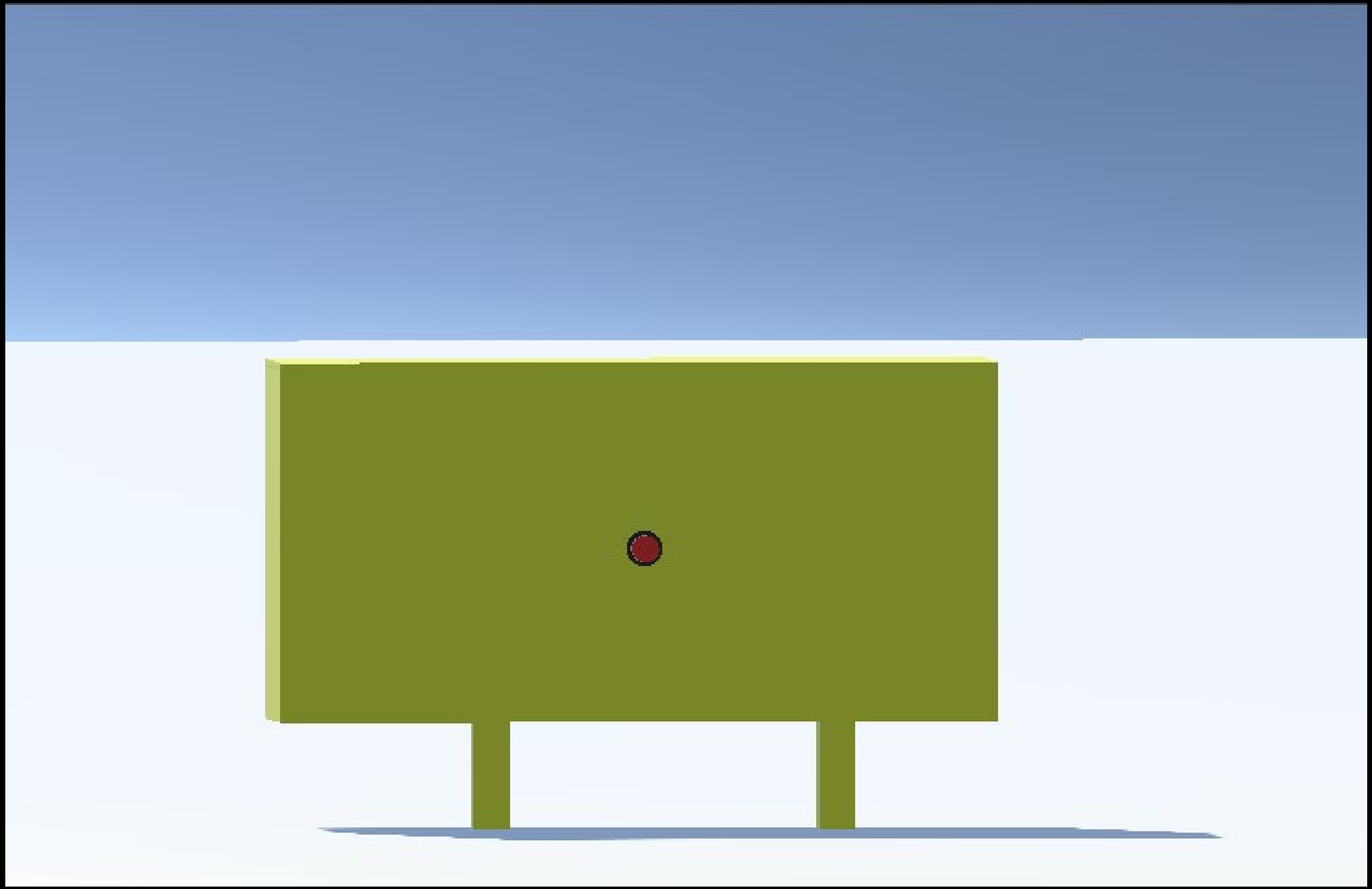
Arduino UNO + Button + Switch + Rotary Encoder + Multiplexed Keypad

Results:

- Arduino communicates input devices' state to laptop at 2600 Hz - 2900 Hz
- The laptop can read and store state bitstrings in Unity
- Accurately reads the state of 19 inputs with two limitations:
    - Keypad 'Ghost' Presses
        - Mitigate: Don't require simultaneous inputs
    - Rotary Encoder Skips
        - Mitigate: Use a potentiometer

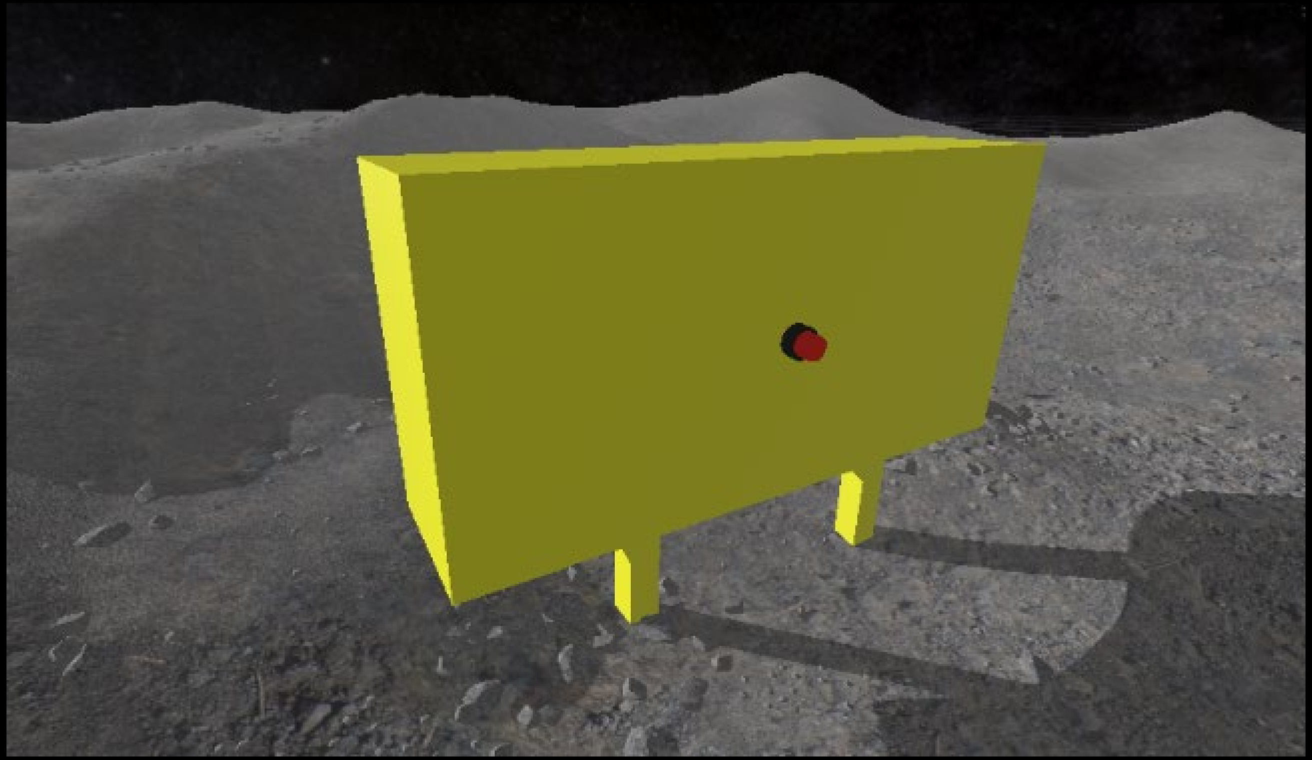
HR Latency Model & Test

HR Latency Void Test Environment



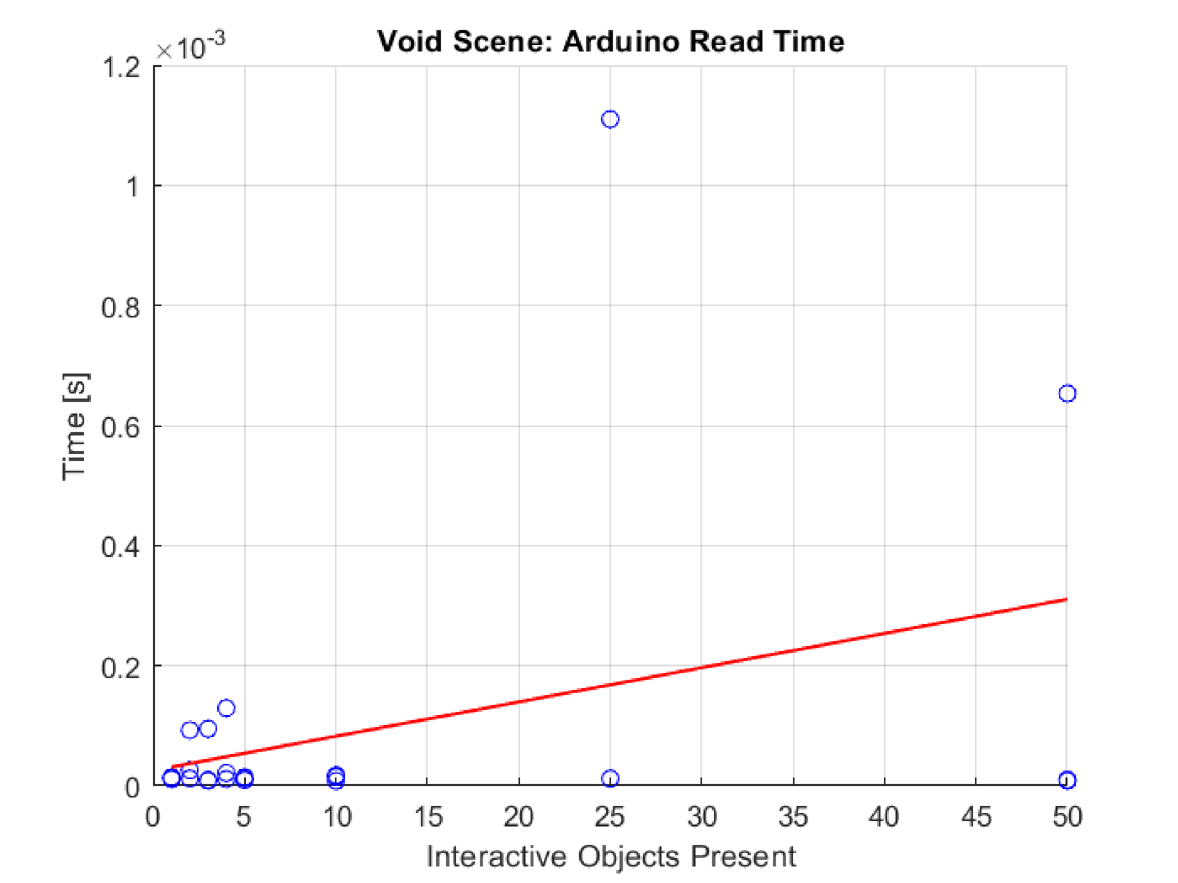
- Team built static panel
- Simple 1D plane
- Default Unity scene basic lighting
- Interactable button element developed by team
  - Includes collision box with pop up text to display interactability range
  - On button click, displays text, turns on several point lights and shows animation of button pressing and depressing

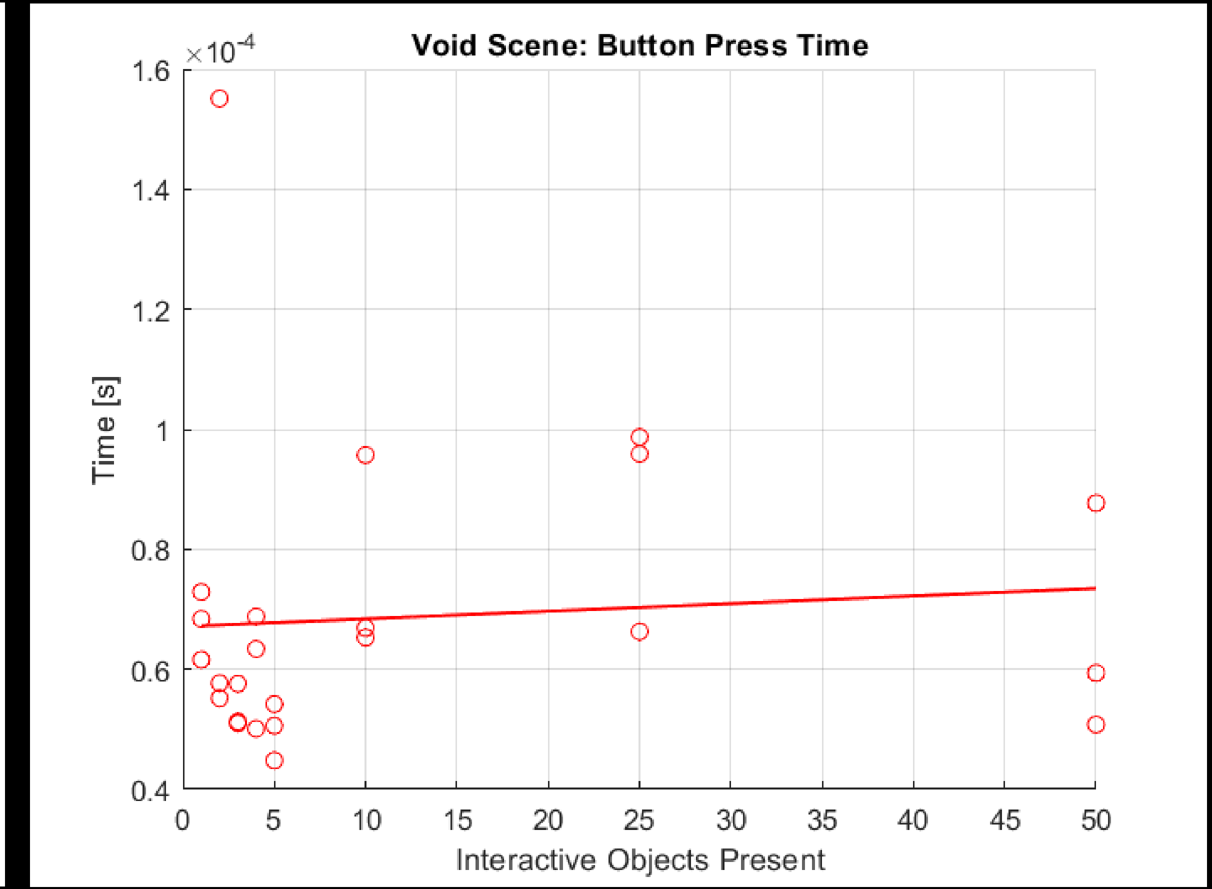
HR Latency Moon Test Environment



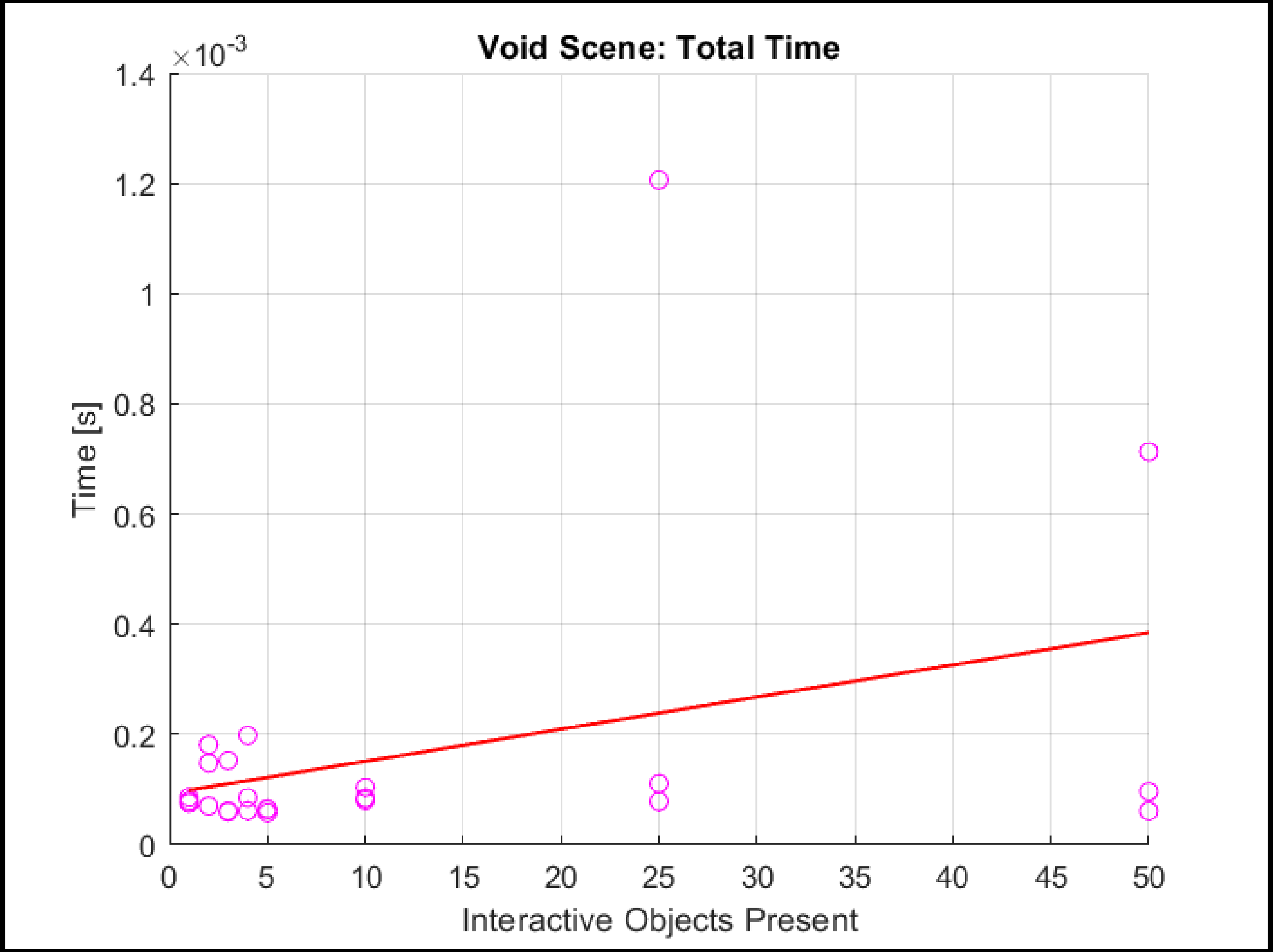
- Pre-built Unity moon environment available for free from Unity Asset store from developer Arcsine Technologies
  - Includes terrain, lighting and particle textures
- Team built static panel
- Default Unity scene basic lighting
- Interactable button element developed by team
  - Includes collision box with pop up text to display interactability range
  - On button click, displays text, turns on several point lights and shows animation of button pressing and depressing

Unity Processing Result Trends (Void)

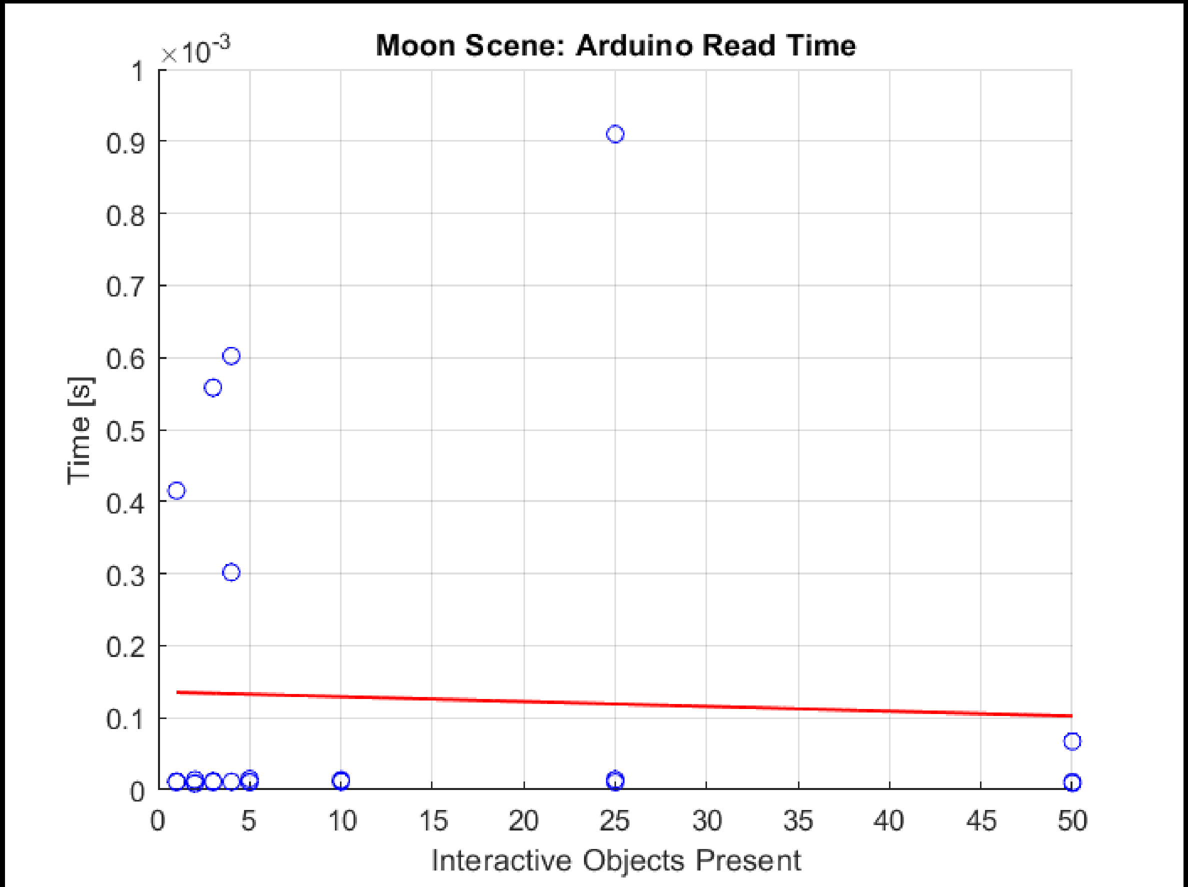


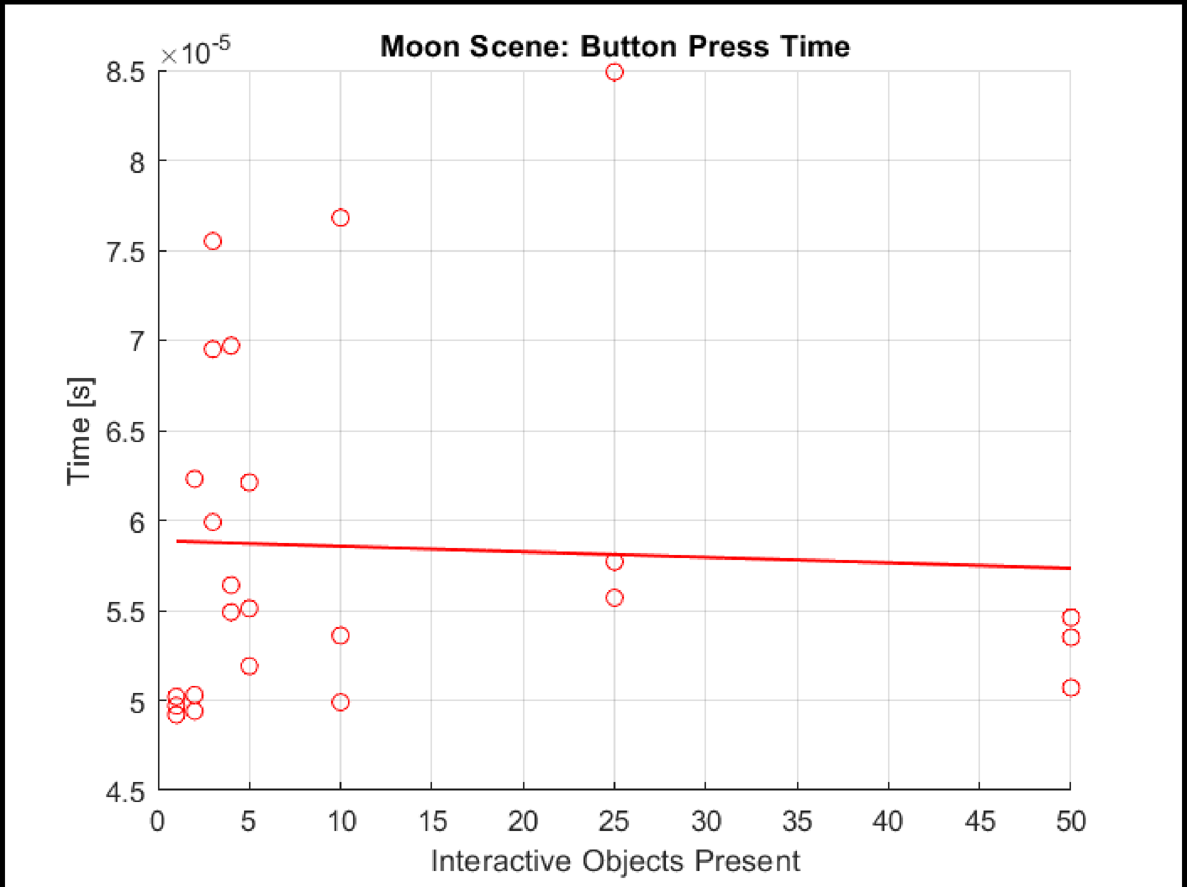


Unity Processing Result Trends (Void)

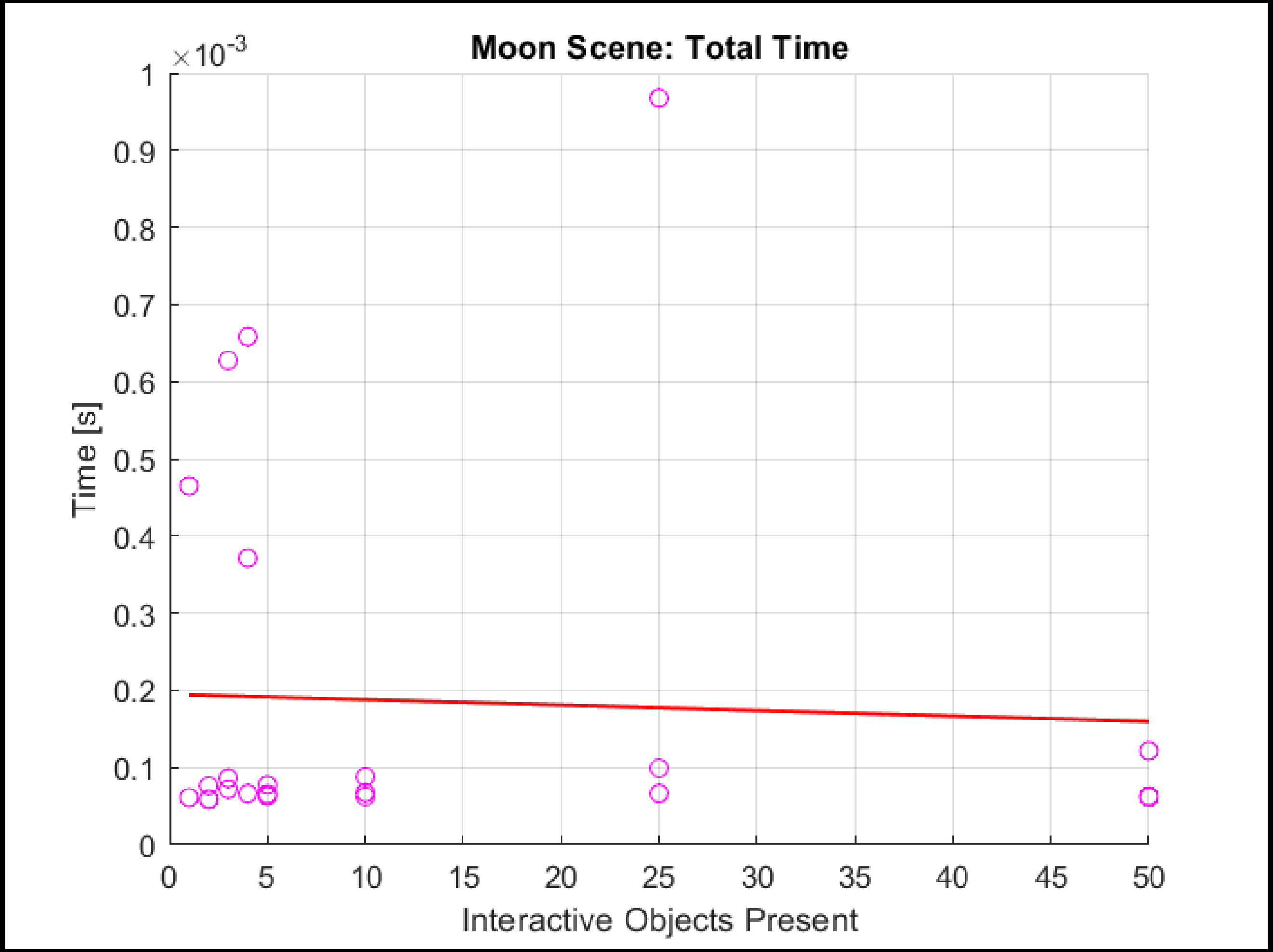


Unity Processing Result Trends (Moon)





Unity Processing Result Trends (Moon)



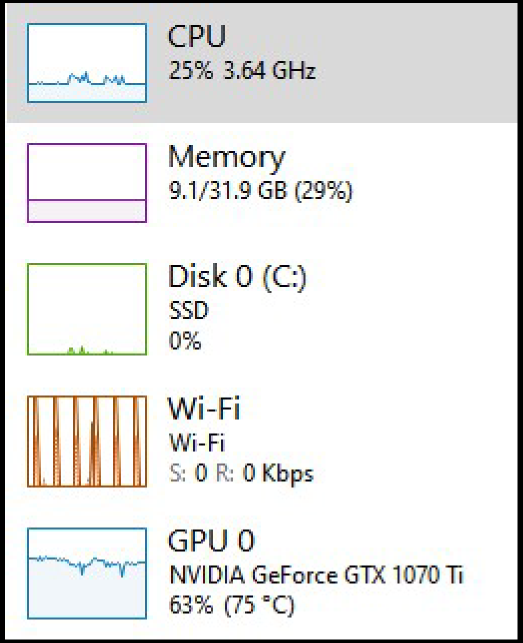
Latency Calculations

- Arduino Reads in Data
  - Switch time takes 0.00092ms (from experimentation) to avoid bouncing
- Arduino Processes Data
  - Clock speed of 84MHz ($\frac{1}{84,000,000} = 0.0119\mu s$ per operation)
- Arduino Baud Rate
  - Must send 4 bits for potentiometer + 9 for buttons + 4 for switches
  - Sends 4800 bits per second
  - Takes $\frac{(4+9+4)}{4800} = \frac{17}{4800} = 0.00354s$
- Unity Reads in Data from Serial Port
  - 0.068ms (from experimentation)
- Unity Processes the Interaction
  - 0.065ms (from experimentation)
- Meta Quest 2 Displays Picture
  - Operating at 120 FPS ($\frac{1}{120} = 8.33\ ms$)
- Total Time $0.00092\text{m}s + 2 * 0.0119\mu s + 0.00354s + 1.1ms + 0.16ms + 8.33ms = 13.13ms$

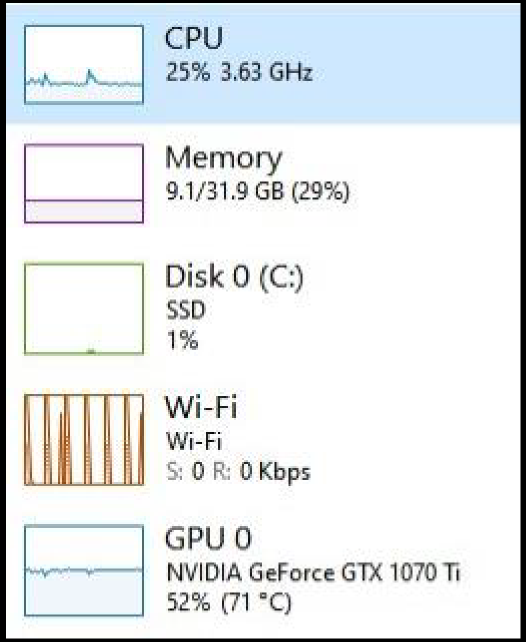
- HTC Base Station Sends State
  - Worst case 60Hz = $\frac{1}{60} = 16.6ms$
- Unity Reads in Data from Bluetooth
  - 0.068 ms (assumption)
- Unity Processes the Interaction
  - 0.065ms (from experimentation)
- Meta Quest 2 Displays Picture
  - Operating at 120 FPS ($\frac{1}{120} = 8.33\ ms$)
- Total Time $16.6ms + 0.068ms + 0.065ms + + 8.33ms = 25.15ms$

Processing Workload

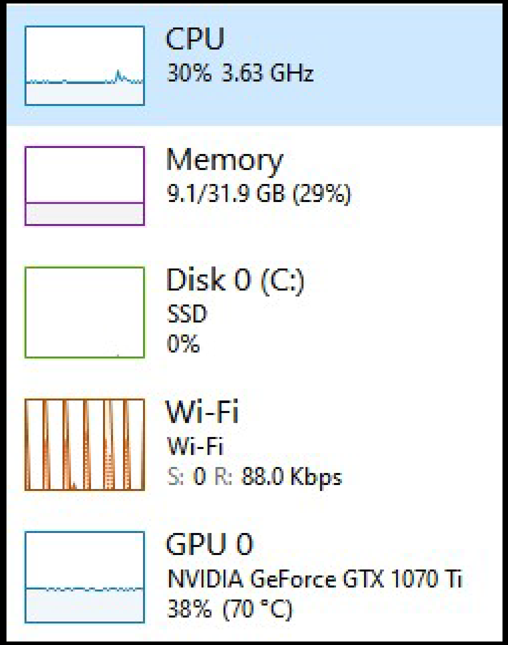
Processing Workload Test



1 Interactable



50 Interactables

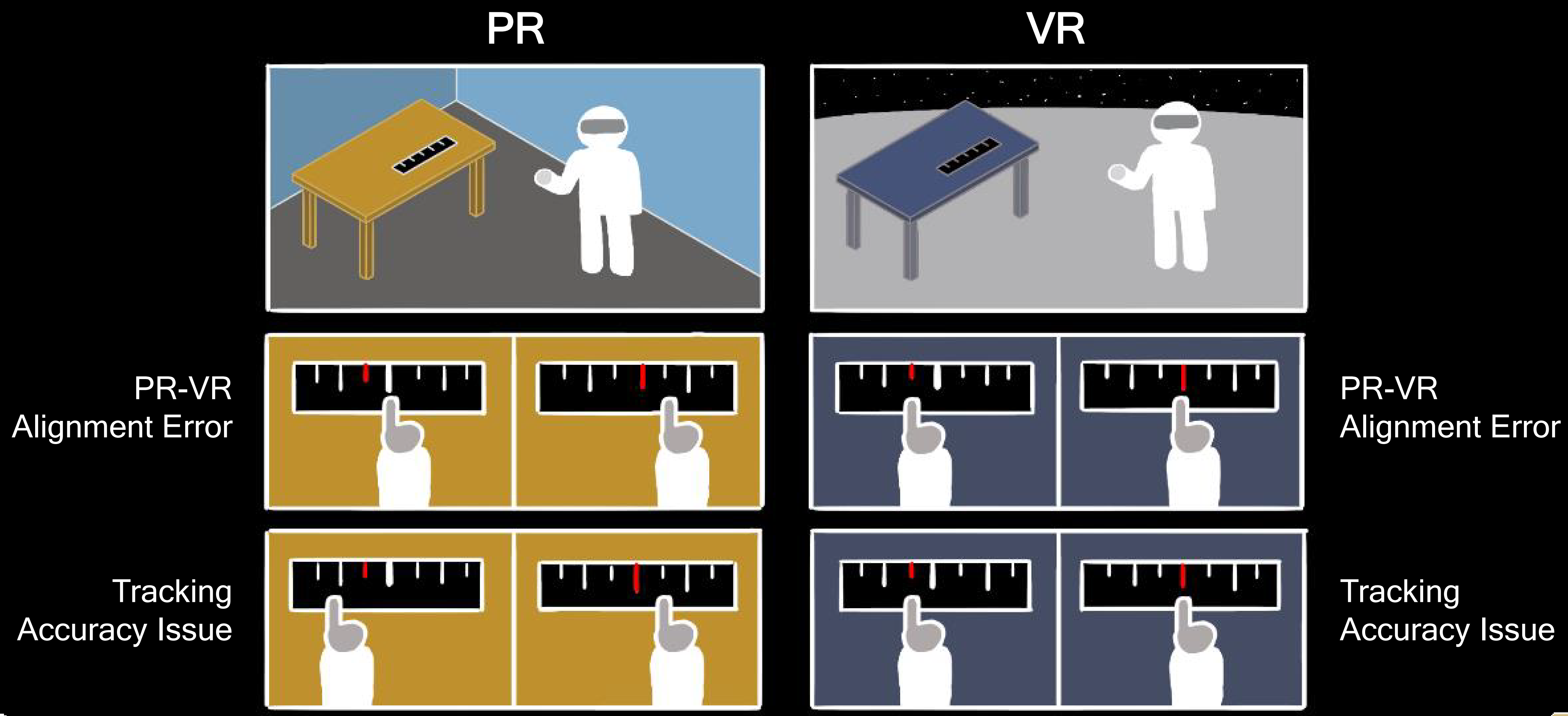


200 Interactables

Hardware Used
Processor: AMD Ryzen 5 2600 Six-Core
Graphics: NVIDIA GeForce GTX 1070 Ti
Memory: 32 GB DDR4

Hand Tracking Accuracy Test

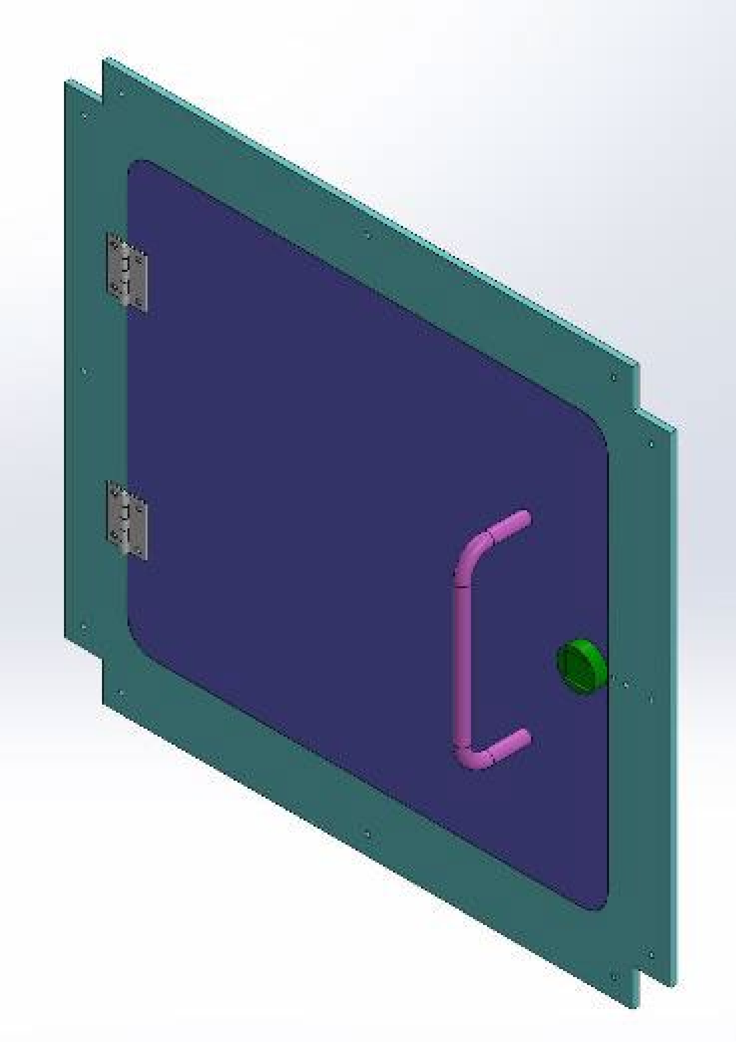
Hand Tracking Accuracy Test Plan



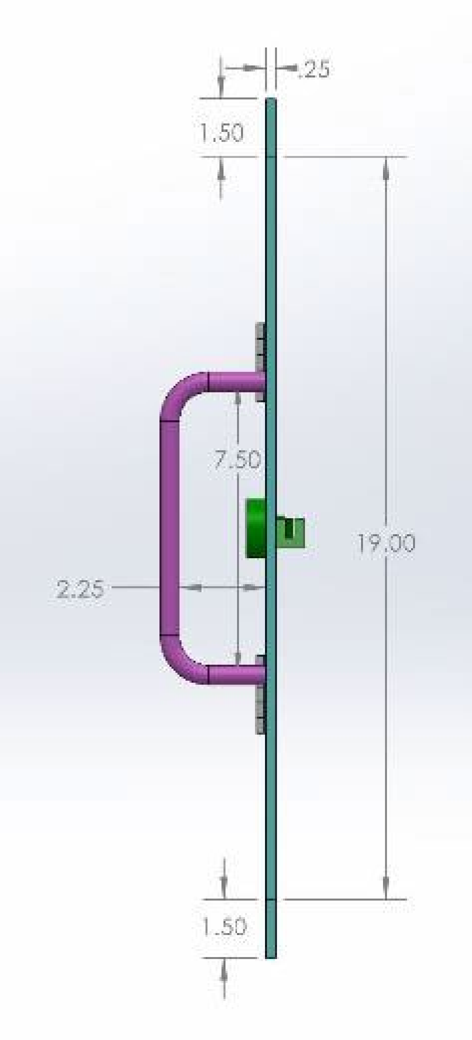
EVA Tool, ORUs, Door & Locking Mechanism Design

Door Panel

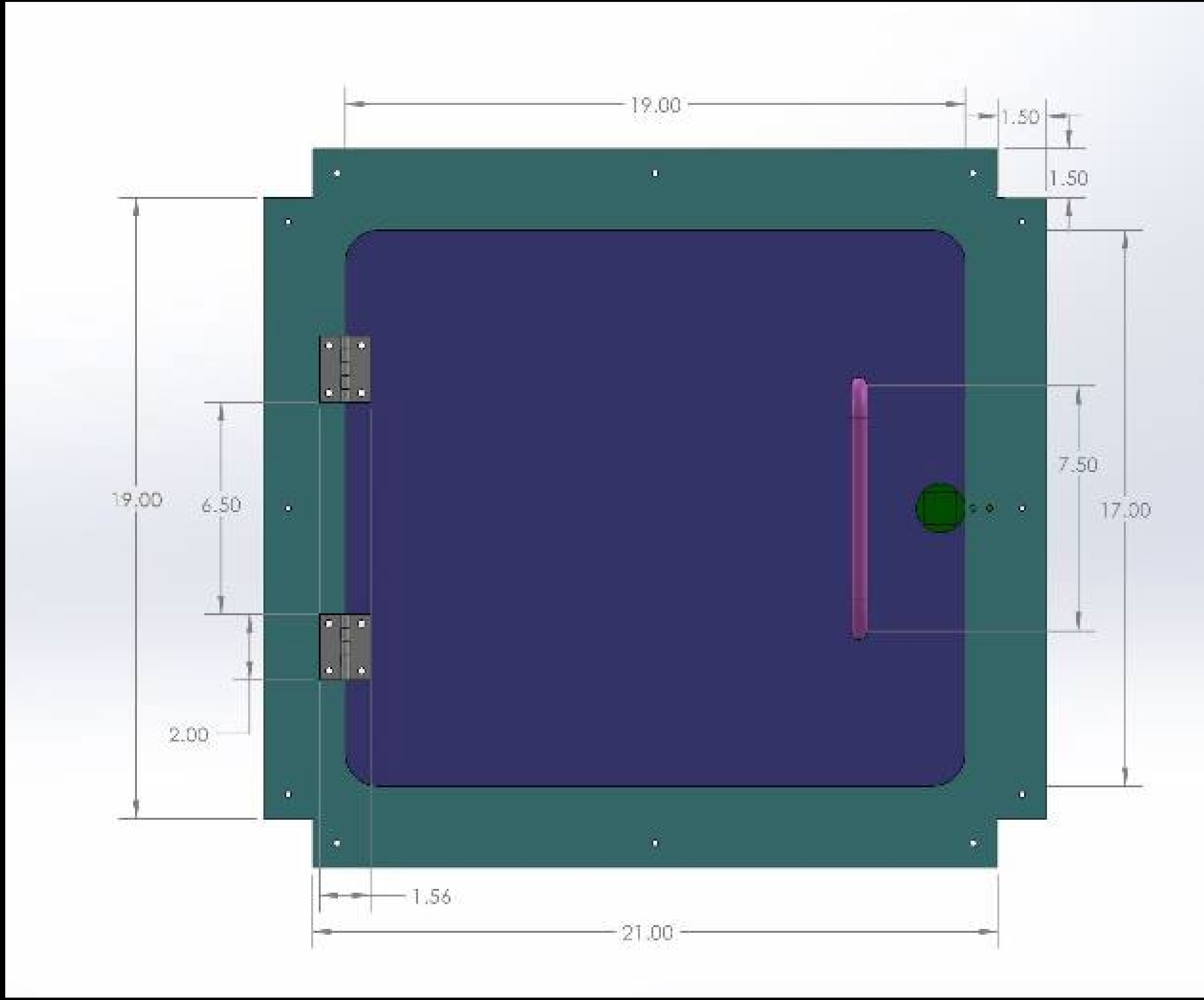
ISO View



Side View



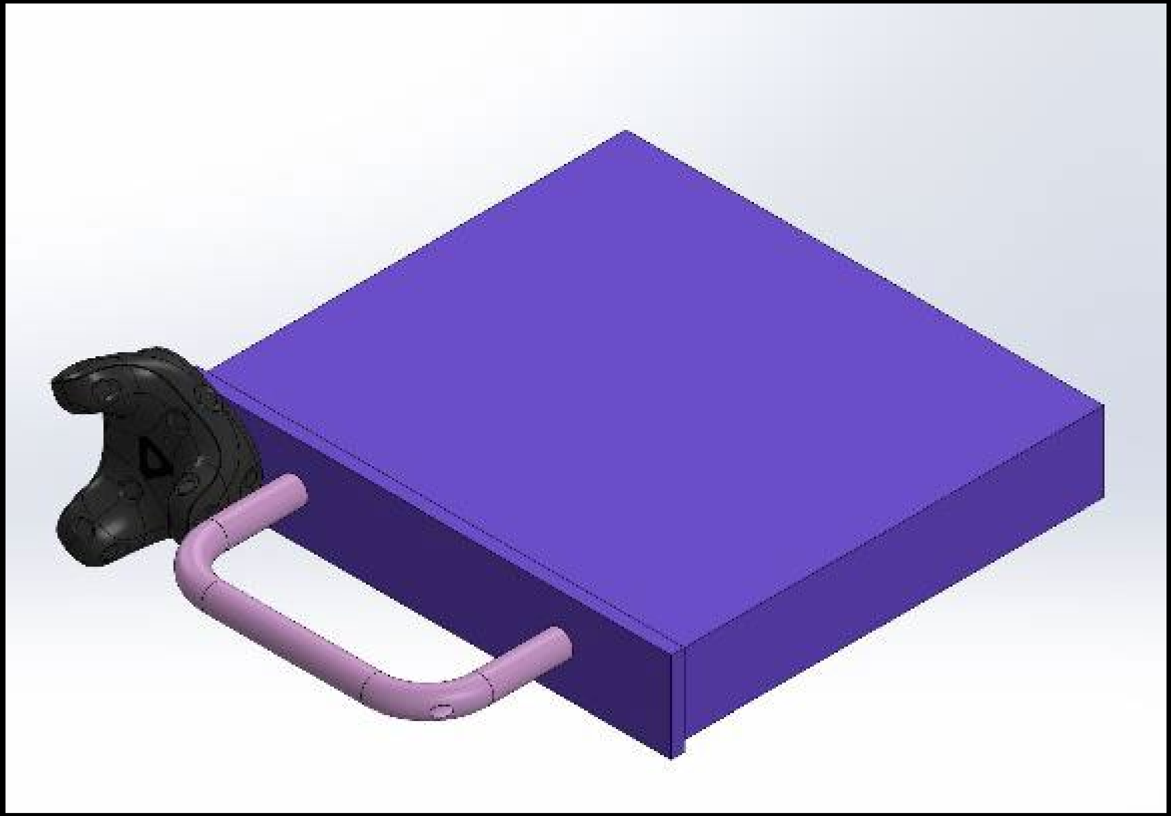
Front View



Units = inches

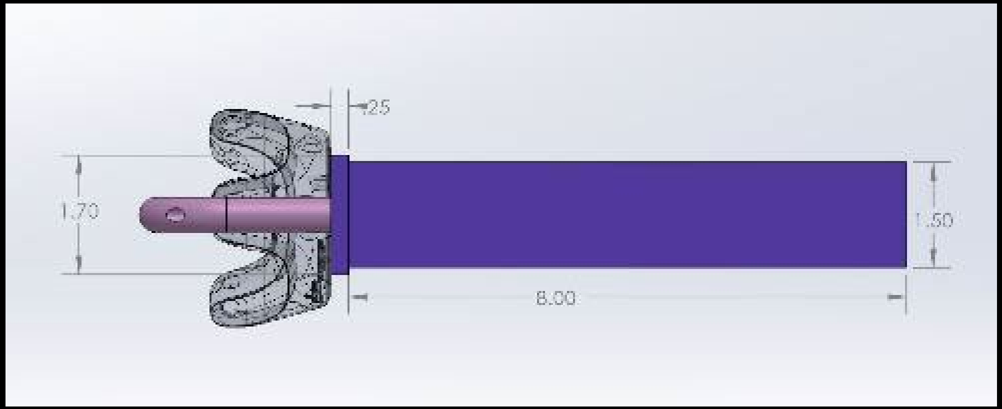
ORUs

ISO View

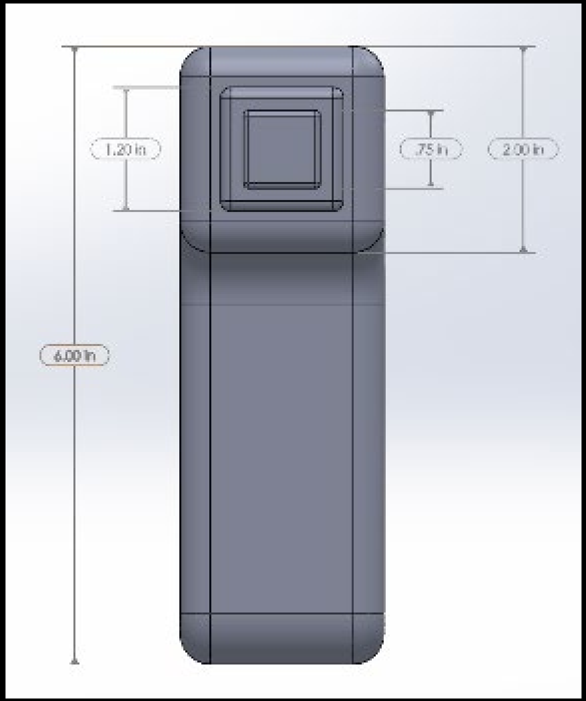


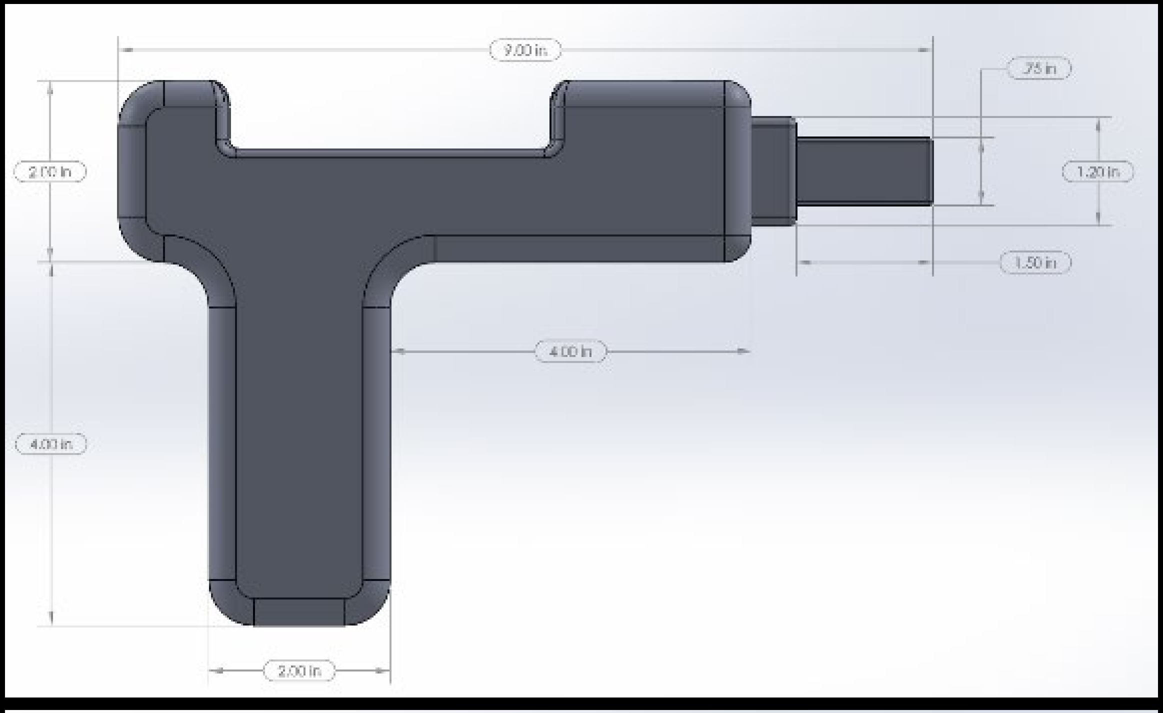
Front View

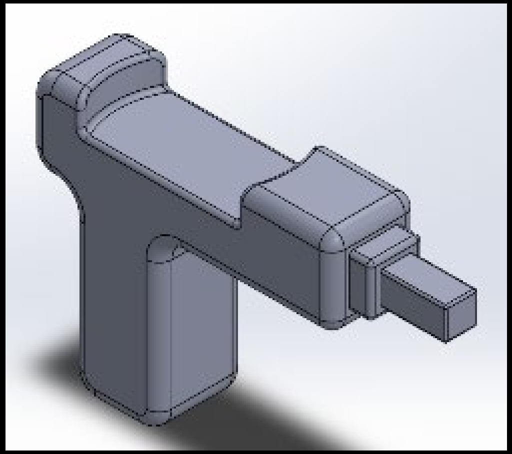
Side View

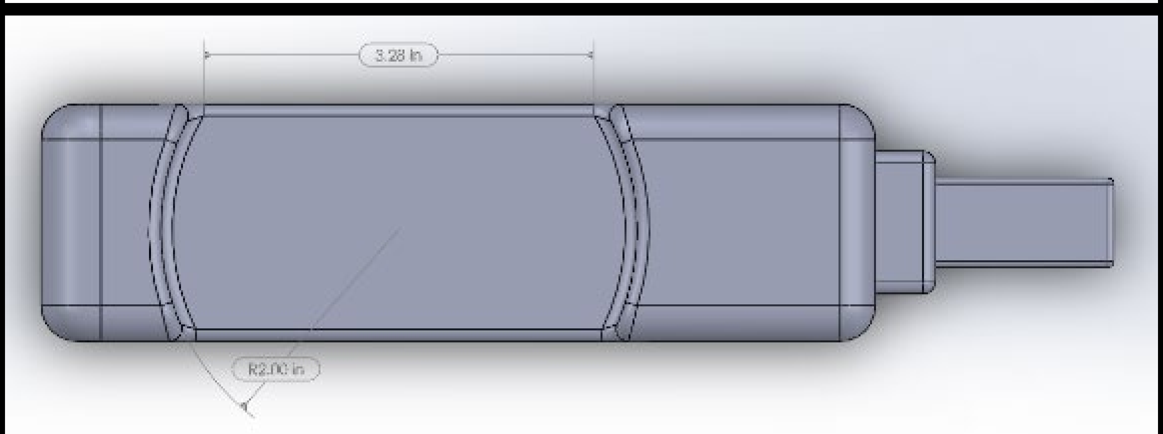


EVA Tool Design



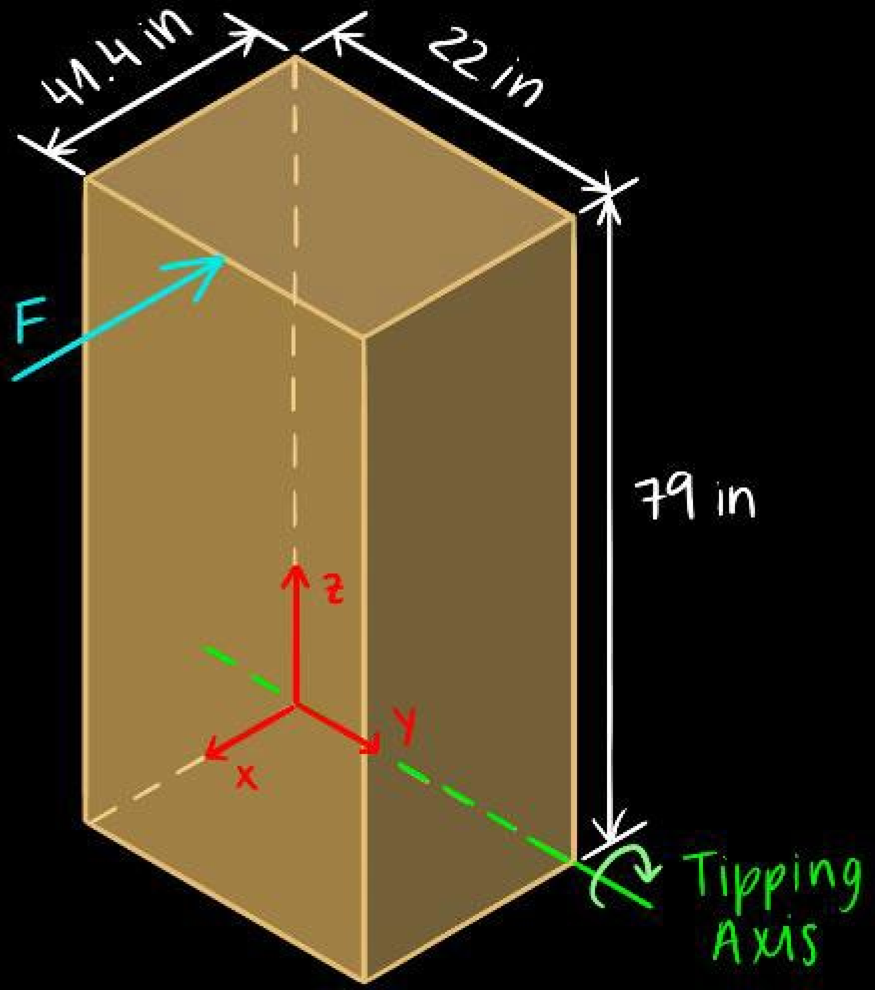


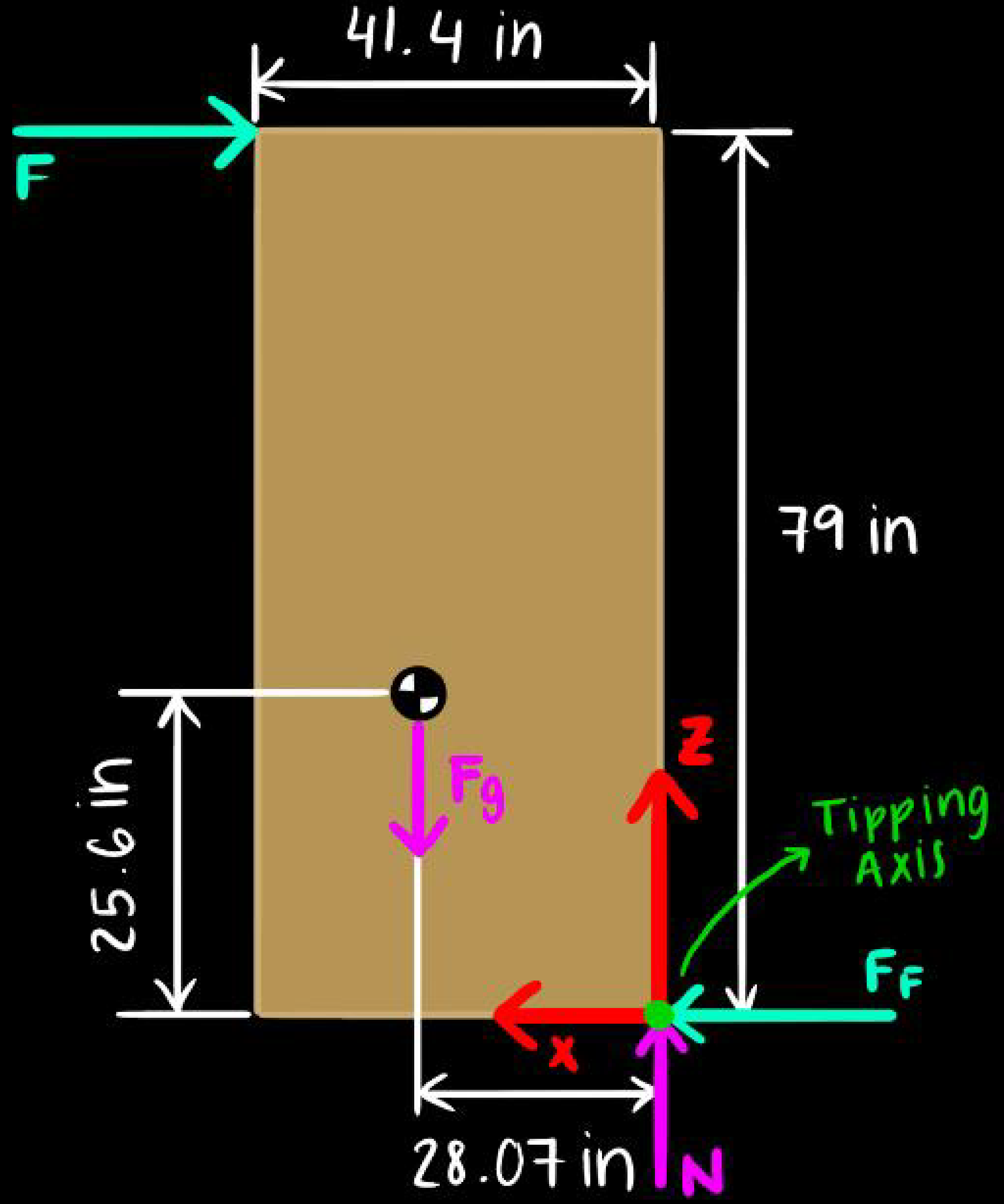




EVA Panel Tipping Model

Tipping Model





Moment Balance - PUSH

Convert to SI: 79 in $\simeq$ 2.01 m
41.424 in $\simeq$ 1.05 m
28.07 in $\simeq$ 0.71 m

Tipping over:

$$M_F > M_g + M_W$$

$$M_g = F_g(0.71\,m) = mg(0.71\,m)$$
$$M_g = (26.32\,kg)(9.81\,m/s^2)(0.71\,m) = 184.13\,Nm$$

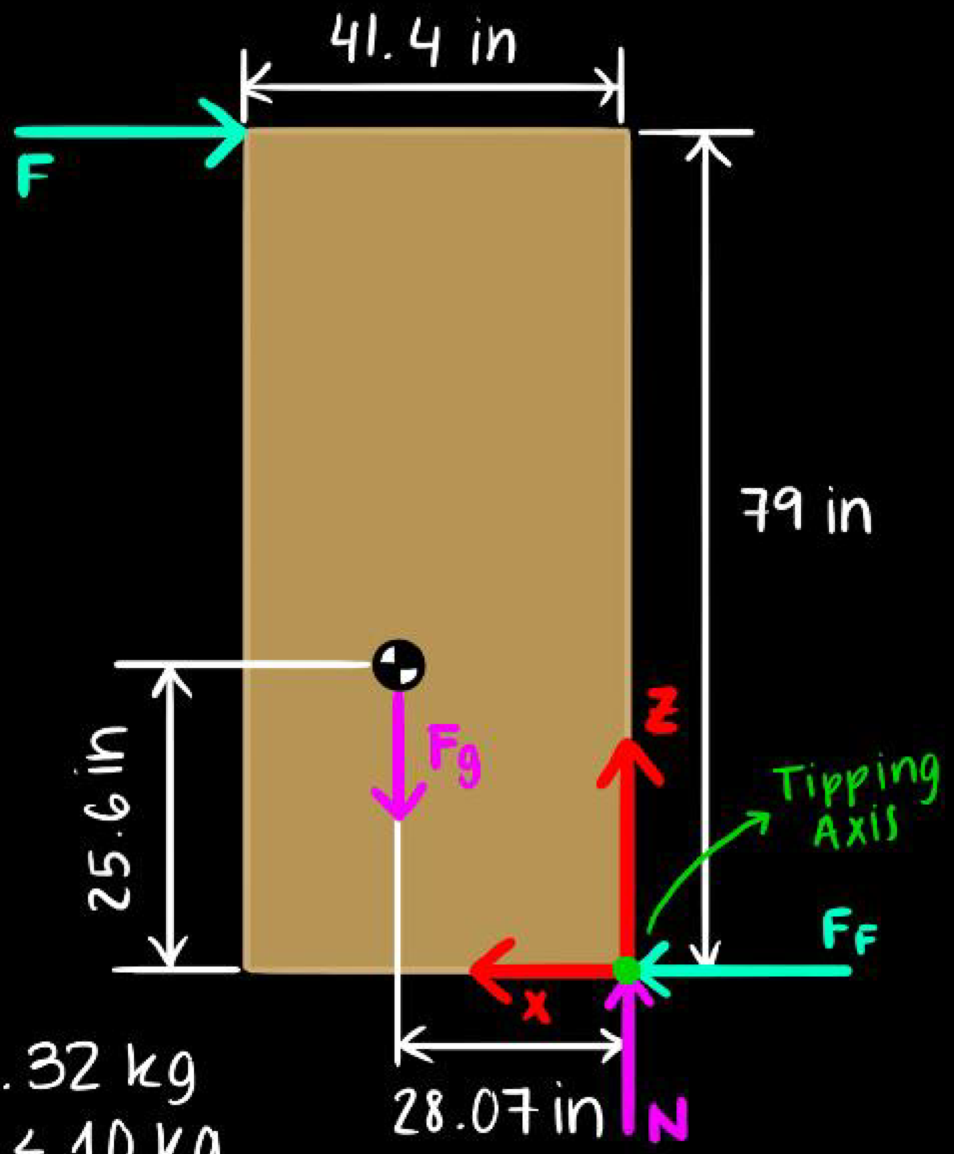
$$M_F = F(2.01\,m)$$
$$M_W = F_{gw}(x_w) = m_w g x_w = m_w x_w (9.81\,m/s^2)$$

$$F(2.01\,m) > 184.13\,Nm + m_w x_w (9.81\,m/s^2)$$

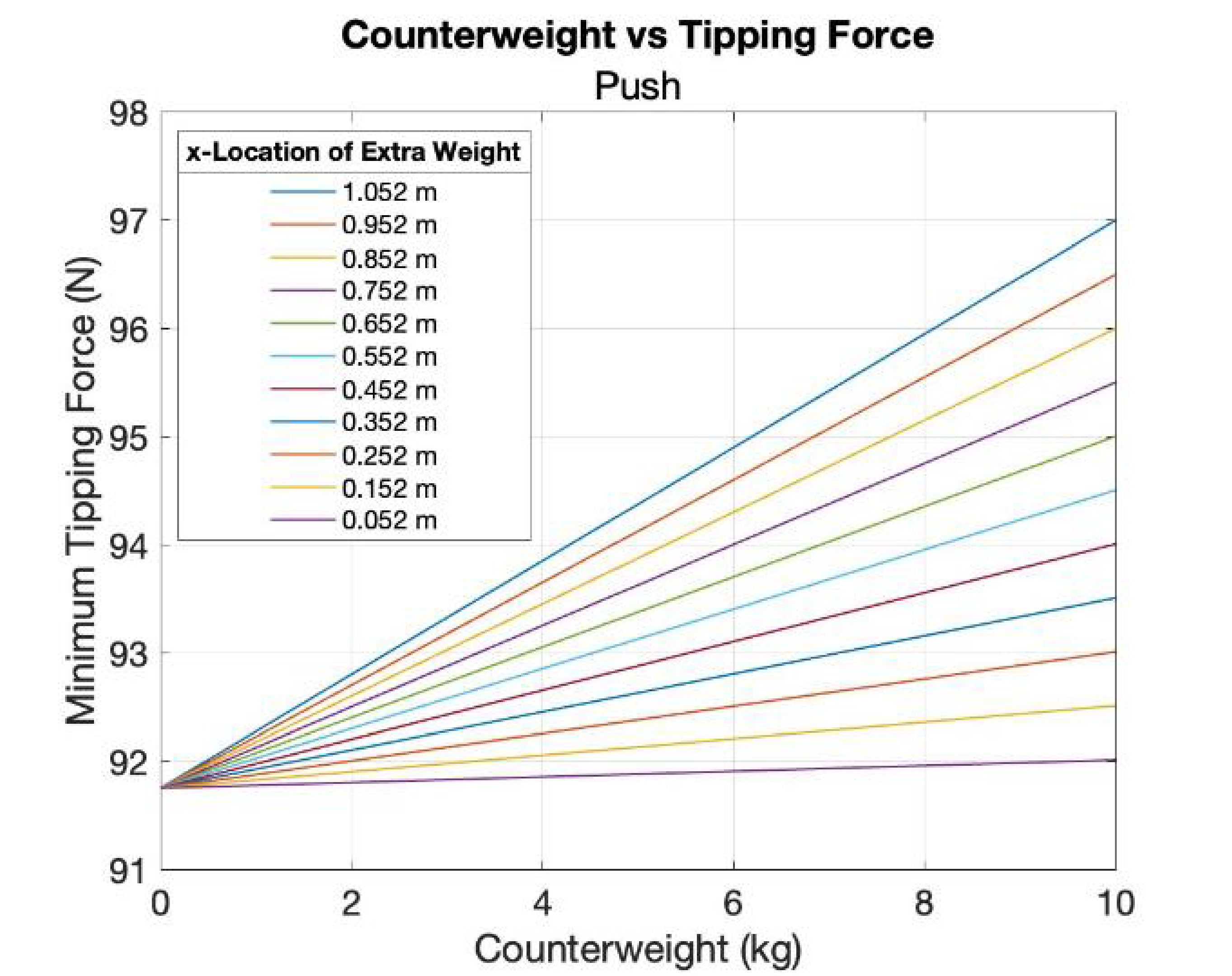
$$\boxed{F > 91.76\,N + (4.88\,s^{-2})\,m_w x_w}$$

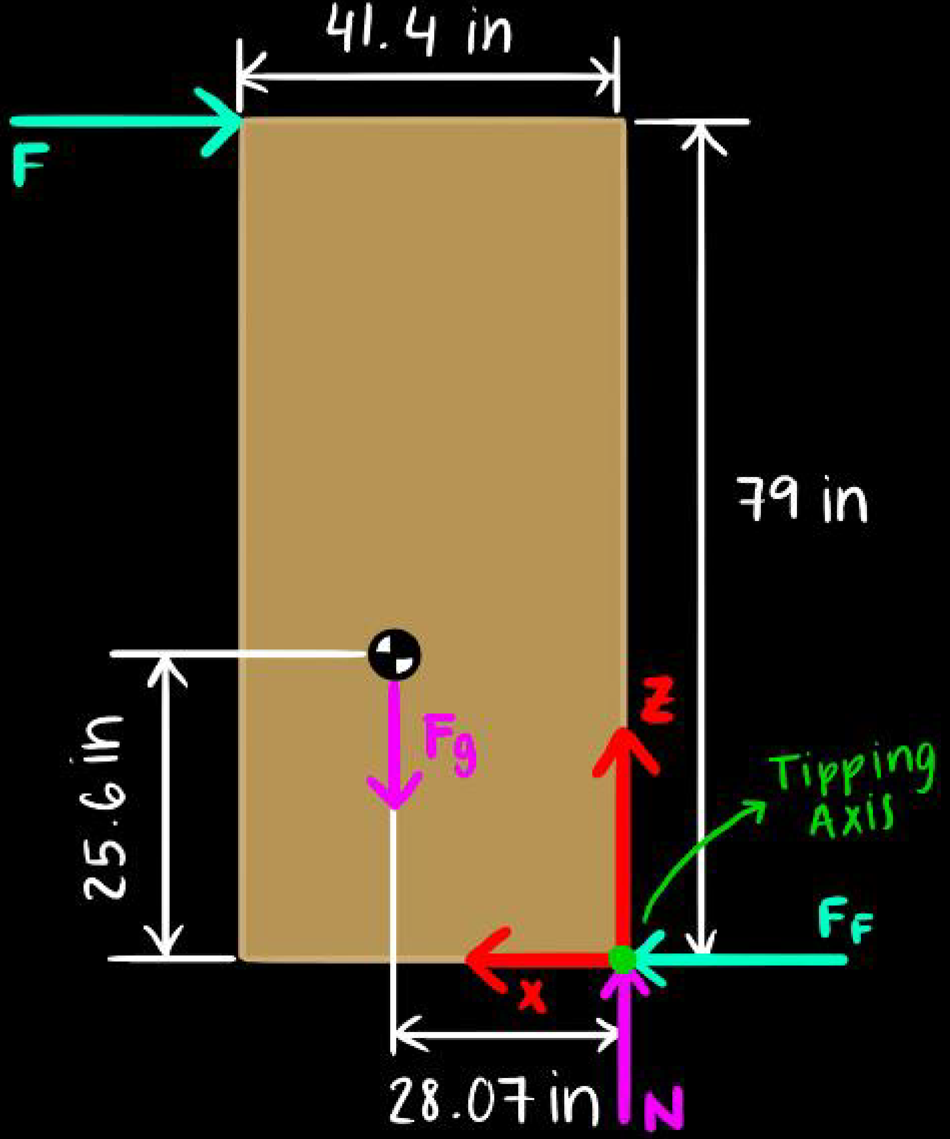
Plot F as function of m_w and x_w

$m = 26.32\,kg$
$0 \le m_w \le 10\,kg$
$0 \le x_w \le 1.05\,m$



Moment Balance - PUSH





Moment Balance - PULL

Tipping over:

$M_F > M_g + M_w$

$m = 26.32\ kg$

$0 \le m_w \le 10\ kg$

$0 \le x_w \le 1.05\ m$

$M_g = mg(1.05\ m - 0.71\ m)$

$M_g = (26.32\ kg)(9.81\ m/s^2)(0.34\ m) = 87.60\ Nm$

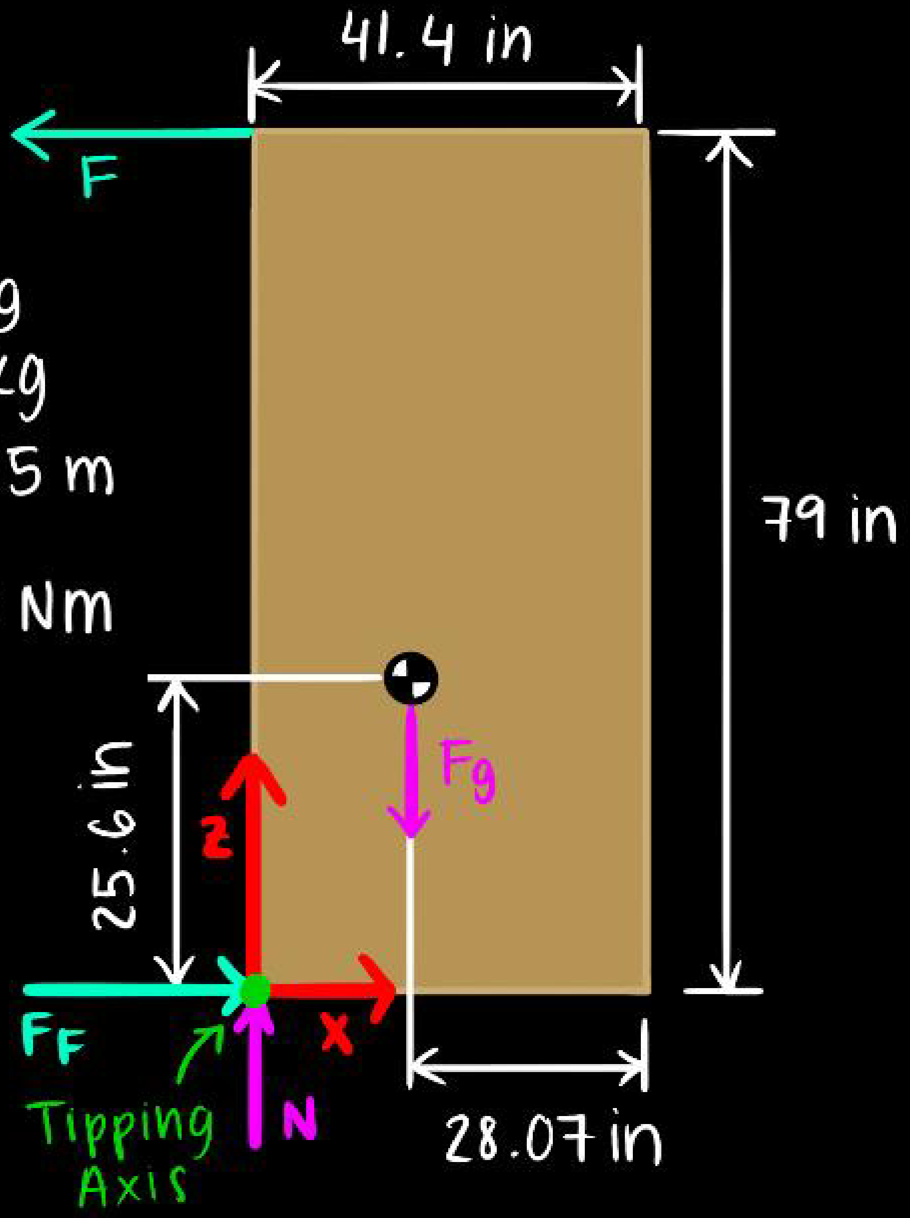
$M_F = F(2.01\ m)$

$M_w = m_w(9.81\ m/s^2)\,x_w$

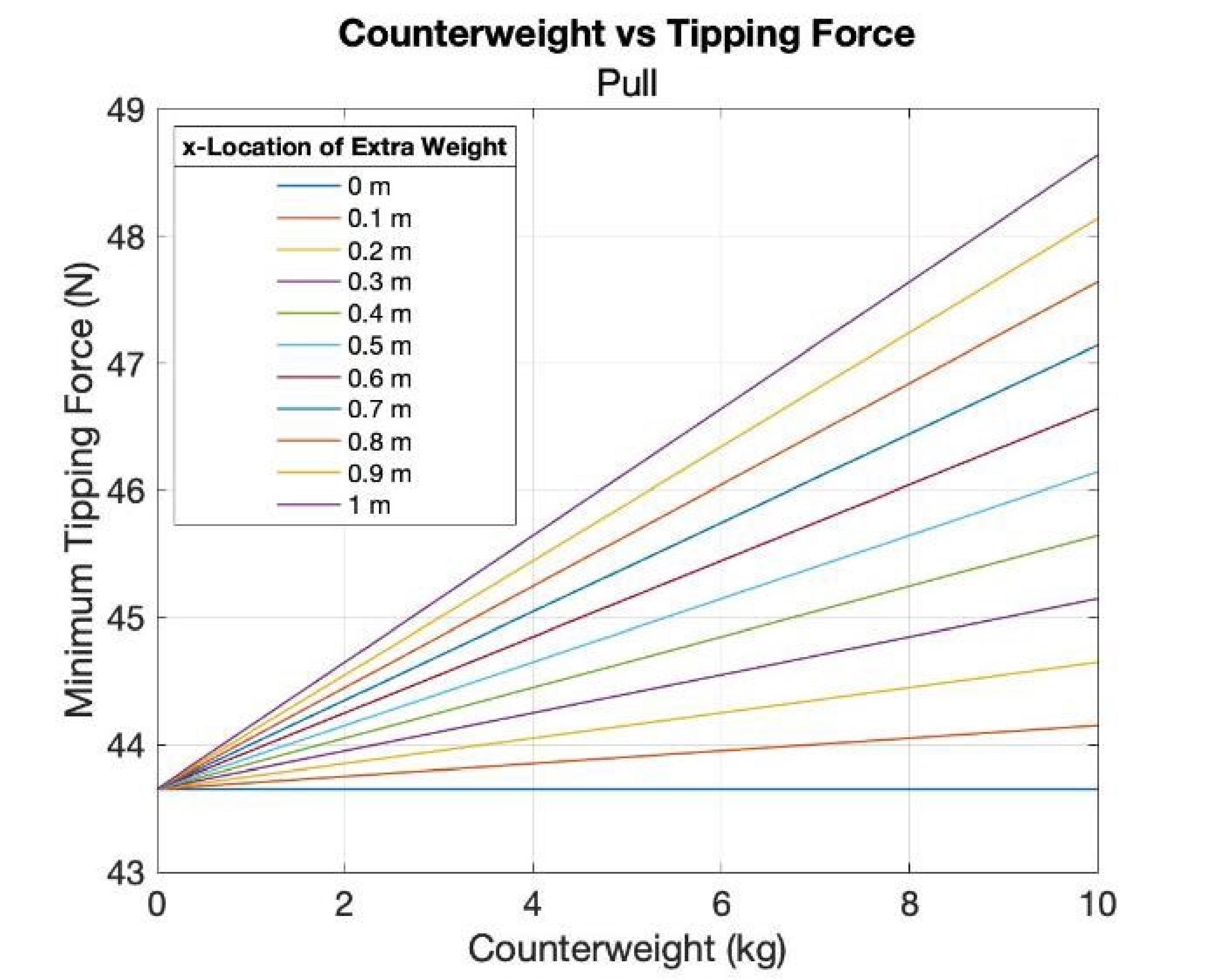
$F(2.01\ m) > 87.60\ Nm + (9.81\ m/s^2)\,m_w x_w$

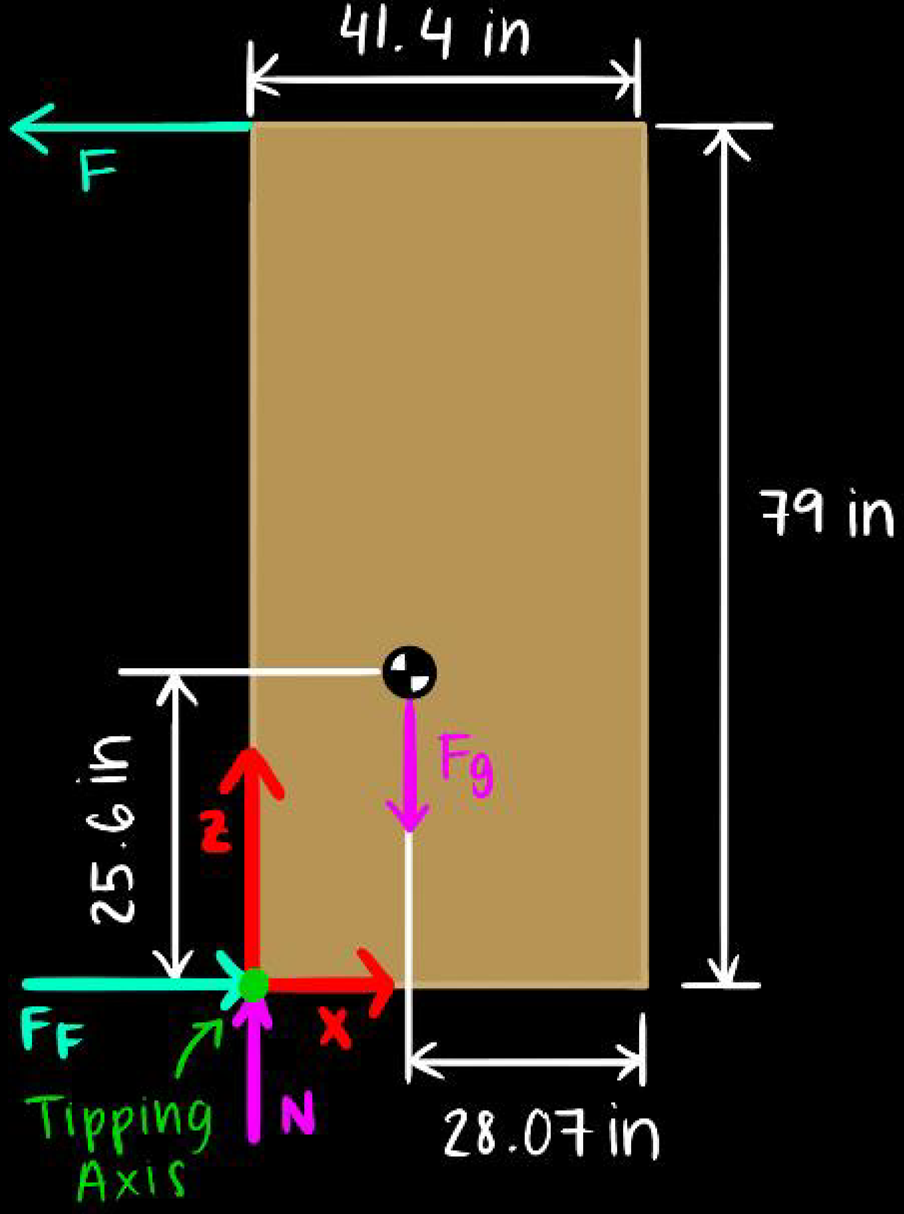
$$F > 43.65\ N + (4.89\ s^{-2})\,m_w x_w$$

Plot F as function of m_w and x_w

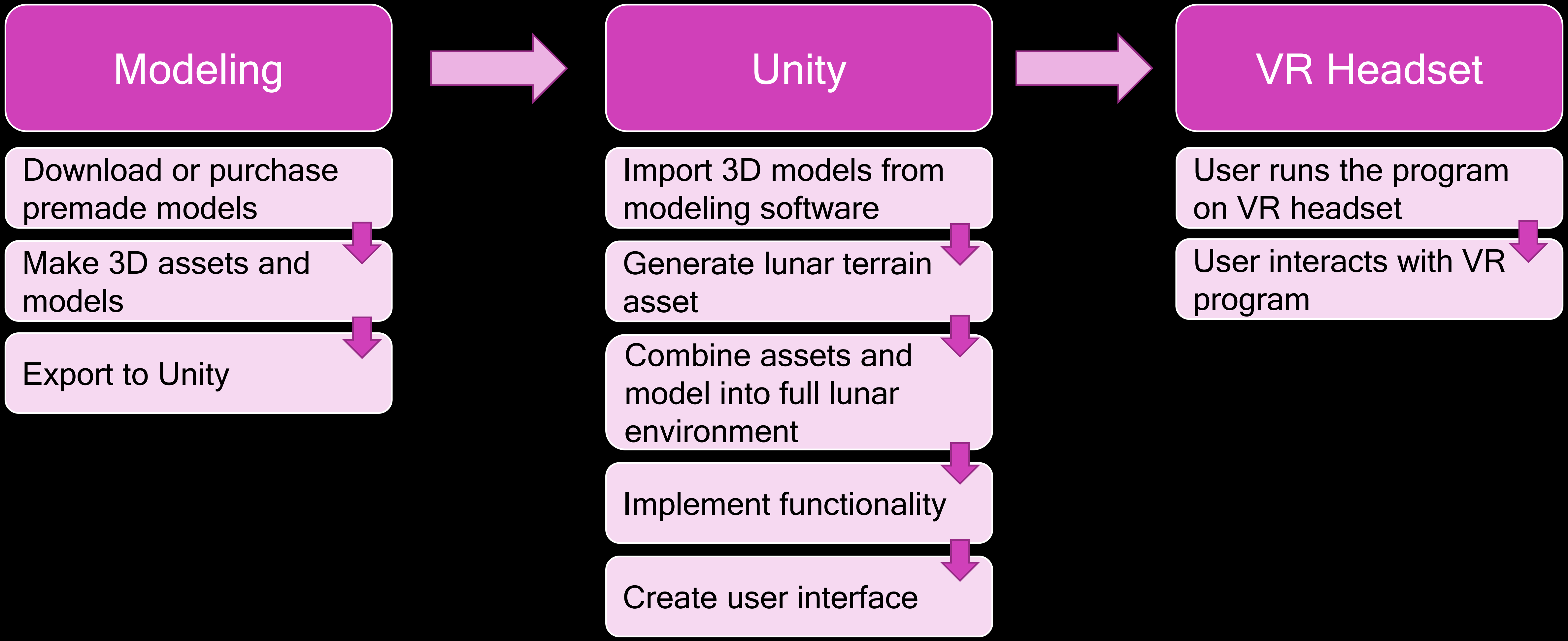


Moment Balance - PULL





Software Process Flow



Full Budget: Hardware 1/2

Hardware		Supplier	Qty	Cost/Unit	Cost
Particle Board 5/8 2x4	Used as siding and eva panel on the stand	HomeDepot	1	$15.82	$15.82
Fiberboard 1/4 2x4	Used as a base for the EVA panel stand, provides stability and a way to add weight	HomeDepot	1	$14.24	$14.24
Wood Screws #10 2in 50pc	Used for EVA stand and arm harness	HomeDepot	1	$10.83	$10.83
Flat Aluminium Bar 96x1x1/8	Used for arm harness as the structure	HomeDepot	2	$22.93	$45.86
Pine Board 2x2x8'	Used for the EVA stand	HomeDepot	10	$15.20	$152.00
Pine Board 2x10x8'	Used for the EVA stand	HomeDepot	1	$16.57	$16.57
Resistance Loop Exercise Bands	Used to create resistance within the arm constraint mechanism	Amazon	1	$10.87	$10.87
1 inch buckles	Used to create adjustable straps for the arm harness	Amazon	1	$10.99	$10.99
25 1/4" Inch Stainless Steel Bearing Balls	Used to adjust the weight of the mock tools we create to give the user a sense of realisim	Amazon	1	$5.65	$5.65
HH-66 Vinyl Cement, 4 oz. can	Vinyl glue, to be used for prototyping the arm constraint hardware	Amazon	1	$13.99	$13.99
Ball Bearing Roller	Used for locking and unlocking EVA panel door	McMaster	1	$7.05	$17.68
Shoulder Bolts 1/4 diameter 3/8	Used to construct EVA panel frame	McMaster	8	$2.34	$18.72
Teflon Washers - 1D 1/4in	Used to construct EVA panel frame	McMaster	1	$9.94	$9.94

Full Budget: Hardware 2/2

Teflon Washers - 1D 0.197in	Used to construct EVA panel frame	McMaster	1	$5.00	$5.00
Nuts - pack of 100	Used to construct EVA panel frame	McMaster	1	$2.20	$2.20
Threaded inserts for PLA	Used to construct EVA panel frame	McMaster	2	$10.00	$20.00
MDF Sheet	Used to construct EVA panel frame, ORUs	HomeDepot	1	$54.33	$54.33
Gorilla Glue	Used to construct EVA panel frame	HomeDepot	1	$12.98	$12.98
3/8 Hex Nuts	Used to construct EVA panel frame	HomeDepot	4	$0.21	$0.84
Threaded Zinc Rod	Used for the EVA stand	HomeDepot	1	$1.97	$1.97
10-32-1 1/4 Machine Screw	Used for the EVA stand	HomeDepot	12	$1.38	$16.56
10-32-1 Machine Screw	Used for EVA stand and arm harness	HomeDepot	1	$1.38	$1.38
MDF Sheet 4x8' 1/4"	Used for EVA panel stand	HomeDepot	1	$54.33	$54.33

Full Budget: Software

Software		Supplier	Qty	Cost/Unit	Cost
HTC Vive 3.0 Tracker	Tracking pucks that allow for VR tracking of physical objects	Amazon	4	$129.98	$519.92
HTC Base Station 2.0	Base stations communicate with the Vive Trackers, send info to the headset	Amazon	2	$249.95	$516.89
Base Station Tripod (2 pack)	Allows the base stations to be held up for better communication to the trackers.	Amazon	1	$45.00	$45.00
Batteries (AA)	Used to power Oculus controllers	HomeDepot	1	$8.87	$8.87
Dlink Air Bridge	Used to provide a stable connection between Oculus headset and computer running unity	Meta	1	$100.00	$100.00

Full Budget: Electrical

Electronics		Supplier	Qty	Cost/Unit	Cost
Round Momentary Buttons (35 mm)	Buttons below the screen to control what the screen says/switch through tasks	Amazon	1	$15.49	$15.49
Rotary Potentiometer - 10k Ohm, Linear	used to track the motion of the hinge of the door	Amazon	1	$9.98	$9.98
Arduino Shield	Used to create the button panel on the EVA stand	Amazon	1	$17.90	$17.90
Square push buttons	Used for the buttons on the EVA panel	Amazon	1	$12.99	$12.99
Red and Black Wires	Used to connect electronics in EVA panel	Amazon	1	$9.98	$9.98

Resources

VR/HR Resources 1/2

1. https://www.pcmag.com/news/htcs-vr-hand-tracking-system-just-got-a-lot-better
2. https://www.raywenderlich.com/9189-htc-vive-tutorial-for-unity
3. https://www.vive.com/us/
4. https://soundgearlab.com/how-use-bluetooth-headphones-oculus-quest-2/#:~:text=Although%20Oculus%20quest%202%20has,headphones%20to%20the%20headset%20with
   https://www.biorxiv.org/content/10.1101/2022.02.18.481001v1.full
5. https://learn.microsoft.com/en-us/hololens/hololens-core-components
6. https://www.breezecreative.com/dynamic-floor?gclid=CjwKCAjwg5uZBhATEiwAhhRLHv7BDOQdIQ6NFyaNNPwlXDQECx_ZjURp68v1mIBcf_zOKrb3PoV6sRoCnFQQAvD_BwE
7. https://hi5vrglove.com/store/hi5glove
8. https://www.manus-meta.com/software/polygon
9. https://www.ceva-dsp.com/ourblog/what-is-an-imu-sensor/#:~:text=An%20IMU%20is%20a%20specific,considered%20a%209%2Daxis%20IMU.
10. https://pixycam.com/pixy-cmucam5/
11. www.vr-compare.com
12. https://sid.onlinelibrary.wiley.com/doi/10.1002/jsid.999

PCs Resources 2/2

1. https://www.worldbrace.com/custom-best-shoulder-brace-support-manufacturer/
2. https://dunbarmedical.com/wearing-shoulder-brace/
3. https://www.braceability.com/products/shoulder-support-brace
4. https://www.menshealth.com/fitness/g25803874/best-compression-sleeves/
5. https://www.bauerfeind-sports.com/us/compression-sleeves-arm/
6. https://www.compressionstore.com/products/circaid-profile-foam-arm-sleeve
7. https://www.verywellhealth.com/what-is-a-cast-for-broken-bones-made-out-of-2549317
8. https://www.hiltonphoto.co.uk/joby-gorillapod-3k-tripod-with-ball-socket/