University of Colorado - Boulder

Department of Aerospace Engineering Sciences

ASEN 4018 - Senior Projects I

Project Definition Document (PDD)

Hybrid Environmental Immersive Simulation Training (HEIST)

Approvals

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Acronyms

AR	=	Augmented Reality
ARGOS	=	Active Response Gravity Offload System
CPE	=	Critical Project Element
EVA	=	Extravehicular Activity
FBD	=	Functional Block Diagram
FR	=	Functional Requirement
HEIST	=	Hybrid Environmental Immersive Simulation Training
HR	=	Hybrid Reality (VR + RW experience)
HUD	=	Heads-Up Display
NASA	=	National Aeronautics and Space Administration
NBL	=	Neutral Buoyancy Lab
OOP	=	Object-Oriented Programming
PR	=	Physical Reality
RW	=	Real World
SKADI	=	Ski Jump Athletic Development Interface
UI	=	User Interface
UX	=	User Experience
VR	=	Virtual Reality

I. Problem or Need

Preparing astronauts for operations in space has historically been a very difficult task. Sensory immersion in the training environment is difficult to achieve, as there are many major differences between Earth and space environments (e.g. gravity, visual surroundings, physical restrictions, etc.). With the recent revival of interest in human space exploration in the past decade, the need is now greater than ever for cost-efficient, high-immersion astronaut training programs to prepare the next generation of explorers for increasingly complex space operations. Companies are looking for ways to create adaptive and integrated hybrid-reality simulations to prepare their future space explorers for their journey to discover and develop new worlds.

The Hybrid Environmental Immersive Simulation Training (HEIST) project aims to fill this need by using a hybrid reality system to create an immersive training environment simulating the visual, auditory, and tactile aspects of a Lunar environment. If successful, the system developed by the HEIST team will drastically reduce the cost of training astronauts, while simultaneously making astronaut training more immersive, safe, and effective. These improvements may save a program millions of dollars in training costs and will allow for the training of more astronauts as crew sizes continue to grow.

II. Previous Work

The HEIST team and the associated other 2022-2023 Senior Projects under the sponsorship of Dr. Allison Anderson are similar in objective and means to several existing space-related training simulations and virtual reality (VR) applications. In the previous 2021-2022 cohort of Senior Projects groups, Team Ski Jump Athletic Development Interface (SKADI) utilized a hybrid reality (HR) training system for ski jump training for athletes. The implemented VR system sought to display a downhill ski slope while the user was secured atop a pneumatic platform to simulate changes in incline. Though the purpose of this project was distinctly different from the project application for HEIST, the VR software (Unity Engine) is the same as that which will be used by HEIST and the VR headset hardware (Oculus Quest 2) is still available for checkout and use at the Ann and H.J. Smead Aerospace Engineering Sciences laboratories.

NASA has several existing weightlessness simulation methods which seek to create immersive training apparatus. The Neutral Buoyancy Lab (NBL) located in Houston, Texas, consists of a 6.2 million gallon pool in which trainees are able to wear spacesuit mock-ups and are held at neutral buoyancy within the pool, thus simulating micro-gravity. Large-scale mock-ups of mission equipment are used within the NBL to train subjects for spaceflight. Similarly, NASA's Active Response Gravity Offload System (ARGOS) uses a crane attached to each trainee which provides a simulated reduced gravity environment that responds to human-imparted forces, thus again providing a pseudo-zero-gravity training experience. However, neither of these devices utilize a visually-augmented or extended virtual reality component and the simulation of zero-gravity is not a major focus of virtual reality simulations. Because of this, these projects are less applicable to HEIST. However, NBL and ARGOS do use mock-ups and models of mission equipment for training, which will be a hybrid reality component of the HEIST system. These two labs were expensive to design and build and continue to be expensive to maintain, something many private companies cannot afford. The HEIST system would remove the cost restriction as well as providing a more adaptive program to each companies personalized goals.

Ann and H.J. Smead Aerospace Engineering Science's Bioastronautics laboratory has an implementation which is closest to that which HEIST seeks to achieve. One such study by Banerjee et al. sought to use a sliding spectrum of Physical Reality to full Virtual Reality to interpret user interactions with a space habitat mock-up. Testing began with a fully physical reality (PR) model of a habitat mock-up including a science station, sleeping quarters, and galley among other points of interaction. As testing progressed more layers of virtual reality were added to the physical model, including an augmented reality (AR) test wherein the utilized headset projected VR elements onto reality, a hybrid reality (HR) test which fully utilized a virtual visual environment with physical elements for interaction and finally a fully VR simulation with no physical elements. The study concluded that none of these methods (PR, AR, HR and VR) could be discounted as less valuable than the others due to the multiple levels of applicability, but did acknowledge that an HR build was the most time-consuming of the builds. HEIST seeks to utilize a HR model and increase the immersiveness as well as increase the technical fidelity between the real world and virtual components of the HR simulation.

III. Specific Objectives

To satisfy the design problem, the objective of the HEIST project is to create a hybrid reality (HR) lunar environment training in which the user can interact with real-world objects and tools while also being immersed in a virtual simulation. The success of the HEIST project will be measured by the achievement of the following objectives, organized into two levels as shown below. Level 1 defines the absolute minimum that must be accomplished for the project to be considered a success. Level 2 includes goal objectives that may be attempted to further satisfy customer needs as time and cost permit.

Objective	**Level 1 (absolute minimum)**	**Level 2**
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/panel to integrate from the RW to the VR environment, resulting in a HR environment.	The project must allow for the integration of multiple tools and/or panels in HR environment.
Lunar Environmental Conditions	The project will represent lunar lighting, temperature, **or** auditory inputs.	The system will simulate lunar lighting, temperature, **and** auditory inputs.
Movement Constraints	The project will incorporate range-of-motion constraints that limit arm and upper-body mobility more than with regular clothes.	The project will incorporate range-of-motion constraints that limit arm, upper-body, and hand mobility.

The HEIST project deliverables to the customer will include a fully functional lunar VR simulation along with several RW assets to enable HR training. The project will also provide procedural and safety guidance documents to allow for simple user implementation and usage. This will include a manual to help the user efficiently navigate the simulation. The system will be tested by using human subjects unfamiliar with the project to evaluate UI/UX design and usability of the system. Functionality of the system will be ensured by creating and executing procedures that verify each of the project requirements are met (e.g., object tracking testing may involve measuring the error between physical asset motion in the RW and virtual asset motion in VR and ensuring it is within an acceptable range).

Objective	Level 1 (absolute minimum)	Level 2
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 VR with PR elements	The project must allow for inputs from static objects to be tracked into the VR environment.	The project must allow for the tracking of dynamic objects and their movement into the VR environment.
Lunar Environmental Conditions	The project will represent lunar lighting, temperature, **or** auditory inputs.	The system will simulate lunar lighting, temperature, **and** auditory inputs.
Movement Constraints	The project will incorporate range-of-motion constraints that limit arm mobility more than with regular clothes.	The project will incorporate range-of-motion constraints that limit upper-body mobility more than with regular clothes.
Adaptability	The project must be able to input one extra training scenario **or** exercise.	The project must be able to input various training scenarios **and** exercises.

IV. High Level Functional Requirements

Requirement ID	Functional Requirement
FR 1	The user shall view a functional VR simulation of a lunar EVA.
FR 2	The PR shall inhibit movement of at least one part of the body.
FR 3	The user's actions in PR shall correlate to effects in VR.
FR 4	The user shall be in no danger while operating in the HR environment
FR 5	The customer shall be able to implement their own training scenarios in the hybrid reality environment.

FR 1: The user shall view a functional VR simulation of a lunar EVA.

This requirement guarantees the basic ability to use the virtual reality (VR) system. The user must be able to enter a functioning VR environment and interact with it. This is one of the core objectives of this project. Further, creating immersion and a realistic training situation is critical. The temperature, lighting, and other environmental factors on the moon can significantly impact how training operations are conducted. If the environmental conditions cannot be adequately simulated in VR, the training will not be relevant to the actual mission operations. If this VR functionality is not achieved, the entire system would be hindered.

FR 2: The PR shall inhibit movement of at least one part of the body

This requirement seeks to simulate the physical conditions experienced during a lunar EVA. EVA spacesuits cause a restriction of joints and limit the range of motion, in order for the simulation to be immersive to that point, PR limitations on at least one part of the body are also relevant to creating an immersive and effective training experience.

FR 3: The user's actions in PR shall correlate to effects in VR.

In order to increase sensory immersion and differentiate HEIST from existing simulations, the system must allow the user to interact with objects in the real world that have a virtual representation in the simulation. The VR simulation must represent the physical object with the same dimensions, position, and orientation in space relative to the user as it has in the real world. It should also translate the user's interaction with the PR element into the VR environment. This creates the hybrid reality central to HEIST's objective.

FR 4: The user shall be in no danger while operating in the HR environment

This requirement incorporates the overall goal of HEIST in creating and maintaining a safe operating environment. While the project will be as immersive as possible, it is paramount that there is no possibility of anyone involved being in danger at any time due to partaking in the simulation.

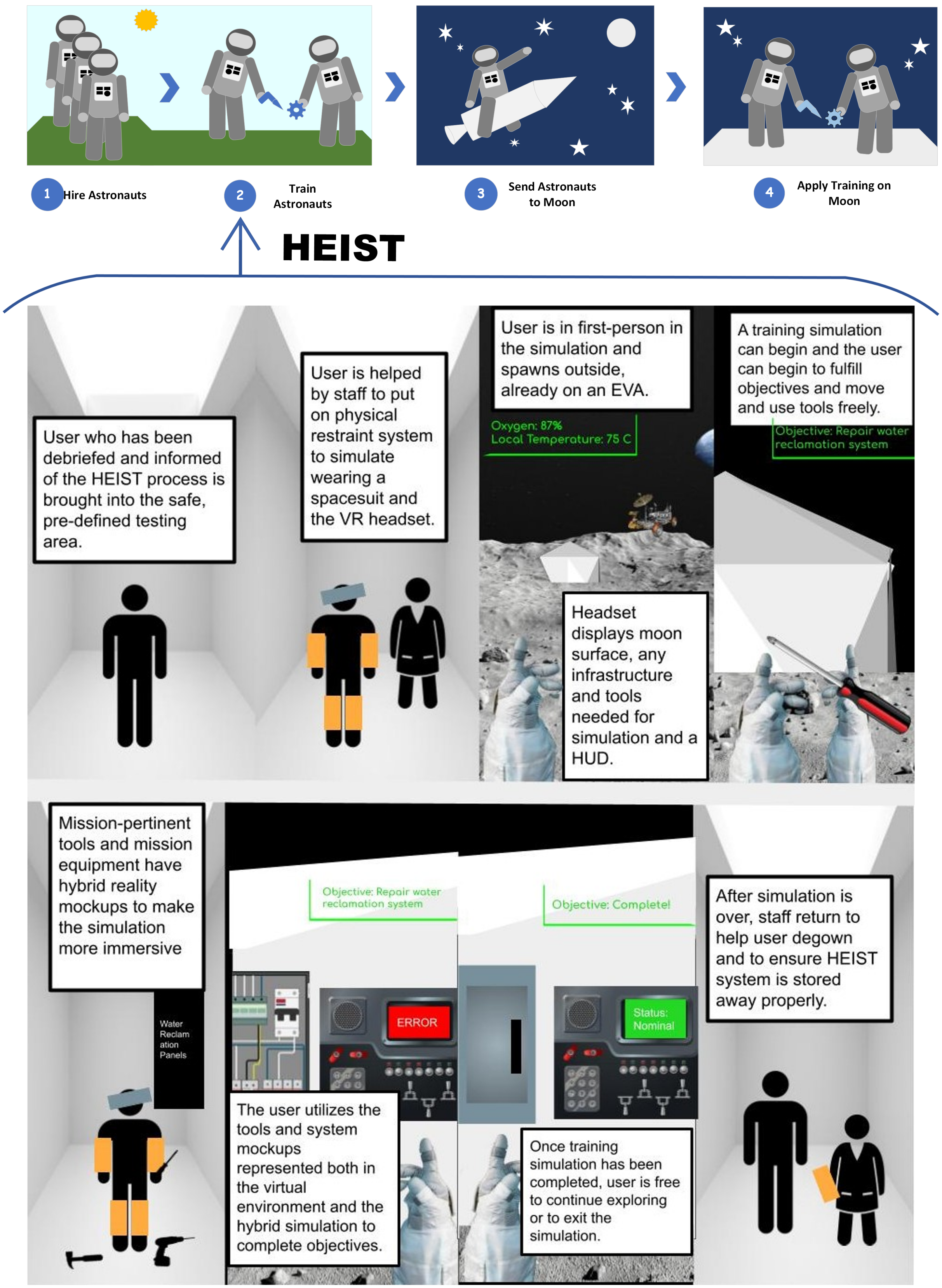
FR 5: The customer shall be able to implement their own training scenarios in the hybrid reality environment.

This requirement ties to the usability of the system for training purposes. It is really useful for a training program to be able to simulate different scenarios and operating conditions. It gives the customer the capability to use the system in a number of different ways concurrent with their objectives moving forward.

A. Objectives Out of Project Scope

This project is part of the larger goal of creating a training environment for future lunar astronauts. However, HEIST will only address on a portion of this. More specifically: providing a hybrid reality training capability that could then be merged with other simulation tools to improve the quality of the training experience. Some of these tools which we will not be focusing on include simulating the gravity environment of the Moon, the feel of the surface/terrain of the Moon, a full model of a lunar base, multi-user simulations, a full wearable body suit, or vehicles. It will also not allow the user to cross extensive amounts of terrain, as the simulation will focus solely on the area need for habitat maintenance.

B. CONOPS


1 Hire Astronauts
2 Train Astronauts
3 Send Astronauts to Moon
4 Apply Training on Moon
HEIST
User who has been debriefed and informed of the HEIST process is brought into the safe, pre-defined testing area.
User is helped by staff to put on physical restraint system to simulate wearing a spacesuit and the VR headset.
User is in first-person in the simulation and spawns outside, already on an EVA.
Oxygen: 87%
Local Temperature: 75 C
Headset displays moon surface, any infrastructure and tools needed for simulation and a HUD.
A training simulation can begin and the user can begin to fulfill objectives and move and use tools freely.
Objective: Repair water reclamation system
Mission-pertinent tools and mission equipment have hybrid reality mockups to make the simulation more immersive
Water Reclam ation Panels
Objective: Repair water reclamation system
ERROR
The user utilizes the tools and system mockups represented both in the virtual environment and the hybrid simulation to complete objectives.
Objective: Complete!
Status: Nominal
Once training simulation has been completed, user is free to continue exploring or to exit the simulation.
After simulation is over, staff return to help user degown and to ensure HEIST system is stored away properly.

V. Critical Project Elements (CPEs)

Number	Critical Project Element	Explanation
CPE1	Human Safety	Given that this system is designed to be physically operated and worn by humans, there is a minimum level of safety required. This includes physical and psychological safety. Users should be screened before interacting with the system to ensure the training does not put them in any kind of danger.
CPE2	Data Transfer Between PR and VR	In order to feed the information from PR elements to the VR environment, the system should have a way to determine the position and attitude of every physical asset relative to the user. The system should also transmit such information to the simulation. The physical assets should also have a way to communicate how the user is interacting with them to the simulation.
CPE3	Usability	The user must be able to interact with real-world objects within the HR Environment. These must be mock-ups of tools or parts of the virtual lunar habitat. Therefore, they should be adapted to have a morphological resemblance to traditional tools/interfaces of space missions. The hardware function is to be tracked into the VR simulation and will send data regarding user interaction, which is essential for a proper HR experience.
CPE4	Robustness	The system shall be designed such that it runs with at least minimum system specifications and has redundancies such that it can run even with unpredictably heavy system loads and will remain functional for the long term.
CPE4	Reliability	The system shall be designed such that it's launch, process of running and power down are predictable and repeatable
CPE4	Movement Restriction	The system should constrain the movement of the user's upper-body joints to simulate the reduced range of motion inside a lunar EVA spacesuit. This provides an additional level of immersion into the training experience.
CPE6	Training Versatility	The project must include versatility for the customer to input their own training exercises and scenarios. This is necessary due to the wide array of situations that astronauts could run into. The HEIST team does not know all of the events that companies need to train their astronauts for and so it is imperative that the final HR environment allows the customer to create their own training in conjunction with the environment.

VI. Sub-System Breakdown and Interdependencies

A high-level sub-system breakdown of all subsystems necessary for HEIST's design is as follows:

Electronics/Sensing:
- Distribute power to the entire system
- Cable management
- RW object tracking

Depends on: Physical Assets (mechanical & data connection)

Data Handling
- Interpreting data from object tracking system
- Calculating RW object positions from tracker data
- Relaying RW object positional information to the simulation in the correct format
- Data path of the system allowing for information flow between subsystems

Depends on: Electrical (power & data connection), Software (data connection)

Software:
- Handle dynamic parts of simulation (propagating switch/button effects in the VR world, etc.)
- Calculate user's POV from location, head angle, etc. and display the correct image in the headset
- Orient and display RW assets in the VR world
- Simulate the environmental elements of a lunar EVA mission
  - Thermal
  - Lighting
  - Auditory

Depends on: Data Handling (data connection), Electrical (power connection)

Physical Assets:
- Simulate astronaut tools (recreate size, shape, texture, Moon weight, tools needed for mission, etc.)
- Simulate physical movement restrictions due to EVA spacesuit

Depends on: None

A diagram of the subsystems, their interdependencies, and their connections (data, power, or mechanical) is shown in the figure below:

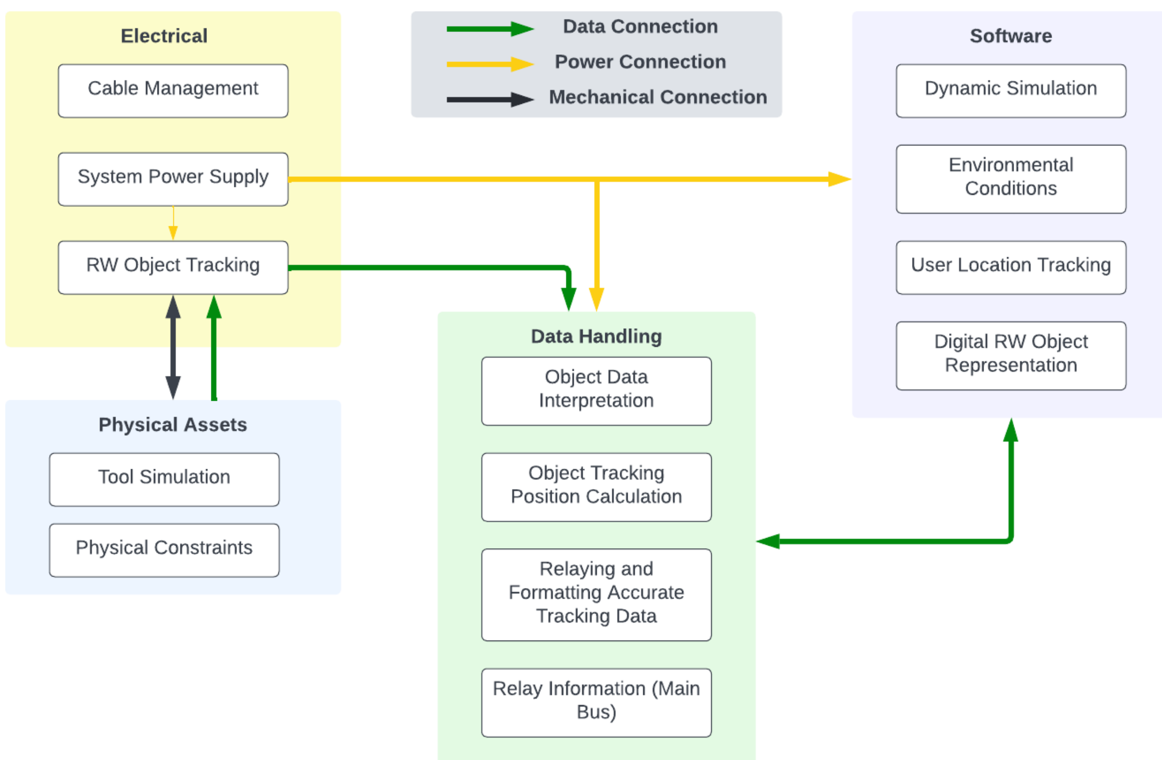


Fig. 1 Subsystem Interdependencies Diagram

VII. Team Skills and Interests

Team Member	Skills/Interests	Corresponding CPEs
Trayana Athannassova	General Programming (MATLAB, Java, C++, C, HTML/CSS, Javascript, Python) & OOP, Astronaut Wellness/Psychology, Human-Computer Interaction, Space Security & Defense	CPE1, CPE2, CPE5
Sruthi Bandla	General Programming (MATLAB, C++, Python), Blender, Altium	CPE1, CPE3, CPE4, CPE5
Sebastian Boysen	MATLAB, CAD Modeling (SolidWorks), Prototyping, Hardware Testing, Electrical Design and Testing	CPE2, CPE3, CPE4
Rachael Carreras	General Programming (ROS, Github, Python, MATLAB), Astronaut training and interactions in space, Electronics, testing, assembly, prototyping	CPE1,CPE2,CPE3,CPE4, CPE6
Julia Claxton	Electronics Design and Implementation, Prototyping, Coding (MATLAB, C++), Blender	CPE2, CPE3, CPE4
Lucy Davis	General Programming (MATLAB, C++, Python), Graphic Design, Electronics, Fabrication	CPE1, CPE2, CPE3, CPE5
Matthew Grewe	General Programming (MATLAB, C, C++, Python, Scala, OpenGL), Computer Graphics, Fabrication, Manufacturing, Mission Safety, Electronics, Physics, Prototyping	CPE1, CPE2, CPE3, CPE5, CPE6
Akanksha Nelacanti	General Programming (MATLAB, Python, ROS, Github), Manufacturing, Electronics, Human-Robot-Computer Interaction, Prototyping	CPE2, CPE3, CPE4, CPE5, CPE6
Hattie Rice	General Programming (MATLAB, C++, HTML, Python), Electronics Design and Assembly, manufacturing and assembly	CPE1, CPE2, CPE4, CPE5, CPE6
Esther Revenga Villagra	General Programming (MATLAB, C++, HTML/CSS, Python), Electrical Design, Assembly and Testing, Safety Protocol Design, Physics	CPE2, CPE3, CPE5, CPE6
Alicia Wu	General Programming (MATLAB, Python, Ruby, HTML/CSS), Manufacturing, Prototyping, Testing	CPE2, CPE4, CPE5, CPE6
Steven Young	General Programming (MATLAB, C++), Fabrication, Electronics, Manufacturing	CPE1, CPE2, CPE3, CPE4

VIII. Resources

CPE	Resource/Source
CPE1	Dr. Allison Anderson, Tutorials (YouTube, software specific, etc.)
CPE2	Machine Shop, PILOT 3D Printing
CPE3	Electronics Shop, Prof. Trudy Schwarz, Prof. Bobby Hodgekinson
CPE4	CU Boulder Bioastronautics Professors, Idea Forge (CU Boulder)
CPE5	Dr. Allison Anderson (human testing subject safety experience), CU Boulder Bioastronautics safety & human testing standards
CPE6	Dr. Allison Anderson (creating new training exercises using the environment), CU Ann and H.J Smead Aerospace Engineering Sciences - Bioastronautics safety & human testing standards

References

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[2] Banerjee, N. T., Baughman, A. J., Lin, S.-Y., Witte, Z. A., Klaus, D. M., and Anderson, A. P., "Development of alternative reality environments for spacecraft habitat design evaluation," Virtual Reality, vol. 25, Aug. 2020, pp. 399–408.

[3] "Full-size reduced gravity simulator for humans, robots, and test objects," NASA Available: https://technology.nasa.gov/patent/MSC-TOPS-60.

[4] "Ski Jump Athletic Development Interface (skadi)," Ann and H.J. Smead Aerospace Engineering Sciences Available: https://www.colorado.edu/aerospace/academics/undergraduates/senior-design-projects/past-senior-projects/2021-2022/ski-jump-athletic.

[5] NASA, Sonny Carter Training Facility: The Neutral Buoyancy Laboratory, 2014.