University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018
Project Definition Document (PDD)
LunaSim

1. Approvals

	Name	Affiliation	Approved	Date
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2. Personnel

2.1. Project Customers

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3. Problem or Need

With the Artemis program returning humans to the Moon, astronauts need to be trained for the living and working conditions on the lunar surface. A major obstacle to performing this training on Earth is gravity; the Moon's surface gravity is approximately one-sixth of that on Earth. With current training systems, there are limitations to how the environment replicates partial gravity. Current environments inhibit natural movement, restricting it to a single dimension of translation (as on a treadmill), or are severely lacking in the duration of reduced gravity, such as parabolic flights. LunaSim will create a partial gravity offloading system for lunar astronaut training simulations. This will create a medium-duration hybrid-reality immersive environment that will enhance the validity and effectiveness of the training.

4. Previous Work

NASA has developed numerous simulations in order to train crew members and prepare them for the demands of low gravity environments. While a more accurate reduction in forces can be achieved through parabolic flight trajectories (such as the path of the "Vomit Comet"[1]) or through underwater training (such as the Neutral Buoyancy Lab (NBL)[2]), the scope and budget of this project may not allow for complete offloading in these manners. Instead, LunaSim will likely draw more inspiration from gravity offloading simulations such as NASA's Active Response Gravity Offload System (ARGOS)[3], which utilizes an overhead cable system and a harness to reduce the load on the test subject.

ARGOS, the NBL, and parabolic flights can all simulate microgravity and/or lunar gravity, so our project is not unique in that regard. However, LunaSim is unique in its size and budget limitations. ARGOS and the NBL are both incredibly large, so determining a way to scale down to the limitations of a university lab without limiting the crew member's natural motion or immersion in the simulation presents a novel challenge. Similarly, parabolic flights are incredibly expensive, require extensive infrastructure, and limit microgravity exposure to under a minute, which is much too short to meet the requirement of a one hour EVA. Therefore, LunaSim will need to expand beyond these previous solutions in order to meet the size, cost, and duration requirements set forth by the customer.

NASA has also utilized virtual and mixed reality environments to simulate extraterrestrial EVAs through the Human Physiology, Performance, Protection & Operations (H-3PO) lab[4] and through the Crew Health and Performance Exploration Analog (CHAPEA)[5], an analog interplanetary habitat that uses both virtual reality and a physical "sandbox" for their simulated EVAs. However, neither H-3PO nor CHAPEA integrate gravity offloading with virtual reality, making our problem a unique challenge to be solved.

5. Specific Objectives

Table 1: Specific Project Objectives

Category	Level 1 Objectives	Level 2 Objectives
Gravity Offloading	Provide gravity offloading in the vertical z-direction to replicate lunar gravity.	Provide variable gravity offloading to replicate the gravity of other planetary bodies.
Movement	Allow the user to translate in 3 dimensions.	Support free and unrestricted translation in all axes simultaneously, including jumping.
	Allow the user to rotate side to side about the z-axis.	Allow the user to rotate about the 3 primary axes.
Safety	Include proper safety features and protocols to prevent any bodily harm or damage to any equipment or component.	
User Accessibility	Allow participants of varied sizes and weights.	Allow for comfortable use of any user support mechanism.
	Fully function for one user.	Allow multiple users to be integrated into the simulation.
Control System	Develop a control system able to determine the proper force to apply to the user to simulate lunar gravity.	Develop a control system able to determine the proper force to apply to the user to simulate the gravity of other planets.
Structure	Support the load of a human test subject with a sufficient margin of safety.	Support the load of the test subject, a spacesuit, any hybrid reality equipment, and interactable environmental objects with a sufficient margin of safety.
Immersion	Produce minimal noise so as to maintain the user's sense of immersion in the hybrid reality environment.	Produce minimal noise and provide tactile feedback (such as the sensation of walking on the lunar surface) to enhance the user's sense of immersion in the hybrid reality environment.
Ease of Manufacture	Maintain relatively low cost and require minimal advanced manufacturing to replicate in order to make it accessible to labs of all resource levels.	

6. High Level Functional Requirements

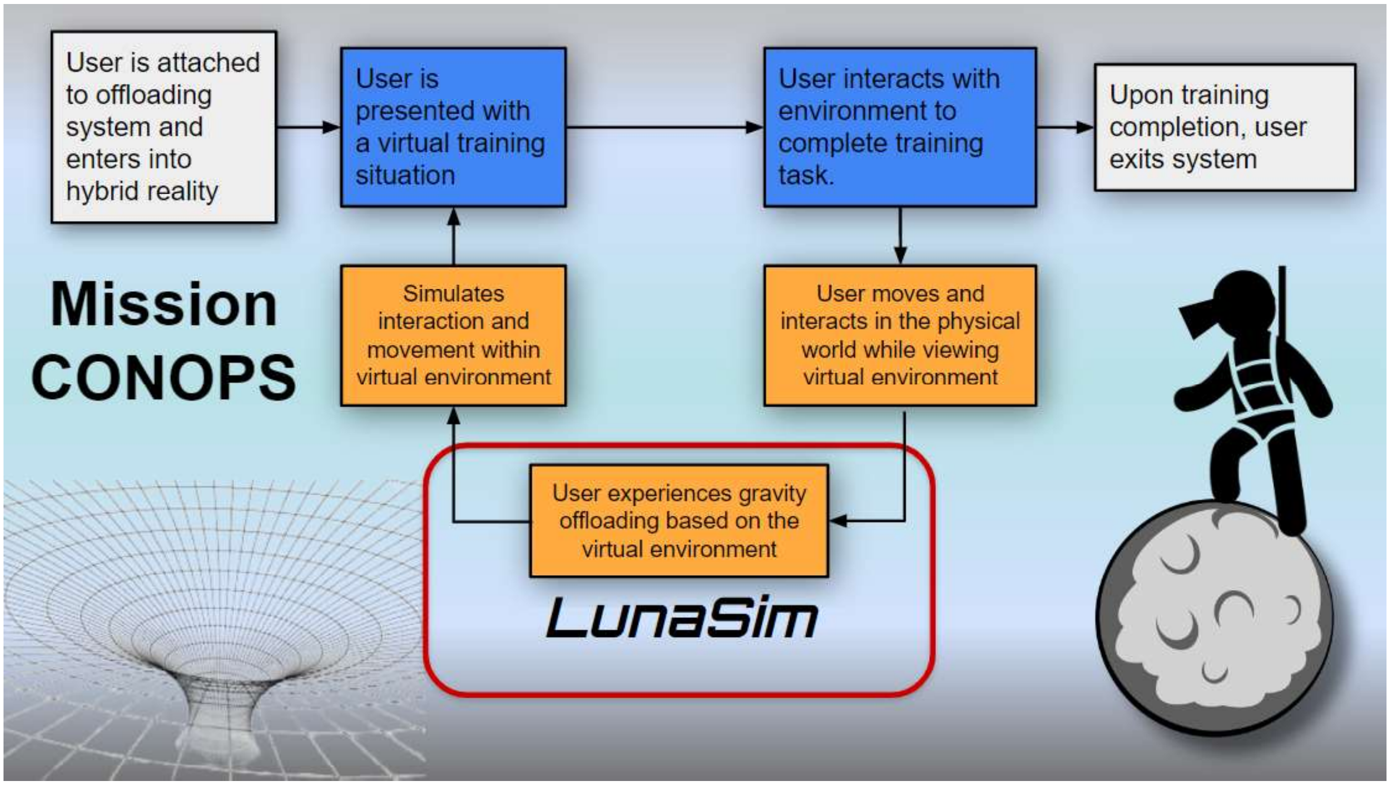

Figure 1: Overall Mission CONOPS

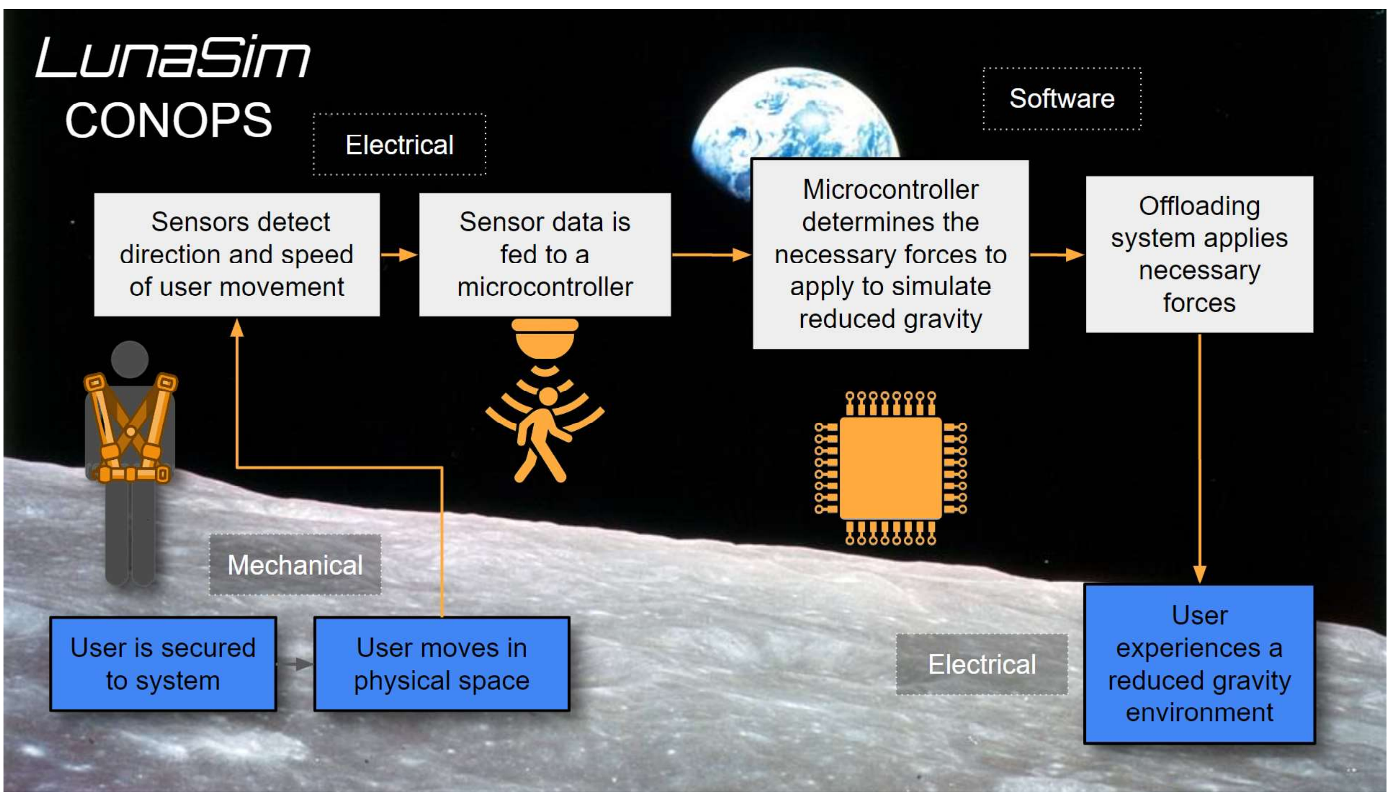

Figure 2: Gravity Offload System CONOPS

The LunaSim team is working as part of a larger effort towards developing an astronaut training environment. The high-level functional requirements for the LunaSim team are listed in the table below.

Table 2: High-level Functional Requirements

FR	Requirement	Rationale	Source
FR.1	The LunaSim team shall develop an accessible, low-cost, reduced-gravity training environment for potential future astronauts.	Training simulation facilities will be needed to prepare for the Artemis III+ manned missions to the lunar surface.	Customer-defined
FR.2	The apparatus shall function for up to 1 hour continuously.	Allows the user to realistically experience the effects of 1/6th gravity over an extended duration.	Customer-defined
FR.3.1	The device shall simulate the gravity of the lunar environment.	User's can execute training procedures to prepare for lunar surface missions.	Customer-defined
FR.3.2	The device shall allow free translational movement.	Movement capabilities must mimic mission necessities to perform a variety of technical tasks.	Customer-defined
FR.4	The project shall positively represent the CU Aerospace Engineering department and the University of Colorado Boulder.	Continues the positive connection with the community at large while serving the university mission.	CU/AES-defined
FR.5	The project shall provide value to sponsoring organizations Blue Origin and EchoStar.	The sponsoring organizations must have their requirements met in order to justify their investment in this project.	CU/AES-defined
FR.6	The project shall aid development of student skills and value to potential employers.	The objective of ASEN 4018 is to prepare students for the workforce by providing an opportunity to develop industry skills in the safe learning environment of the classroom.	CU/AES-defined

Table 3: Constraints

Category	Constraint	Explanation	Source
Cost	The total cost of the project shall not exceed $4000.	The budget is defined for each senior projects team by CU/AES.	CU/AES and sponsor funding
Schedule	The project must be designed, built, and tested by May 2023.	Determined by the duration of the class. Course deadlines will drive the schedule for PDR, CDR, and other major milestones.	CU/AES-defined
Facilities	The total footprint of LunaSim is not to exceed 9' x 10'.	This is the space available in the lab in which LunaSim will be ultimately housed.	Customer-defined
	The system must be able to be powered by the wiring available in the CU Bioastronautics Human Research Lab (HRL) and similar laboratories.	In the interest of accessibility, we want the system to function easily in any lab space. Our lab currently has standard 120V outlets, but installation of higher voltages may be possible.	Customer-defined
	System noise must be kept to a minimum, except during construction.	Excessive noise would reduce immersion for the user and disturb neighboring laboratory spaces.	Customer-defined
	The system must not produce dust, debris, or otherwise disturb the surrounding environment.	LunaSim will exist in a shared lab space, so it is crucial to coexist with surrounding experiments.	Customer-defined
Operations	The system must remain operational for TBD years.	LunaSim is planned to be used for research and training that will last TBD years, and therefore must be able to last in fully operational condition for the full duration of the research.	Customer-defined
	The system must operate within the constraints of the lab environment.	LunaSim will be used inside of the CU Bioastronautics HRL, and therefore must be easily operated by student researchers within the noise, size, power, lighting, and other constraints of the lab.	Customer-defined

Table 4: Out-of-Scope Requirements

Category	Requirement	Rationale	Source
Integration	It is not necessary for LunaSim to integrate with the hybrid reality work of the other project teams.	The objective of this phase of the project is to explore the trade space. Virtual reality and physical systems will be integrated at a later phase.	Customer-defined
Working Environment	It is not necessary for LunaSim to simulate environmental conditions relating to temperature or terrain.	These conditions fall outside the scope of the project and are not necessary to meet customer requirements.	Customer-defined
	It is not necessary for LunaSim to simulate the physical restrictions of wearing a spacesuit.	The mobility limitation effects of wearing a spacesuit are beyond the functional requirements of the gravity offloader, and our resources do not include access to one.	Customer-defined

7. Critical Project Elements

Table 5: Critical Project Elements

Critical Project Element	Rationale	Constraints
CPE.1 *Gravity Offloading*	LunaSim must provide gravity offloading equivalent to lunar gravity, or 1.62 m/s^2, in order to accurately simulate the lunar environment and create an immersive test experience. The primary objective of this project is simulating partial gravity, so this is a necessity for success.	A logistical and testing restraint is for the user's movement, since the physical space may not have enough clearance. The budget is also only $4000, so as implied in Section 4, LunaSim may act as more of a proof of concept.
CPE.2 *Lunar Environment*	As an extension to ***CPE.1***, LunaSim must to some degree simulate the physical lunar environment or astronaut working conditions to further provide a more accurate simulation.	A testing constraint is that the environment must not disturb the lab space (such as including dust).
CPE.3 *Safety*	The structure and user interface must not endanger any person's physical safety or health at any time. The system is designed for human simulations, so safety is of the utmost importance.	With potentially many moving components and the high weight capacity of the structure, much testing will need to be done to ensure that the system is safe to use in all conditions.
CPE.4 *Hybrid Reality (HR) Integration*	The suspension system must be able to integrate with the hybrid reality system. To create an entire immersive experience for the astronaut, both aspects (HR and suspension) need to be able to work together.	A logistical and testing constraint is that the HR system and its physical integration are beyond the scope of LunaSim.
CPE.5 *Control System*	The control system must be able to accurately measure the weight of the user and be able to convert force measurements into data for the gravity offloading system **(CPE.1)**. In addition, the control system should be able to accurately compensate for a user moving in 3 dimensions at a variety of rates.	The control system has the potential to be highly complex and unintuitive. It will also need to have a fast rate of return due to the mission objective which will be computationally expensive.
CPE.6 *Structure*	The structure must be able to carry the weight of the user, as well as the gravity offloading system **(CPE.1)** and any components connected. It should have sufficient strength to remain rigid under heavy loads, accelerations, and impulses. The structure must also allow for motion in both x and y axes in coincidence with the user.	Because the structure is likely to be large and made out of strong materials, it will likely be very expensive to manufacture. It is likely that the combination of the gravity offloading system and the structure will swallow most of the $4000 budget. Additionally, large structural components will require large amounts of force to test strength.

8. Sub-System Breakdown and Interdependencies

A. **Electrical**
   a. Sensors
   b. Microprocessor
   c. Electrical power systems (EPS)

B. **Mechanical**
   a. User support mechanism
   b. Support structure
   c. Lunar environment

C. **Software**
   a. Control system

D. **Safety**
   a. Emergency stop
   b. User protection

9. Team Skills and Interests

Table 6: Team Skills and Interests

Technical Areas of Interest	**Corresponding CPE(s)**	**Team Member(s)**
Mechanical and Manufacturing	*CPE.1, CPE.2, CPE.3, CPE.4, CPE.5*	Blake, Brennan, Ian, James, Kevin, Lauren, Max, Mia, Parker, Paul, Zoe
Electrical	*CPE.1, CPE.4*	Blake, Chandler, Kevin, Lauren, Max
Software	*CPE.1, CPE.5*	Chandler, Ian
Safety	*CPE.3*	Chandler, James, Kevin, Max, Mia, Paul
Testing	*CPE.1, CPE.2, CPE.3, CPE.6*	Blake, Brennan, Chandler, James, Lauren, Max, Mia, Parker, Zoe
Non-Technical Areas of Interest		**Team Member(s)**
Program Management		Blake, Lauren, Parker
Systems Engineering		Chandler, James, Lauren, Max, Mia
Communications and Training		Brennan, Chandler, James, Lauren, Max, Mia, Zoe
Finance		Lauren

10. Resources

Table 7: Resources

Critical Project Elements	**Critical Item(s)**	**Resource/Source**
CPE.1	*TBD metal for structure, metalworking equipment*	Customer funding and possibly a grant from the Engineering Excellence Fund. Testing may require human participants outside of our team, and somewhere to safely perform manned and unmanned tests
CPE.2	*Lunar Environment, Lab Facilities*	CU Bioastronautics Human Resource Lab (HRL), Aerospace Lab Facilities
CPE.3	*Safety Knowledge*	Training on OSHA safety standards and best practices, any safety guidelines from the lab itself
CPE.4	*Electrical components, VR technology*	Aerospace Electronics Lab, Customer Funding, VR Team Project Design
CPE.5	*Software (TBD)*	Customer Funding/Licensing, OIT (MATLAB, etc.)
CPE.6	*Manufactured materials, CAD Software*	Aerospace Machine Shop, ITLL, SolidWorks

11. References

[1] Dunbar, B. (2004, October 29). *Zero-Gravity Plane on Final Flight*. NASA. Retrieved September 7, 2022, from https://www.nasa.gov/vision/space/preparingtravel/kc135onfinal.html

[2] NASA Lyndon B. Johnson Space Center. (n.d.). *Sonny Carter Training Facility: The Neutral Buoyancy Laboratory*. NASAfacts. Retrieved September 7, 2022, from https://www.nasa.gov/centers/johnson/pdf/167748main_FS_NBL508c.pdf

[3] Hess, M. (2013, January 22). *Active Response Gravity Offload System*. Engineering Human Space Exploration. Retrieved September 7, 2022, from https://www.nasa.gov/centers/johnson/engineering/integrated_environments/active_response_gravity/

[4] Hille, K. (2020, January 29). *Scientists Tap Virtual Reality to Make Discoveries*. NASA. Retrieved September 7, 2022, from https://www.nasa.gov/feature/goddard/2020/scientists-tap-virtual-reality-for-discovery

[5] Mars, K. (2021, December 7). *CHAPEA*. NASA. Retrieved September 7, 2022, from https://www.nasa.gov/chapea