University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)
Remote Intra-Vehicular Robotics (RIVeR)

Monday 14th September, 2020

1 Approvals

	Name	Affiliation	Approved	Date
Customer	Loren McDaniel	SNC	Loren McDaniel Digitally signed by Loren McDaniel DN: E=loren.mcdaniel@sncorp.com, CN=Loren McDaniel, OU=LOU Users, OU=SNC LOU, DC=sncorp, DC=intranet, DC=com Reason: I am approving this document Date: 2020.09.14 17:16:15-06'00'	
Course Coordinator	Jelliffe Jackson	CU/AES		

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2.1 Project Customers

Name:	Loren McDaniel
Email:	loren.mcdaniel@sncorp.com

2.2 Team Members

Project Manager: Kyle Li Email: kyli8681@colorado.edu Phone: 720-275-2127	Lead Systems Engineer: Lindsay Cobb Email: lindsay.cobb@colorado.edu Phone: (415) 450-7535
Name: Logan Vangyia Email: lova2860@colorado.edu Phone: 314-691-8445	Name: Nicholas Miller Email: nimi1223@colorado.edu Phone: 973-903-9779
Name: Marin Grgas Email: magr4013@colorado.com Phone: 310-779-9322	Name: James Tiver Email: Jati6685@colorado.edu Phone: 970-213-6307
Name: Jordan Abell Email: joab9590@colorado.edu Phone: (303) 887-9295	Name: Bruce Barnstable Email: brba0083@colorado.edu Phone: 720-877-1437
Name: Jett Moore Email: jemo0269@colorado.edu Phone: 303-990-2507	Name: Brandon Torczynski Email: brto2556@colorado.edu Phone: 808-308-3630
Name: Alex Ferguson Email: alfe2986@colorado.edu Phone: 724-393-7211	Name: Peter Amorese Email: peam6502@colorado.edu Phone: 720-456-9880

3 Problem or Need

Sierra Nevada Corporation (SNC) has desgned the LIFE^{TM} Habitat (Large Inflatable Fabric Environment) under Phase 3 of NASA's Next Space Technologies for Exploration Partnerships. The habitat is designed to fulfill the needs of a long term, deep space mission to the Moon or Mars.

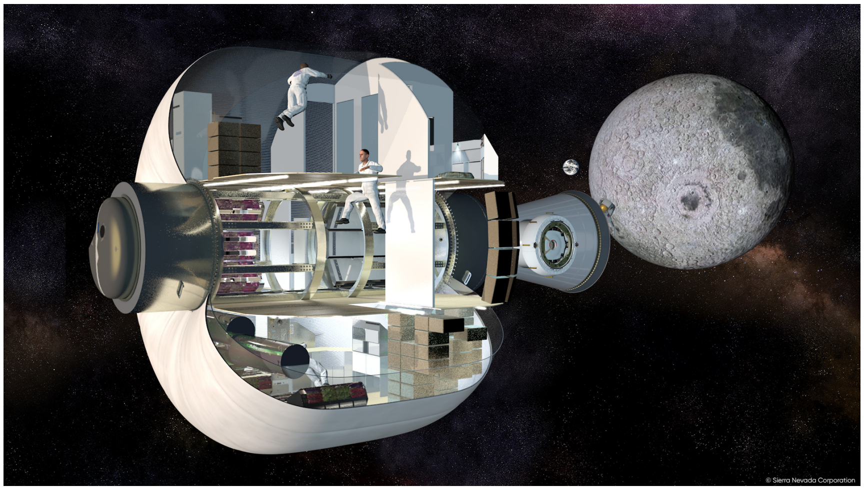

Figure 1: SNC's LIFE Module [1]

Once the LIFE module has been inflated it will be necessary to outfit the module and manage cargo prior to crew arrival. Cargo unloading and storage to outfit the LIFE module must be done while the module is uncrewed. The cargo will need to be transported through multiple hatches and passageways to be stowed in a determined location in an organized fashion. Project RIVeR's goal is to develop a detailed architecture and concept of operations for a cargo transportation and management system to outfit the LIFE module semi-autonomously. This architecture will include all the steps necessary to facilitate the transportation and organization of cargo from a cargo transport vehicle to the LIFE module. To validate and test this system, a robotics demonstration will be constructed to translate cargo bags through the core of the LIFE module. This will include a mechanical translation system integrated with a robot that grapples and controls cargo bags. A base design standard for cargo bags will also be established based on the current requirements for the ISS.

The benefits of this system will be to automate cargo management with no physical human interaction. This project will help forge the use of autonomous robotic systems for use in zero gravity environments. It will remove significant workload from future astronauts and allow them to dedicate more time to scientific experiments, exploration, and their mental health.

4 Previous Work

An essential piece of the architecture of moving cargo is the ability to transport the bags from the core of LIFE module to their intended storage area. There are a few relevant designs from past space missions that provide important information.

First is MIT and NASA's SPHERES [2], which stands for Synchronized Position Hold, Engage, Reorient, Experimental Satellites. SPHERES is a team of three 18 sided polyhedron robots about the size of a volleyball that were in service on the ISS from roughly 2006 to 2017. SPHERES was powered by AA batteries and propelled itself using compressed carbon dioxide. SPHERES performed many experiments for NASA during it's years of use involving the feasibility of semi-automated robots to complete routine tasks that astronauts do not have time to do.

The successor to SPHERES was the Astrobee being launched to the ISS in 2018 and still currently in use [3]. There are three Astrobee robots on the ISS each being cube shaped at 12.5 inches on each side. Unlike SPHERES, Astrobee uses rechargeable batteries that can be replenished at Astrobees docking station on the ISS. Astrobee propels itself around the ISS using 2 motorized fans that can be adjusted in different directions. Improving on SPHERES wireless communication, Astrobee is able to use a multitude of cameras and sensors to move cargo around the ISS and aid astronauts in recording results of experiments.

In the 2016-2017 academic year, a Smead Aerospace Engineering Senior Projects team designed and built CASCADE, the Cubesat Activated Systematic CApture DEvice, in collaboration with Sierra Nevada Corporation. The motivation behind CASCADE was to identify and capture a rotating, free-floating object. The design utilized an arm mechanism with 5 degrees of freedom (DOF), the "Crust-Crawler Modular Arm". This mission also included a vision system including a LIDAR system and several IR cameras and an autonomous capture software.

In the 2013-2014 academic year, a Smead Aerospace Engineering Senior Projects team designed and built PIRANHA, the Proximity Identification, characterization And Neutralization by thinking before Acquisition project, in collaboration with Lockheed Martin. The project addresses the problem of the growing number of space debris gathering in Earth's orbit. PIRANHA was integrated with a pre-existing orbital Debris Capture System (DCS) in order to introduce intelligence for detection, thinking, and communication. The design was composed of a rotating vision system containing servos, a camera, and a rangefinder. The project's capabilities included pointing and control, visual detection of debris, and visual size determination of debris.

All these previous projects have facilitated various objectives this project will attempt to build upon. The Astrobee and SPHERES robots demonstrate the potential avenues of mobile flexibility that a free-flying robotics system could offer for a hypothetical logistics system. These systems in conjunction with the CASCADE and PIRANHA projects demonstrate what sensor systems, manipulators, electrical, and software components would be needed to build up the various components of a module-wide logistics system.

5 Specific Objectives

The objective of Project RIVeR is to develop and demonstrate a system architecture to transport and store cargo throughout Sierra Nevada Corporation's LIFE module. This system will be capable of moving cargo from an exterior cargo hatch to designated storage locations within the LIFE module without an on-board crew. The team will make assumptions about the capabilities of other robotic systems who will be responsible for retrieval and hand-off of the cargo.

The physical objective is to demonstrate the ability to move a cargo bag from the Cargo Arrival hatch to the opening within the Core. The hatches are labeled in Figure 2 as locations A and B. The bags will be moved from the hatches to the middle of the Core (colored blue) where there is an opening to the other decks.

The objective for the architecture design is to have a high level solution to move the bags from the transport vehicle hatch to an organized storage location within the module. The later stages are purely conceptual designs that will integrate with the hardware solution. The IVR designed will be responsible for moving the cargo bags from the core to the other decks of the module. They will then order and stack the bags in an organized fashion.

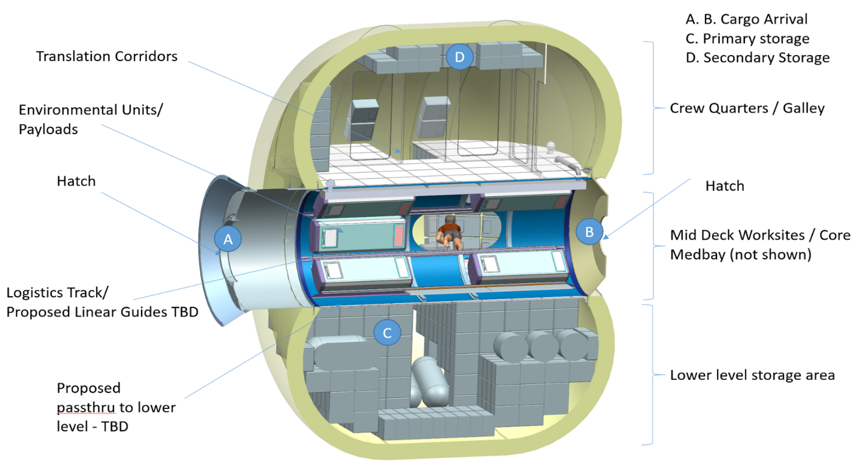

Figure 2: LIFE Module

Table 1: Levels of Success

Level	Motion of Bags	Electrical & Sensing	Architecture Design
Level 1	Construct a system that is capable of translating a cargo bag in one degree of freedom	Operate within TBD voltage and current	Establish the IVR system capabilities after operations in the Core
Level 2	Translate cargo bag TBD feet in one direction using robotics	Send communication to robotic system that will translate a bag	Start to finish integration plan to move cargo from the transport vehicle to its determined location. Identify specific tasks for the IVR at each stage
Level 3	Maneuver bags through an opening of TBD dimensions	Sense where in the core a bag is during translation	Initial design of the IVR that would interface with the hardware being built
Level 4	Successfully interact with a hatch system	Sense the location of a bag and capture it	Detailed design and CAD models for IVR system at each stage of the architecture.

6 High Level Functional Requirements

6.1 Requirements

Architecture

- The architecture shall include a start to finish process to move cargo from a cargo arrival hatch to a designated location. *In order to solve the given problem to any degree, the architecture must include a methodology to transport cargo within the environment.*

- The system shall be able to stow bags in a specified configuration. *Specifying a configuration for the goal poses of the cargo is necessary for defining the organization and completeness of an operation*

- The system shall complete a given task without any physical human interaction, not including a remote operator. *A key factor in defining the motivation behind the problem is the need for the system to be used without direct physical human interaction. The mission states that humans will not be in the physical vicinity to interact with the task.*

Hardware

- The system shall be capable of moving cargo bags of TBD mass. During this process, the cargo bag should be secured to the robot responsible for transporting it. *When working in a zero "g" environment, net force on the bag is needed only to accelerate the bag in a certain direction. This is necessary for moving and rotating any objects that the system interacts with. This requirement must be stated in terms of the net force value in order to specify a requirement that can be met when testing in zero "g", or regular Earth gravity.*

- The "end-effector" must have the ability to change functions depending on the given task. *In order to satisfy the NASA requirements, the system must have the ability to alter hardware in order perform different tasks.*

- The system shall be able to pass bags through an opening with cross sectional area of TBD. *The given environment has walls and openings that act as obstacles when navigating from the initial location to the goal location. In order to complete a task that involves moving a piece of cargo from one compartment to another compartment in the environment, the system must allow for bags moving through the opening, with given size constraints.*

- The components shall be able to function in a temperature range of TBD to TBD degrees Celsius. *It is important that all components of the system remain within a specified temperature range in order to guarantee the safety and integrity of the system, and the environment that the system is operating within.*

- The system shall be able to interact with a hatch in order to move a bag though the opening. *Being able to interact with a hatch that separates environment compartments is part of the initial problem statement. Since there will be no human interaction, there must be an autonomous or remote method of opening and closing a hatch, while also allowing for cargo to be moved through the opening.*

Software and Sensing

- The system shall be able to identify the location of a bag during the movement process within a margin of TBD. *Localization of the robot is needed to determine the position of the bag, as well as maintaining control of the robot and cargo.*
- The system shall be able to either autonomously decide, or give the operator the means to decide if the given task has been completed or failed beyond recovery. *Without the means to gain information about the status of the given task, there can be no way to guarantee that the task has been completed or failed beyond recovery.*

6.2 CONOPS

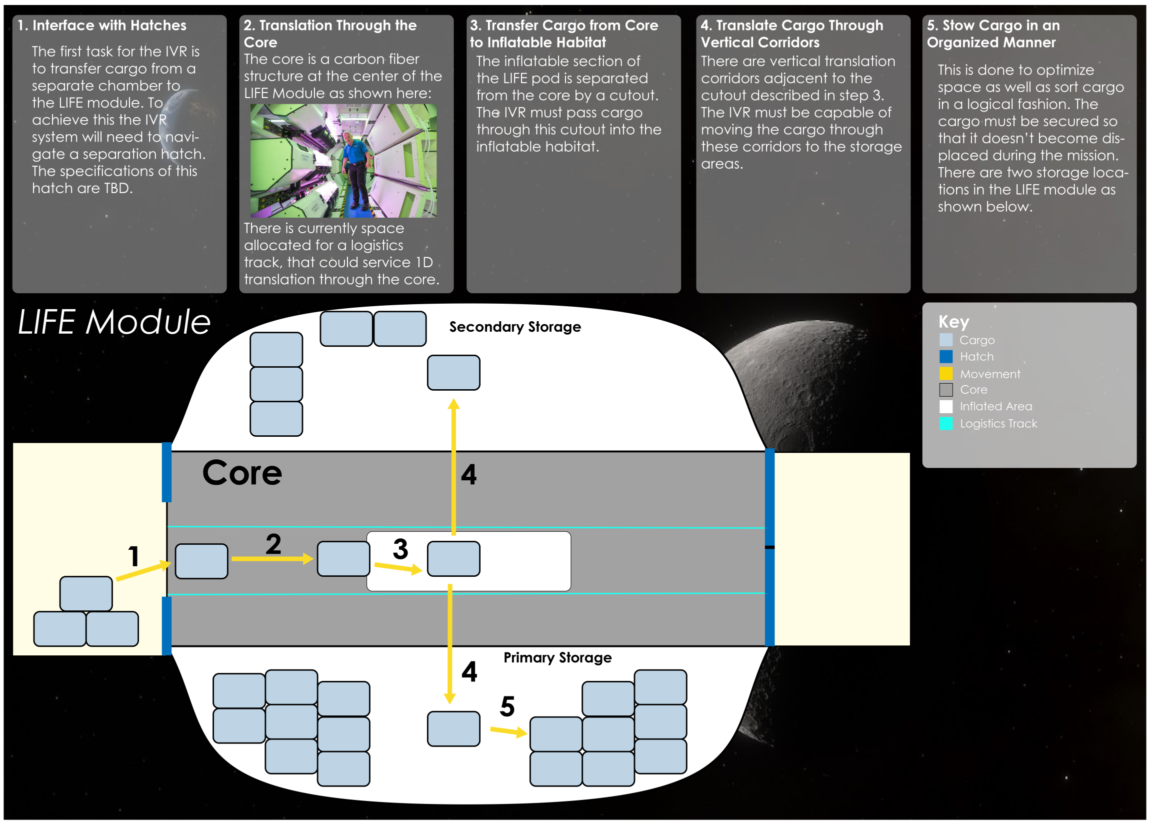

Figure 3: CONOPS for IVR system in LIFE module. Photo Credits: Top Left(Houston Chronicle)

The CONOPS shown in figure 3 entails the IVR functionality within the LIFE capsule. The primary capability of the IVR is to transport cargo from a separate module to one of the storage areas. The largest obstacles for this task are: interfacing with hatches, translating through the core, transferring cargo to the storage areas and then stowing the cargo in an organized fashion.

7 Critical Project Elements

Critical Project Elements are described here descending from a macro-scale into more detailed aspects of the project. These elements will drive the design and focus of the project which will ultimately interface with the LIFE module.

7.1 System Architecture

The high level architecture for the entire intra-vehicular robotics system will determine the capabilities and interfaces required at each stage of the unloading process for cargo. This will be a very high level concept of operations for the system that will move cargo bags from a supply vehicle to the predetermined location within the LIFE module. This will not be the focus of the project but it will be necessary to design the architecture around the the hardware that the team will build. The goal of the system architecture is to have an integration plan beyond the single stage hardware demonstration. Nothing in the system architecture will be constructed, nor will any specific hardware or sensors be decided. This is a very high level design exercise.

7.1.1 Transport from Core to Storage Areas

Once the cargo bags reach the edge of the core, they will be transported to different floors of the LIFE module. This will require a IVR system to navigate the bags through passageways to their storage locations.

7.1.2 Stacking Process

Once the bags reach their storage location, they will need to be stacked in an organized fashion. This will require some design of the bags that will allow them to be secured by the IVR.

7.2 Robotic System Translator

7.2.1 Robotic System

The customer has expressed interest in integrating a robotic arm into the LIFE module core where it would fulfill several operations before and during crewed missions. They have selected a robotic arm for purchase but this has yet to be approved by SNC. While a robotic arm may be an option, other solutions will first be explored to ensure the best design is implemented for the requirements of RIVeR. The capabilities of the IVR system will be agnostic to a solution. The robotics hardware will be an off the shelf system to reduce complexity.

Tasks that will be demonstrated using the robot will be focused on, but not limited to, translating a cargo bag of TBD size and mass within the Core of the LIFE module. High level success criteria will include maneuvering the bags through obstacles and hatches. The robot may be tested in a mock-up environment provided by SNC. Task completion can be defined around the final placement of cargo.

Key Elements of the Robotics:

1. Software

2. Electrical/Power Integration
3. Structural Integration and Bag Capture Mechanism
4. Dynamic Controls
5. Sensing

7.2.2 Translation System

To translate the cargo bags within the module Core, a structural system will be designed to allow movement in one degree of freedom. The system will be controlled by an operator to stop and start movement. It must interface with the LIFE module core and meet the structural and safety requirements of operating with crew.

7.3 End Effector

An end effector must be integrated into the robot that will interface with a chosen bag design for cargo transport. The effector must be exchangeable for completing other dexterous tasks such as operating tools (though not included in this project). This will be an off the shelf component that will be integrated into the robotics system. The dynamic capabilities of the end effector will need to be controllable by the system.

7.4 Cargo Bags

NASA has not designed or set a standard for the cargo bags that will outfit the Lunar Gateway. Part of the system architecture will have cargo bags being transported by different types of robots. The team will need to set a design constraint on the cargo bags so that they will effectively interface with each of the different possible robots within the architecture. The initial design will be based on the requirements set for the ISS with the option for adjustments. This will be a high level design focusing only on the capture mechanism for the robot.

8. Team Skills and Interests

Table 2: Team Skills and Interests

Team Member	Skills/Interests	CPEs
Lindsay Cobb	Systems Engineering, Structures, CAD	CPE 7.1.1, CPE 7.2.2, CPE 7.4
Logan Vangyia	Electronics, Thermodynamics, Systems	CPE 7.1.1, CPE 7.2.1, CPE 7.3
Jett Moore	Electronics, Structures, Systems	CPE 7.1.2, CPE 7.2.1, CPE 7.2.2, CPE 7.3
Nicholas Miller	Systems Engineering, Software, Electronics	CPE 7.1.1, CPE 7.3, CPE 7.4
Marin Grgas	Structures, Thermodynamics, Systems	CPE 7.1.1, CPE 7.2.1, CPE 7.3
Kyle Li	Numerical/probability analysis, thermodynamics, structures, CAD	CPE 7.1.1, CPE 7.2.1, CPE 7.3, CPE 7.4
James Tiver	Structures, Electronics, Thermodynamics	CPE 7.1.1, CPE 7.1.2, CPE 7.2.1, CPE 7.3
Bruce Barnstable	Software, Electronics, Structures	CPE 7.2.1, CPE 7.2.2, CPE 7.4
Jordan Abell	Controls, Software, Systems Engineering, CAD	CPE 7.2.1, CPE 7.2.2, CPE 7.3
Peter Amorese	Software, CAD	CPE 7.1.1, CPE 7.2.1, CPE 7.2.2
Brandon Torczynski	Systems Engineering, CAD, Manufacturing/Fabrication	CPE 7.1, CPE 7.1.1, CPE 7.1.2, CPE 7.4
Alex Ferguson	Software, Thermodynamics, Structures	CPE 7.1.1, CPE 7.2.1, CPE 7.2.2

9. Resources

Table 3: Resources

Critical Project Elements	Resource/Source
Software	Dr. Zachary Sunberg, Tomoko Matsuo, Dr. Nikolaus Correll
Electrical/Power Integration	Pilot Lab, Dr. Jade Morton, Dr. Robert Marshall
Structural Integration and Bag Capture Mechanism	Pilot Lab, Kurt Maute, Francisco López Jiménez
Dynamics Controls	Pilot Lab, Bobby Hodgkinson, Trudy Schwartz, Dr. Bradley Hayes, Dr. Nikolaus Correll, Dr. Dale Lawrence
End-Effector	Pilot Lab, Bobby Hodgkinson, Trudy Schwartz
Sensing	Dr. Nicholas Rainville, Dr. Jade Morton, Dr. Dennis Akos

References

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[3] Kanis, Simeon. "What Is Astrobee?" NASA, NASA, 8 Nov. 2016, www.nasa.gov/astrobee.

[4] C. Galindo, J. -. Fernandez-Madrigal and J. Gonzalez, "Improving efficiency in mobile robot task planning through world abstraction," in IEEE Transactions on Robotics, vol. 20, no. 4, pp. 677-690, Aug. 2004, doi: 10.1109/TRO.2004.829480.

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