MMEVR: An Autonomous and teleoperated modular robotic free-flyer for EVA Operations

by
Vittorio Netti

A thesis submitted to the Department of Mechanical Engineering,
Cullen College Of Engineering
in partial fulfillment of the requirements for the degree of

Master of Science in Space Architecture

in Aeronautical / Astronautical Engineering

Chair of Committee: Prof. Olga Bannova

Committee Member: Prof. Larry Bell

Committee Member: Mr. Larry Toups

Committee Member: Mr. Kriss Kennedy

May 2021

Acknowledgments

The completion of this work would not have been possible without the support of SICSA Director, Dr. Olga Bannova, Prof. Larry Bell, Prof. Kriss Kennedy and Prof. Larry Toups. Without their constant and valuable effort in providing feedback and funding to fuel my research, sharing knowledge, ideas and concepts, this research would not have gone so far.

I would like to also thank my colleagues that greatly assisted me since the beginning, especially Albert Rajkumar that supported my work like it was its own.

Finally, I extend my deepest gratitude to my parents for providing me the foundation and unconditional support to my endeavors. I thank you all for your support and contributions leading to the completion of this paper.

Abstract

EVA operations are currently the highest-risk task actually performed by humans in space and at the same time one of the most useful assets in human space missions. Despite the growing need for enhancement of EVA capabilities, the EVA technologies, such as spacesuits, stayed almost unaltered for more than 40 years, while new concepts are currently developed (xEMU).

MMEVR (Multi-Mission Extra Vehicular Robot) is a proposed design for a multipurpose EVA robot with high dexterity and mobility, which purpose is to collaborate with humans in Extra-Vehicular, in-space Operations and highly repetitive tasks.

This paper presents the outcomes of the first year of research, including the Concept of operations, a preliminary design concept, and considerations on the technological integration between different off-the-shelves components. The use of COTS (Commercial Off-The-Shelf) components is a main design driver for the whole system, as well as the integration level between existing space infrastructures and mission architectures such as the ARTEMIS program and the Lunar Gateway.

MMEVR presents a new modular architecture that allows astronauts to configure the robot to follow specific mission requirements.

The robot provides 2 to 4 additional robotic limbs and a navigation unit to perform autonomous tasks or collaborate with human crews during EVAs. The robot mobility is based on the joint use of RCSs (Reaction Control System) and CMGs (Control-Moment Gyroscope).

MMVR can be operated in 3 different control modes: Autonomous, teleoperated or robotic augmentation for EVA suits. The design concept includes an ISPR (International Standard Payload Rack)-integrated control module for teleoperated scenarios and a standard docking interface with space assets such as orbital and deep space modules or spacecraft.

MMEVR incorporates the lessons learned from the MMU, Safer, Robonaut, DEXTRE, and other space robotic assets to achieve unprecedented flexibility for the future generation of In-Space operations.

Table Of Contents

List of Tables

List of Figures

1 Vision Statement

Rising automation levels in space missions will enable the future-proof maintenance and integration capability that is needed to boost the larger scale applications. As today, In-orbit servicing for space assets is one of the main research topics for the industry, pursued by many aerospace companies and space agencies. Even if In-orbit service operations have a long history, their complexity did not allow high automation levels. Recently, developments of more and more feasible Artificial Intelligence algorithms and robotics enabled new possibilities for in-orbit operations, but we need to develop new assets that will make use of such advancements. These new assets will disclose the doors of new space applications while enhancing space safety performing the most dangerous operations in place of humans.

2 Issue

In the history of In-Space operations, EVAs play a fundamental role in Human Space Exploration. The needs for functional EVAs start with the firsts space stations, as the Salyut and Skylab. Such prolonged In-Space presence required hardware maintenance capabilities impossible with the technical level in automation at the time. For this reason, EVAs were the only option to perform external repairs and hardware installation. EVA suits and procedures had been extensively tested during previous space programs such as Mercury and Apollo. With the ISS and STS programs, automation capabilities increased dramatically, and many operational scenarios, previously conducted exclusively through EVAs, have been performed by the Canadarm and other robotic assets, such as DEXTRE. The use of these new automated systems, not only increased the safety of astronauts but also enabled a new generation of In-Space operations. On the contrary, while robotic capabilities were growing exponentially, EVAs hardware has evolved slowly during the last 50years. The Space Suit currently used on ISS, the EMU, it is the same developed for the STS program, and the new xEMU suit, under development for the last 20 years, has just started the first underwater test campaign given firsts Artemis missions and modern EVA spacesuits shares very similar limitations to the body movement than 50 years ago.

3 Proposal

The object of the base research behind MMEVR was to develop an asset capable of augmenting human dexterity and manipulation capabilities during EVA, skills usually limited by spacesuit design. MMEVR should also be capable of conducting In-Space operations within short-time notice. (e.g,. Emergency operations), so without the help of a human crewmember wearing a spacesuit. MMEVR is not just a robot, but a complex "plug-and-play" platform that includes every system component needed to perform in-space operations. MMEVR is spacecraft agnostic and can be interfaced with international space assets thanks to the use of the International Docking System (IDS).

The three main system components of MMEVR are: The robot, the service module and the control station. The robot is a modular free-flyer that provides from two to four 10 Degrees of Freedom (DoF) arms to perform in-space assembly and maintenance.

The service module works both as a pressurized maintenance workstation for the robot and as a payload airlock to deploy the robot and other payloads outside the spacecraft. It is transported to space through a Dragon Cargo XL capsule or as a stand alone payload of a variety of medium sized lifters.

The control station is a modular rack that includes a robotic haptic exoskeleton that allows a human crew member to control the robot arms through teleoperations.

4 Project Statement

MMEVR provide a range of in-space capabilities that will be needed to automate the most dangerous and complex human and robotic operations. This capability is fundamental to enable large scale applications such as orbital complex infrastructures and safe interplanetary travels across the solar system. History of human spaceflight taught us that space hardware is subject to deterioration and damage derived from the extended exposure to the space environment (radiations, debris impact) but also untested conditions of such hardware on earth. Until now we relied almost completely on human work (EVA) to accomplish the necessary maintenance tasks, due to the low feasibility or flexibility of robotics. Human EVA are extremely dangerous and require thoughtful planning and preparation. These characteristics make them unfit for emergency scenarios, where a fast reactivity is required to deal with dangerous situations, potentially lethal for the crew and the mission. The ideal future scenario is to have available autonomous robotics assets that, using advancement detection and diagnostic capabilities, could identify the source of the problem and react accordingly without human intervention. MMEVR aims to play this role, offering incremental robotic and autonomous capabilities to automate EVA operations in the most flexible way. To accomplish this final objective, MMEVR development is divided into three phases, to integrate and validate higher and higher levels of automation in space operations.

Table 1. MMEVR Phased development (automation capabilities)

Phase	Automation Level	Mode	Crew Control
I	Low	Teleoperated/Cooperative	High
II	Medium	Teleoperated	Medium
III	High	Autonomous	Low

The phased development allows to enhance operation safety and to validate the robot integration with human operations during development, raising progressively the confidence in the platform until it reaches its final operational capabilities.

5 Scope Of Project

5.1 In scope

The project will focus on the following factors:

- ConOps
- Main System Design
- System Architecture
- Use Cases

5.2 Out of scope

The project will not focus on the following factors:

- Design of the subsystems of the robot
- Provide Guidelines on the Information Infrastructure
- Provide budget assessments and hardware development timelines

6 WORK PLAN

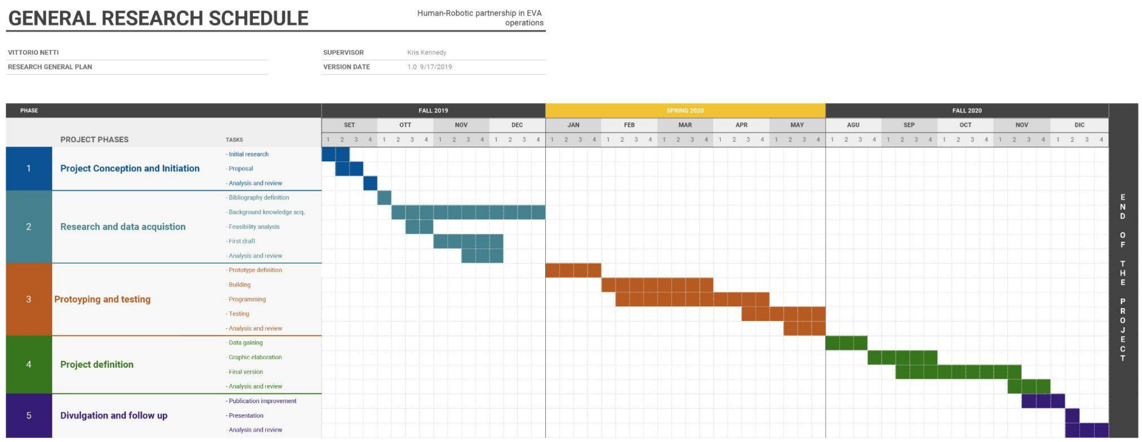

Figure 1. Work plan. Source: Author

The Work Plan of this research was originally articulated in 3 semesters, starting in Spring 2019: the first was mainly dedicated to the project definition, literature review and first the preliminary design. The second semester has been occupied by the preliminary design evaluation, ConOps definition and finally an approach to the final design.

Originally the third semester should have been dedicated to the mockup design and construction for testing purposes, but during the second semester, a multi-platform approach to the testing has been selected, integrating the original choice of the physicial mockup with a more innovative approach based on the use of Immersive Technologies such as Virtual Reality.

That choice forced a postponed deadline for the research that has been completed in the Spring 2021 semester.

7 Human-Robotic Collaboration in EVA Ops

7.1. HRI in Space

Human Robotic Collaboration in Space operations is not a totally new concept in space exploration. Preliminary designs of space robotics for assembly of large space structures have been imagined since the '50s. But it's not until the 1970 that these concepts found applications. On 17 November, the Lunakhod 1 Rover, built by Soviet Union, landed on the moon, making history as the first teleoperated rover on the surface of a celestial body. Lunakhod was remotely teleoperated from earth, with a 2.5s delay between the commands input from earth. From that historical moment, teleoperations in space became a fundamental asset for robotic and manned missions. We have to wait until the '80s, with the Space Transportation System (STS) to see the first collaborative operations between humans and robots. The Shuttle program made large use of robotics, such as the Canadarm[1], developed by the Canadian Space Agency (CSA) and the NASA Manned Maneuvering Unit (MMU). Both robotic assets were designed to be operated by humans to provide additional EVA capabilities. The Canadarm has been one the most important technologies to enable In-Space Construction capabilities, allowing the assembly of the International Space Station (ISS). It generated an entire new range of space operations and iteration of the technology itself (Canadarm2 and soon Canadarm3, with autonomous capabilities). The idea of Telerobotic and Human-Robot Collaboration came as an answer to a very specific question about space operations: how can we provide the high dexterity and flexibility needed to enable complex mission profiles in space?

The first answer to this question has been to develop Extravehicular Activities (EVA). The robotic technology during the ‘60s was not advanced enough, so the most natural way to deal with the problem was to allow humans to operate in the space environment, in the same way as on earth has been done for decades in subsea operations (civil and military). The first generation of spacesuits was largely inspired by deep divers equipment, and it allowed to perform the firsts maintenance operations in space: in 1973, the Skylab lost a portion of external thermal shielding, forcing the crew to perform the first in-space servicing operation. Without that intervention, the first american Space Station would have been inhabitable. The not-nominal scenario required the manipulation and dexterity capability that only a human could provide at the time.

Figure 2. Skylab Maintenance EVA, 1973, Source: NASA

Nevertheless, EVA posed a big challenge at the time, represented by the limitations to human strenght and dexterity due to the Extravehicular Mobility Unit (EMU) space suits. The suit was operating at 3.7 Psi, and was directly derived from the A7L developed for the Apollo program. The elbow, wrist and shoulder joints were allowing a limited range of movement and the EVAs were very short. With the development of the Canadarm, in 1981 we had the first collaborative operations between humans and robots in Space. The Canadarm, operated directly from the Space Shuttle deck, was a really flexible asset for the Space Shuttle, and essentially single-handedly enabled the assembly of the ISS. During the most complex construction tasks (such as the Main Truss assembly) both the Canadarm and the Canadarm 2 have been used together, in what was called the "Canadian handshake". Aside from the construction and Assembly tasks, the Canadarm 2 is currently still largely used on the ISS for a range of tasks, from providing a mobile working platform for astronauts to modules and commercial spacecraft docking and repositioning.

Figure 3. Canadarm 2 supporting an EVA, 2012 Source: NASA

From that moment of validation for space robotics, many other assets has been developed and tested: Dextre, the MMU, Robonaut are just some of them, of which we will talk later in this paper.

7.2 Extra Vehicular Activities (EVA)

In the history of In-Space operations, EVAs play a fundamental role in Human Space Exploration. The needs for functional EVAs start with the firsts space stations, as the Salyut and Skylab. Such prolonged In-Space presence required hardware maintenance capabilities impossible with the technical level in automation at the time. For this reason, EVAs were the only option to perform external repairs and hardware installation. EVA suits and procedures had been extensively tested during previous space programs such as

Mercury and Apollo. With the ISS and STS programs, automation capabilities increased dramatically, and many operational scenarios, previously conducted exclusively through EVAs, have been performed by the Canadarm and other robotic assets, such as DEXTRE. The use of these new automated systems, not only increased the safety of astronauts but also enabled a new generation of In-Space operations. On the contrary, while robotic capabilities were growing exponentially, EVAs hardware has evolved slowly during the last 50years.

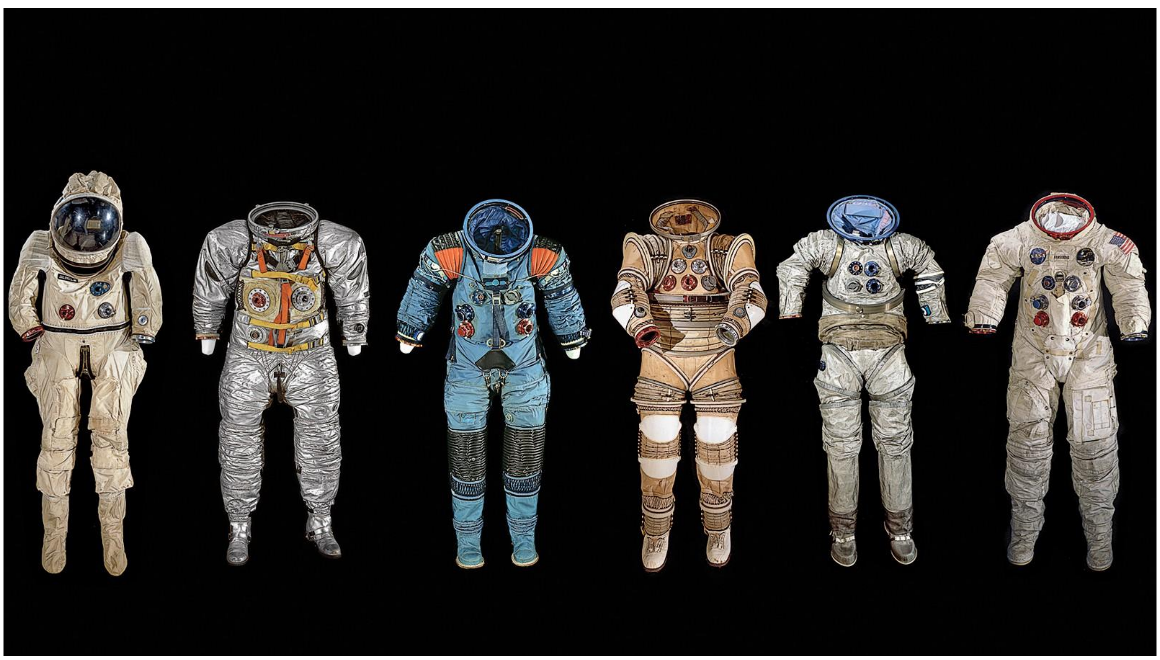

Figure 4. EVA Spacesuit evolution: From Mercury to Apollo, 2018, NASA

The Space Suit currently used on ISS, the EMU, are directly derived from the STS program, and the new xEMU suit, under development for the last 20 years, has just started the first underwater test campaign given firsts Artemis missions and modern EVA spacesuits shares very similar limitations to the body movement than 50 years ago.

7.2.1 Purposes and Risks

Currently, NASA describes the range of the uses for EVA operations in the Human Integration Design Handbook (HIDH)[3]:

- Payload or mechanical override
- Maintenance and repositioning
- Extravehicular experimentation
- Payload, equipment, and personnel transfer
- Large space or planetary surface construction
- Satellite deployment and retrieval
- Servicing and repair
- Inspection

This is a wide range of uses of which are of primary concern for the success of an exploration-class mission.

Involving humans in direct space environments, EVAs are intrinsically dangerous. On top of that, EVAs equipment widely limits the manipulation and mobility of the astronauts. Again, in the NASA HIDH are listed also the limitations of EVAs:

- Sensory degradation.
- Limited duration.
- Limited crewmember mobility and dexterity, force application, and endurance.
- Operations time and resource overhead requirements.
- Working volume and access limitations
- Hazards to the EVA crewmember.

Acknowledging those limitations, in sector 14 of the Man-System Integration Standard Manual, NASA propose one only possible alternative to EVAs in the future:

“Sophisticated machine systems may relieve the EVA crewmember of routine and hazardous tasks as the technology for automation, teleoperation, and robotics evolves. Applications of robotics and teleoperation should be designed to achieve an optimum mix of human and machine resources, and substitute control as safety, productivity, and cost effectiveness warrant. Systems that employ machine applications should not be designed to preclude the use of EVA as backup.

The successful employment of alternatives to EVA is strongly dependent upon a foreknowledge of the worksite and tasks to be performed. For new and complex situations, EVA will remain the method of choice.”.

7.2.2 EVA Challenges

Following the NASA Guidelines we can assume a set of Design Criteria for a future asset capable of significantly reduce the level of risk and complexity of EVA operations:

- Safety
- Compatibility with human operations
- Automation levels
- Expendability
- Reliability
- Autonomy

7.2.3 xEMU

The Exploration Extravehicular Mobility Unit (xEMU) is the next generation space suit currently under development from NASA and ILC Dover. It is the dedicated EVA suit system design for use during lunar flight dynamic phases (if needed), microgravity EVAs, and lunar surface excursions.

The Exploration EVA (xEVA) System allows crewmembers to conduct excursions outside a habitable vehicle in order to perform exploration, research, construction, servicing, and repair operations.

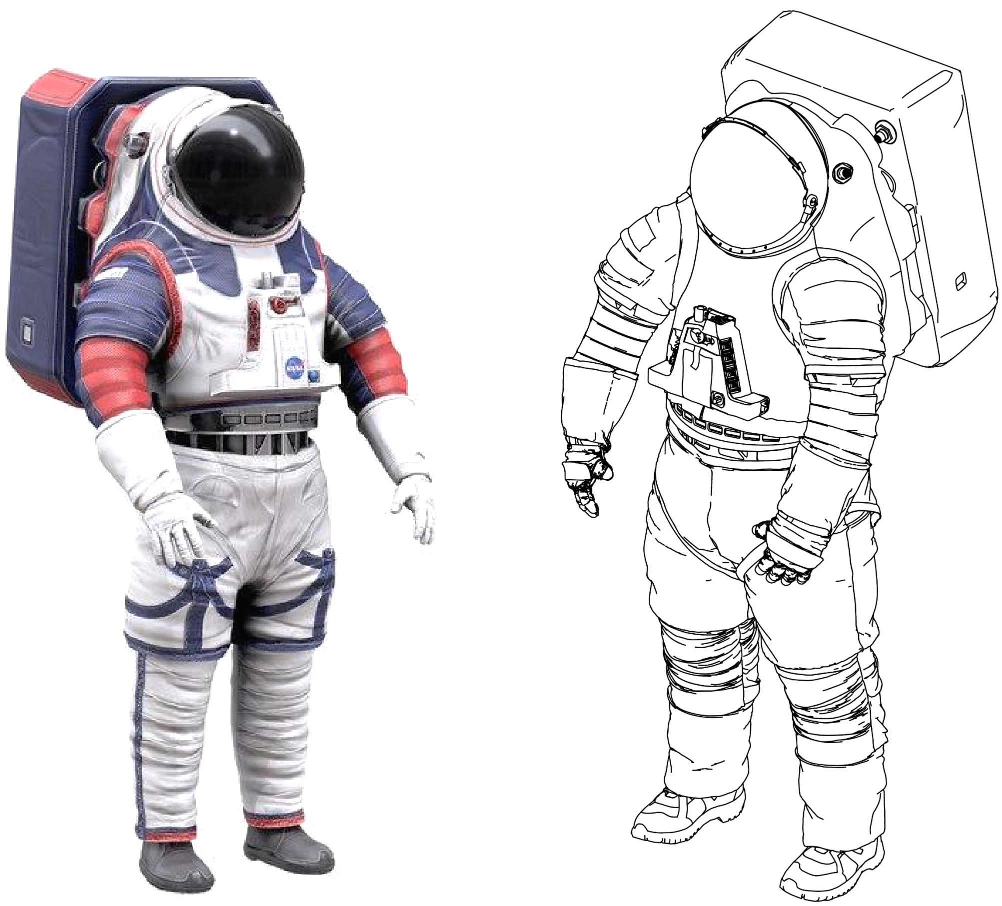

Figure 8. The last developments of the xEMU suit, 2019, NASA

The xEVA System will enable and help accomplish the science goals for lunar surface missions. The system includes the xEVA suit, the Exploration Servicing, Performance and Checkout Equipment (xSPCE), and the Flight Support Equipment (FSE).

A few key xEVA surface suit capabilities include, but are not limited to, as follows:

General Requirements:

- Rear-entry spacesuit
- Suit pressures range from 0.4 psid to 8.2 psid, with a nominal EVA pressure of 4.3 psid
- Supports EVAs of up to 8 hours in duration (6±2 hours)
- Capability to operate for up to 2 hours of contiguous exposure in a shadowed area, including Permanently Shadowed Regions (PSRs)

Mobility:

- Translation via walking, crawling/scrambling on hands and knees, and climbing ladders
- Walking up/down/across a slope of up to 20° and on traverses of up to 2 km away from the lander (depending on terrain) [Note: Apollo 14 walked ~1.45 km from the lander, and Apollo 15 traversed on slopes of ~17°]
- Traversing down into and out of craters, volcanic terrains, and shadowed regions
- Performing tasks while standing and kneeling
- Capacity to carry some tools on the suit (attached directly or via a harness)

For the sake of this research, the xEMU has been selected as a Space Suit of reference to underline the future-proof aspect of the platform. xEMU represents a major breakthrough for Space suit technology and possibly it will be the next standard EVA asset for at least the next 50 years of human space exploration missions, including Lunar, Martian and Microgravity scenarios.

7.3 Space Robotics

Implementation of Robotics with In-Space operations is a fundamental capability for future space missions, especially for long-duration, long-range operations. During the whole ISS lifetime, more than 1400hrs of EVA has been performed[2] for different purposes, with an average duration of 6 hours for session. Most EVAs performed during the Space Station assembly involved the use of Canadarm and Canadarm2 to complete the In-Orbit construction tasks.

Figure 6. The Canadarm during a payload transfer operations between the Endeavour and the ISS, 2009 NASA

Currently, we lack in-space robotics capable of proving useful in most of these scenarios, that is the main reason for which human EVAs are currently the only option to perform these operations. There are two contributing causes for this condition: the first is that some of these scenarios are consequential to not-nominal operations and they need to be performed within a short time. This makes them incompatible with current robotic assets that need extensive and multilayered planning.

The second reason is that most of these scenarios involve the need for high dexterity and flexibility to manipulate a vast range of tools and delicate hardware, features for which, current in-space robotics is not suitable.

There have been different robotics assets onboard the ISS. Most of them are proof-of-concept hardware, such as Robonaut, Cimon, Project Sphere, Astrobee[4]. Just some of them have manipulation capabilities, and even fewer of them have proven useful to ease crew workload.

About In-space operations, the biggest issue is that EVAs are particularly long and weary for astronauts. The effects on the body and psyche after each session can last for days or even weeks. A single EVA also requires accurate planning and 4 hours of pre-breathing, features that define the 24h minimum EVA preparation time.

Figure 7. Shane Kimbrough, Peggy Whitson & Thomas Pesquet pictured during EVA Preparations, 2017, NASA

8 Preliminary design concepts

8.1 Adaptive Architecture

Due to the great success of the private initiative, we are experiencing the proliferation of multiple space designs in just a few years. The next EVA standard (xEMU) will probably need to deal with different requirements from the original ones. The new platform should be flexible to adapt to different functional requirements in terms of software, architecture and form factor. For each aspect have been evaluated three options representing three different strategies on a scale from most conservative to most innovative, assuming the most innovative as possibly sperimental (TRL 5) or with a small flight experience. Different technologies have been evaluated on the basis of feasibility, Level of Development, Cost, Integration complexity and Manutebility.

8.2 Form Factor

Form factor is a main Design Driver in this evaluation. The scale factor is decided by the Design Criteria of the compatibility with human EVA. The platform will interact directly with the xEMU and with human crew, interacting with anthropometric tools and interfaces. Since the two main functions of the system are Mobility and Manipulation, the system architecture will include at least a navigation system and a manipulator unit.

The requirement of different levels of automation define the need for a detection system and a computing unit. The Autonomy is represented by a power source and power distribution system.

8.2.1 Options

Following the three option guideline for the form factor We considered the hardware modularity and the software interoperability:

The Robot concept sticks as much as possible to the anthropometric requirements of the xEMU and use of tools and assets designed around humans.

Table 2. Form factor options evaluation table

Systems	Conservative	Equilibrated	Innovative
Manipulation	Single Arm	Two arms	> more than 2
Navigation	Integrated	Maintainable	Modular

For the manipulation System, the two arms option has been selected as the most natural choice, because they have already been tested during the Canadarm-Canadarm2 joint operations and because it is compatible with the Direct Control and Teleoperations. The navigation system has not been deemed of primary concern (deambulation can be provided in from the Manipulation system) and so achievable through experimental systems[5].

8.3 Automation Level

The object of the base research behind MMEVR was to develop an asset capable of augmenting human dexterity and manipulation capabilities during EVA, skills usually limited by spacesuit design. MMEVR should also be capable of conducting In-Space operations within short-time notice. (eg. Emergency operations), so without the help of a human crewmember wearing a spacesuit. The level of Automation Should be adaptive, evolving together with the technology: With reinforcement learning algorithms, the robotic component can learn during the first phases of operations to optimize the control for the autonomous phase.

8.3.1 Options

The three Automation options are defined not as a precise choice between three options but as an evolutive Design that gains new capabilities during the development.

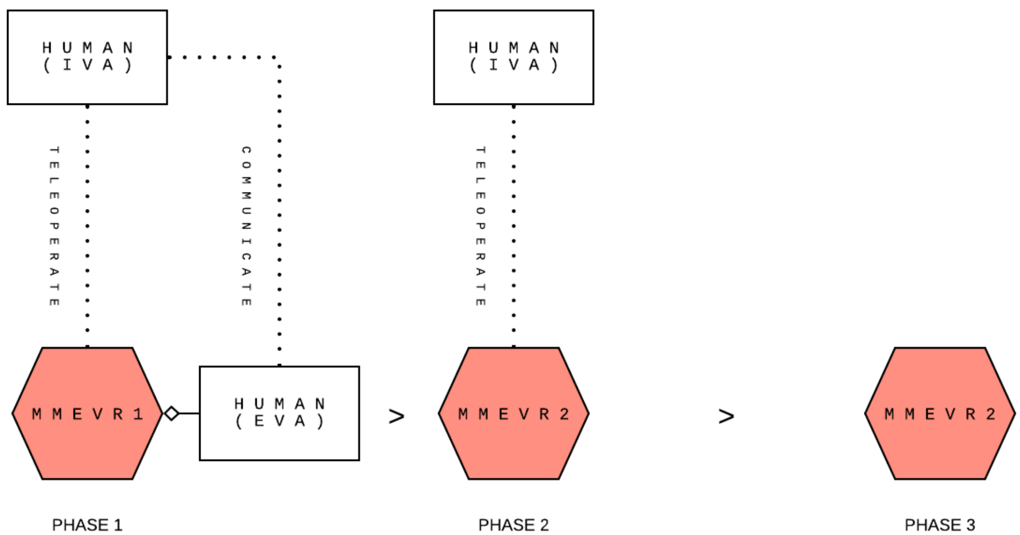

Figure 8. Diagram of the automation level development

8.4 Comparative Analysis of options

The analysis accounts for the most diffused strategies about hardware modularity in Space Applications, realizing that the full modularity adds too much complexity and failure point. It also brings a general larger mass due to the interfaces needed between modular parts. On the contrary, a Monolithic architecture leads to low maintainability and in a general shorter lifespan. (low upgradability).

Table 3. Comparative Architectural Analysis table

Options	Conservative	Balanced	Innovative
Hardware Architecture	Fully Integrated	Partially Modular	Fully Modular
Software Architecture	Monolithic	Partially Modular	Fully Modular
Automation Level	Direct Control	Teleoperations	Autonomous

The Software architecture has been evaluated similarly, considering Full modularity too unstable, and addressing the need for a central core control software that will interact with the sourbotines through specific translators.

9 Case Studies Summary

9.1 Manned Maneuvering Unit (MMU)

The Manned Maneuvering Unit (MMU) was an astronaut propulsion unit in the form of a spacesuit seat. The MMU was provided with 24 RCS nozzles and 2 tanks of 5.9Kg of Nitrogen each. It`s main purpose was to provide precise maneuvering capabilities in Space without the need of a teter. Used aboard the Space Shuttle on three occasions to retrieve satellites and performance testing. Considered too dangerous and with too limited use cases, it has been retired after the Challenger Disaster.

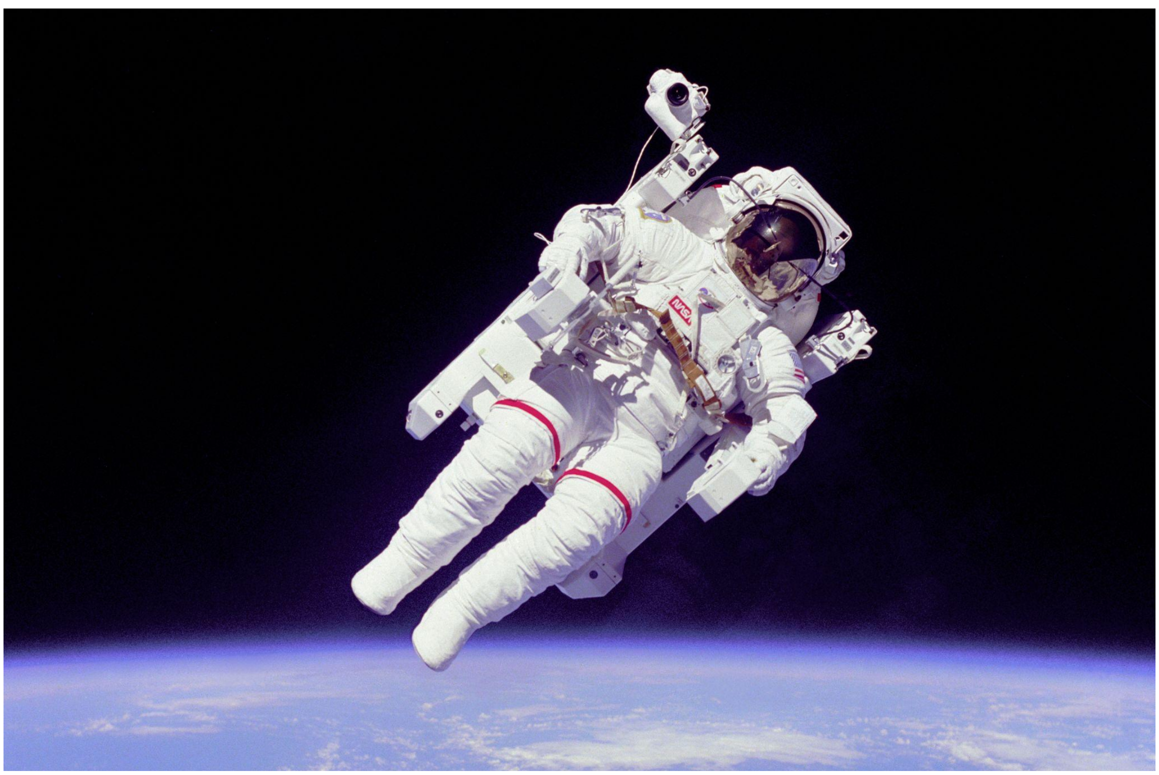

Figure 9. Bruce McCandless uses a Manned Maneuvering Unit during the STS-41-B mission, 1984, NASA

Strenght:

- High movement precision
- Simple (Low failure rate)
- Reduce Mobility physical effort in space
- Long range
- Long Autonomy

Weaknesses:

- Difficult to dose the thrust
- Requires a lot of training
- Rely on human manipulation capability
- Few use cases
- Short flight experience

Opportunities:

- Enabling new EVA capabilities and Scenarios
- Easily scalable to personal equipment

Threats:

- Untethered
- No safety in case of failure
- Same-system redundancies

9.2 Robonaut

Robonaut was an experimental Anthropometric robot designed with a Modular/Evolutive approach, capable ideally of IVA, EVA and planetary operations. It was able to use human-centered design tools but it suffered many unforeseen problems at both the electrical and software components. The project has been currently halted for its extreme complexity and excessive development cost.[6]

Figure 10. Robonaut 2 during the Mobility Unit Integration testing, 2014, NASA

Strenght:

- Anthropometric
- Modular
- Evolutive Architecture
- Capable of IVA and EVA
- High Dexterity
- Many Use Cases

Weaknesses:

- Extremely complex architecture
- Technology not completely development
- Expensive
- Complex Maintenance

Opportunities:

- Allows high levels of automation
- Enable spacecraft management without human intervention
- Easily adapted to future architectures

Threats:

- No direct control in case of emergency
- Requires a lot of crew time during operations.

9.3 Special Purpose Dexterous Manipulator (SPDM):

The Special Purpose Dexterous Manipulator (SPDM), or DEXTRE, is a robotic telemanipulator in service on the ISS. Developed by MDA for the Canadian Space Agency (CSA) it provide high dexterity payload manipulation capability to the Canadarm2. Each of its 2, 7 Dof arms is capable of switching tools and from 2011 also of refueling operations.

Figure 11. DEXTRE grappled to the end effector of the Canadarm2, 2019, NASA

Strenght:

- Very Flexible
- Interchangeable tools
- Evolutive
- Safe

Weaknesses:

- Complex
- Big dimensions (EVA only)
- Not Anthropometric
- Needs EVA for mainteinance

Opportunities:

- Test high level of automation in assembly and payload management
- Enable In-Space servicing (refueling, docking, repair, assembly)

Threats:

- Always exposed to space environment
- No direct control in emergency scenarios

9.4 SWOT Analysis of the proposed concept

The SWOT Analysis is a tool to assess and evaluate different features of a platform to assume Design Criteria useful in the definition of the final design. In this case we will consider the Preliminary proposed Design criteria for the analysis. The considered features (from which the name SWOT derives) are:

Strenght:

- Extremely flexible
- Evolutive
- Modular
- Dedicated IVA maintenance space and deployment airlock
- Adaptable to multiple spacecraft architecture
- Many redundancies (differentiated systems)

Weaknesses:

- Expensive
- Complex operations with low levels of automation
- Not compatible with big space structures

Opportunities:

- Enable unprecedented levels of architectural flexibility
- Provide a standardized platform for national and private space assets.
- Overcame the contemporary and future Spacesuit limitations of human skills

Threats:

- Untethered (Direct Control mode)
- Complex In-space docking operations

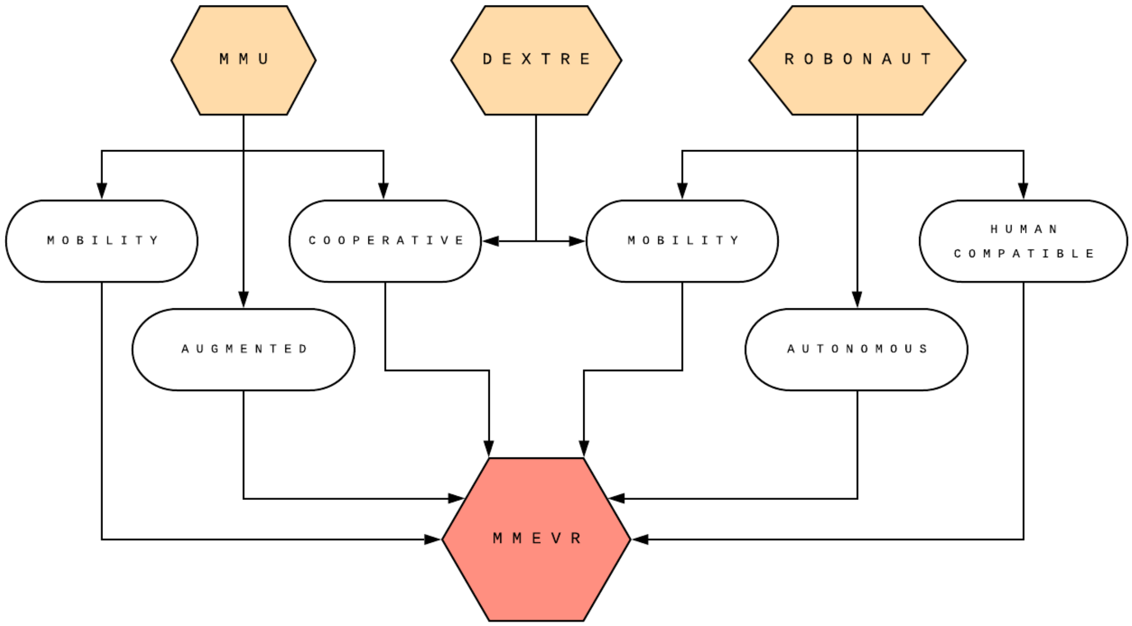

Figure 12. Diagram of the Case Study analysis

10 Final Design

10.1 MMEVR

MMEVR is a complex robotic platform for in-orbit servicing composed of three main elements: The service module, the control station, and the multi limb modular robot. The infrastructure is designed to be adapted for any modern and near-future spacecraft and its flexibility allows MMEVR to be implemented without massive changes in the target vehicle or the crew workflow. All the system components make substantial use of COTS, reducing the R&D time needed to reach the testing phase.

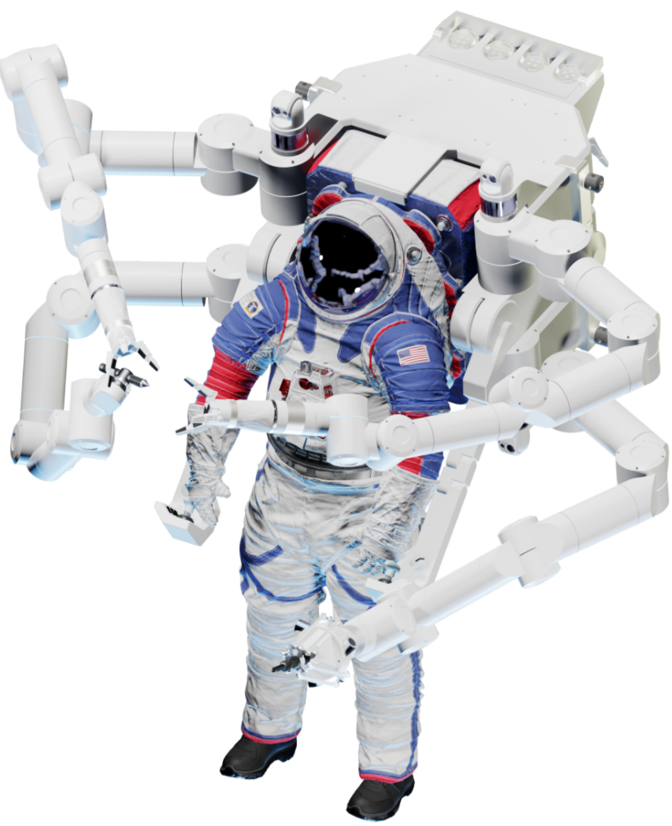

Figure 13. MMEVR in Cooperative mode with an astronaut with an xEMU, Author

10.1.1 The Robot Module

The robot module is a modular, multi-component robotic platform that can be reconfigured to respond to different In-space servicing needs. The core unit, the MMEVR is a two limb free-flyer capable of high dexterity. The body, made of Aluminum 2219, hosts 4 Li-ion Battery packs, a dual central processing unit, a Reaction wheel group, a stereovision camera-lidar system, and three small docking ports. It is also capable of hosting a multi-toolbox on the back.

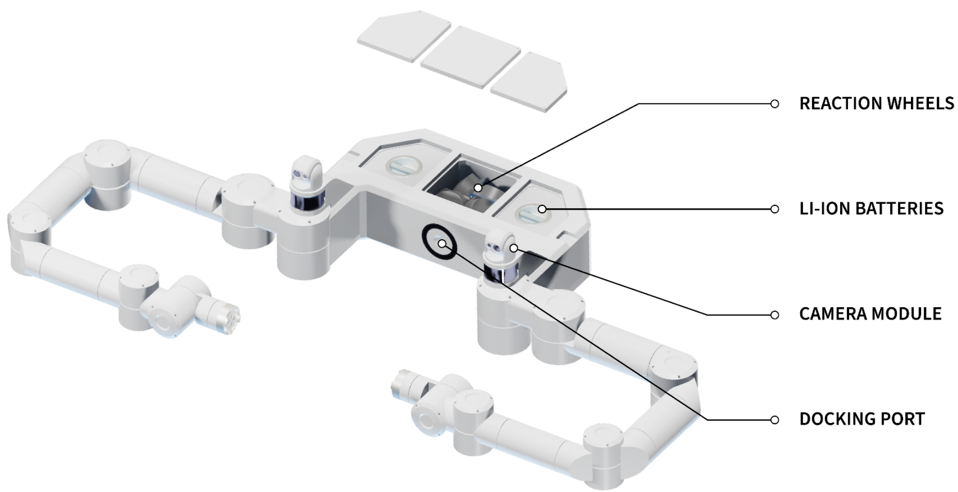

Figure 14. Exploded diagram of the Robot Module, author

A robot module can work in a stand-alone configuration or join together with a navigation module or in a triple-module configuration with the navigation module and another robot module. Each limb is a 10 Dof high dexterity robotic arm capable of a 2.2m reach in any direction. The limb unit is designed to reach the workspace in front of the astronaut's chest, without obstructing the helmet vision angle or the stereo vision camera system. MMEVR provides from 2 to 4 additional arms to the astronaut and vectorial navigation capabilities if the navigation module is mounted.

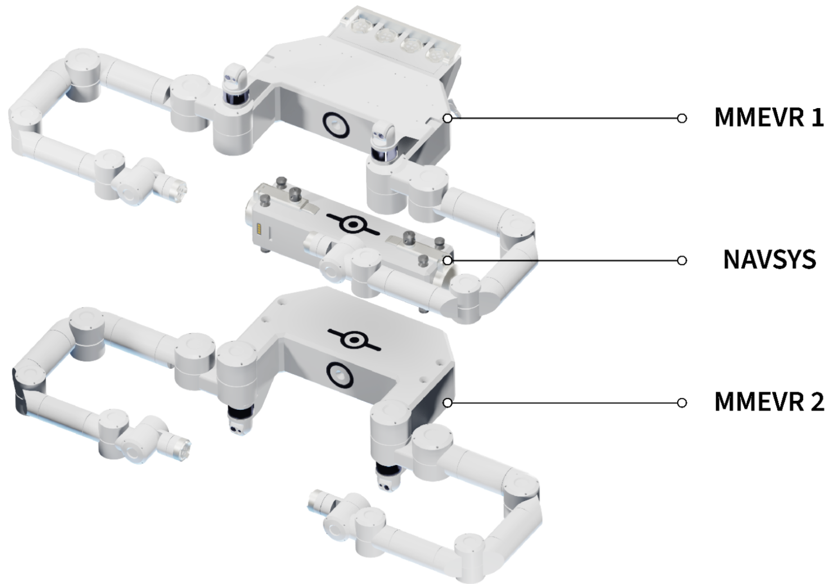

Figure 15. Exploded diagram of MMEVR, author

The astronaut does not directly control the arms that can be teleoperated from the control station inside the spacecraft or controlled by the local robot AI. The limbs can be used both for enhancing the dexterity of the astronaut or climb and secure onto the spacecraft external shell, avoiding the need for additional retention systems. The camera-lidar stereovision system provides real-time images and distance-to-target to the crewmember using the control station inside the spacecraft. The four Li-ion battery packs are used in a two buses configuration for which two batteries (one main and one for backup) control one limb, one computer, and one camera-lidar system.

Without an interfaced navigation system, the MMEVR robot module can still crawl onto the spacecraft using the EVA handles on the external shell and using the Reaction wheels for precision orientation. The Reaction wheels are provided in a tetrahedral configuration, one for each ax and another one for redundancy.

In order to dock with the service module of other MMEVR components, three docking elements, derived from the design of the ARCADE, ESA docking experiment. Each docking port includes a radial laser alignment system and autonomous docking/undocking capabilities.

10.1.2 The NAV Module

The Navsys (Navigation System) is an additional module that provides four RCS vectorial units for a total of 20 orientable nozzle thrusters and 2 separated composite tanks filled with 18 Kg of nitrogen. The RCS units transform the MMEVR in a full free-flyer robot. To reduce the size of the tanks, the Navsys RCS and the MMEVR reaction wheels work in tandem, limiting the use of the RCS to vectorial displacement and using the reaction wheels for the orientation.

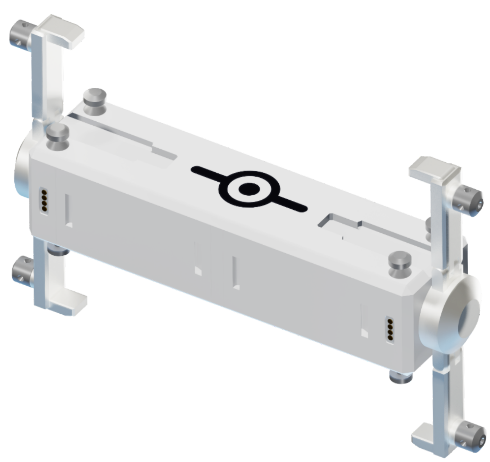

Figure 16. The NavSys module deployed, author

The Navsys inherit the lesson learned from the MMU and SAFER, expanding the MMEVR mobility. Thanks to Navsys, the MMEVR platform became capable of satellite and hardware retrieval both in autonomous or teleoperated mode.

When Navsys is used in conjunction with EVA suits, the RCS control is operated from the MMEVR harness, in a similar way to the MMU, that also provides the hardware interface between the xEMU suit and the MMEVR system. The RCS control interface is very similar to the MMU, and it is based on two 4-axis joysticks placed on the harness armrests. The armrests can be regulated in length to adapt to the different astronaut's height. In case of pressure failure of the two nitrogen tanks, the canisters can be expelled from the Navsys module through a preloaded spring mechanism. The onboard dual computer will provide real-time thrust calculations to include the center of mass displacement caused by the movements of the limbs. The same input will also be provided for orientation correction to the CMGs.

10.1.3 Tools

The MMEVR is provided with four exchangeable tools to cover the most use cases possible. The tools are initially stored in a toolbox in the rear part of the robot module and they are docked to the end effector of the arms through an endpoint interface that provides data, power and mechanical mating.

The four tools are:

- Adaptive gripper (anthropocentric)
- Laser Melting printer (Titanium and Aluminum)

- Electron laser beam (derived from STS program)
- Adhesive retrieval clamp (from JPL`s GECKO project)

Each robot can host a combination of 4 tools for 2 arms. Tools are directly controlled from the Robotic Control Station inside the spacecraft.

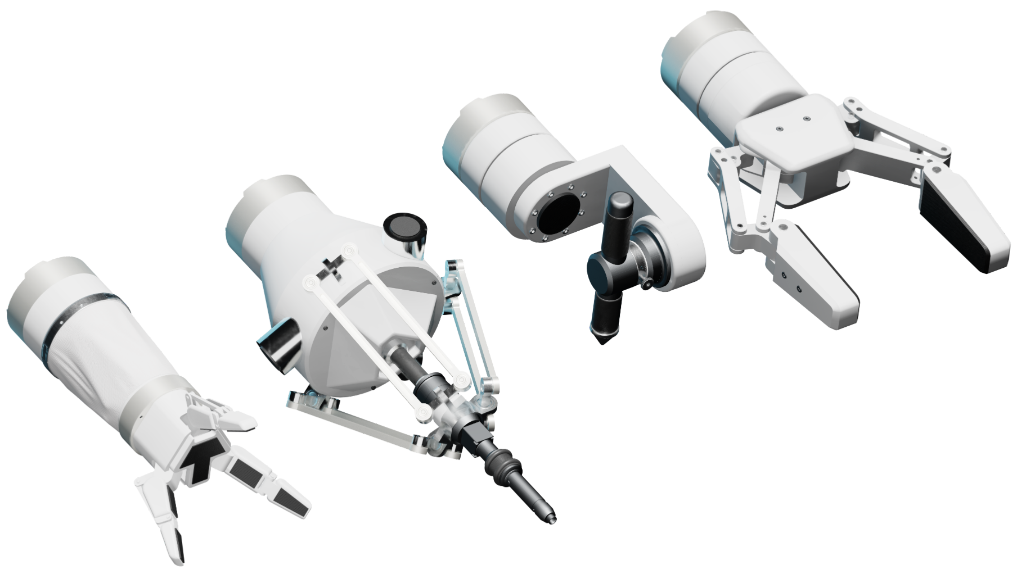

Figure 17. The four interchangeable MMEVR tools

10.1.4 The Awareness and Detection System

The Awareness and Detection system use mainly three different technologies:

- Stereo Cameras
- Laser Lidars (fixed and rotary)
- Object Recognition and tracking algorithms

While the Stereo Cameras and the rotatory Lidars (in 2 groups of 2 for each Robot Module) provide 3D situational awareness in almost real-time, the fixed lidars provide precise measurement of the relative distances within the near-space objects.Machine Learning algorithms for Object tracking and recognition are fundamental to develop the autonomous capabilities of the Robot.

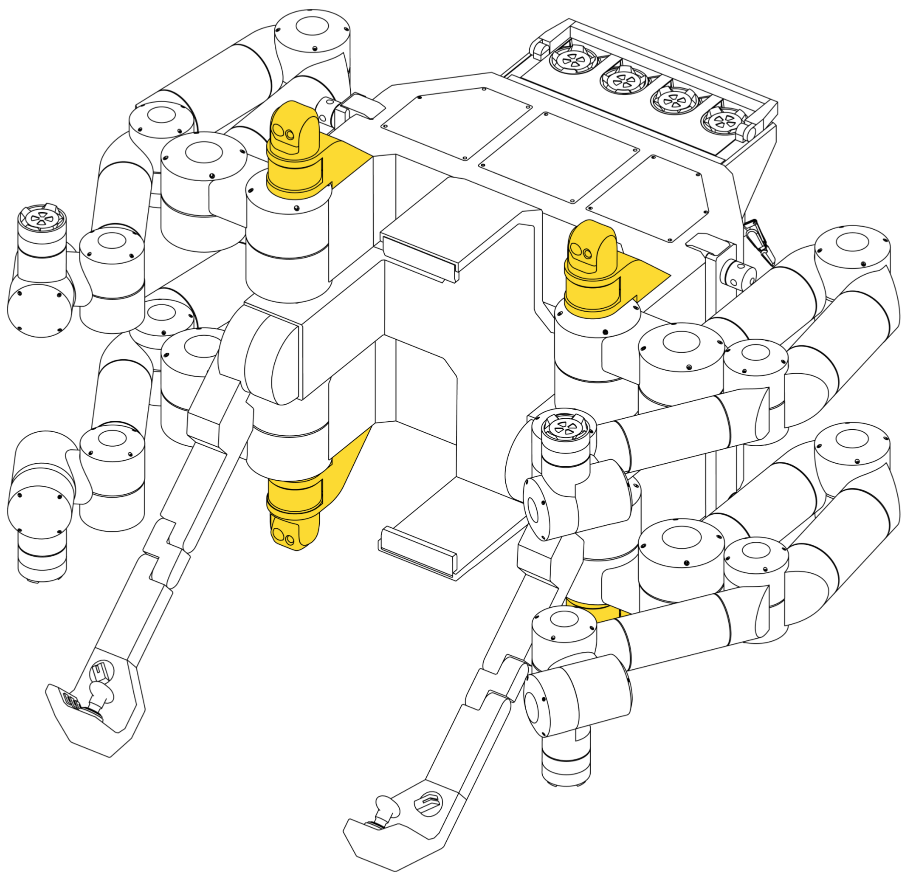

Figure 18. Diagram of the detection and awareness Subsystem, author

10.1.5 Docking Interfaces

The Micro Docking system is a central technology for MMEVR that still needs to be fully developed. It is based on a non-androgynus docking system developed for cubesat and smallsat. The system has a passive component and an active one. The passive-Spring damper guarantees a soft docking while maintaining a high level of reliability even in case of power failure.[7]

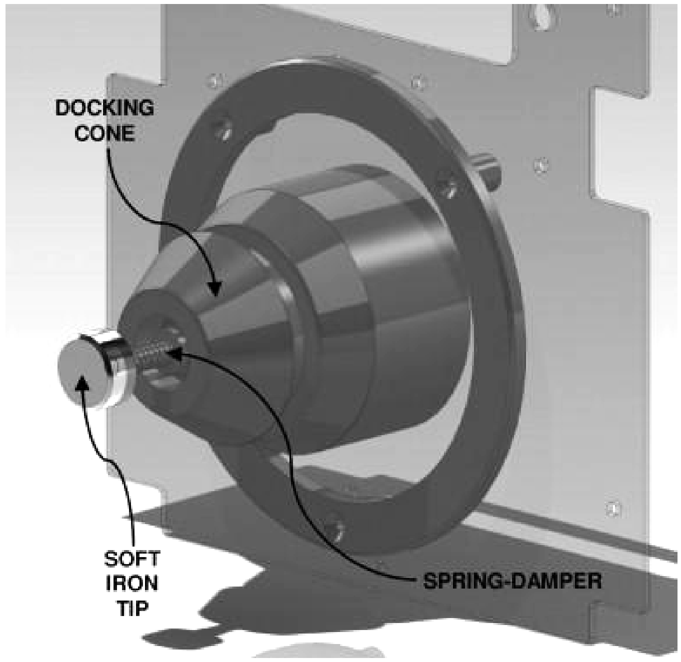

Figure 19. The ARCADE Docking Interface, UniPd, 2017

10.2 The Service Module

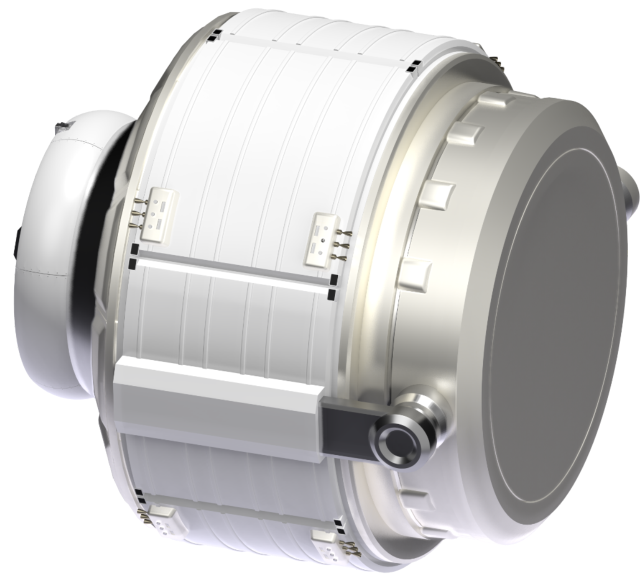

Figure 20. The Service Module, author

The service module is a fundamental component of the system: it hosts and deploys the MMEVR, acting both as a robotic maintenance station and an Airlock. It is based on a shorter version of the Cygnus spacecraft and it is provided with an IDSS interface to be docked to the main spacecraft. The bottom of the module can rotate on itself, revealing the robot for the docking and undocking phase, in a similar way to the Nanoracks Bishop airlock. Due to this feature, the module needs to be depressurized every time that the robot is deployed. It is normally kept unpressurized if there is no need for a human presence inside. One Service Module can host one complete system (two robot modules and one Navsys module) and it includes the tools and instrumentation needed to perform maintenance and repairs on the different modules. One additional robotic is installed on a radial rail inside the module, to perform autonomous and teleoperated maintenance procedures on the robot. When pressurized, the module can host two crewmembers working at the same time. The docking interface that normally hosts the robot can be also used to deploy other hardware, such as small satellites or payloads to be installed outside the spacecraft.

Figure 21. MMEVR Deployment sequence, author

10.3 THE CONTROL STATION

The control station is installed inside the main spacecraft using any standardized payload rack, such as the ISPR. It is used by the crew to control the robot when it is teleoperated. While it is still in the design phase, the most probable design will include a dual 10 Dof chest exoskeleton that will be worn by the operator, to give direct and real-time inputs to the robot limbs. The Control Station will also provide the necessary inputs to train the AI for future autonomous operations and it will also be used as a training platform for human crewmembers. Even if They share the same DoF number, the robotic limbs and the exoskeleton limbs have different joint configuration, so to control the arm, the hand's controller on the exoskeleton will be bound to the end effector of the robotic limbs. The rest of the joints will move accordingly, avoiding to obstruct the field of vision of the astronaut/stereo camera system. When not used, the control station is folded and stored inside the same payload rack that hosts the command and control processing hardware.

10.3.1 Exoskeleton Design

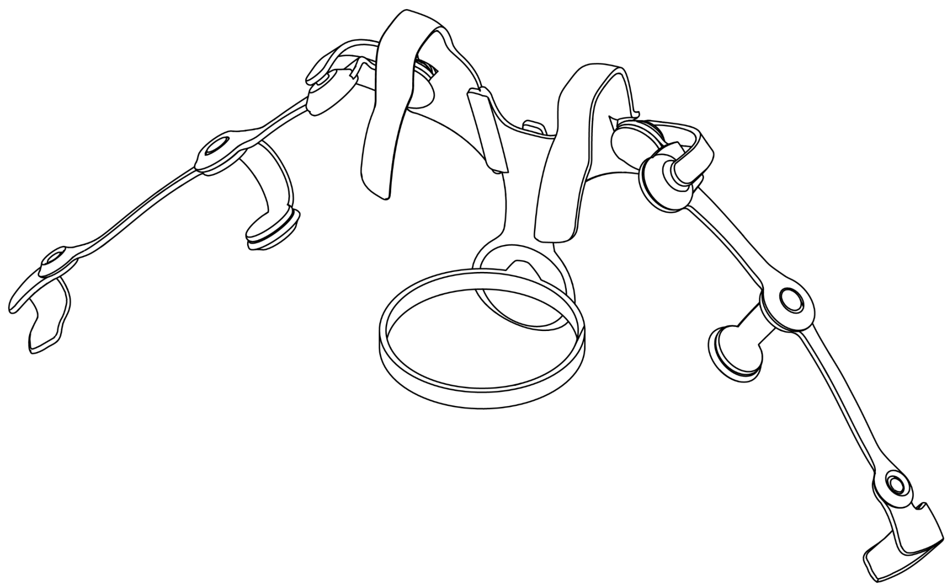

Figure 22. Preliminary anthropometric exoskeleton design, author

The exoskeleton has been identified as a great tool to ensure the precision interpretation of the pilot`s movement. Even if the Robot Arms don't have dynamic correspondence with an human arm (7-Dof versus 10-DoF), the input of the movement is the endpoint of the exoskeleton (the hand position sensor), while the rest of the robot`s joints will move accordingly to the algorithm. The Exoskeleton can be folded inside its own control rack to occupy less space possibile in the spacecraft while not used. It is powered through the spacecraft power lines and it uses the onboard antennas to connect with the robot. The secondary function of the exoskeleton is the one to provide a data input for the Reinforcement Learning algorithms that determine the evolutive automation capabilities.

10.3.2 Control Mode Switch

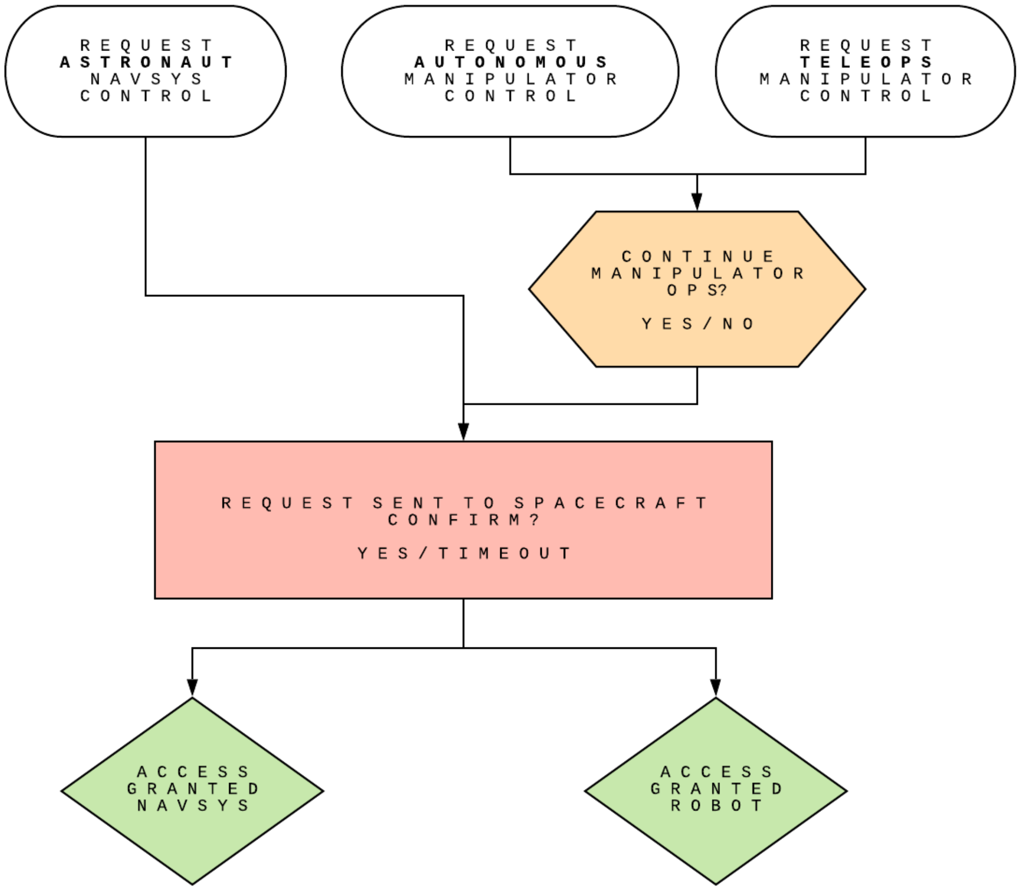

Figure 23. Control Mode Transfer Diagram, author

The transfer between IVA, EVA and autonomous control happens through a safety protocol that always requires human intervention. Every change of control status needs to be authorized following a decisional chain that has on its top human with most direct control on the robot (the astronaut in cooperative mode with the robot). If a human in EVA is not available, the control transfer needs to be authorized from one crewmember in IVA.

10.4 System Architecture

The three main components of MMEVR can be sent to orbit together or separately to the main spacecraft. The robot and the control Station will fit inside the module for the launch phase. If launched separately, the MMEVR is delivered to orbit using any medium-lift launch vehicle such as Falcon9, Antares 230, or Atlas V. It also can be delivered with the Dragon Cargo XL to be compatible with the Commercial Lunar Resupply Program. After it reaches the spacecraft, the Service module is docked and connected to the main power and data bus, and the Control Station is moved and installed inside the spacecraft. The data and communication infrastructure is managed through the service module, except the command and control for teleoperated operations, that is processed through the Control Station in the main spacecraft. The reason why the control Station is not installed in the service module is that the module is depressurized during each robot docking/undocking sequence, making it impossible to control it manually during these phases. Each robot component is equipped with an X band antenna to be operated separately, while when docked together, the multiple antennas work as a redundancy system. While in stand-alone mode, the object avoidance system is activated. The system relies on the quad stereoscopic camera and lidar infrastructure, and it works in background mode. In an LoC scenario, the system will activate, keeping the robot at a constant, safe distance from the spacecraft until recovery protocols startup.

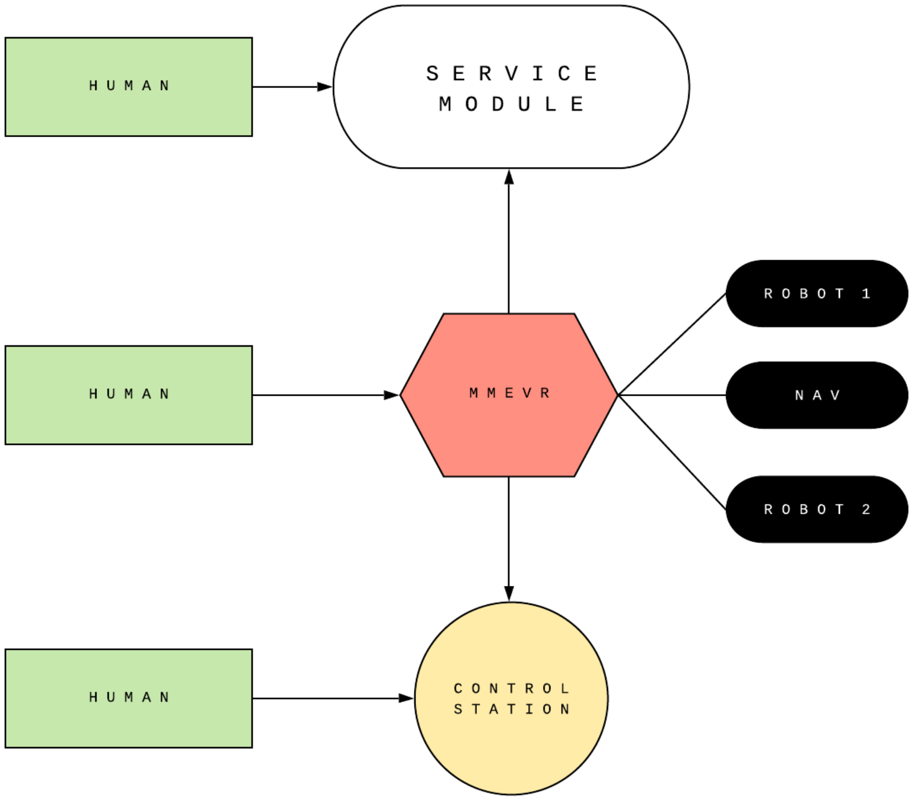

Figure 24. System components diagram, author

The range of tasks that MMEVR can perform covers the entire span of EVA operations listed by NASA HIDH. As previously stated, MMEVR is capable of both autonomous and teleoperated operations and it can work in collaboration with a crewmember, stand-alone, or together with other robotic assets.

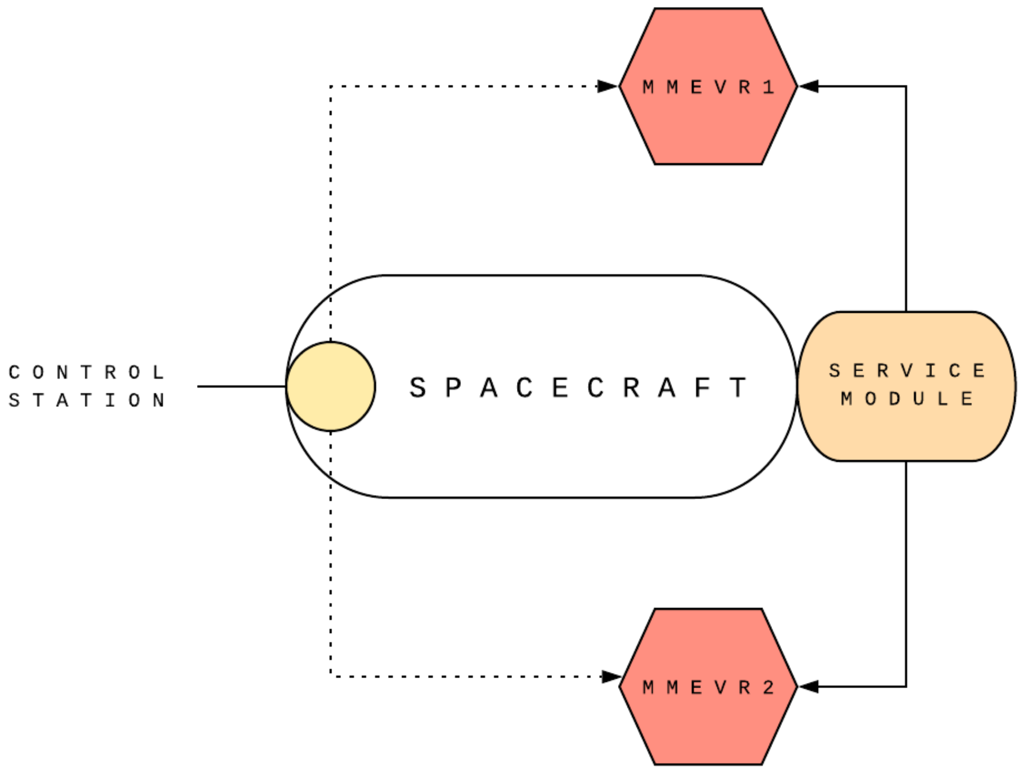

Figure 25. System architecture diagram, author

In any of these scenarios the robot is deployed independently from the service module airlock, and it will self-assemble in the desired configuration using its own limbs and the reaction wheels. If it needs to work in conjunction with a crewmember in EVA, it will dock with the astronaut harness. After the deployment, the Service module will close again, to protect the docking interfaces, but it will remain unpressurized. The robot module will be powered by the service module power source until a few moments before the module depressurization. At that point, the robot power source will be shifted to the internal batteries. The robot can use its own limbs to crawl on the external shell, or it can use the combination of RCS and CMG to fly around the spacecraft or even a combination of the two navigation methods to reach the area of operations. Once the mission ends, the robot will go back to the service module, it will wait for the airlock to open and it will dock again to the docking surfaces placed on the internal door of the airlock.

10.4.1 Con-Ops (Autonomous Mode)

MMEVR it's a highly flexible asset designed to grow its capability over time. This flexibility is achieved through the implementation of growing autonomous capabilities. As for the Canadarm3, different Machine Learning algorithms will operate the robot subsystems to conduct autonomous inspections and maintenance operations on the spacecraft. Different families of algorithms will be used to manage the different robot subsystems, such as the stereovision system or Gyroscopes optimization. The use of the different algorithms and the system infrastructure of the AI will be the subject of another related research, but the different algorithm typologies involved in the control of the MMEVR autonomous functions are here listed:

- Clustering
- Global Optimization
- Pattern Recognition
- Computer Vision
- Data-Mining
- Intelligent Agent
- Natural Language Processing
- Decision Support

The autonomous framework will be trained on a triple-layered infrastructure based on Simulations, Astronaut training, and teleoperated missions. Following this procedure, the framework will have access to a very large training database created on real operations. At the same time, different autonomous protocols relative to different subsystems can be tested on real missions independently, increasing progressively the general automation level of the robotic platform. Once the full autonomous capability is reached, MMEVR will be able to perform inspections and small repairs in total autonomy, effectively reducing the astronaut workload and eliminating the need for human EVA to the most complex operations.

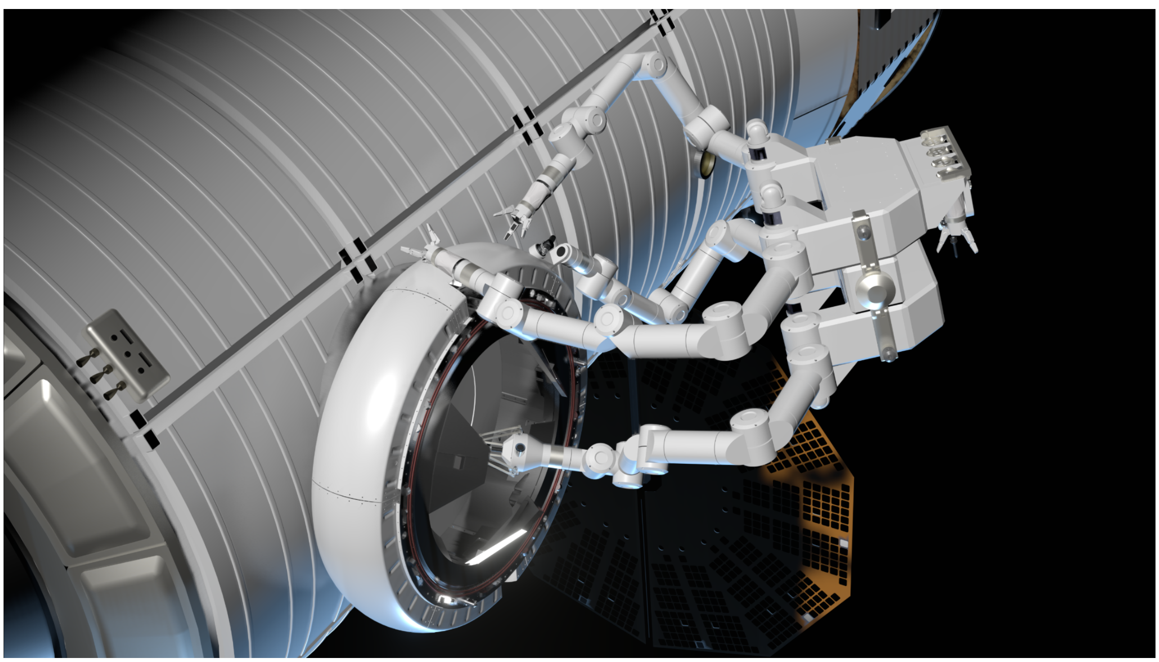

Figure 26. Simulation of Autonomous mode of operations, author

10.10.2 Con-Ops (Teleoperated Mode)

MMEVR is designed to overcome the limits posed by Spacesuit technology, providing more dexterity, range of motions, strength, and mobility for the astronauts. The system uses a harness specifically designed to be interfaced with the backpack of the xEMU suits. The harness provides, Data, power, and structural connection between the robot and the spacesuit, but also the command and control functions of the Navsys. While the harness is connected to the suit prior to the EVA, the robot will be interfaced after that both the astronaut and the robot are outside the spacecraft: normal airlock dimensions don`t allow the final assembly to happen before the EVA. During the EVA, the astronaut needs to maintain steady communication with the Robot operator inside the spacecraft and constant data feedback from the robot status. This information is displayed in the astronaut helmet through laser-based AR projections. A small interface near the navies control system on the armrest allows the astronaut to directly control emergency protocols such as the canister expulsion or the emergency undocking of the robot. The collaboration between the astronaut and the robot operator is fundamental and needs extensive training for human-robotic operations.

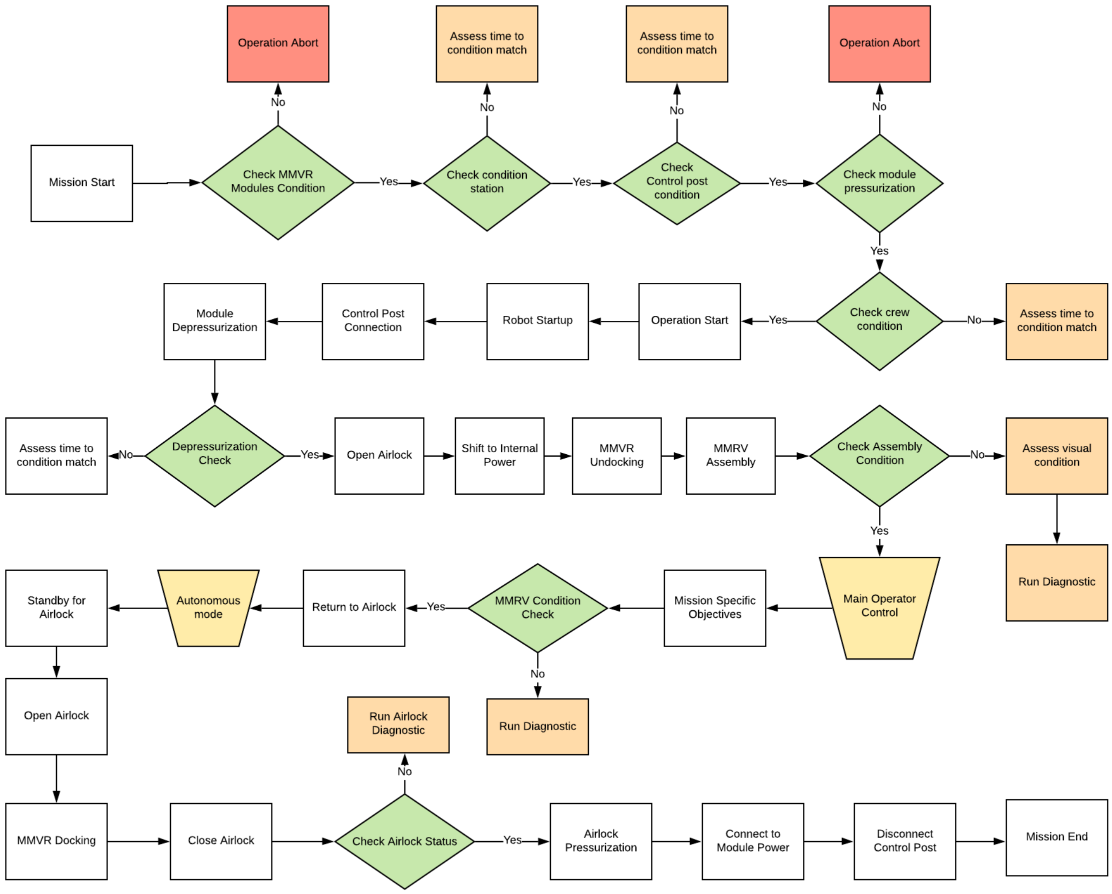

Figure 27. ConOps teleoperated mode, author

11 Platform Validation and Testing

11.1 A framework for Human-System Integration of space hardware

Human-system integration is a fundamental task of the space hardware design process for human-rated missions. The current approach makes use of high fidelity mockups as the primary evaluation method of the design iterations and their compatibility with human ergonomics. This comes at a cost of resources and implementation time, following a process that did not encounter particular innovation in the last decades. While the industry is struggling to implement new evaluation techniques that include humans-in-the-loop, commercial immersive technologies spiked their development in the last years, at the point that commercial VR headsets available to everyone, do not differ in terms of technical specifications from high-end industrial products, reserved for R&D purposes. These technologies should be harnessed to mitigate the dependency on physical prototyping of assets and help condense the design process, drastically reducing R&D time and providing a higher level of immersion if compared to traditional evaluation platforms. However, there is a gap in the general understanding of how to effectively utilize these emerging technologies and apply them to space hardware development. The aim of this paper is to propose a framework for human-system integration testing of space hardware using immersive technologies which utilizes relatively inexpensive components Off the Shelves (COTS) to build a new industry standard for human-rated hardware design.

11.2 State of art in Immersive Technology

Immersive technologies are facilitating the advancement of different fields in the industry helping their transition to the digital space. Virtual Reality is being used to increment the immersive capabilities of the entertainment industry but also architecture, industrial design and even medicine. These capabilities are already used to enhance the immersion level of simulations for training purposes by the DoD and different attempts have been made by NASA, ESA and their industry partners to implement them in the preliminary design processes. Different industries have also advanced immersive technologies for different purposes, developing researches that can easily be reintegrated in the aerospace field, such as the underwater VR headsets designed by the University of Nevada[10]. Regardless, the Entertainment industry is still the biggest stakeholder of such technologies, and their advancements are mostly driven by their use in movie production and videogame sector, which strands led to the creation of full-body tracking suits, haptic devices and innovative human-machine interfaces that have the potential to shape their use for space hardware development in the near future.

11.3 Framework Description

The implementation in space applications of immersive technologies has yet to define an industry standard for testing human-system integration. Iterative design processes can greatly benefit from a standard testing framework, to minimize the R&D needed to incorporate these technologies into the most diffused system engineering infrastructures. As the first step towards the implementation, The framework needs to address possibilities and limitations of current and near-future technologies, adapting them to a vastly accepted evaluation methodology for humans-in-the-loop testing. The objective is to integrate a new evaluation process in the testing loop without disrupting the current design validation standard, but offering a new capability that will provide more in-depth analysis to improve the design phase, interfacing with current evaluation standards. Finally the framework should be flexible enough to enable the integration of new capabilities generated by the fast development that characterize these technologies.

11.4 METHODOLOGY

The methodology behind the framework is designed to provide a guide for the future testing in immersive technologies. Different technologies have characteristics that are intrinsically different, which, depending on the experiment, will require the collection of unique data points. The modified System Usability Scale (mSUS[8]) will provide the specific data points (rating scores) of these tasks for hardware performance evaluation and along with the standardized Task-Load Index (TLX[9]) for human performance evaluation, a robust dataset can be collected. This data will be interpolated with a set of sensory data (biofeedback) from different users, allowing a quantitative evaluation method to be used as a control group of the qualitative ones provided by the users through the mSUS and TLX systems. The workflow is so iterated on different design options and, in case of hardware designed to improve current capabilities, compared with real data from past missions. An evaluation matrix is generated to confront the scores attributed to the different design options in order to find the solution that generates the best compatibility with the widest user`s sample.

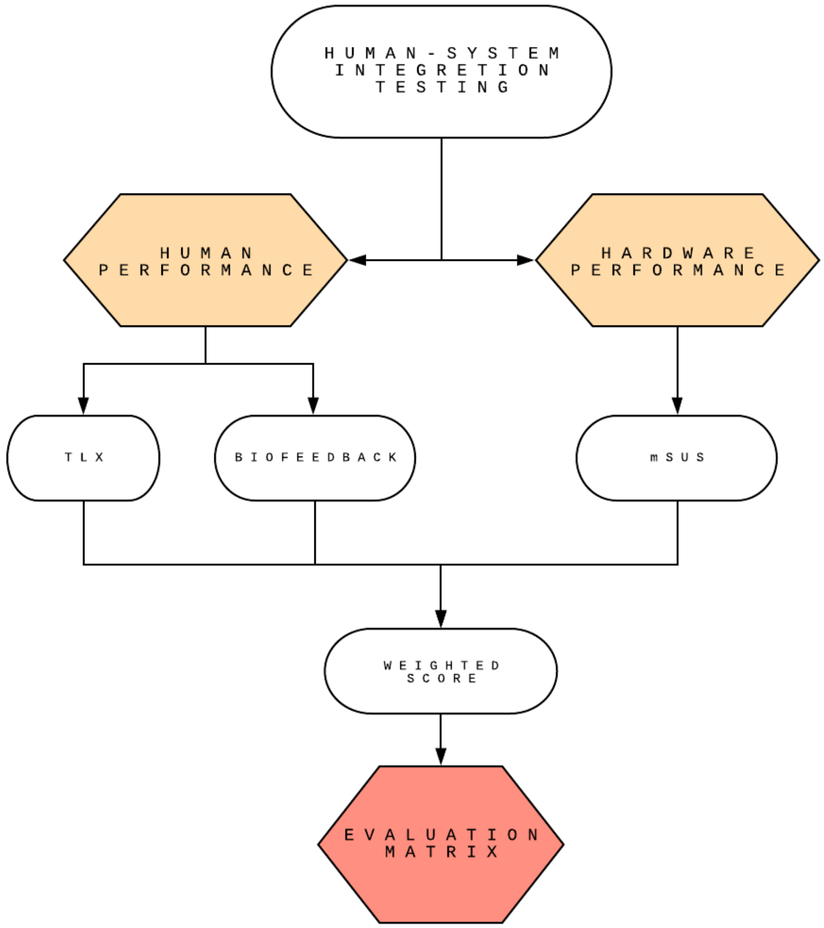

Figure 28. Framework structure diagram, author

11.5 Experiment

The methodology behind the framework is designed to provide a guide for the future testing in immersive technologies. Different technologies have characteristics that are intrinsically different, which, depending on the experiment, will require the collection of unique data points. The modified System Usability Scale (mSUS) will provide the specific data points (rating scores) of these tasks for hardware performance evaluation and along with the standardized Task-Load Index (TLX) for human performance evaluation, a robust dataset can be collected. This data will be interpolated with a set of sensory data (biofeedback) from different users, allowing a quantitative evaluation method to be used as a control group of the qualitative ones provided by the users through the mSUS and TLX systems. The workflow is so iterated on different design options and, in case of hardware designed to improve current capabilities, compared with real data from past missions. An evaluation matrix is generated to confront the scores attributed to the different design options in order to find the solution that generates the best compatibility with the widest user`s sample.

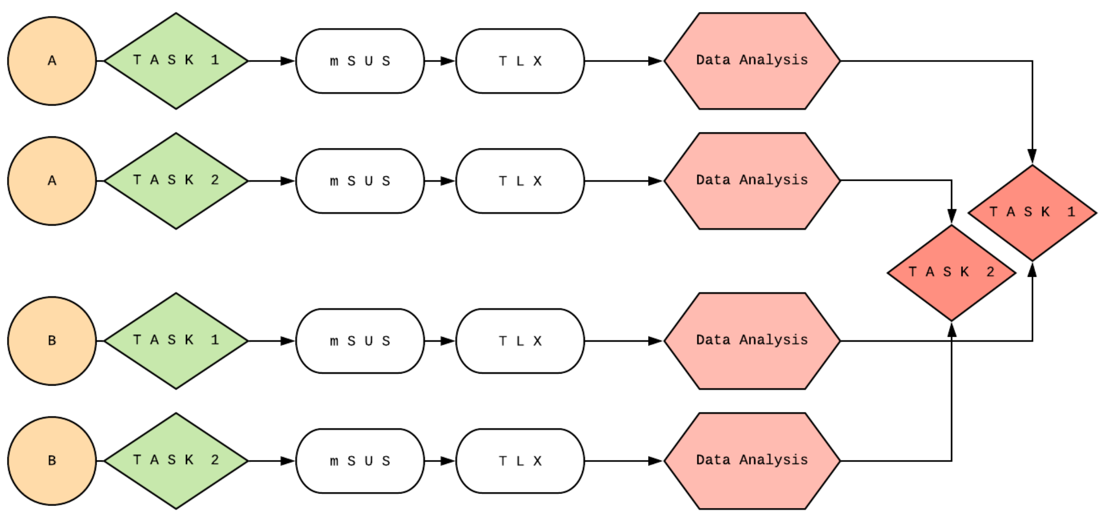

Figure 29. Experiment Structure diagram, author

11.5.1 Define the number and nature of tasks and users

The number and nature of tasks depend on the testing objectives of the hardware. For this specific research, we tested 6 users each with 2 experiment runs, one for each task. The results of weighting mSUS, TLX and biofeedback data are recorded into a common evaluation matrix. Since the objective of the test is to validate the immersive framework, compared to contemporary testing standards, the two tasks will be repeated two times: one with use of VR and one without. The time needed to build a high fidelity, functional mockup will be accounted when comparing the two methodologies.

11.5.2 DEFINE DATA COLLECTION METHOD

The data collected consist of both Qualitative and quantitative data. Quantitative data are obtained through techniques like biofeedback monitoring, timed images and video recordings. The qualitative portion makes use of surveys-based methods such as mSUS and TLX.

The modified System Usability Survey (mSUS) is an adaptation of SUS, that can be used for global assessments of systems usability. The mSUS is designed to evaluate the usability of the hardware from an human perspective. This survey looks to provide data regarding the effectiveness of the users in completing the proposed tasks, the quality in their output, efficiency in performing tasks, and users' subjective reactions to using the system.

The NASA Task Load Index (TLX) is a task workload assessment evaluation tool. Its main rating scales are mental demand, physical demand, temporal demand, performance, effort, and frustration. The TLX is used to study the user performance while interacting with the hardware.

11.5.3 DATA ANALYSIS

In order to process experiment results into design criteria, the output of the framework is expected to be a quantitative ranking of the proposed design solutions but also preserve the depth of the data collected. For this purpose, the biofeedback data from the users are used to evaluate the stress and effort levels developed during the experiment. The final score is obtained using the human performance evaluation to adjust the hardware performance evaluation[11].

11.5.4 Experiment Objectives

The main objective of the MMEVR human-system integration experiment is to explore the robot collaboration capabilities in regular spacecraft maintenance scenarios and to understand how the hardware performance is affected by the human component and conversely, how the human capabilities in space are affected by the hardware component.

11.5.5 Experiment Structure

To validate the design of MMEVR, it has organized a test campaign that relies on the Immersive Framework for task design and evaluation. As already stated, MMEVR can be used in two modes: teleoperated (collaborative) or Autonomous (Stand Alone) this bring to the definition of two different testing scenarios, one in which the user is impersonating the astronaut in EVA with the task to collaborate with the robot (controlled by an human operator) and one in which the user is directly controlling the arms to accomplish the tasks. Two different tasks have been designed using routine EVA maintenance missions protocols performed on the ISS as a model. The Lunar Gateway has been used as future-proof simulation environment for both the tasks:

- TASK 1: perform a battery swap on the exterior of the ESPRIT module.

- TASK 2: investigate malfunctioning on the main axis of the Canadarm 3 robotic arm and exchange the electric motor.

To make use of immersive technologies, a VR simulation of the microgravity lunar environment has been developed including a highly detailed model of the Lunar Gateway and MMEVR. At the same time a full-scale, medium fidelity mockup of MMEVR has been built in the SICSA workshop. The mockup is provided with a fixture that allows the user to position the mockup in the correct position relative to the user.

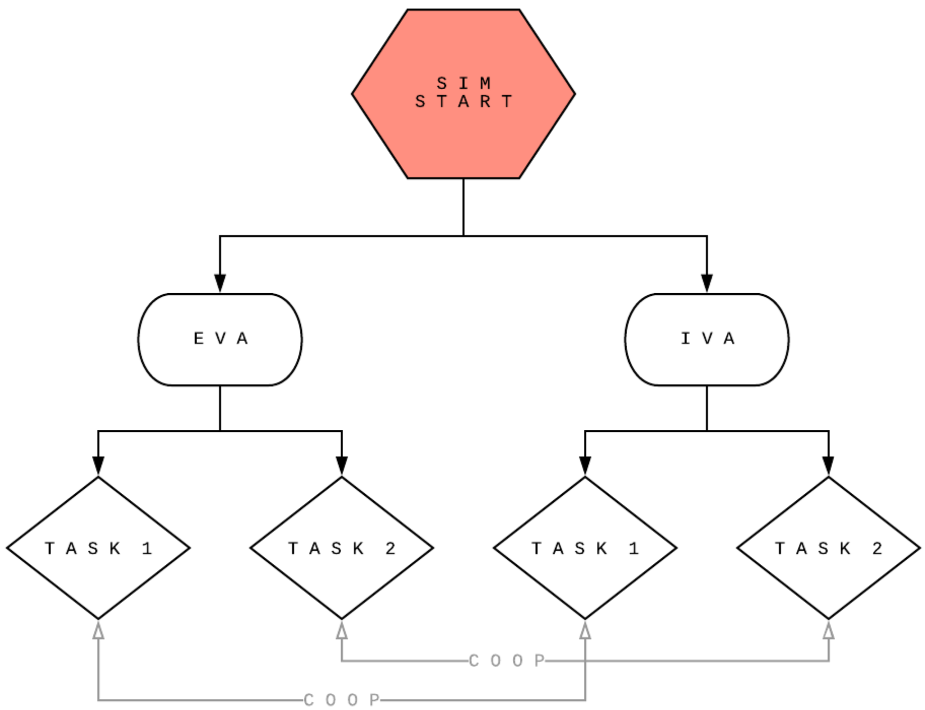

Figure 30. Simulation Structure Diagram, author

With all the assets ready, the next step has been to use a mix of VR trackers, VR controllers and a VR headset to bind the position of the mockup to the position of the virtual model in the simulation: thanks to this feature, we have been able to track the exact position of the mockup, allowing the user to interact physically with it in the simulation.

This setup, built around commercial VR hardware will be used to perform the tasks in the simulation, keeping the advantages of both the immersive environment regulated by real physics and the physical interaction, typical characteristic of mockups.

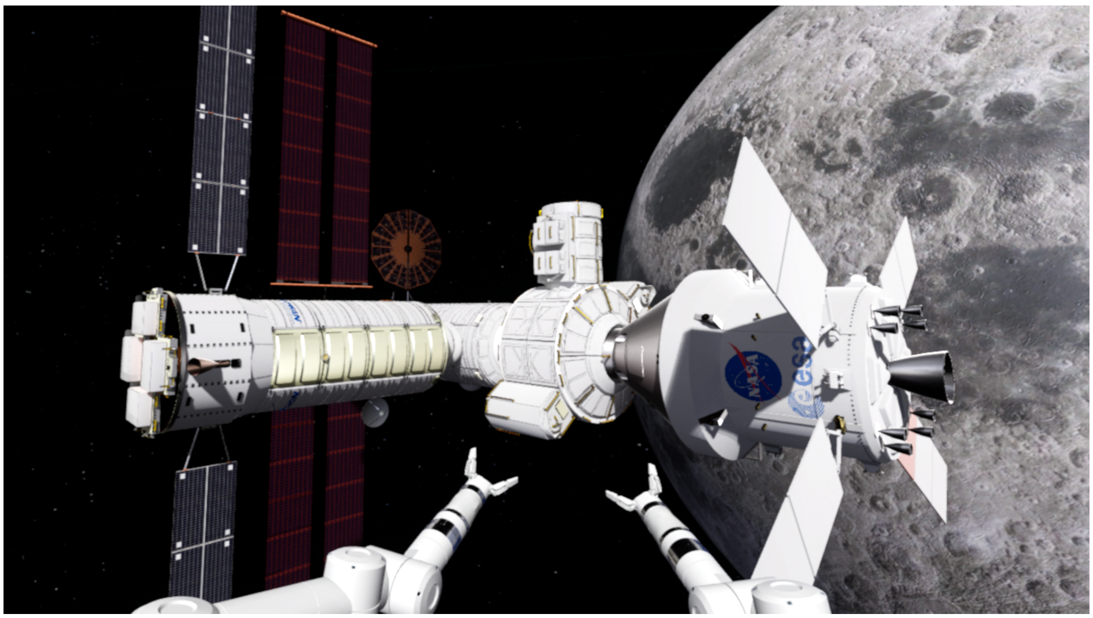

Figure 31. VR Simulation environment, author

11.5.6 Order of operations

Following the framework description through experimental objectives and structure, has been defined a basic experiment Concept of Operations defined by the sequence of tasks performed by the different users:

- User A: Task 1 > mSUS 1 > TLX 1 > Data analysis
- User A: Task 2 > mSUS 2 > TLX 2 > Data analysis
- User B: Task 1 > mSUS 1 > TLX 1 > Data analysis

- User B: Task 2 > mSUS 1 > TLX 2 > Data analysis
- User C: Task 1 > mSUS 1 > TLX 1 > Data analysis
- User C: Task 2 > mSUS 2 > TLX 2 > Data analysis
- User D: Task 1 > mSUS 1 > TLX 1 > Data analysis
- User D: Task 2 > mSUS 1 > TLX 2 > Data analysis
- User E: Task 1 > mSUS 2 > TLX 1 > Data analysis
- User E: Task 2 > mSUS 1 > TLX 2 > Data analysis
- User F: Task 1 > mSUS 1 > TLX 1 > Data analysis
- User F: Task 2 > mSUS 1 > TLX 2 > Data analysis

The same users will also perform the same tasks without the use of the VR simulation after 60 days, in order to compare the data obtained from conventional and immersive testing, for a total of 24 experiment runs over 3 months of testing.

Figure 32. Mixed Reality Testing session, author

11.5.7 Scalability

At the beginning of this paper it has been stated that the objective of the Immersive framework is to attempt the definition of a standard for VR testing of human-rated Space hardware. To accomplish this objective we used proven evaluation tools in the aerospace Industry, such as the mSUS and TLX with commercially available assets of immersive technologies. The main difference between the current testing standard and the one proposed in this paper is to enable higher levels of fidelity while reducing the efforts to produce functional physical mockups. This capability also allows to position the human-integration testing phase in the preliminary design, thanks to the faster integration workflow. This enables unprecedented iteration levels for this purpose.

12 Risks And Mitigations

The MMEVR typical mission profile poses different risks in terms of physical interaction with Space hardware. In-space navigation, docking and manipulation will require a high level of precision and reliability of both hardware and software. The risk of in-space collisions, failure of the locomotion and orientation systems (RCS reaction wheels) or in the detection systems (cameras, lidars) can lead to potentially catastrophic failures for the whole spacecraft. Teleoperations instead expose the platform to the risk of human error and not nominal Human-robotics collaboration protocols.

In order to Mitigate the Risks caused by those factors, we concentrate on mitigation strategies and active countermeasures.

Mitigation Strategies:

- Mechanical and electrical redundancies (differentiated subsystems)
- Multilayered safety protocols
- Evolutive controls roadmap

Countermeasures:

- Pyrotechnical charges to separate docked components and the arms of the robot
- Emergency control overrides for autonomous systems
- “Brainless” control mode (spacecraft or ground computer)
- Omnidirectional situational awareness

13 Path Forward

Some aspects of this project are still in development, and some minor aspects of the design can change accordingly. These are six key points on which the MMEVR research will focus in the next six months

- Control station design.
- Human Machine Interaction
- Power requirements
- Cost evaluation
- Explorative prototype design and assembly
- Communication infrastructure

14 Conclusion

MMEVR is a potential revolutionary asset that can step up the EVA operations in a multiplicity of In-space environments and enables unprecedented capabilities for servicing, inspections, and maintenance. It allows a totally new level of safety for astronauts and shortens the time response to potentially catastrophic emergencies. It synthesizes the recent advancements in the research on in-space robotics, AI, and HRI to achieve multi-mission flexibility and multi-vehicle compatibility. MMEVR aspires to be the first of a new generation of space assets needed to reach long-range mission capabilities in terms of reliability and resiliency.

References

[1]Sachdev, S. S., *Canadarm—a review of its flights*, Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, Vol. 4, No. 3, 1986, pp. 268–272. https://doi.org/10.1116/1.573952, URL http://avs.scitation.org/doi/10.1116/1.573952

[2]Garcia, M., *Space Station Spacewalks*, 2015.

[3] National Aeronautics and Space Administration, *NASA Human System Integration Handbook REV1*, Tech. rep., National Aeronautics and Space Administration, 2014.

[4] Flores-Abad, A., Ma, O., Pham, K., and Ulrich, S., *A review of space robotics technologies for on-orbit servicing*, , 7 2014.

[5]Vittorio Netti. 2020. *Design of an autonomous and teleoperated modular robotic free-flyer for eva operations*. Accelerating Space Commerce, Exploration, AIAA

[6]Robert O. Ambrose, Hal Aldridge, R. Scott Askew, Robert R. Burridge, William Bluethmann, Myron Diftler, Chris Lovchik, Darby Magruder,and Fredrik Rehnmark. 2000. *Robonaut: NASA's space humanoid*. IEEE Intelligent Systems and Their Applications 15, 4 (7 2000), 57–62. https://doi.org/10.1109/5254.867913

[7]Boesso, A., and Francesconi, A., *ARCADE small-scale docking mechanism for micro-satellites*, Acta Astronautica, Vol. 86

[8]John Brooke. 1995. *SUS - A quick and dirty usability scale*. Research(11 1995).

[9]Sandra G. Hart and Lowell E. Staveland. 1988. *Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research*. ElsevierScience Publishers B.V. (North-Holland)Human Mental Workload (1988), 139–183.

[10]Christian B. Sinnott, James Liu, Courtney Matera, Savannah Halow, Ann E. Jones, Matthew Moroz, Jeffrey Mulligan, Michael A. Crognale, EelkeFolmer, and Paul R. MacNeilage. 2019. *Underwater virtual reality system for neutral buoyancy training: Development and evaluation.* Proceedings of the ACM Symposium on Virtual Reality Software and Technology, VRST. Association for Computing Machinery, New York, NY, USA, 1–9. https://doi.org/10.1145/3359996.3364272

[11]Robert J. Stone, Peter B. Panfilov, and Valentin E. Shukshunov. 2011. *Evolution of aerospace simulation: From immersive Virtual Reality to serious games*. RAST 2011 - Proceedings of 5th International Conference on Recent Advances in Space Technologies. 655–662. https://doi.org/10.1109/RAST.2011.59669218