Title	**:**	XARM-SA-ESR
Abstract	**:**	Executive Summary Report
Contract N°	**:**	4000138082/22/NL/GLC/ov
Technical Officer	**:**	Cristian Englert

DOCUMENT APPROVAL SHEET			
Responsibility	**Name and Position**	**Company**	**Signature and Date**
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1. Introduction

Figure 1. Poster of X-aRm

The outer space is commonly perceived as one of the most hazardous environments for human beings. Nowadays, the training of astronauts relies on a wide range of courses and facilities to prepare them for any situation they may encounter in space. The combination of these training technologies has successfully prepared multiple generations of astronauts. However, these assets lack flexibility to customise the training process, and are limited in scalability to accommodate an increasing number of trainees.

Interestingly, many of the technologies used to train astronauts involve manipulation and navigation tasks that require force feedback, which is crucial for the learning process. Previous studies have emphasised the importance of force feedback for multiple critical training tasks in space. Astronauts heavily rely on the sense of force for numerous activities in the space environment. For instance, astronauts aboard the International Space Station (ISS) use a spacesuit called the Extravehicular Mobility Unit (EMU) to perform installation or maintenance tasks known as Extravehicular Activities (EVA). During these missions, astronauts navigate in the space environment by pushing and pulling from handrails, experiencing inertial forces derived from their mass, or performing mechanical tasks using Pistol Grip Tools (PGT).

The hypothesis of this work states that the use of multimodal stimuli from Virtual Reality with exoskeleton devices to train future astronauts provide a higher flexibility, scalability, customisation, safety, and immersion compared to traditional training methods.

2. Implementation

The objective of this European Space Agency (ESA) funded initiative is to develop a flexible, scalable and immersive technology demonstrator to train the upcoming generations of astronauts. A novel exoskeleton design is proposed based on custom, brushless direct current (BLDC) motors to provide high reliability, robustness and force-feedback transparency. This exoskeleton, combined with a VR headset, ambitions to create a multimodal setup that will blend multiple stimuli to increase the perception of users and reduce the training reality gap. Two use cases are foreseen for this activity:

- The primary consists on performing an Extravehicular Activity in the International Space Station.
- The secondary one consists on navigating in a lunar landscape and interact with milli-gravity conditions.

2.1 Architecture

X-aRm follows a teleoperation architecture that handles how to control the exoskeleton remotely. The objective is to provide the user an interface that represents the information in an intuitive way. The proposed teleoperation system relies on a bilateral communication. In other words, a *VR Simulation* represents the virtual movements, which are determined by the exoskeleton pose and interface buttons, managed by the *Control* module. At the same time, the *VR Simulation* and the *Haptics Engine* generate soft and stiff forces that are applied to the exoskeleton. The *VR Simulation* has been developed using Unreal Engine 5 and is able to generate forces with slow response times like inertial ones when pushing or pulling from a handrail in microgravity. However, this software cannot compute collisions at high frequencies, necessary to emulate fast-response forces like contacts with the environment. Thus, the Chai3D *Haptics Engine* is synchronized with a replica of the VR Simulation to compute such forces. All these commands are sent to the *Control* module while a *User Interface* has also been developed to configure, command and monitor the performance using a web-based application.

All the communications are handled by a custom Server that centralizes the data in an efficient manner using TCP-IP. The fast-response, stiff forces must handle high frequencies of 1000Hz to be considered as real-time. Slower-response forces can be handled with frequencies of 60-100Hz like the inertial ones when making displacements in microgravity. Other type of slow-response force is the spring-effect in the elbows due to the inflation of the spacesuit or EMU. In other words, the nature of the forces draw the real-time requirements.

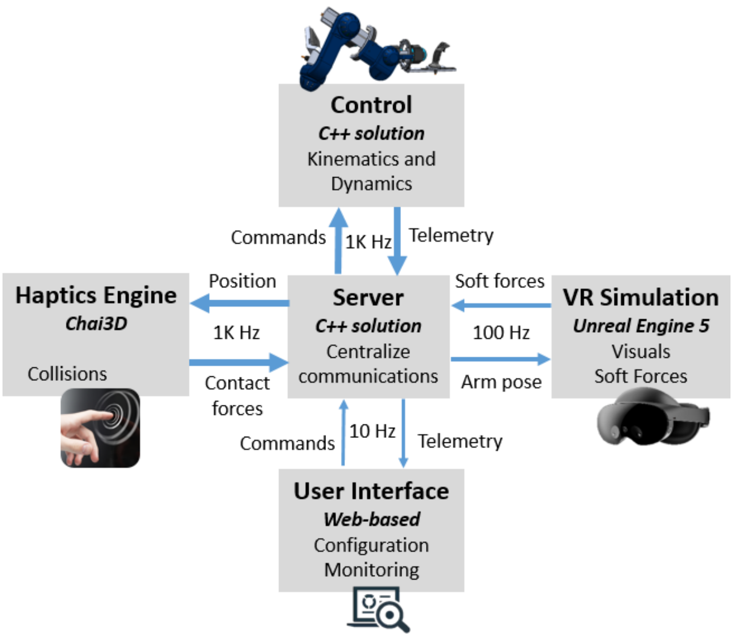
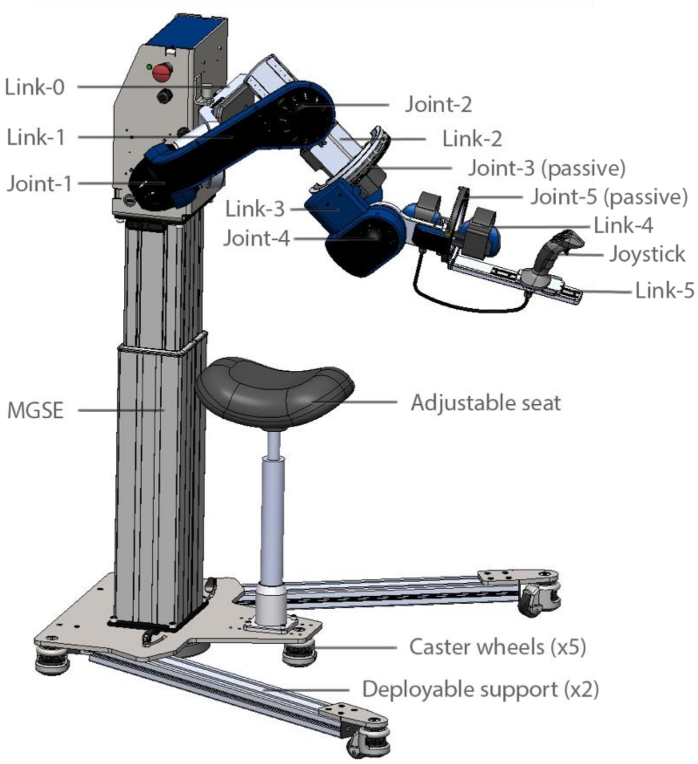


Figure 2. X-aRm software architecture diagram

2.2 Exoskeleton Design and Control



The X-ARM project developed an anthropometric exoskeleton as a robust technology demonstrator with core design focus on transparency and comfort.

The exoskeleton is set in a *Mechanical Ground Support Equipment* (MGSE) and covering 5 degrees of freedom (3 active + 2 passive with sensors) including shoulder, upper and lower arm motions. It is designed with five revolute joints. Each of the articulated links are assembled around a rigid aluminium frame for robustness and surrounded by a protective 3D printed casing. The structural parts of the exoskeleton are made of aluminium 7075-T6.

Two active joint sizes have been custom-designed and implemented in the exoskeleton. A heavy-duty one (87Nm) for joint 1 and joint 2 (shoulder active joints) and a small duty one (28Nm) for joint 4 (elbow active joint). Active joints are composed of a BLDC frameless motor coupled with a Harmonic Drive transmission. The joint includes mechanical, structural and guiding parts that ensure the correct functioning of each element independently and as part of an assembly. Integrated *Hall*, incremental, absolute and torque sensors features the joints for control purposes. The joint has a hollow shaft for hosting cables inside the exoskeleton structure.

Following the compact and integrated design, all the controllers of the motors have been disposed locally near each joint. Each active joint is fitted with a set of identical electronics parts: *Capitan XCR-E* motor controller with imbedded EtherCAT module; a RGB LEDs module to display status; and custom-made interface board modules for the BLDC sensors.

Regarding the ergonomic aspects, three segments of the exoskeleton frame can be adjusted to the user's body arm and wrist size variance. The system is designed to host a wide percentile range P10-P95 of adult European Male/Female body size. Spring loaded and self-locking buttons must be pressed together to release the adjustment. If only one button is pressed, the adjustment link remains locked. This is a safety feature to prevent uncontrolled unlocking and change of link's length during operations. The pins will self-lock after release.

The interface with the arm is attached to the structure by two comfortable paddings and two Velcro straps: one for the forearm and the other for the upper arm. The paddings are wrapped around the user's arm and are secured by two soft Velcro. The user are able to strap themselves to the exoskeleton without need of external support. The Velcro should be tightened until a firm (but not strong) grip is obtained. The main padding and the straps can be directly removed and washed for hygiene.

Users can also decide whether they prefer to use the system while seated or in a semi-standing saddle seat with the back spine straight. The second option is recommended for a higher immersion in microgravity and for longer and more comfortable trainings. Two support frame elements can be deployed on the side of the MGSE to increase the stability of the system. These elements can then be folded to reduce the footprint of the setup for an easier relocation using integrated caster wheels.

The low-level control strategy for the exoskeleton arm encompasses *Proportional-Integral-Derivative* (PID) control, directly delegated to the *Ingenia* servo drives, with each control loop (current, torque, velocity, and position) meticulously fine-tuned for optimal performance. Executing these control laws directly on the servo drives offers distinct advantages, eliminating constraints imposed by communication protocols and mathematical computations, enabling operation at significantly higher rates. This enhances user comfort and system efficiency.

At the high-level control, the serial chain of the exoskeleton is managed from custom kinematics and dynamics algorithms, offering features like active gravity compensation. These algorithms continuously adjust torque outputs based on sensed gravitational forces, offloading the user's arm weight to ensure representativeness of the environment. Consequently, the gravity compensation also reduces fatigue, optimizing user mobility and comfort during prolonged use.

2.3 Virtual Reality Simulation

The X-ARM exoskeleton, previously introduced, will be interconnected with a Virtual Reality simulation to create a feeling of immersion though perception deception. The exoskeleton will provide force-feedback based on the interaction of the user with this virtual environment. At the same time, the simulation will provide visual, aural and vestibular feedback to users.

This simulation environment has been created using *Unreal Engine 5.1*, allowing the representation of multiple complex geometries powered by the *Nanite* technology. The VR headset selected for this activity in 2023 is the *Meta Quest Pro* for its screen resolution and *inside-out tracking*, allowing an easy and standalone usage. It connects to the Unreal Engine simulation wirelessly through the *OpenXR* framework and using the *AirLink* technology.

Realistic and updated engineering models of the ISS, a rigged-exoskeleton of the EMU with constraints, or tools like the PGT have been imported and adapted to the needs of the EVA use case for VR. An interactive tutorial has been created within the VR simulation in which users should follow a step-by-step procedure to make sure that they understand the basics of moving the right arm with the exoskeleton and the left one with a VR controller using *Inverse Kinematics*. In addition, it trains the importance of always being docked with a safety tether to the station handrails, how to move around pushing and pulling from structural elements in microgravity, perform maintenance tasks with the PGT or manually launch a small *CubeSat* to orbit.

In addition, a preliminary demo has also been developed to show the difference of forces and gravity on the Moon surface. For this use case, a realistic landscape has been reconstructed from height-map images from the *Lunar Orbiter Laser Altimeter* (LOLA) satellite and processed for their use in VR.

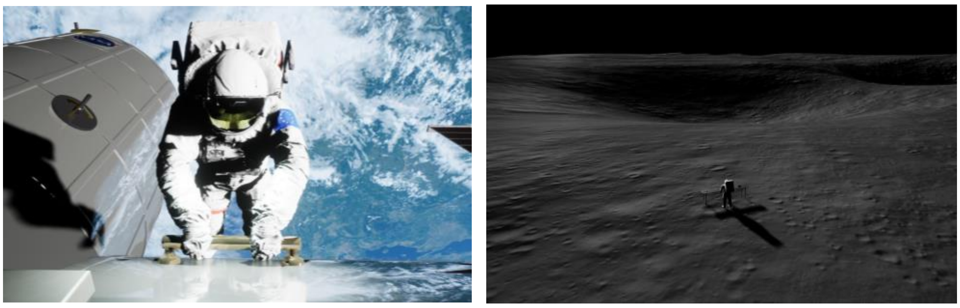


Figure 3. X-ARM Simulation of the EVA use case, showing how the astronaut grabs from a handrail in the Columbus module of the ISS (left) and X-ARM Simulation in a secondary use case in a Moon terrain (right)

The forces generated by the simulation are: *Inertial forces*, understood as those needed to counter the own mass of the trainee after performing displacements with the arms; and the *Spring Effec*t, torque applied to the elbow involved as result of the inflation of the EMU. However, the simulation does not generate *Contact forces*, result of touching the surface of structural elements due to the high frequency requirements. Thus, a Haptics Engine has been used as explained in the following section.

2.4 Haptics Engine

In our research, we employed a haptics engine to generate contact forces for the exoskeleton arm, a critical aspect of enhancing the tactile perception of users and overall experience. In choosing the appropriate haptics engine, we opted for *CHAI3d* over alternatives such as *H3D* due to several compelling reasons. CHAI3d's suitability stemmed from its robustness and ease of integration with our exoskeleton arm system. Its versatile open-source framework allowed for seamless customization and adaptation to our specific requirements. Moreover, CHAI3d's active user community provided invaluable support and a wealth of resources, simplifying the development process.

The VR Simulation environment and the Haptics Engine environment have been carefully synchronized and aligned for a smooth integration. Additionally, it is worth highlighting the significance of frequency requirements to generate Contact forces. Thus, our choice of a haptics engine capable of generating forces at a minimum rate of 1000Hz was instrumental. These high-frequency forces are crucial for providing real-time feedback to the user's sense of force, enabling them to perceive object shapes and dynamic interactions accurately. This fidelity in force rendering is paramount in ensuring the effectiveness, stability and safety of the exoskeleton arm, particularly in tasks that demand highly dynamic control such as the EVA use case with astronauts in microgravity.

2.5 User Interface

The objective of this *User Interface* (UI) is to provide an intuitive and flexible interface to interact with the exoskeleton. It allows users to configure the hardware, monitor all the sensor data and command different testing functionalities.

Figure 4. User Interface. Testing screenshot of the monitoring menu.

3. Results

Robustness tests showed that the system is sturdier than predicted since Finite Element Analysis concluded that 35mm of deflection would happen in the end effector under a force of 3Kg, and the real system only displaced 22mm with 3.75Kg instead. When the system was induced to vibrations for 10 seconds, no electronic, hardware or control issue was identified. In addition, the BLDC motors are also accessible for developers for an easy **maintenance** in comparison to previous iterations based on capstan based transmission while retaining reliability, compactness, transparency and robustness.

The materials and detailed design of the exoskeleton need to be carefully selected and planned to find a good compromise between mass and robustness. Otherwise, as in every serial robot, higher masses require more powerful actuators that are also heavier, ultimately leading to a positive feedback loop. In addition, the use of spring loaded and self-locking buttons has demonstrated to be very useful, user-friendly and robust to easily adjust the exoskeleton to the arm of each user.

In addition, the multi-point contact Velcro straps and fabric padding have proven to be comfortable enough to increase the use of the system for longer periods compared to previous setups. Participants trying the exoskeleton reported high **comfort** thanks to the orthopaedic interface selected for X-ARM. Contact points very only slightly perceived by one participant. All users seem to be eager to use the system for multiple hours comfortably.

All the sensors and actuators were also tested displaying good performance including the motors, absolute sensors, encoders, temperature sensors or torque sensors, and ensure a good system **transparency** with low latency. Motor response for position control displayed delays in the order of 10ms. This allowed creating an accurate active gravity compensation, to allow users feel weightlessness during EVA in microgravity, or different types of gravity for planetary training. In addition, forces generated by the Haptics Engine resulted as very realistic, stable and stiff. One user could easily perceive the shape of objects without any visual feedback by just moving the arm around.

Software applications capable to generate high-frequency forces to simulate contacts with surfaces do not usually provide the same level of visual realism, tools or VR compatibility as game engines like Unreal Engine. Thus, the use of *Chai3d* as haptics engine was decided. The use of Unreal Engine version 5.1 and its VR-compatible components *Nanite* or *Lumen* considerably leveraged the performance while keeping a high visual realism. The use of the Meta Quest Pro as VR headset with inside-out tracking has proven to be more convenient than lighthouse-tracking solutions.

The main limitation of the presented work is that the exoskeleton was designed to be a Technology Demonstrator, purposely featuring 3 DoF instead of 7 DoF as desirable to provide force-feedback in the full arm kinematic chain. However, it shall help us validating that the selected technology is well suited to the next generation of training oriented force feedback exoskeletons. For the EVA use case, the next generation of exoskeleton would ideally have two fully actuated arms, extending the setup proposed in this work, and two additional hand interfaces with force feedback. With the upcoming interest in planetary exploration, legs exoskeletons and a vestibular platform, combined with the arms, hands and VR headset, would be ideal to train astronauts performing complex, combined manipulation and locomotion tasks under different gravity conditions.

4. Conclusion

In summary, X-ARM is a technology demonstrator that shows how state-of-the-art actuation based on custom BLDC motors, an improved structural design, a new arm interface and multiple software improvements made a force-feedback training exoskeleton more robust, transparent and comfortable compared to previous iterations. The hardware and software design has been customized to the needs of astronaut training including the desired session duration, the EMU constraints, the magnitude of the forces generated, the gravity compensation control, the seated configuration or the immersive VR use cases developed.

The hypothesis of this work is that the use of multimodal stimuli from Virtual Reality with exoskeleton devices to train future astronauts provide a higher flexibility, scalability, customization, safety, and immersion compared to traditional training methods. Some of these insights need to be validated with relevant individuals like ESA astronauts and instructors. However, preliminary results show that the hypothesis is correct.

Simulation and Haptic engines have been developed flexible software strategies to allow a fast creation and edition of virtual environments easily. Therefore, unprecedented levels of flexibility and customization are granted. In addition, compared to more conventional training techniques like real-size mock-ups, parabolic flights, air bearing floors, or neutral buoyancy facilities, the X-aRm system stands out to have a smaller footprint and lower associated cost, making it an interesting solution with a larger number of trainees. In addition, X-aRm has been designed with safety as paramount criterion, holding different hardware and software layers of protection against undesired outcomes. Finally, the combination of all the visual, aural, vestibular and force-feedback stimuli lead to a perception deception effect in users and increasing user experience quality. Consequently, the X-aRm concept emerges as a promising tool to effectively train the next generation of astronauts.