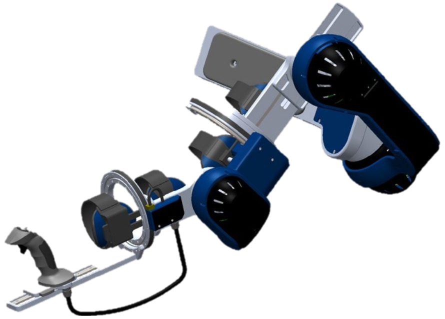


# X-ARM:

## A NOVEL ARM EXOSKELETON COMBINED WITH VIRTUAL REALITY TO TRAIN FUTURE ASTRONAUTS

AR/VR for Space Programmes – Dec 11-12, 2023 – ESA ESTEC

spaceapplications SERVICES

SINCE 1987

# CONTENT

# SHORT COMPANY PRESENTATION

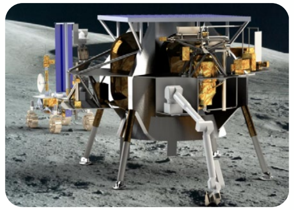
- Founded in 1987
- Aerospace engineering and service
- SME: ~100 employees
- ISO 9100 certified (flight activities)
- **Markets**: Space, Health, Environment, Security

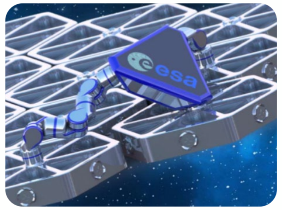

**Commercial Service in ISS:** Ice Cubes

Human **spaceflight training**

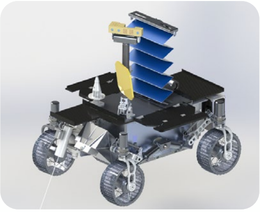
**Operation**

**ESA projects:**
- Space robotics,
- Countermeasure devices,
- VR/AR,
- On-Orbit Servicing, In Situ Resources Utilization, Ground control centers…


ESA ALCHEMIST (ISRU)


ESA MIRROR multi-arm robot


Ice Cubes Service


LUVMI-X lunar rover

**EC / H2020:** Space Robotics Technologies Cluster, terrestrial applications…

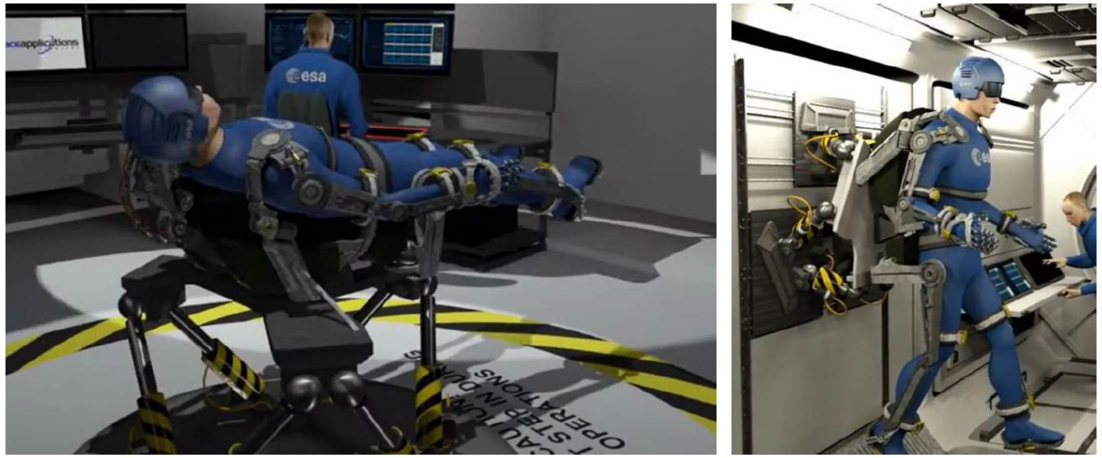
## Context

- The outer space is one of the most hazardous environments for human beings
- Conventional tools to train astronauts combine
  - real-size mock-ups,
  - parabolic flights,
  - air bearing floors,
  - gravity compensation devices,
  - neutral buoyancy facilities,
  - many others.
- These tools are not well adapted to host a large number of individuals
- A growing number of space travellers is anticipated in the next decades

# INTRODUCTION

## Objective

- The ultimate objective is to create a training setup that, compared to conventional tools, offers:
    - higher immersion and safety
    - higher flexibility and customization
    - higher scalability and smaller footprint
    - less supervision and maintenance
- Our vision is to achieve this through perception deception:
    - Force feedback (Exoskeleton)
    - Visual and aural (Virtual Reality Headset)
    - Vestibular platform
    - Others

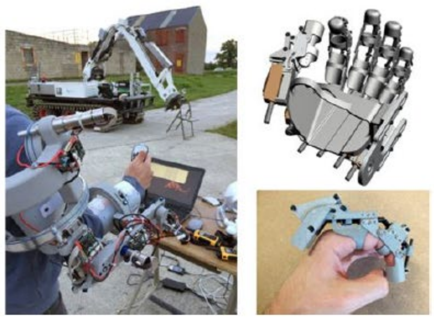


ESA FITS concept

# INTRODUCTION

Space Applications has +13 years of experience designing exoskeletons and countermeasure devices

EXOSTATION



ICARUS

DEXO

SPOC


SOLEUS

ATHLETIC

EXOSUIT

# INTRODUCTION

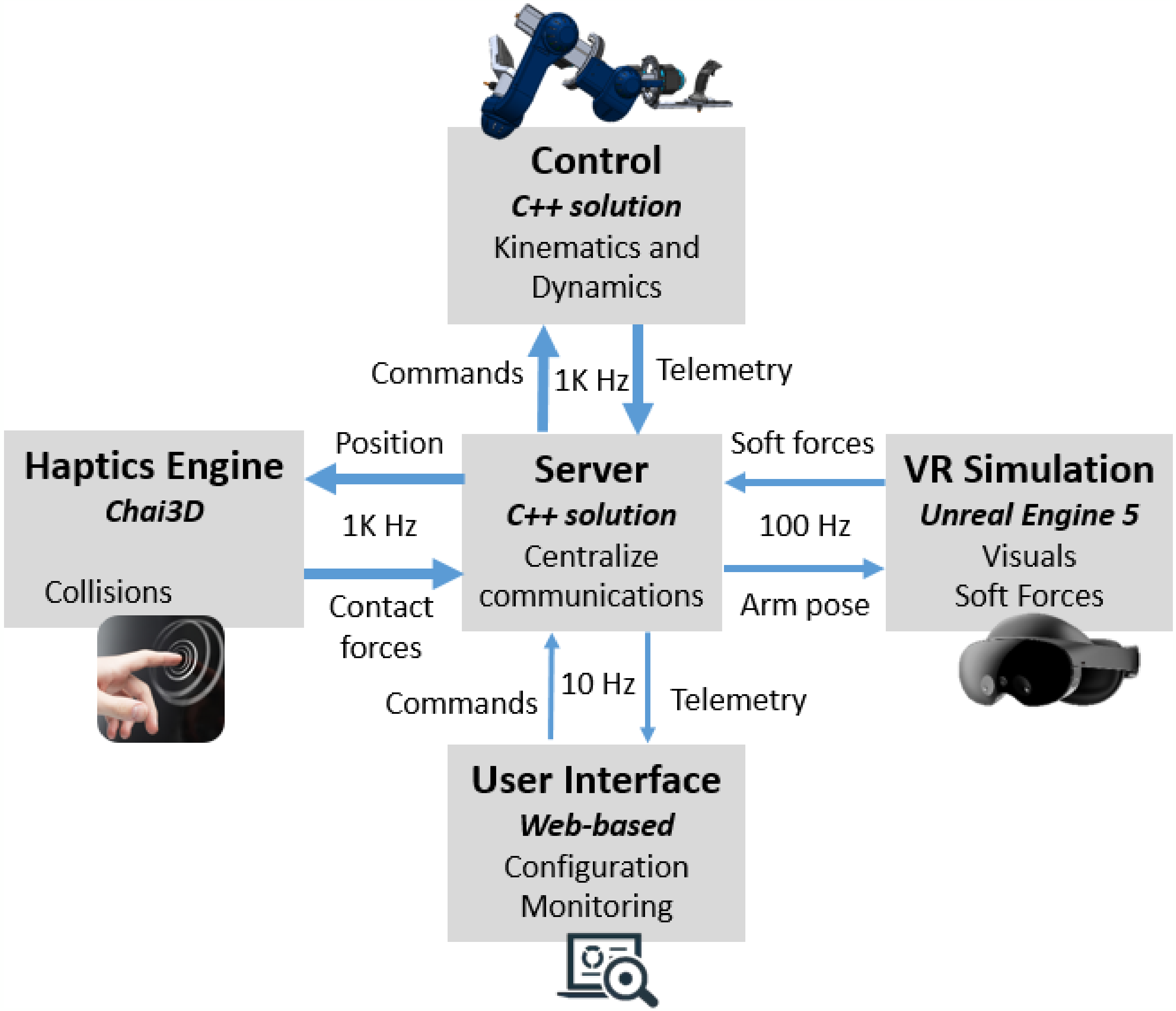
## Objective

X-ARM is a technology demonstrator that shows how custom BLDC motors, an improved structural design, a new ergonomic interface and multiple software improvements can make a force-feedback training exoskeleton more robust, transparent and comfortable compared to previous iterations

## Use Cases

- Extra Vehicular Activities (EVA)
  - Motivated by ISS and Lunar Gateway missions
- Planet exploration
  - Motivated by ARTEMIS mission

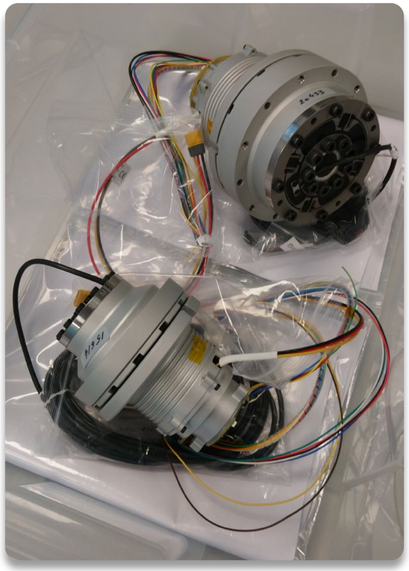
## Architecture



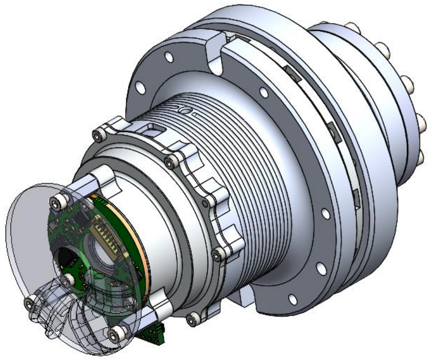
# EXOSKELETON DESIGN

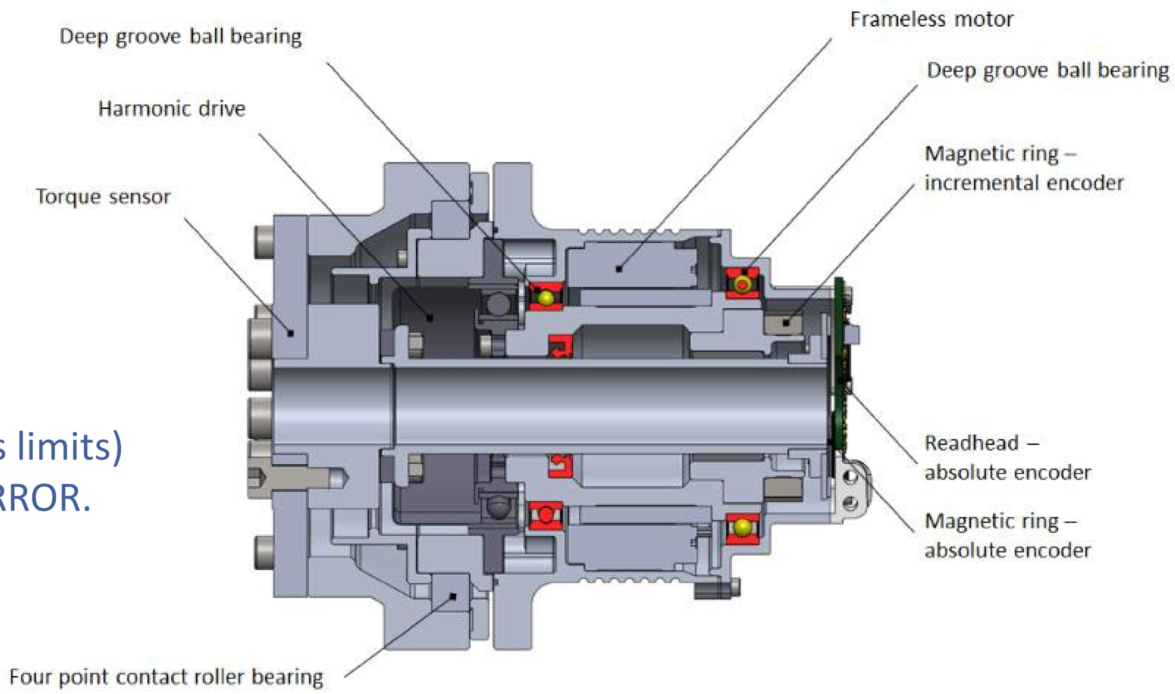
Previous iterations of exoskeletons at SpaceApps used capstan-based transmission, which increased the pulling capacity but were not robust or easy to maintain

## Custom BLDC motors



- Active joint sizes designed for 3 degrees of freedom
  - Heavy duty motor (87Nm): x2 units for shoulder
    Small duty motor (28Nm): x1 unit for the elbow
  - Embedded sensors
    - Hall sensor
    - Incremental encoder
    - Absolute encoder
    - Torque sensor
    - Temperature sensor

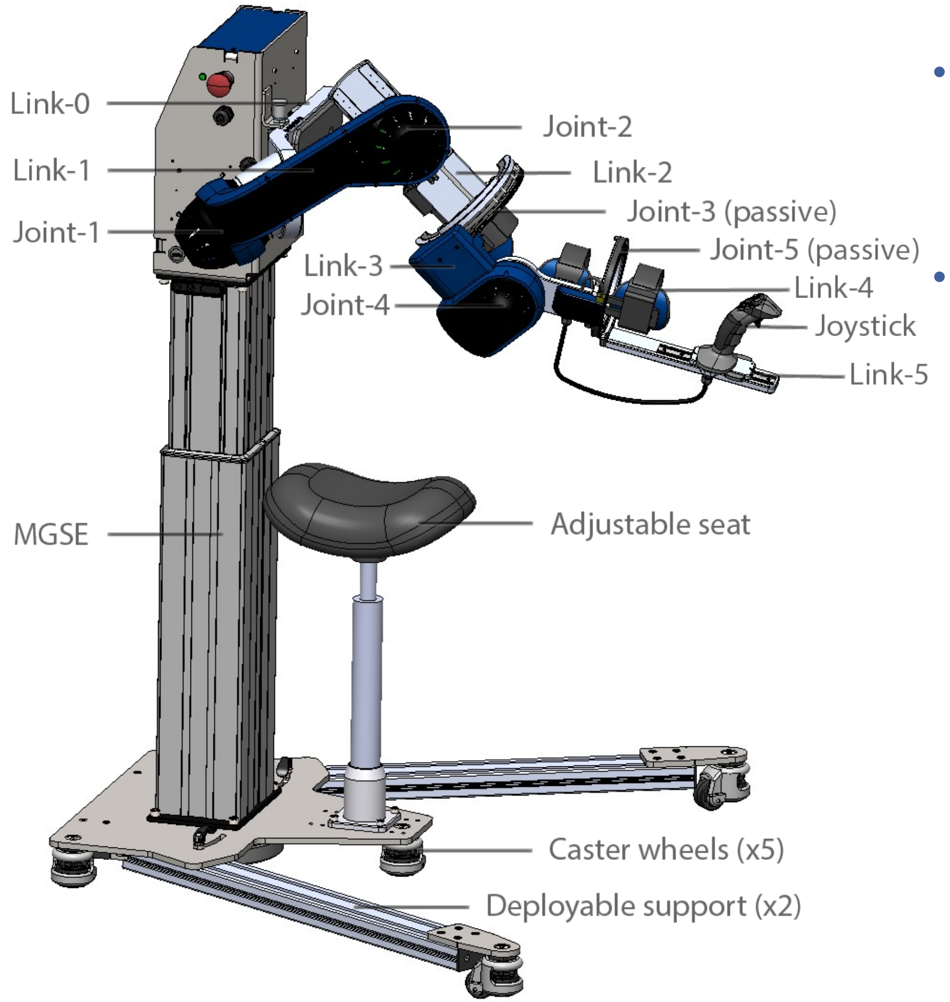


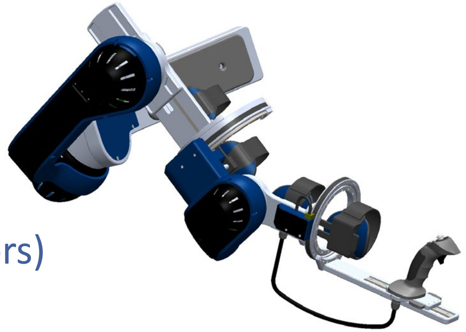



- Direct transmission with hollow shaft offering high robustness
- Dimensioned to needs of astronaut training (forces, constraints limits)
- Design successfully tested in H2020 MOSAR, LUVMI or ESA MIRROR.

# EXOSKELETON DESIGN

## Structural Design



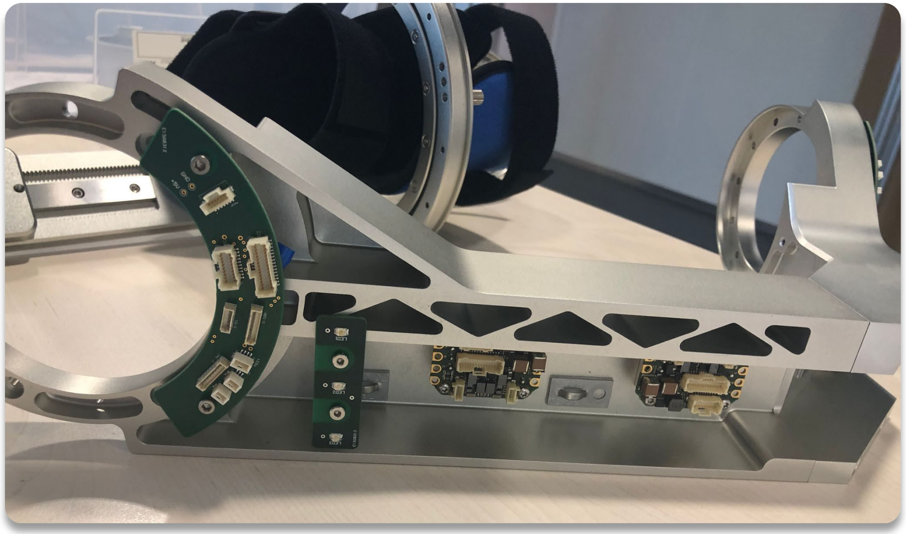
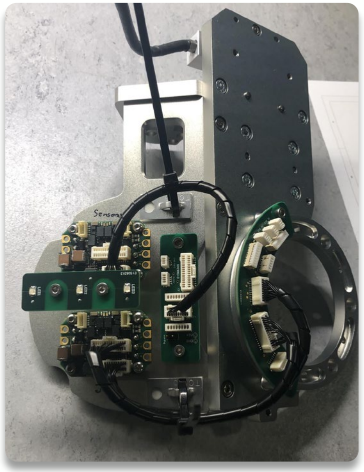
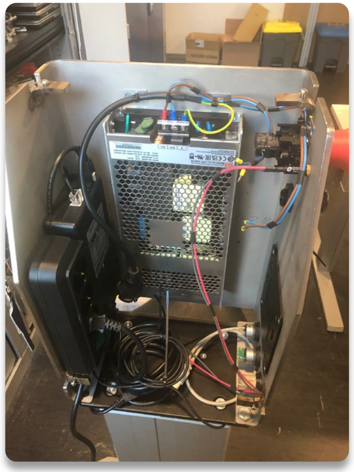



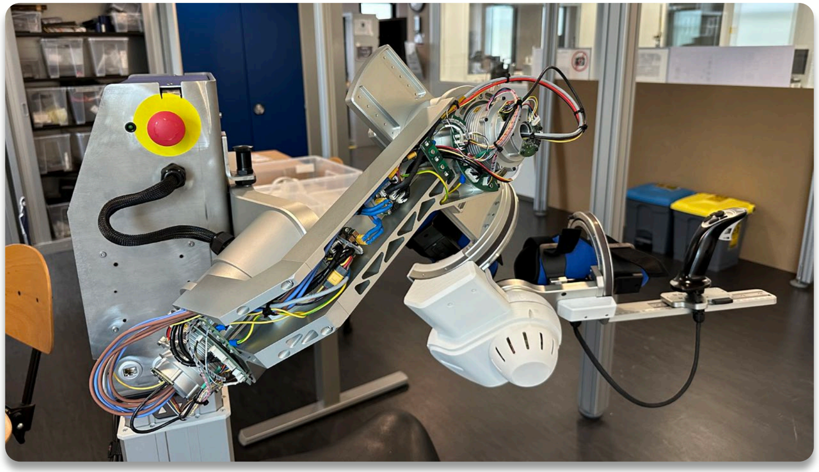
- Technology Demonstrator
  - 3 active degrees of freedom (custom BLDC motors)
  - 2 passive degrees of freedom (sensorized)
- Features
  - Robust: made of aluminum 7075-T6 and with anodized parts
  - Comfortable: ergonomic interface with paddings and Velcro straps
  - Compatible to P10-P90 percentile of adult European male/female range
  - Casing manufactured using Selective Laser Sintering 3D in Polyamide
  - Seated or standing configuration for users
  - Multiple safety protection layers in hardware and software
    - Mechanical end-stops limiting joint range
    - Enable switch
    - x2 emergency buttons
    - Software joint limitations
    - User Interface with “Stop” function
  - Portable with deployable support and caster wheels

# EXOSKELETON DESIGN

## Integration





# SOFTWARE IMPLEMENTATION

## Virtual Reality Simulation

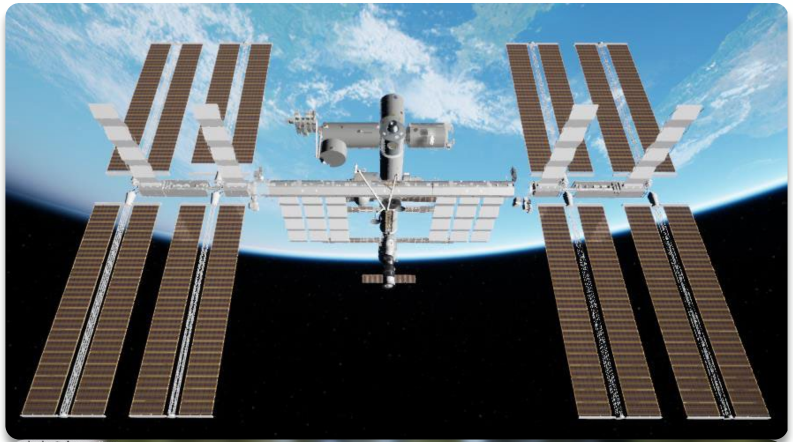
- Developed with Unreal Engine 5.1
    - VR compatible Nanite to virtualize complex geometries
- Standalone VR headset: Meta Quest Pro

- <u>EVA use case</u>

Perform displacements and operations with tools in microgravity
- Microgravity environment with
    - full model of ISS
    - Dynamic Earth model
    - Day-Night EVA training
- Extravehicular Mobility Unit (EMU)
    - Kinematic rig skeleton
    - Physics model
- Interactive tools
    - Handrails
    - Carabiners and Safety Tether
    - Pistol Grip Tool (PGT)
    - Others (CubeSat, screws…)



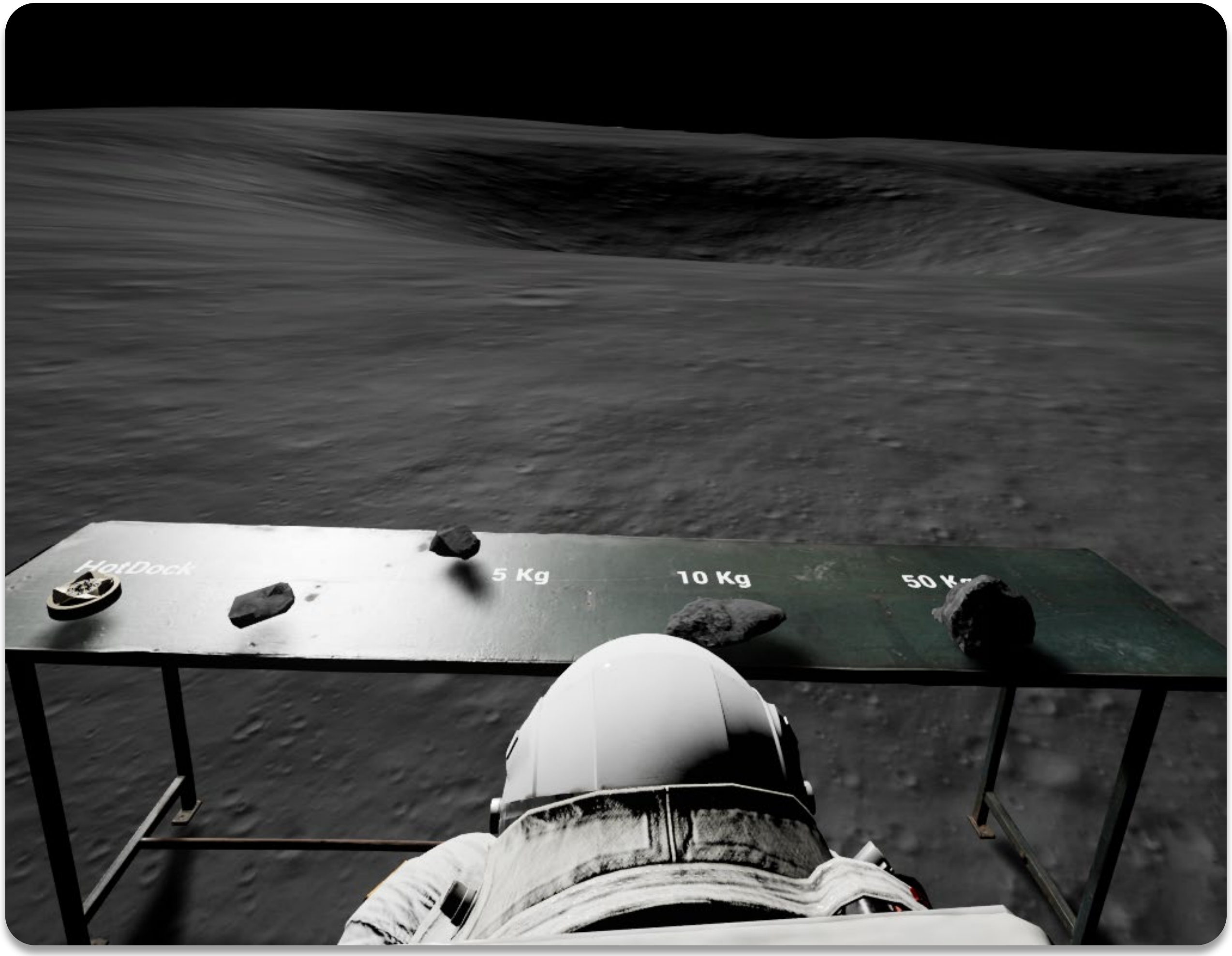





# SOFTWARE IMPLEMENTATION

## Virtual Reality Simulation

- Moon exploration demo
  - Landscape from real moon height maps
    - Data from Lunar Orbiter Laser Altimeter (LOLA)
    - South Pole of the Moon
    - Resolution of 5m/pixel
    - Landscape processed for VR
  - Test non-zero gravity compensation
  - Test grabbing objects of different weights
  - Locomotion in a vast landscape

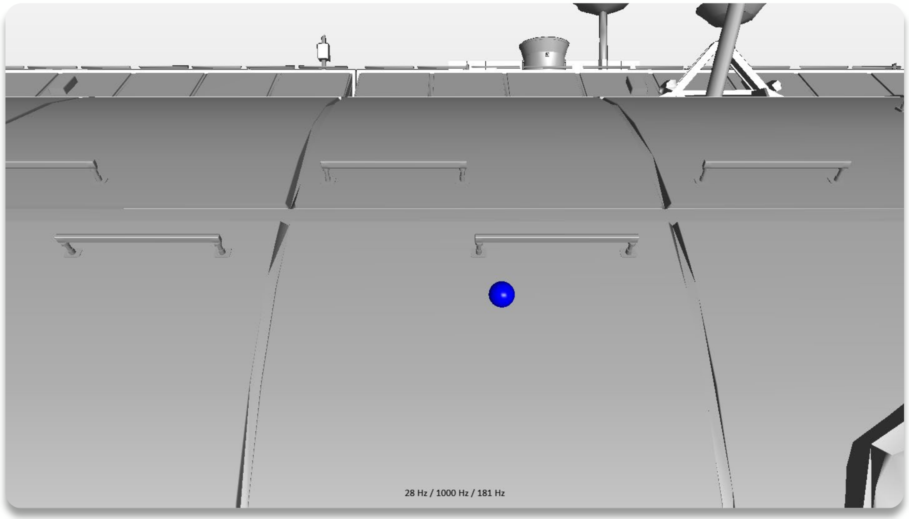


# SOFTWARE IMPLEMENTATION

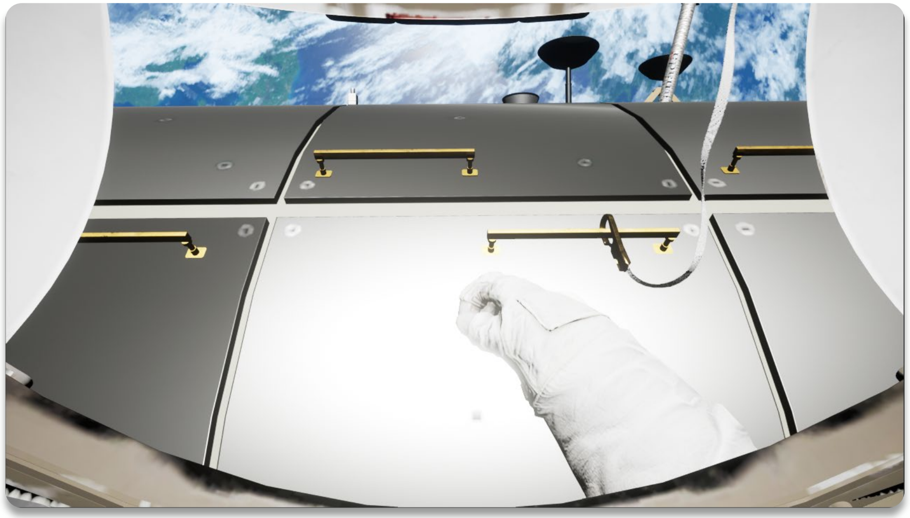
## Haptics Engine

- Chai3D selected as main haptics software
- Fast-response forces. Frequencies of 1000Hz are necessary for stability.
  - Contact forces: result of touching surfaces within the virtual world

- Low-response forces can be generated by Unreal Engine 5.1
  - Inertial forces: Force generated by changing the velocity of a certain object, including yourself
  - Spring force: Force generated by the inflation of the suit that tries to put the arm in a stretched position




Haptic Engine Chai3D (top) and the VR simulation in Unreal Engine (bottom) are synchronized.
The blue ball represents the palm of the right hand and is used for the force feedback calculations.



# SOFTWARE IMPLEMENTATION

## User Interface

- Web-based application.
- Developed using *NASA's OpenMCT* framework

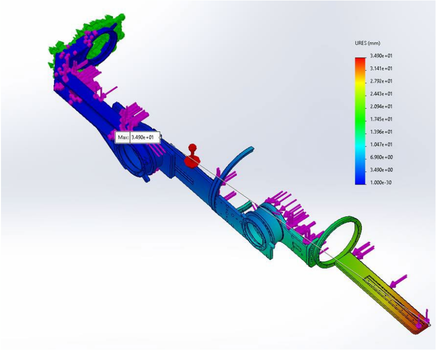
- Functionalities
  - Configuration: Define the exoskeleton properties
  - Monitoring: Visualize the raw data from sensors
  - Commanding: Allow to test the exoskeleton
  - Terminal: Log of the actions with their status

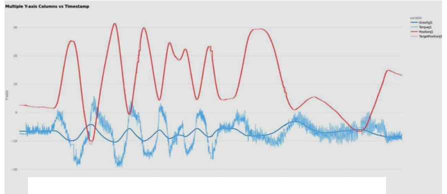
- Other features
  - 3D view in real-time of the exoskeleton using URDF
  - Historic data: retrieve data from past sessions
  - Activate/Deactivate testing experiences
  - Adjust the kinematic and dynamic parameters
  - Test the LEDs and the motors

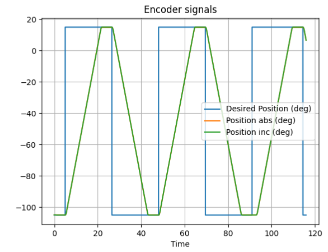
# VALIDATION RESULTS



- **Robustness**: structural deflection was of 22mm with a weight of 3.75Kg in the end effector, half of the predicted deflection by Finite Element Analysis. System showed easier maintenance and accessibility. Resistance to vibration.
- **Transparency with Gravity Compensation**: joint position control with average delays of 10ms and negligible stationary errors. Backdrivability slightly damped but stable and responsive.
- **Comfort**: participants reported through subjective questionnaire high comfort thanks to the orthopedic interface selected. No important contact points or breathability issues reported. Preliminary results show that system could be used for multiple hours comfortably.
- **Sensor readings**: absolute, incremental position sensors and torque sensors were validated with <1% relative errors. LEDs were also tested to visualize exoskeleton status (Idle, Ready, InControl).
- **Force generation by haptics engine**: forces are generated and sent at high frequencies (1000Hz), allowing the feeling of shapes even without visual feedback and in a very stable manner.
- **System Safety Verification**: Enabling button works as first software layer in end-effector joystick. Emergency buttons total reaction time (user reaction + system response) were measured as <1s in average. Don/Doffing times are 70 and 17 seconds in average. Mechanical end-stops work reliably.







# CONCLUSIONS AND FUTURE WORK

- **BLDC custom motors** are well suited to reduce maintenance and increase reliability, compactness, transparency and robustness compared to capstan, cable-driven transmission.
- The selected **ergonomic interface** with multi-point contact Velcro straps and fabric padding is a big improvement compared to previous iterations
- **Unreal Engine** is consolidated as best choice for VR simulation thanks to Nanite
- The use of a haptics engine like Chai3D is nowadays decisive to compute Contact forces
- Contact forces applied are very **stable and stiff**, even more than with desktop haptic devices, allowing to feel the shape of objects even without visual feedback.
- The use of the **VR headset** with inside-out tracking has proven to be more convenient




**Limitations and future work**

- The exoskeleton was designed to be a Technology Demonstrator
    - purposely featuring 3 DoF instead of 7 DoF
    - It helped us validating that the selected technology is well suited to the next generation of training
- Next iteration will be based on dual arms with 7DoF, including exoskeleton hands and a vestibular or offloading platform + VR headset for perception deception.

# CONTACT

## CONTACT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