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Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
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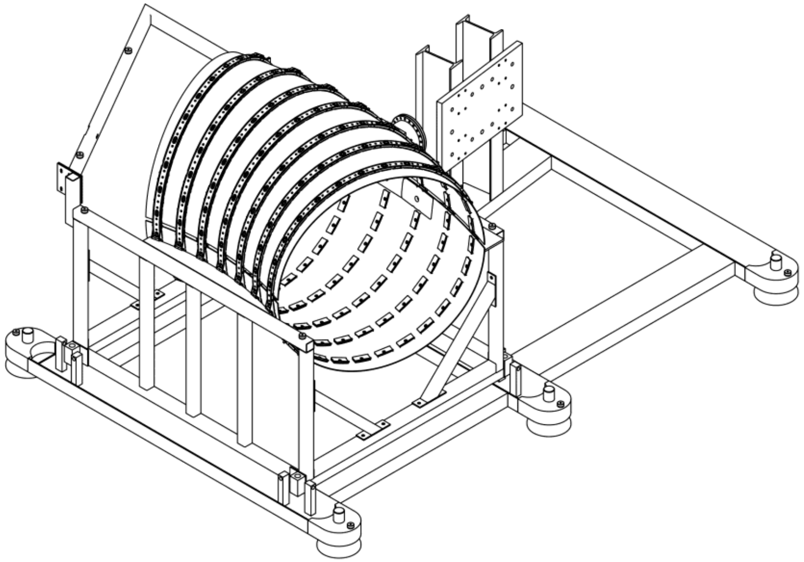
Remote Control of Flexible Robots using Digital Twins

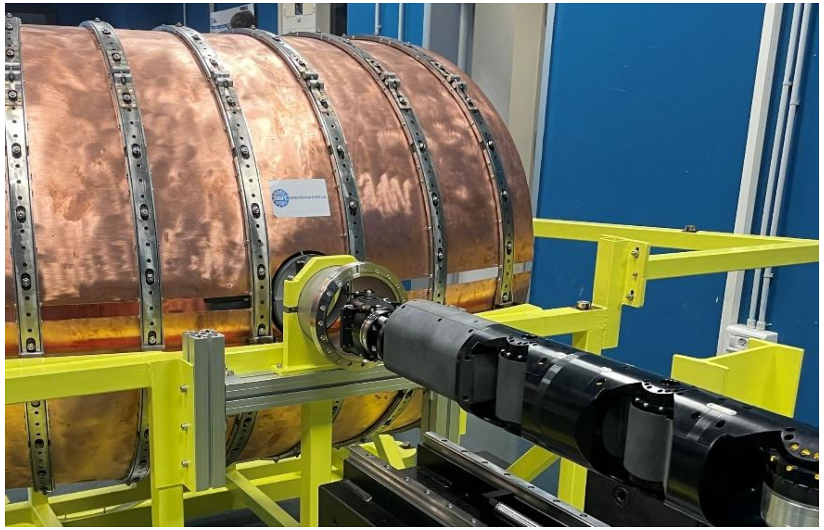
Virtual Reality Simulator and Advanced Control Methods applied to ROMAN

NEFERTARI FARHA-ONE



The FARHA-ONE Mock-Up

- **Full-scale 35° toroidal sector** of the RFX-mod2 device, reproducing geometry, materials, and structural layout
- **Realistic in-vessel constraints** (vacuum vessel excluded) for validation of manipulator kinematics, reachability, and collision avoidance. two copper shells and seven poloidal rings with accurate mounting and stiffness
- **Representative tile and port configuration**: 15 graphite tiles on locking-bush modules, including full inner-port coverage
- **Robot integration and alignment testing** via realistic access port, interface plate, and adjustable support frame
- **Modular and reconfigurable**, enabling testing under misalignments and non-ideal conditions



NEFERTARI FARHA-ONE

ROMAN overview

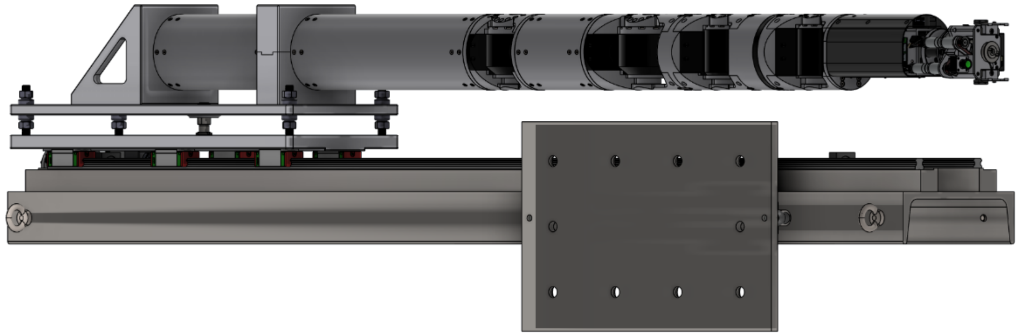
- Custom 7-DoF serial manipulator for in-vessel operations
- Max outer diameter 145 mm

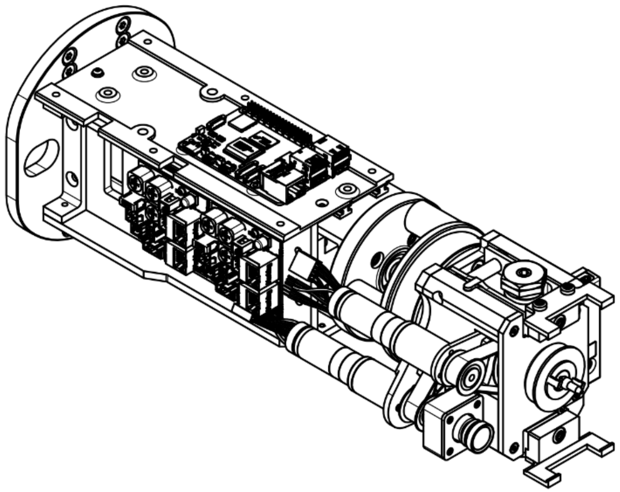
Joint description

- J1 (P): insertion and extraction from vessel
- J2–J4 (R): positioning inside toroidal section with clearance control
- J5–J6 (R): wrist for tile coaxial alignment
- J7 (P): tile approach and locking-bush actuation

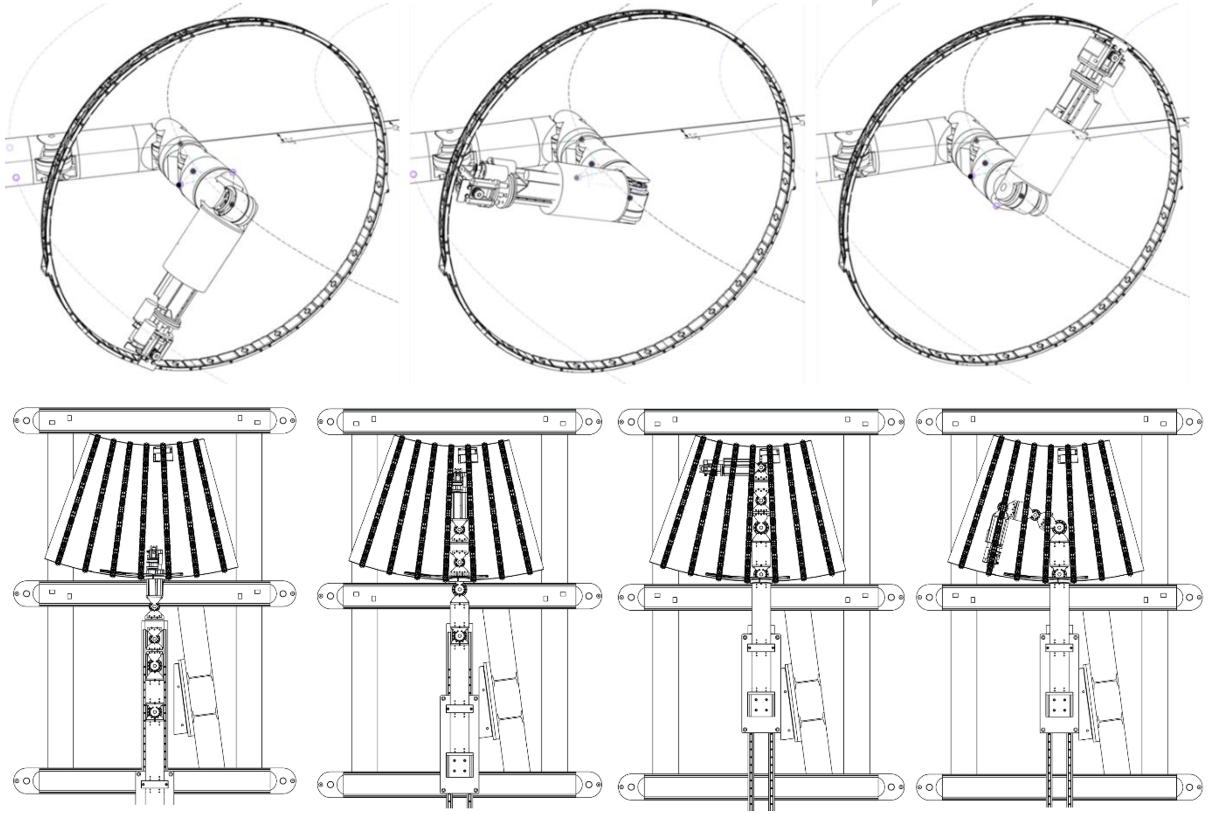
End-effector: TIGER

- Tile Installation and Grasping End-effector for Remote handling
- 2 active DoF: gripper fingers + key-lock screwdrive
- Integrated RGB + ToF sensors for inspection
- 6-axis force–torque sensor for contact monitoring





Manipulator insertion into vessel → Wrist reorientation for sector → Planar arm macro approach → Alignment on toroidal mid-circle → Prismatic approach to tile → Tile unfastening and gripping → Tile disengagement and extraction

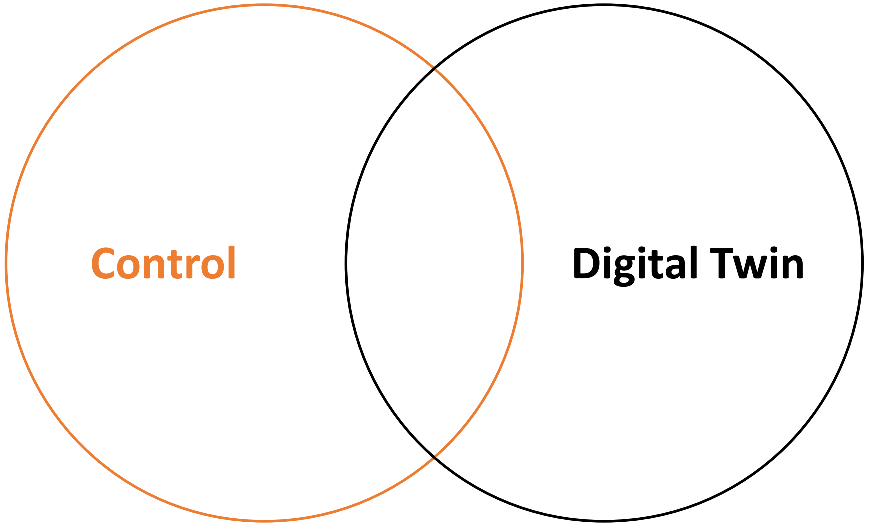


Challenges

1. High fidelity models – **high accuracy** models can be **computational expensive** and need to be integrated in sim environments

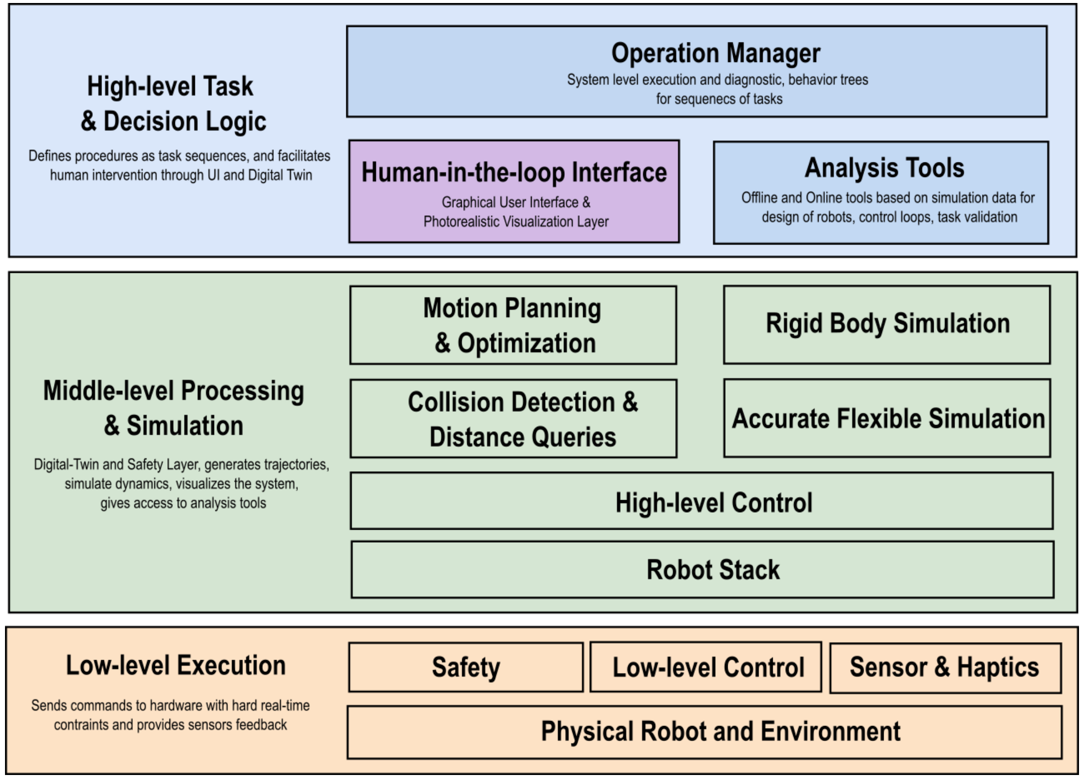
2. Human-in-the-loop – operators need **offline training** and **situational awareness** difficult with a reduced set of sensors and no accurate sim environments

3. Environment interaction – how to manage **collisions and contacts** with complex environments described with dense meshes in real-time operations



No SoA framework addresses all the challenges, making robots **unusable** for safety-critical operations and **less performant** for industrial applications

Architecture Overview



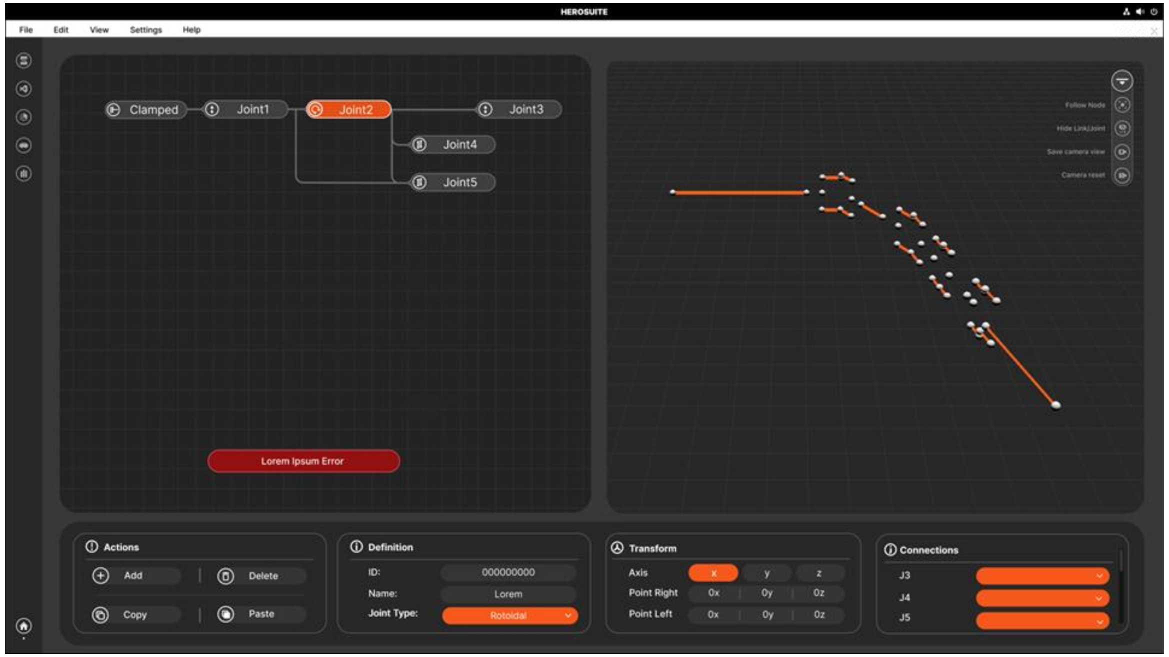
The proposed architecture is logically divided in three layers

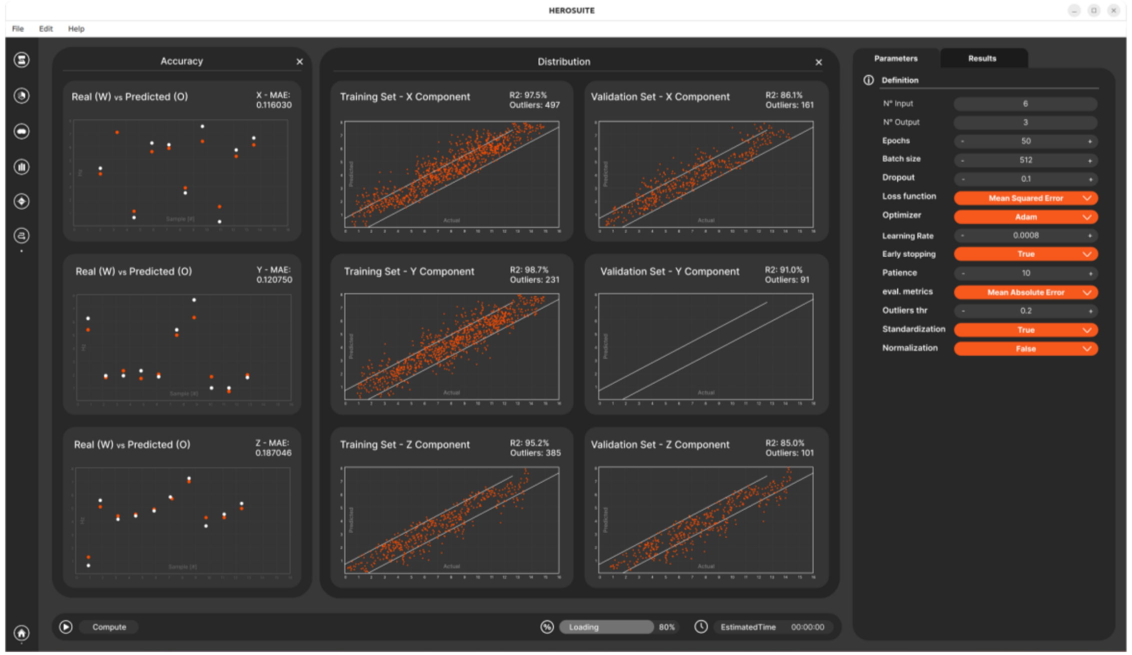
- High Level – Procedures and task definition, human intervention using Digital Twin data
- Middle Level – Digital Twin dynamic simulation, planning and collision detection, advanced control
- Low Level – Deterministic command execution and safety

High-Fidelity Digital-Twin – Modeling

1. Model Creation

Based on the modelling approach proposed in [1] and extending the software implementation to be included in the framework and account for branched structures, an intuitive robot model creation environment has been developed.



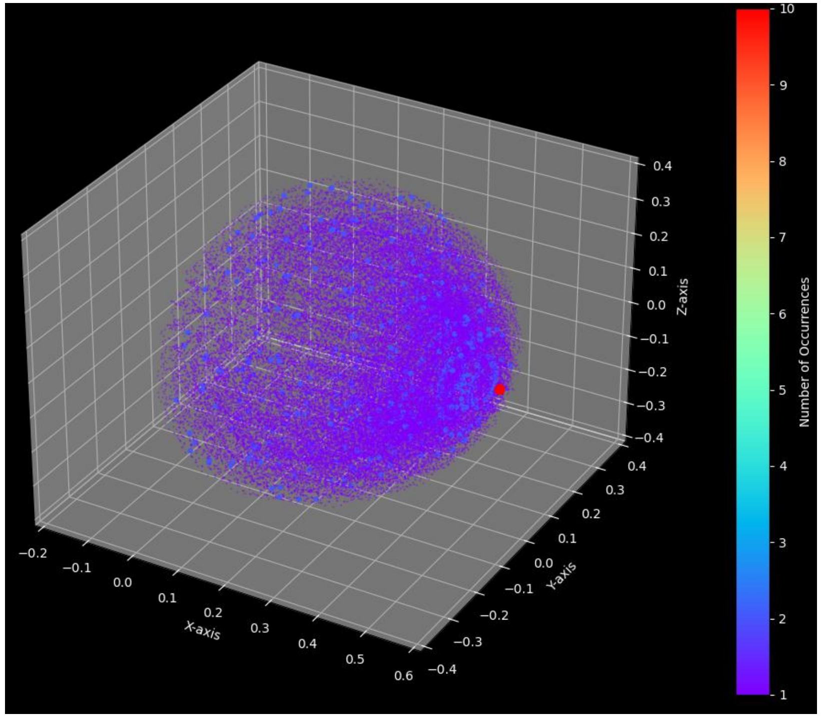


[1] Grazioso, Stanislao, Giuseppe Di Gironimo, and Bruno Siciliano. "A geometrically exact model for soft continuum robots: The finite element deformation space formulation." *Soft robotics* 6.6 (2019): 790-811.

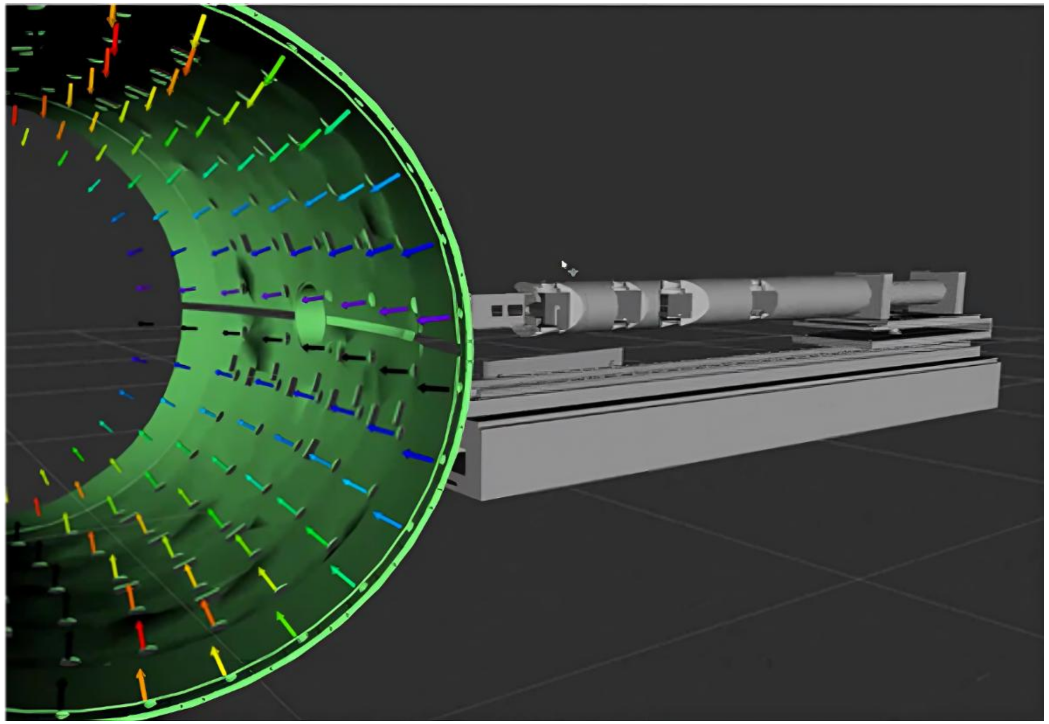
High-Fidelity Digital-Twin – Tools

2. Analysis Tools

Integrated tools for offline and online analysis are integrated in the architecture.

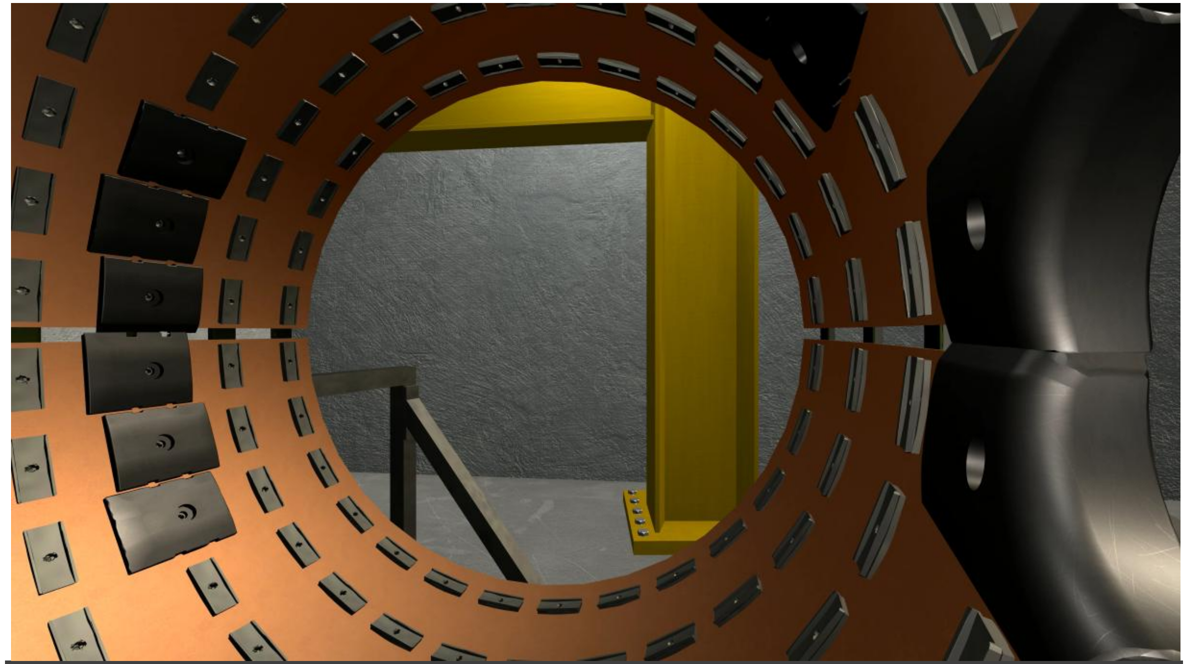


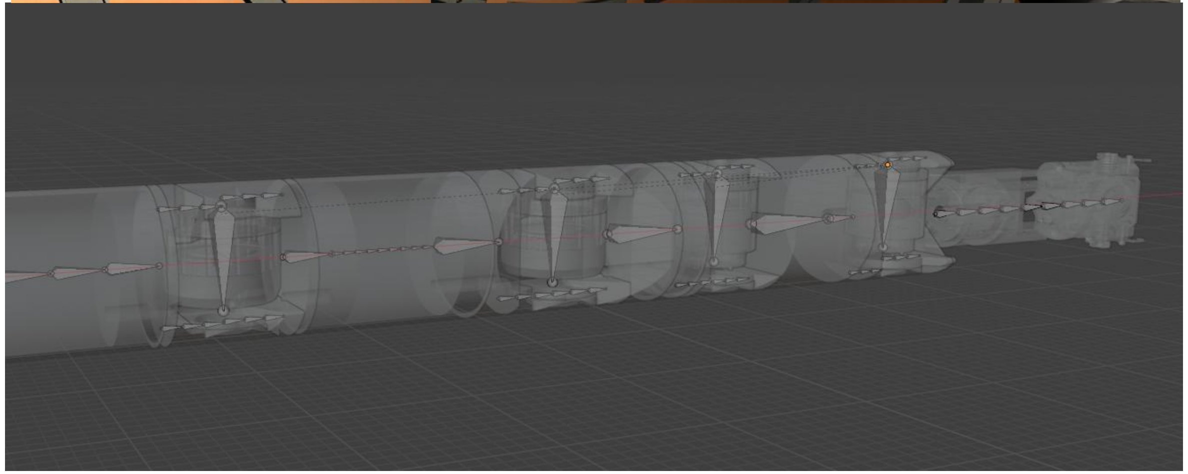
Reachable Workspace Flexible Model



Reachable Workspace Rigid Model

High-Fidelity Digital-Twin – VR





3. Photorealistic Environment Integration

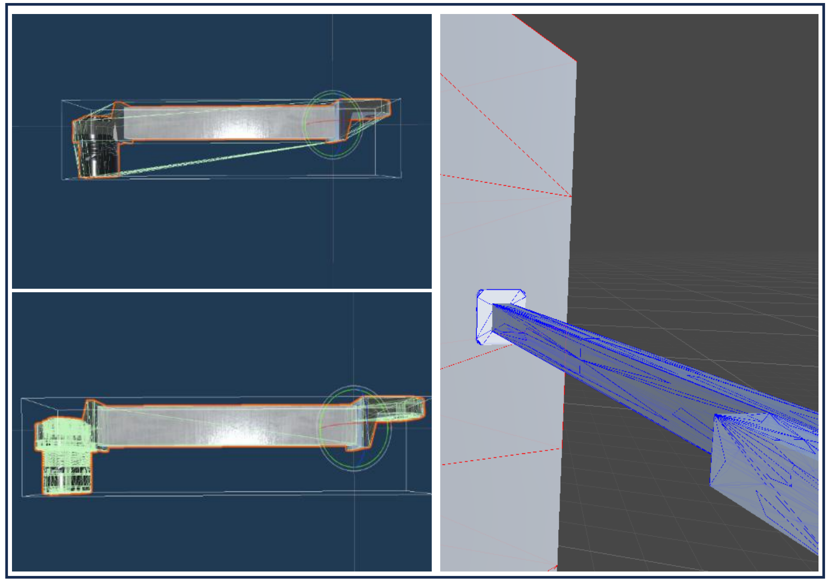
Rigged mesh for visualization

The accurate model is then “rigged”. Each vertex of the mesh is coupled to internal bones, allowing the mesh to deform continuously, providing an accurate visual representation of the manipulator’s flexible behaviour.

Integrated real-time simulation

The photorealistic environment is connected to the accurate simulation to update in real-time and display additional data using the digital-twin to operators

High-Fidelity Digital-Twin – Collisions



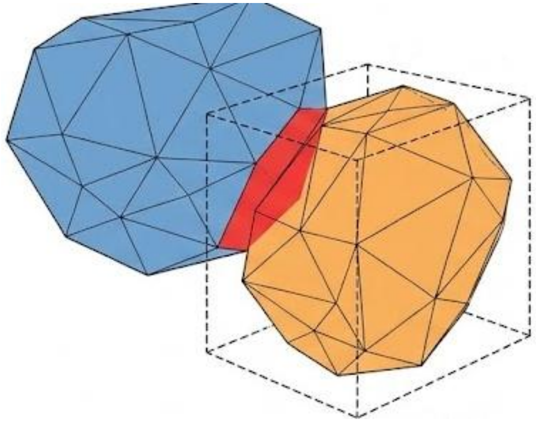
A simple and accurate approach is the use of triangle mesh-mesh intersection tests.

Each triangle composing the link of a robot is geometrically checked to be intersecting with all the other triangles of the environment.

Problems

Scales bad with the number of triangles of the mesh

Doesn't provide direct distance queries for teleoperation and planning



High-Fidelity Digital-Twin – Collisions

The idea is turning a complex 3D world into a fast lookup table

1. The environment is discretized into a **voxel grid**. For every voxel, we calculate the minimum Euclidean distance to the nearest static obstacle.

2. Distances beyond a safety threshold are **truncated** (capped) to save memory and focus precision where it matters (near collisions).

3. This 3D map is stored in GPU with efficient read-only tree structures allowing for O(1) queries

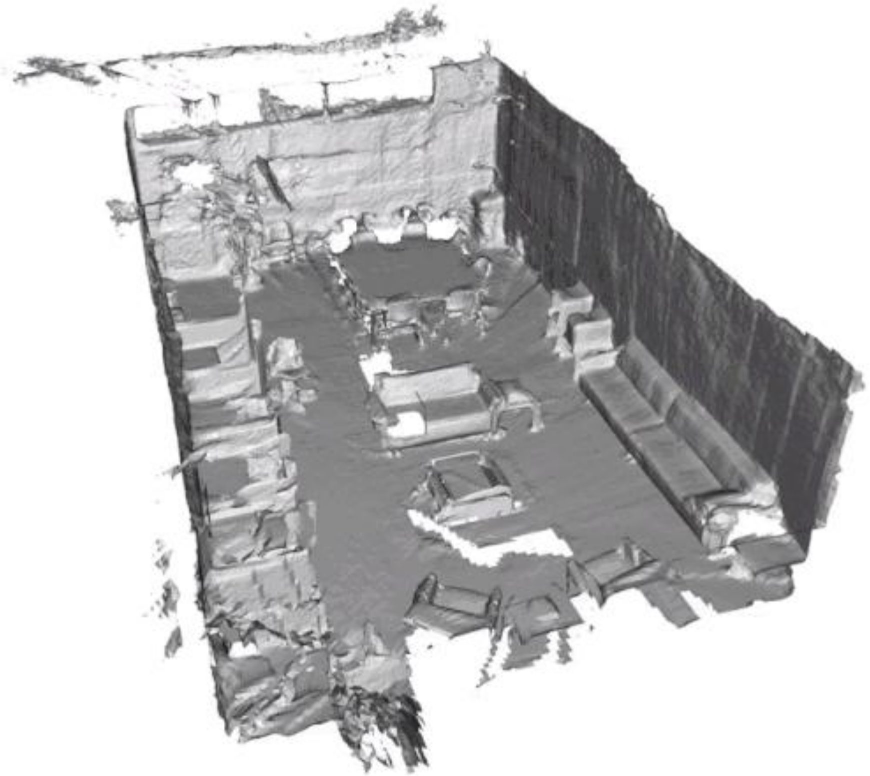


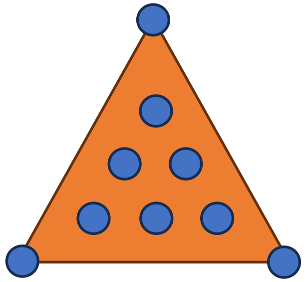
Image from NVBloxCore - NvidiaIsaac

High-Fidelity Digital-Twin – Collisions

At runtime, the robot's mesh points are transformed to world coordinates and used to query the pre-computed GPU map, performing a **mesh-to-field query**

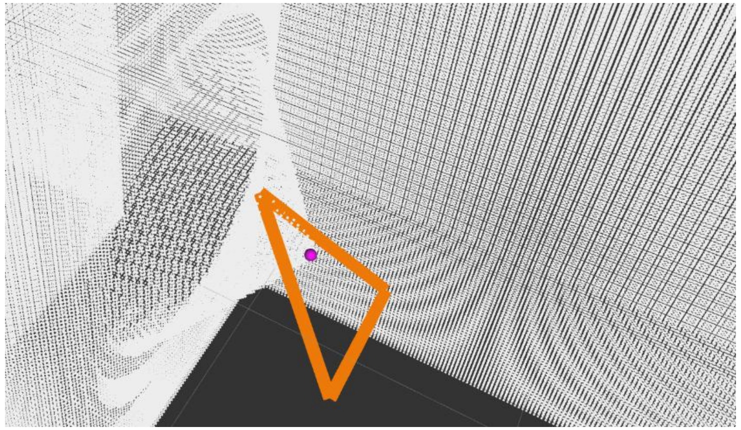
Sampling

- Discrete
- Resolution-accuracy trade off
- Can miss collision
- Inefficient for multiple contacts



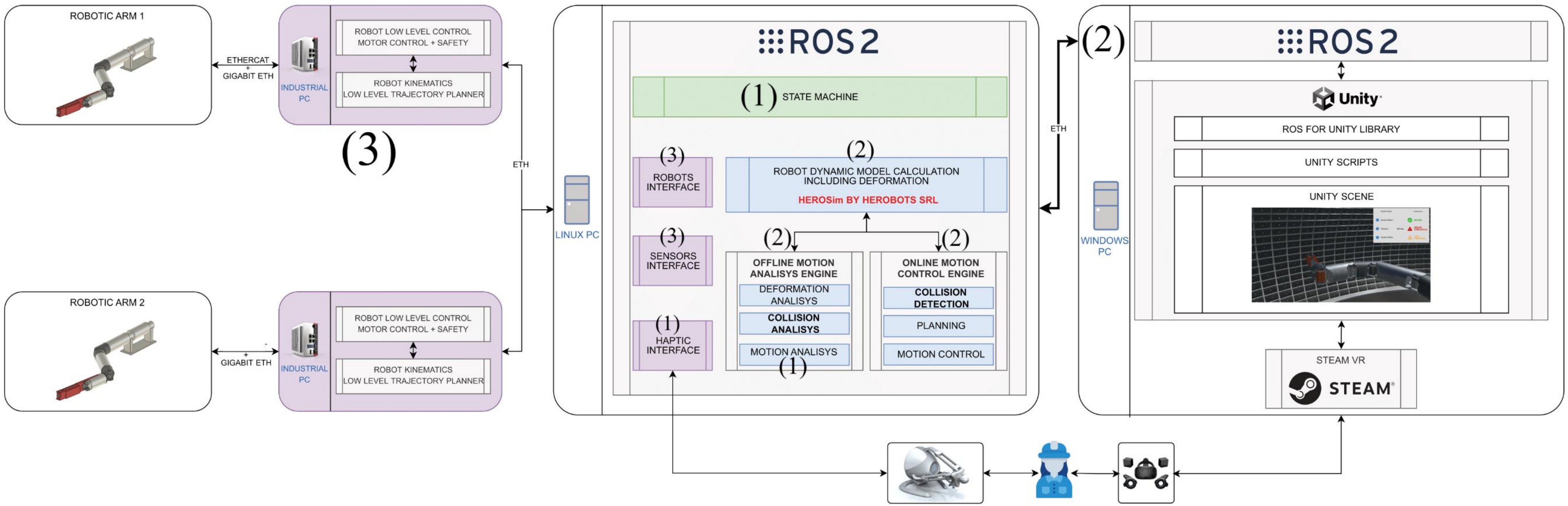
Frank-Wolfe Optimization

- Continuous
- GPU optimized
- Doesn't miss collisions (*)
- Efficient for multiple contacts



Control Architecture of FARHA-ONE

(1) High-level Task and Decision Logic
(2) Middle-level Processing & Simulation
(3) Low Level Execution



Preliminary architecture design for human-in-the-loop control of robotic equipment in remote handling tasks: Case study on the NEFERTARI project *– Giuseppe Andrea Fontanelli,* ***Alessandro Sofia****, Salvatore Fusco, Stanislao Grazioso, Giuseppe Di Gironimo – Fusion Engineering and Design Volume 206, 2024, 114586, https://doi.org/10.1016/j.fusengdes.2024.114586– IRIS Handle (https://hdl.handle.net/11588/986392)*

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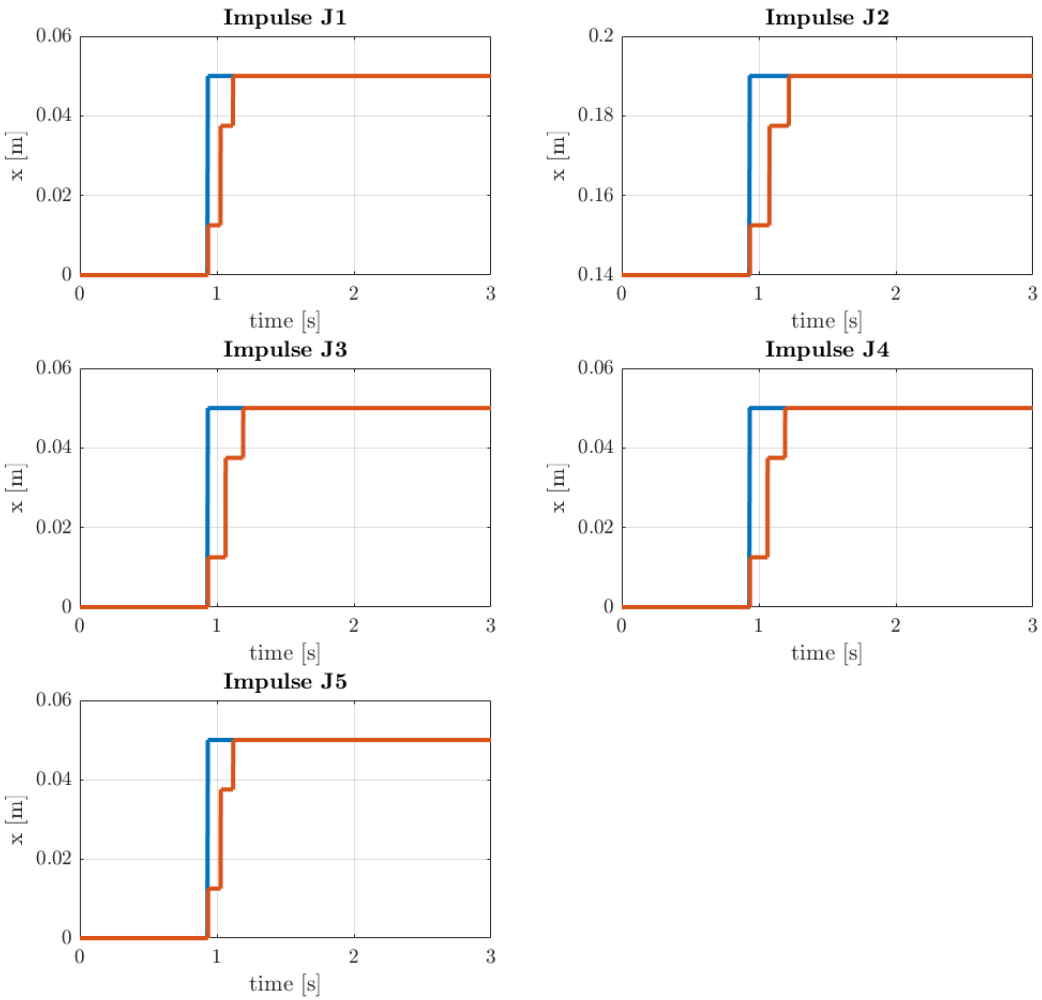
Vibration Control – Input Shaping

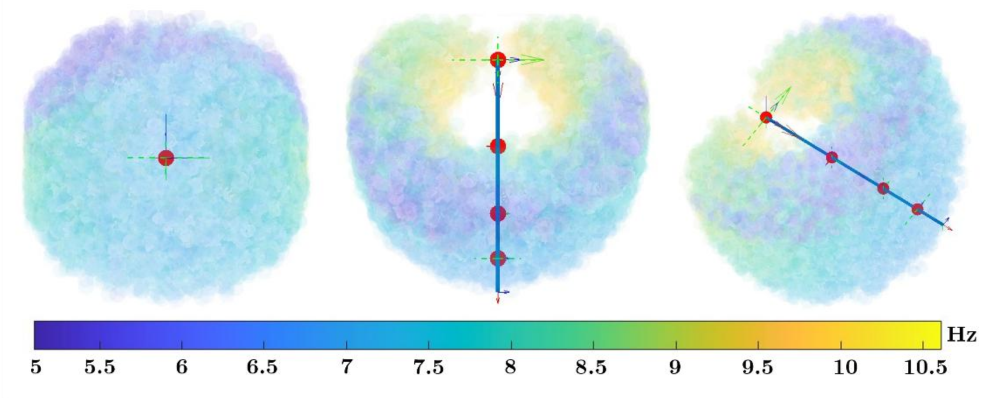
Input shaping is a highly effective model based feedforward control to reduce vibrations induced by the motion of the robot

1. **System Characterization** - estimate the robot natural frequency and damping ratio
2. **Design the Shaper** - Calculate the precise timing and amplitudes of an impulse sequence designed to perfectly counteract those specific system dynamics.
3. **Convolve the Input** – Convolve the original unshaped input with the series of impulses
4. **Send Shaped Command** – Apply the input, with the new zero vibration motion



Vibration Control – Method

Problem



Main challenge is that robot system parameters depend on their configuration, producing a non-linear mapping between joint positions and natural frequency

Estimating system parameters usually requires several experimental tests, to produce this direct mapping

Exploiting the accurate Digital Twin we reduce times for the generation of this mapping and don't need access to the physical robot

Model-based Adaptive Input Shaping driven by configuration-dependent dynamics for vibration suppression

Parallel execution of automatic tool for FFT computation and peak extraction for natural frequency estimation

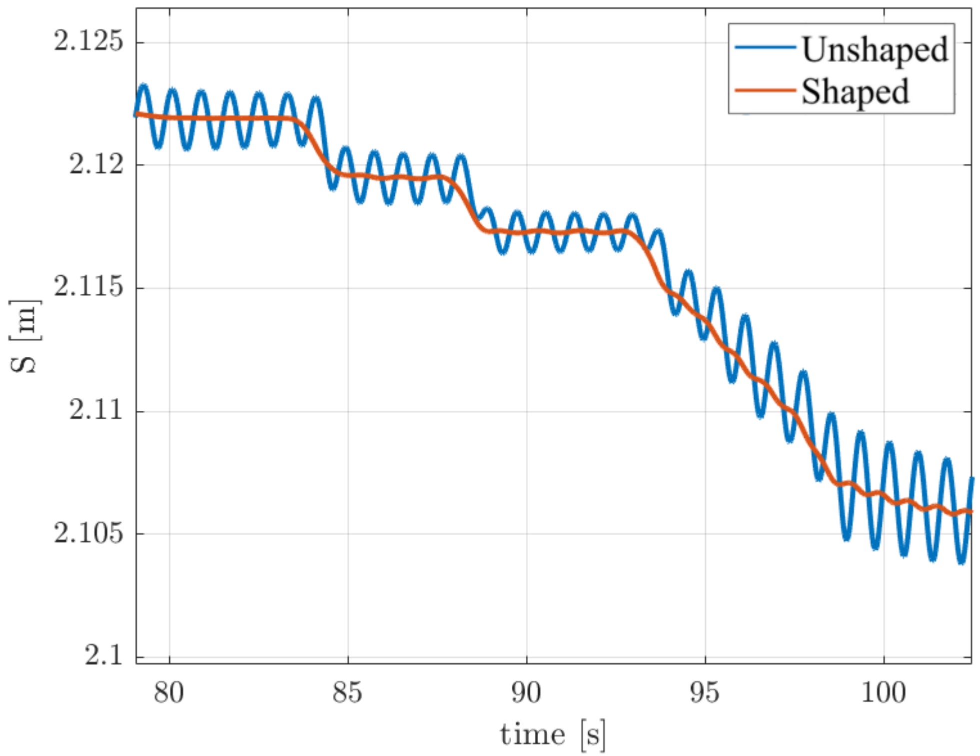
Data is stored in a look-up-table mapping robot configuration to natural frequency

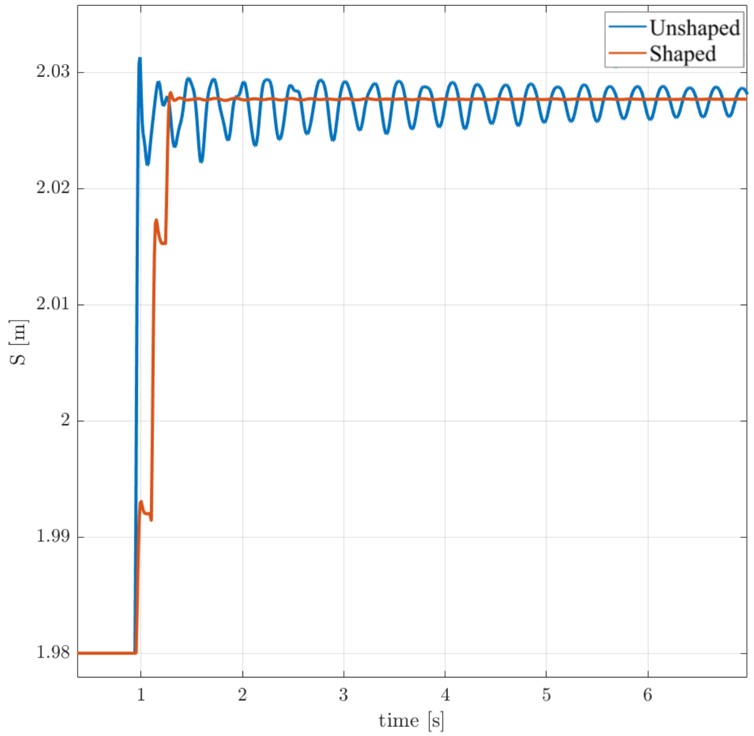
A Neural Network is trained on these synthetic data

The NN inference is used online to obtain the system parameters used as adaptive values to compute the shaper

Signal is filtered and forwarded in real-time

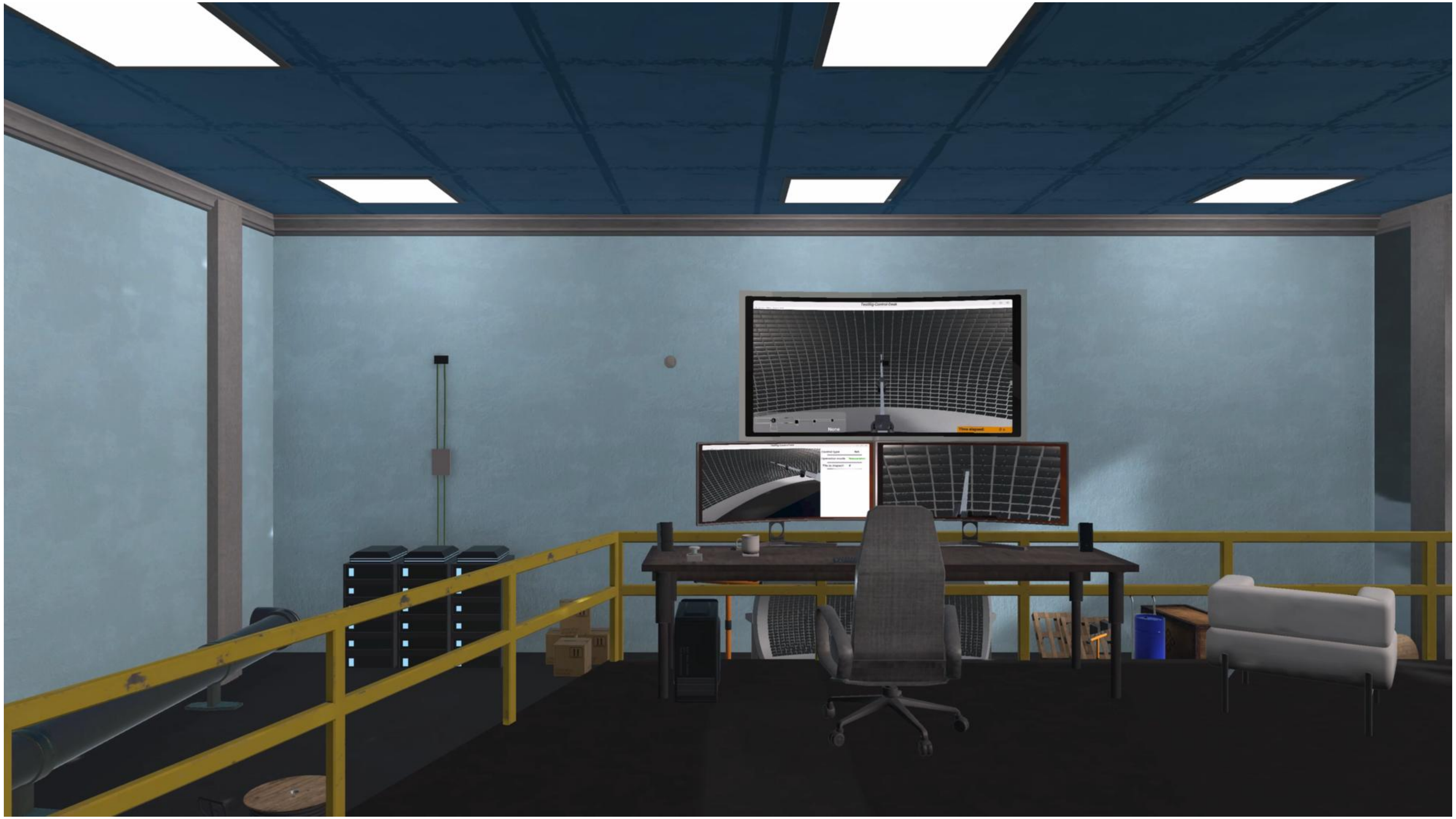
Vibration Control – Results



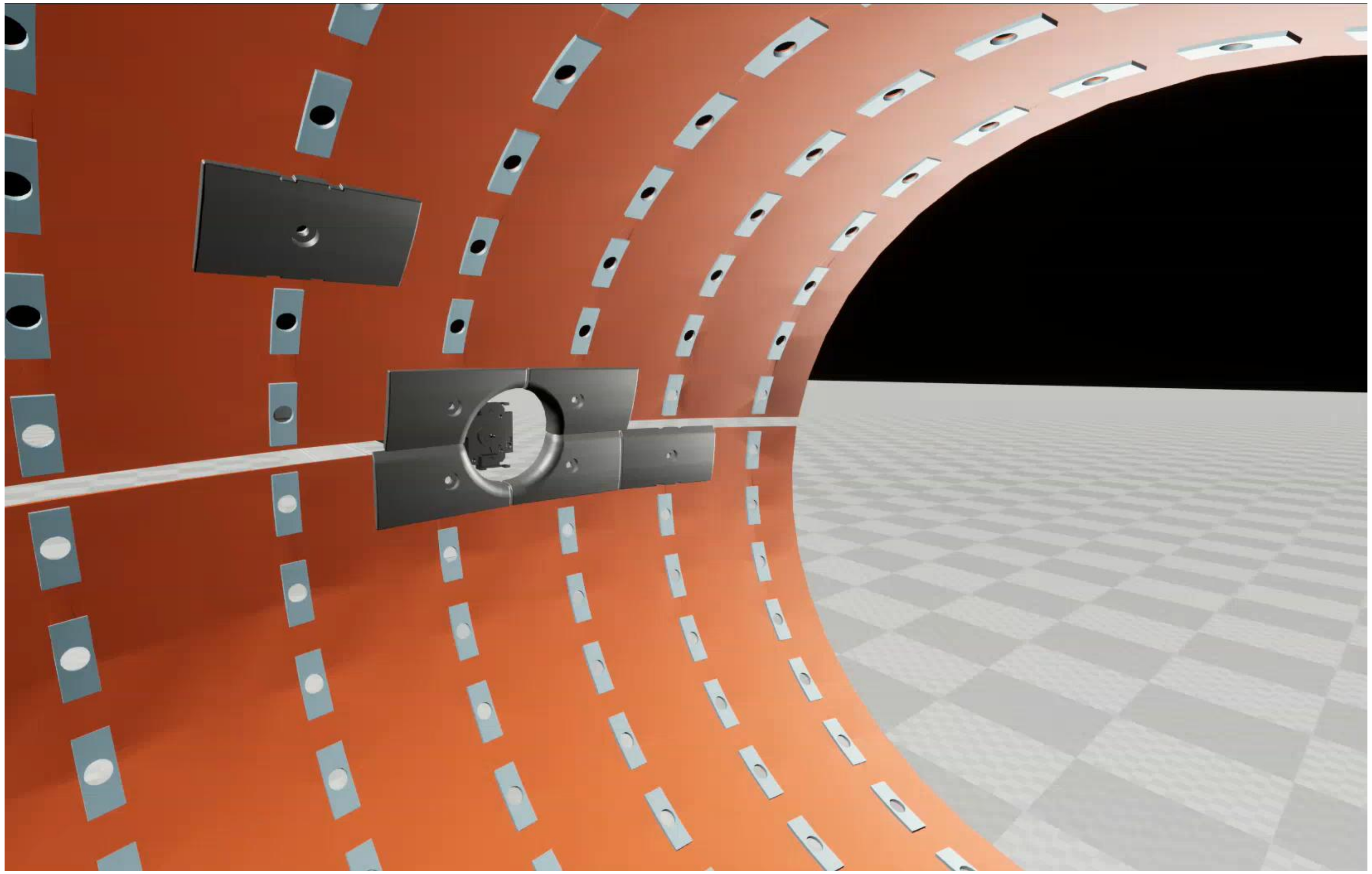


Vibration reduction above 95%, reaching **98%** in autonomous, and teleoperated motions

__Sofia A.__, Fontanelli G.A., Grazioso S., Fusco S., Sabella R., Di Gironimo G. __Accurate Digital Twin and Control of Flexible Long-Reach Robots__. (2026, Submitted)



Application to long-reach: distance queries



Robot

Vertices	124.476
Triangles	56.056

Environment

Voxel dim	0.0005m
Voxel num	>10B

Online Result

Rate	100Hz

HW

Consumer laptop GPU RTX4090

Validated online distance queries and collision detection using flexible meshes for ROMAN in RFX-mod2

Thank You!

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