

The iMETRO Dynamic Simulation: An Open-Source Simulator for Intravehicular Space Robotics Research

Nikki Hart^{1,2}, Nathan Dunkelberger^{2,3}, Erik Holum^{2,4}, Lydia Kavraki¹, Emma Zemler², Shaun Azimi²

¹Rice University ²NASA Johnson Space Center ³CACI International ⁴METECS



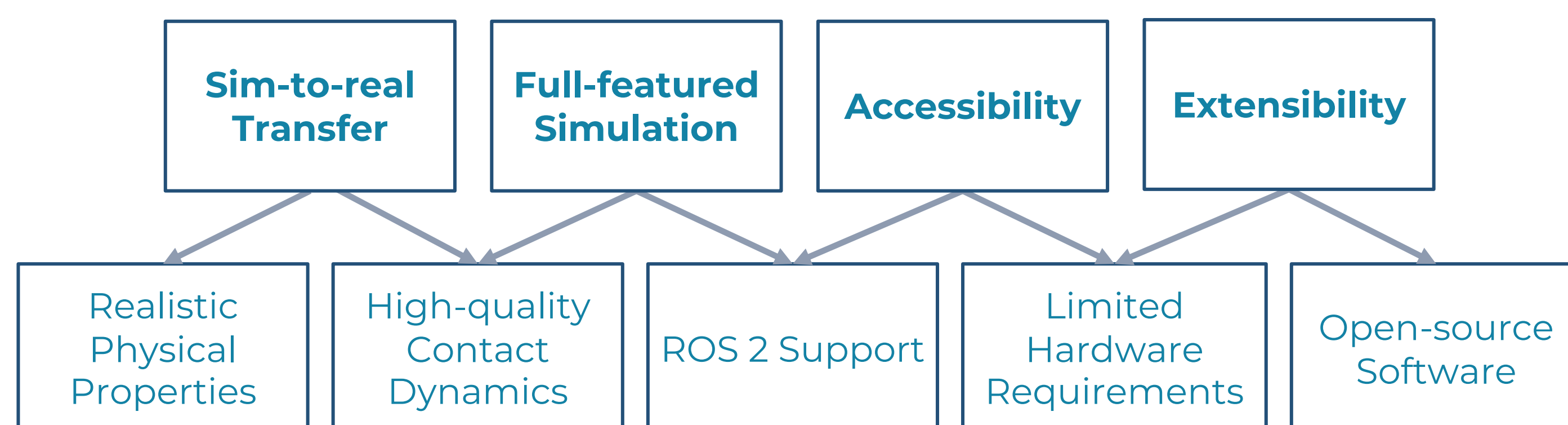
Motivation

- **Intravehicular robotics (IVR)** can save crew time and facilitate exploration objectives as NASA develops a sustained human presence on the Moon and Mars
- Research in this area is typically limited to those with access to realistic, large-scale ground mockups due to the **unique conditions of space vehicle environments**
- Existing IVR simulation environments are either **kinematic simulations**, which do not simulate contact dynamics or sensors, or do not contain **manipulable objects**

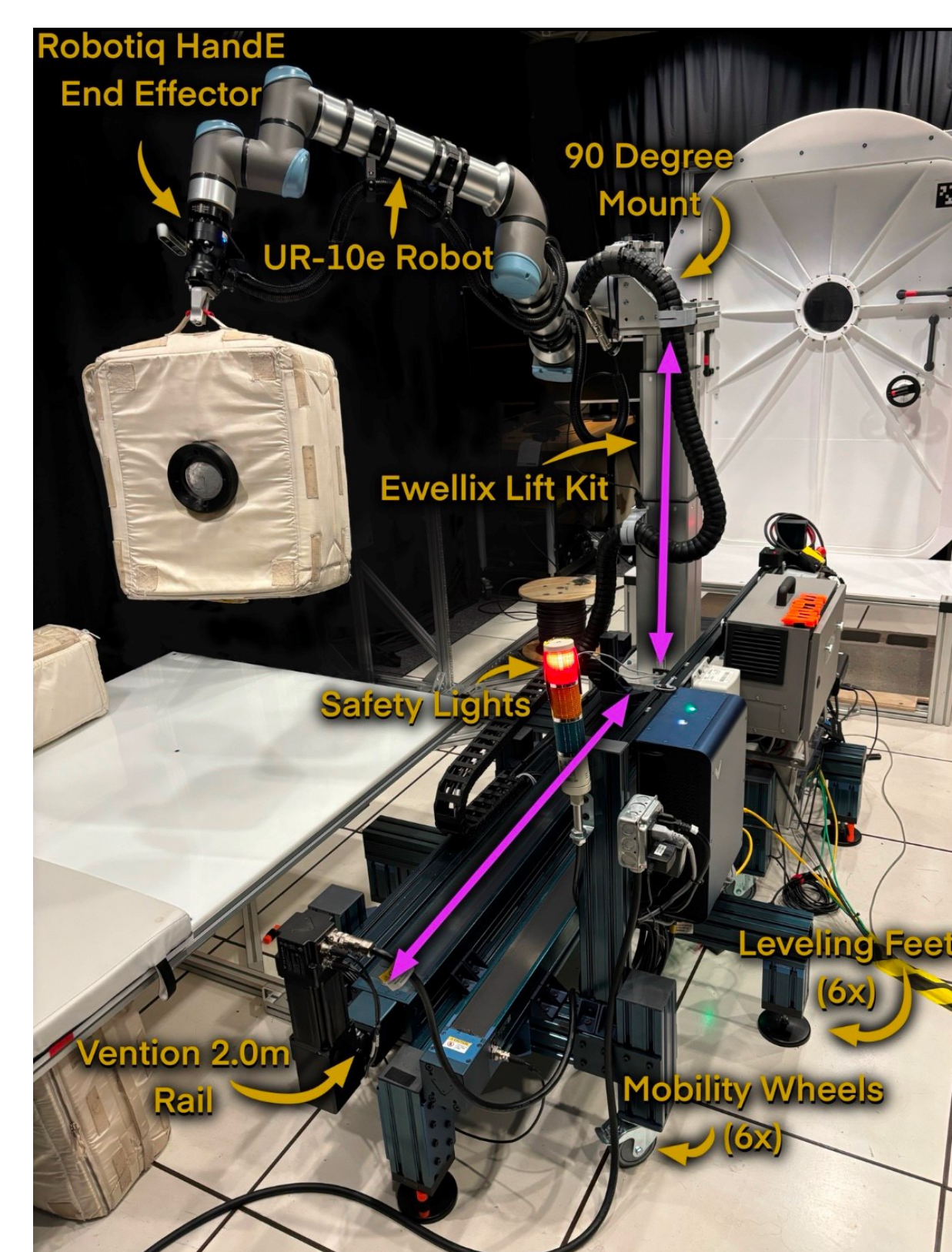
Contributions

- We present the **first open-source dynamic simulation environment** for robot manipulation research in IVR applications
- We provide tools **for MuJoCo and ROS 2 integration** to facilitate the integration of new software and hardware components into the simulated environment
- We demonstrate the **sim-to-real transfer capabilities** of the dynamic simulation environment through an example application demonstration
- We isolate and discuss the challenges we faced to aid future simulation efforts

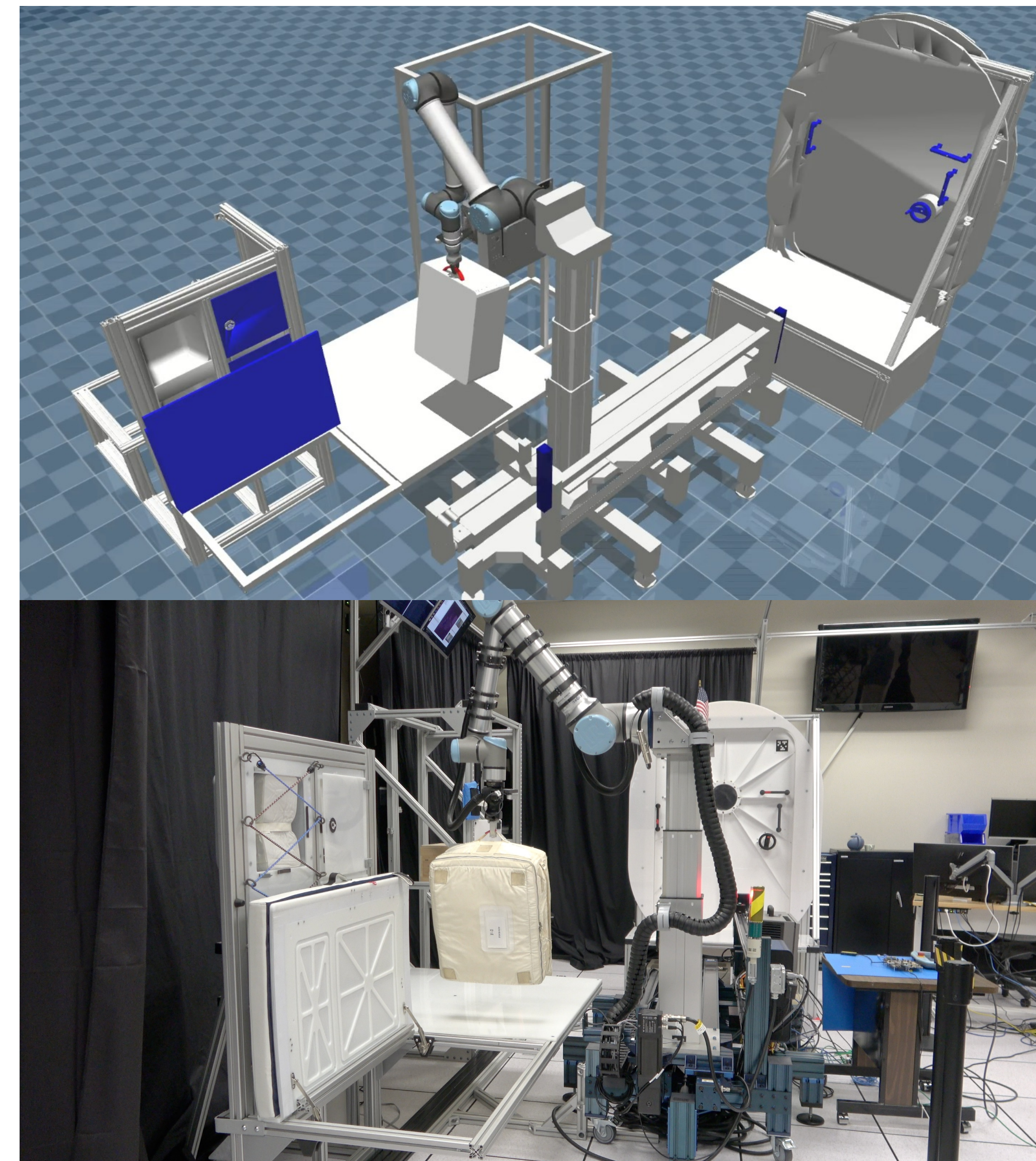
Principles



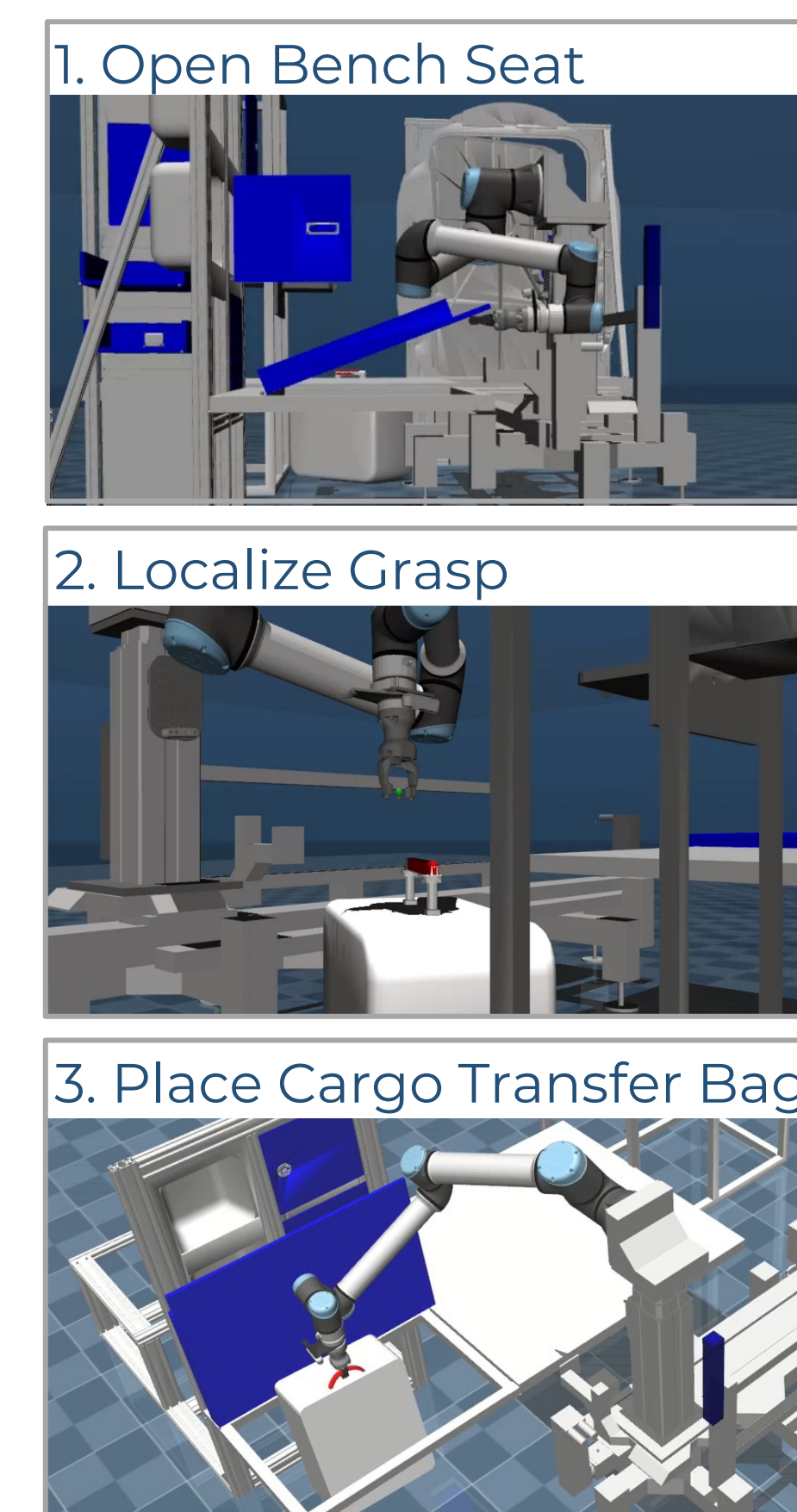
iMETRO Facility



Real-World Experiments



Application Demonstration Techniques



- **Motion planning:** we use the OMPL planners in MoveIt due to ROS 2 integration
- **Digital twin:** we use a digital twin to plan collision-free paths
- **Grasp localization:** we use computer vision to identify the red region of the cargo transfer bag handle as the grasp point
- **Contact-rich manipulation:** the robot opens a heavy bench seat
- **Perception-based behavior:** the robot uses computer vision to localize the object grasp

Results

Demonstration Step	Failure Mode	Modeling Shortfall
Bench Seat Open	N/A	N/A
Traverse to Cargo Transfer Bag (CTB)	E-stop due to robot's proximity to obstacles	Unmodeled camera cable housing
CTB Grasp	CTB handle out of camera frame	Unmodeled structural beams on floor
CTB Lift	Failure to plan	
CTB Place	CTB collision with mockups	CTB modeled as rigid

Lessons Learned

- **Identify changes to models.** Assets in a dynamic, modular environment may change at any time; unexpected results during sim-to-real transfer can identify modeling shortfalls.
- **Simulate uncertainty.** Extensions of this work should consider strategies of embedding uncertainty into the simulation environment to improve the robustness of behaviors developed in simulation.
- **Maintain state of the world.** Future work should consider using perception-based methods to update the state of the digital twin.

Future Work

- **High-fidelity simulation of complex mechanisms.** Future work should evaluate dexterous manipulation of the complex mechanisms in the environment.
- **Quantitative evaluation.** Future work will analyze proprioceptive data and leverage proposed system identification tools to quantitatively evaluate the simulation's fidelity.
- **Model additional robot embodiments and sensors.** Ongoing work includes modeling a dual-arm mobile manipulator. Demonstrations that leverage IMUs, LiDAR, and force-torque sensors should be developed to further evaluate the simulation's fidelity.

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