3D Depth-Sensing Framework for Hand-Object Interaction in Microgravity Environments

Vijay Teja Uppalapati, Neji Mensi
Florida Institute of Technology
vuppalapati2024@my.fit.edu, nmensi@fit.edu

FLORIDA TECH

INTRODUCTION

- Microgravity is a near-zero gravity.
- Microgravity affects the hand-eye coordination that guides accurate reaching and grabbing of objects.
- Real zero-gravity experiments are costly.
- ***Goal***: Develop a **Python-based simulation framework** that models **3D hand-object interaction** under adjustable gravity conditions.

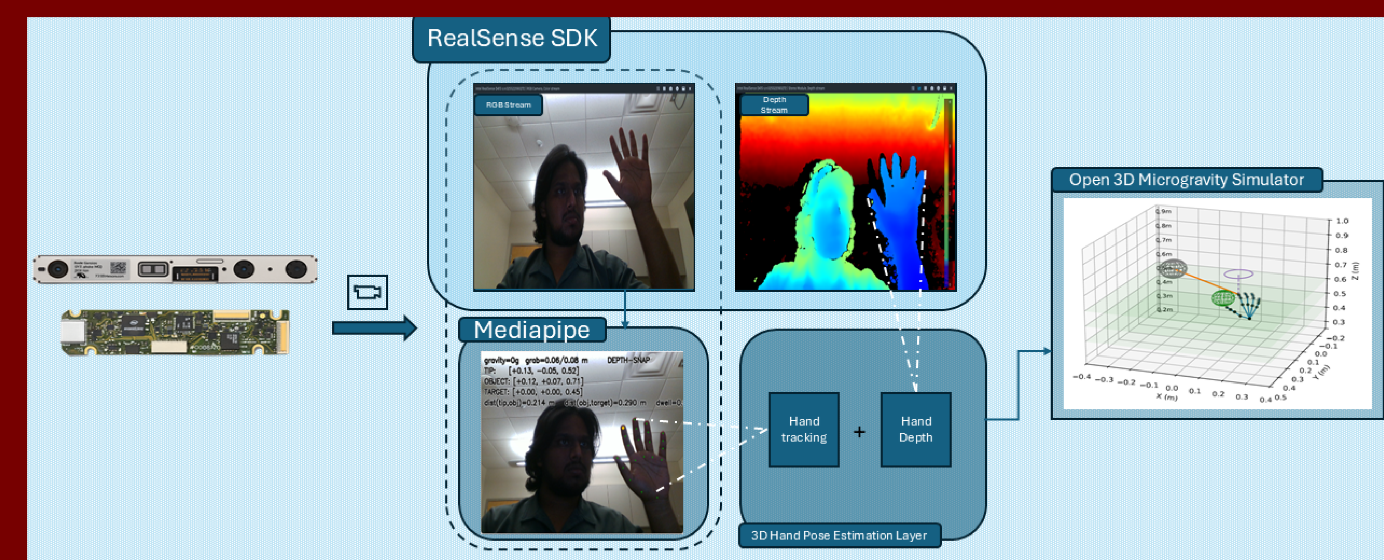
OBJECTIVES

- Develop a **depth-based 3D hand-tracking system** using an active infrared stereo camera.
- Build a **physics-based simulator** that models free-floating object dynamics for **astronaut training and teleoperation missions**.
- Evaluate interaction accuracy under Earth, zero-gravity, and perturbed sensing conditions.

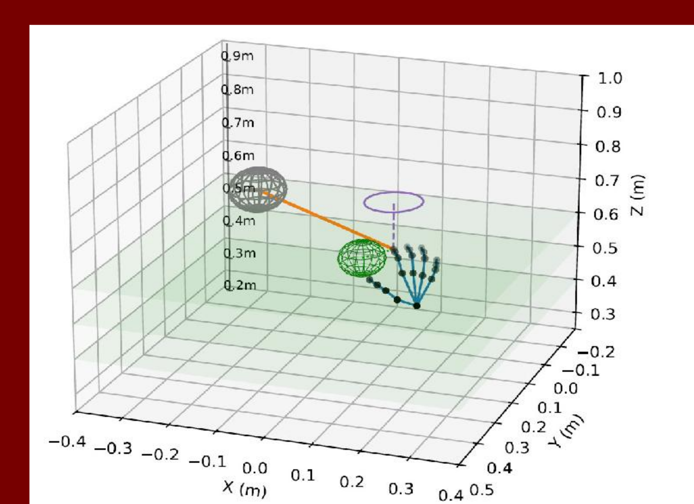
METHODS

- **Hardware:** Intel RealSense D415 (active IR camera)
- **Software:** Python, Open3D, and RealSense SDK.
- **Process:**
  1. Capture synchronized RGB and depth data.
  2. Use MediaPipe to extract 2D hand landmarks.
  3. Map landmarks into 3D space using depth values.
  4. Feed 3D coordinates into a **Newtonian motion model** to simulate microgravity.
  5. Render real-time visualization in Open3D with color-coded object states.
- **Evaluation**: 15 participants performed a 3D pick-and-place task under Earth and simulated zero gravity, with performance metrics: completion time, accuracy, and contact duration.

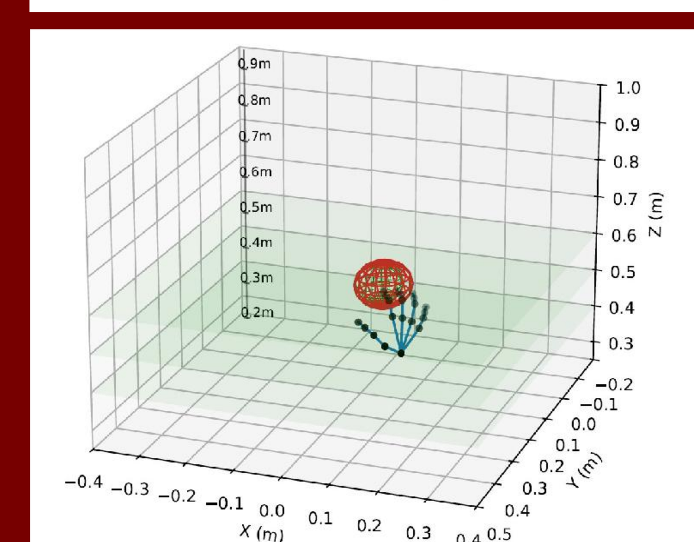
PROPOSED PIPELINE



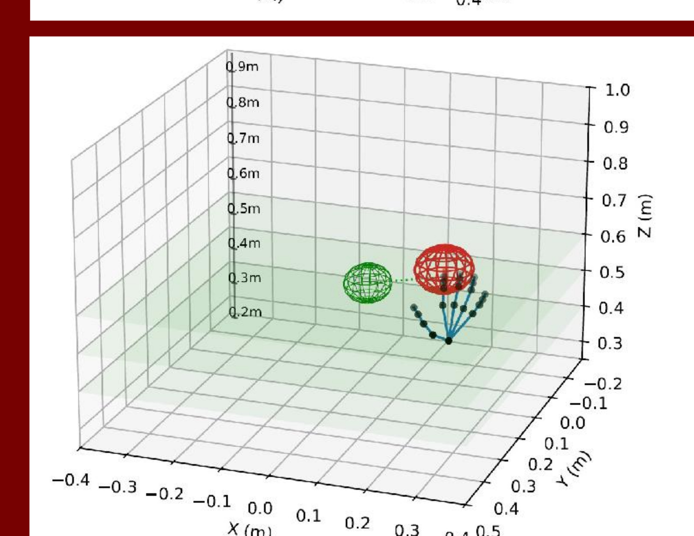
SIMULATION RESULTS



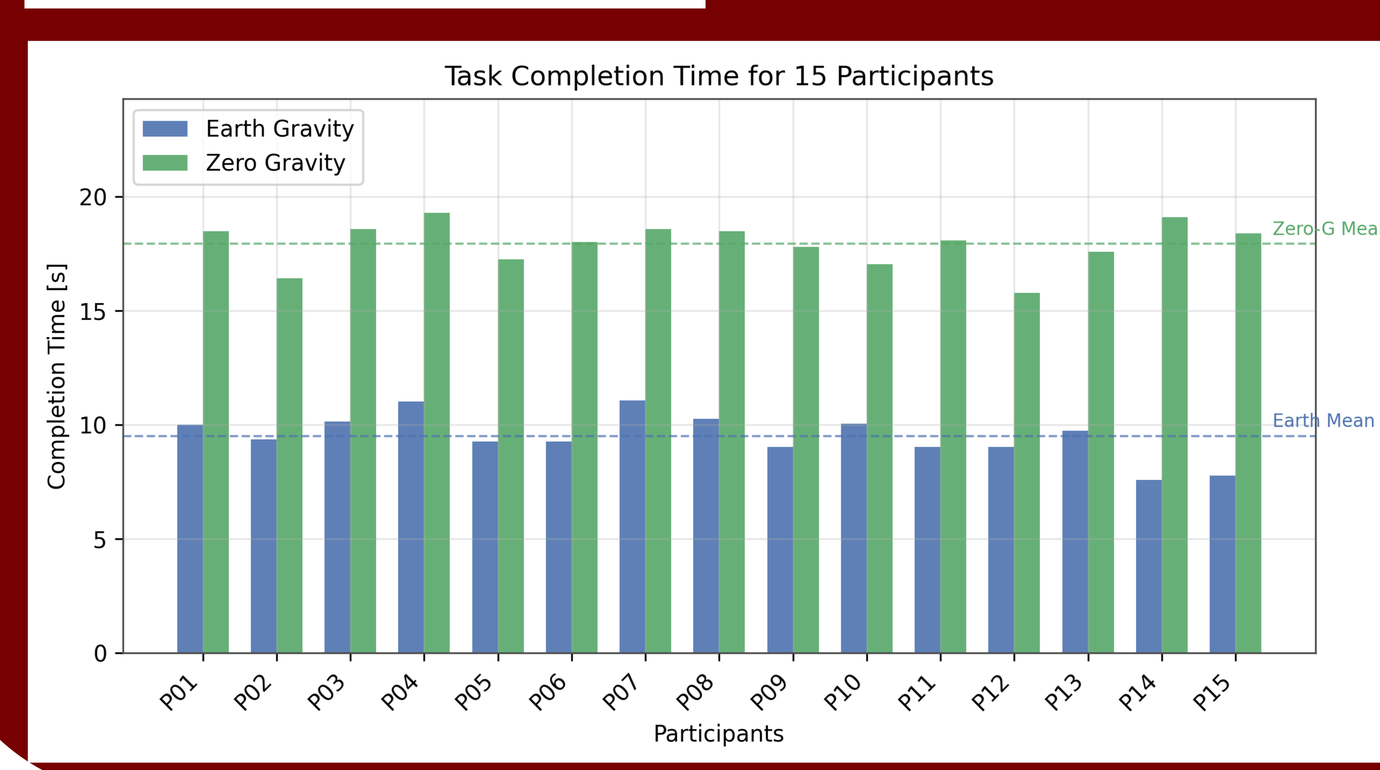
- Free-floating object under zero-gravity dynamics.



- Object attached to the hand during contact.



- Object placed at the destination marker after release.



CONCLUSIONS

- The proposed framework successfully replicates **microgravity interaction dynamics** using only a depth sensor and physics simulations.
- The system demonstrates stable 3D hand-tracking and realistic object behavior.
- Zero gravity introduces measurable delay due to the absence of a gravitational reference.
- The framework provides a **low-cost alternative** to VR or parabolic flight setups for astronaut dexterity research.

Future work

- Integration of an **instrumented glove with Inertial Measurement Units (IMU)** to improve spatial orientation and hand-object alignment.
- Extension to a **multi-camera setup** for a wider field of view and improved depth perception.
- Data collection to train adaptive control models for space robotics.

REFERENCES

- K. Zhou, C. Chen, Y. Ma, Z. Leng, H. P. H. Shum, F. W. B. Li, and X. Liang, “A mixed reality training system for hand-object interaction in simulated microgravity environments,” in 2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), 2023, pp. 167–176.
- Q. Gao, J. Li, Y. Zhu, S. Wang, J. Liufu, and J. Liu, “Hand gesture teleoperation for dexterous manipulators in space station by using monocular hand motion capture,” Acta Astronautica, vol. 204, pp. 630–639, 2023.
- L. Keselman, J. Iselin Woodfill, A. Grunnet-Jepsen, and A. Bhowmik, “Intel RealSense stereoscopic depth cameras,” in Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR)Workshops, July 2017