Laboratory Testbed Development for Modeling Spacecraft Proximity Operations

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Introduction

Proximity operations, such as rendezvous and docking maneuvers, can be challenging for spacecraft in orbit due to changes in their dynamics. A laboratory testbed is being developed to model spacecraft proximity operations with omni-directional robots by using their ground-based data to simulate docking and rendezvous in the orbital frame. This will enable testing and verification of various control algorithms and orbits utilizing hardware.

Figure 1: Illustration of two spacecraft in orbit around Earth performing proximity operations.

Experimental Setup

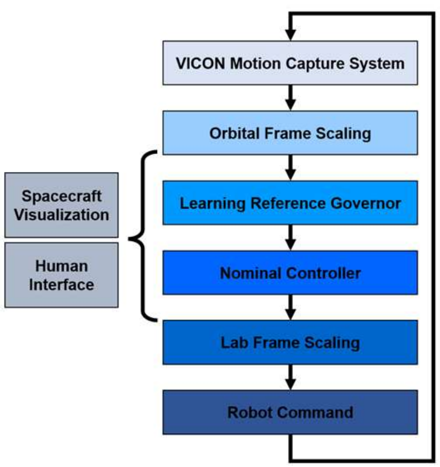


Figure 2: Flow chart of operations for the proximity operations test bed being developed.

Hardware and Software

- **Omni-Directional Robots (x4):** Low-cost robots featuring an in-house, U of Michigan open-source platforms for hardware and software, with applications for education and research.
  - Holonomic motion control and odometry with IMU and wheel encoders. Kiwi drive with 3 degrees of freedom.
  - RP4: high level control with open-source architecture
  - Raspberry Pi Pico: embedded processing
  - Position tracking capabilities via its own odometry or using an external system
- **Vicon Motion Capture System:** External position tracking system for omni-directional robots.
  - Laboratory equipped with 17 cameras
  - Tracking to 1 mm of precision
- **Visualization Software:** Model ground-based motion of robots as spacecraft in the orbital frame.
  - MATLAB modeling capabilities

Figure 3: Fully manufactured omni-directional robot side view (left), front view (center) and top view (right).

System Architecture

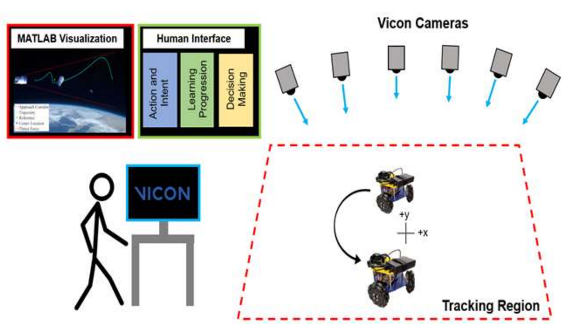
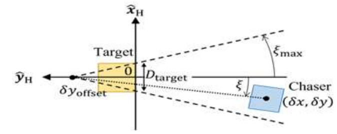


Figure 4: Illustration of fully developed and functioning physical laboratory testbed.

Methods

I. Relative Motion and Dynamics

- Hill's Frame: centered about the Target spacecraft [1]
- Clohessy-Wiltshire equations of motion (eq. 1) [2]



$$\ddot{x} - 3n^2x - 2n\dot{y} = \frac{F_x}{m_d}$$
$$\ddot{y} + 2n\dot{x} = \frac{F_y}{m_d} \quad (1)$$
$$\ddot{z} + n^2 z = \frac{F_z}{m_d}$$

II. Orbital and Lab Frame Scaling [2]

- Length scaling parameter υ and time scaling parameter κ
  - Lab distance is scaled by a factor of $1/\upsilon$
  - Lab velocity is scaled by κ/υ

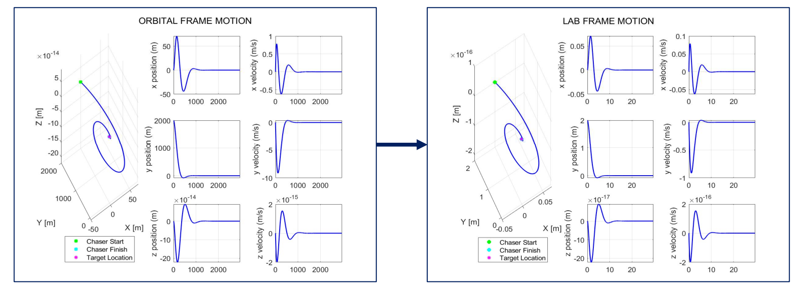
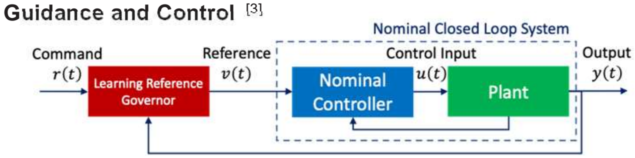


Figure 5: Example of a rendezvous procedure being scaled from the orbital (left) to the laboratory (right) with $\upsilon = 0.001$ and $\kappa = 0.01$.

III. Guidance and Control [3]



Future Work

Future steps will include continuing to investigate and implement an orbital scale visualization via MATLAB as well as a human factors component to this testbed. Testing will also begin including rendezvous with two moving omni-directional robots as opposed to one moving and one stationary, as well as verification of a Learning Reference Governor.

References

[1] Curtis. (2020). Orbital Mechanics for Engineering Students. Elsevier.
[2] Goodyear, A., Petersen, C., Pierre, J., Zagaris, C., Baldwin, M., & Kolmanovsky, I. (2015). Hardware implementation of model predictive control for relative motion maneuvering. 2015 American Control Conference (ACC). https://doi.org/10.1109/acc.2015.7171077
[3] Ikeya, K., Liu, K., Girard, A., & Kolmanovsky, I. V. (2022). Learning to satisfy constraints in spacecraft rendezvous and proximity maneuvering: A learning reference governor approach. AIAA SCITECH 2022 Forum. https://doi.org/10.2514/6.2022-2514