Hardware-in-the-Loop Spaceflight Testbeds

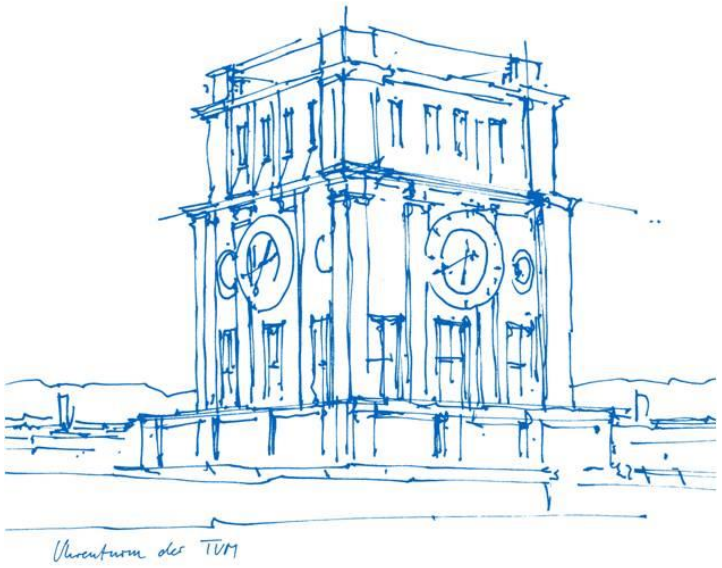
Bridging Systems Engineering Gaps in Graduate Education

Prof. Dr. Marcello Romano

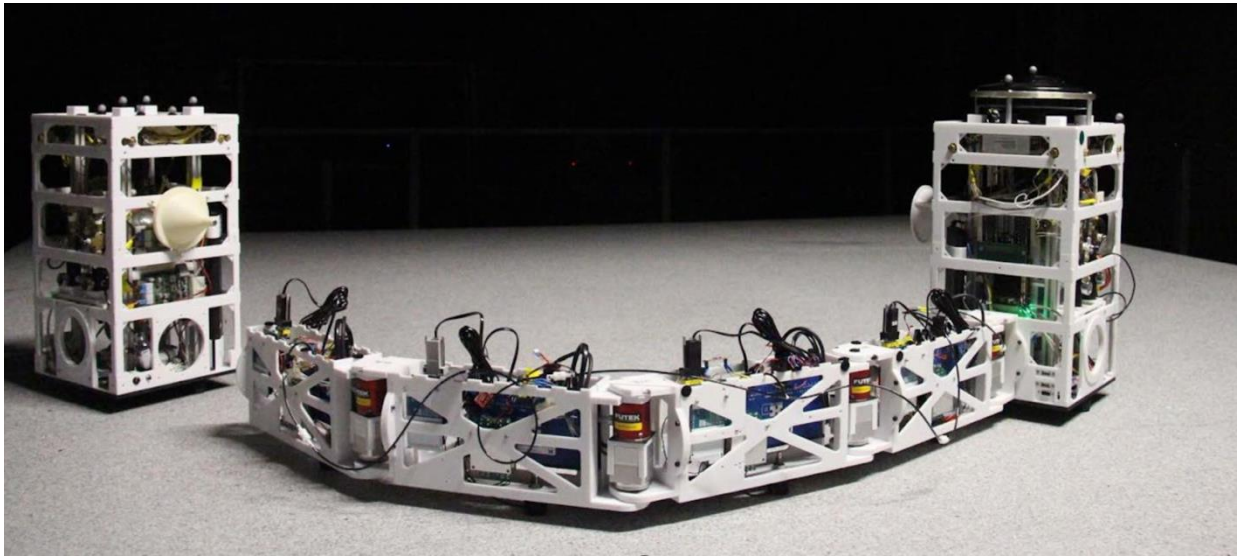
Chair of Astrodynamics
Technical University of Munich (TUM)

Systems Workforce Summit

27-28 October 2026



Frictionless Table Facilities



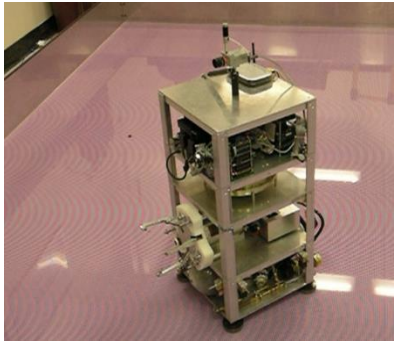
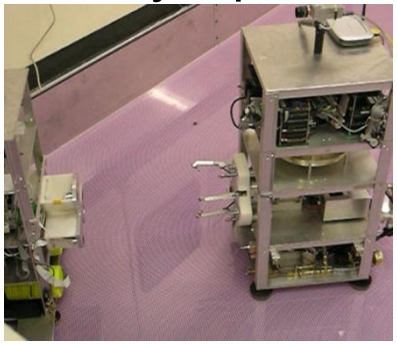
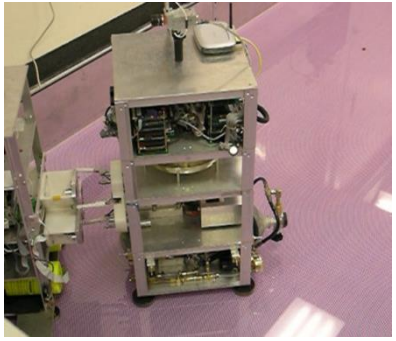
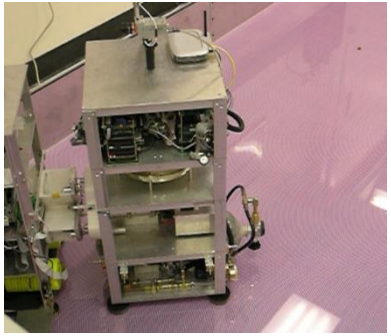
Key subsystems:

- Floating Spacecraft Simulators (FSS)
- Granite Table
- Metrology system
- Real-time software implementation of GN&C algorithms

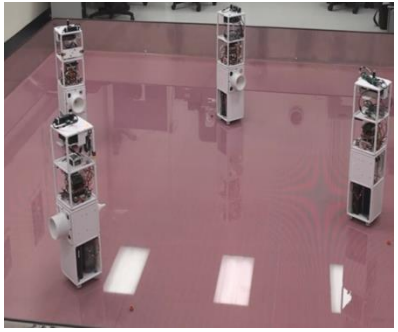
Frictionless Table Facilities: Purpose

Education & research on autonomous Guidance, Navigation, and Control for

- Rendez-vous & Proximity Operations maneuvers

- In-space Assembly maneuvers



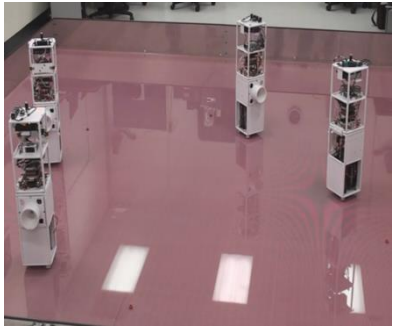
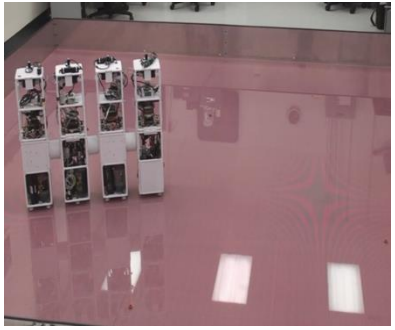
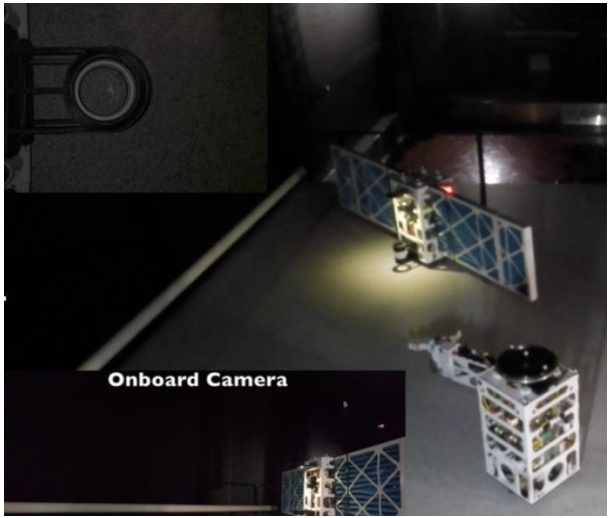
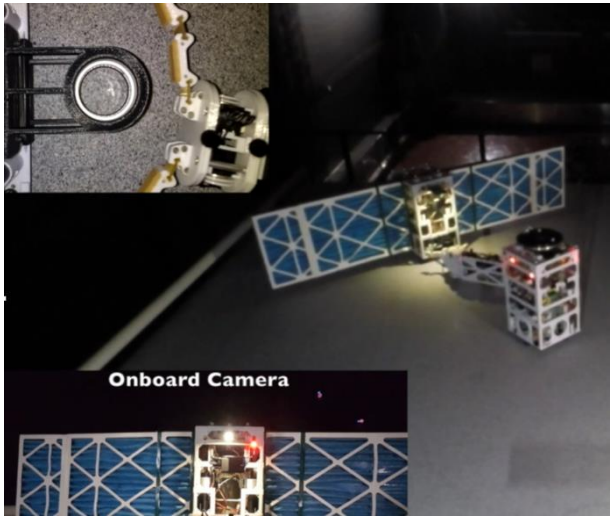



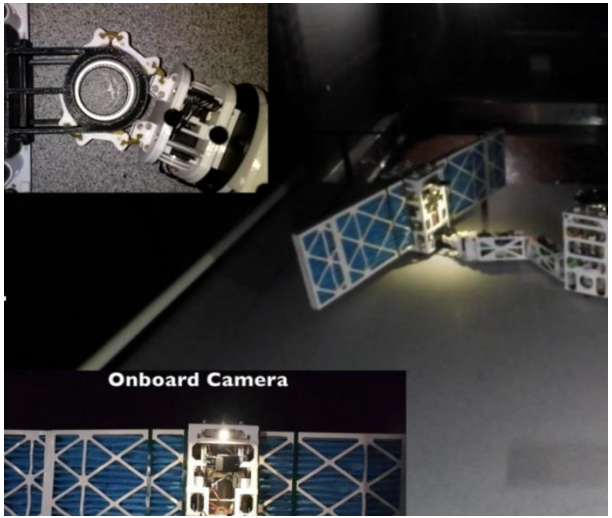
Figure credit: NPS-SRL, Romano

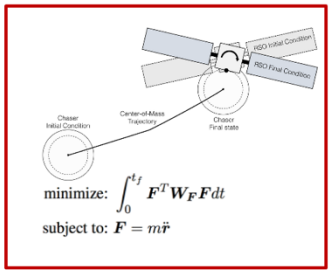
Frictionless Table Facilities: Purpose

- Grasping-of-tumbling-object maneuvers (Servicing, Debris Removal, etc.)

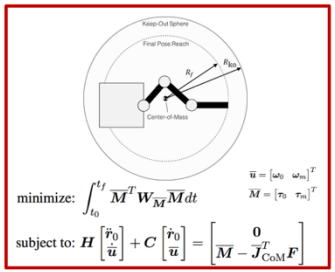








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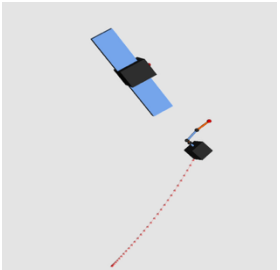
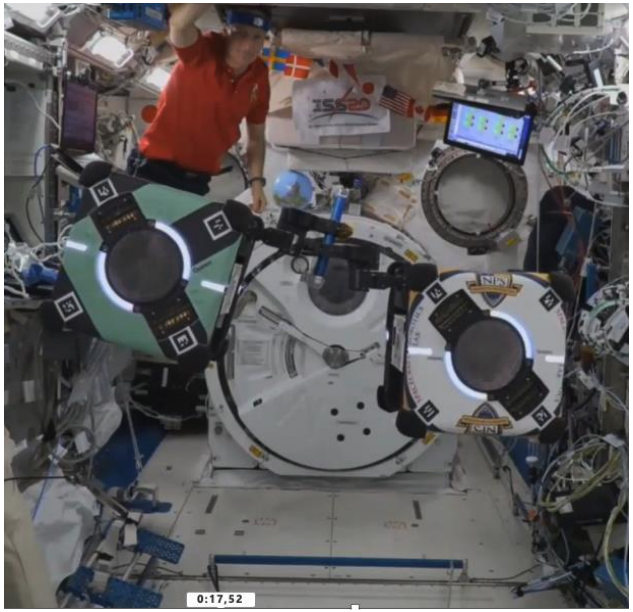
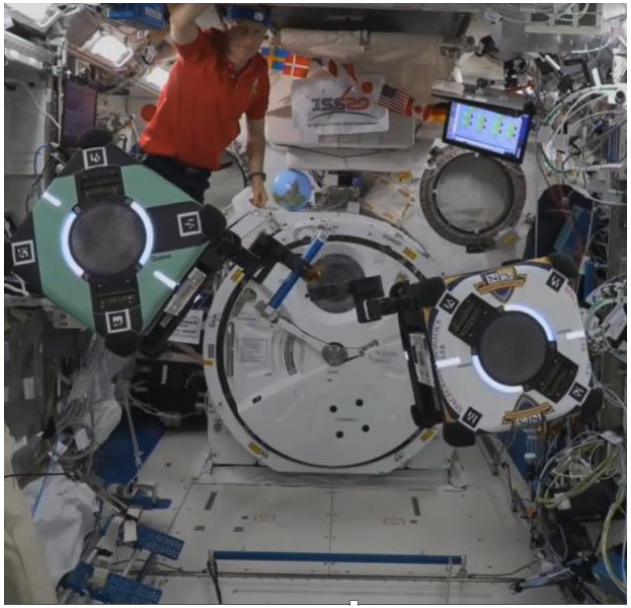


Figure credit: NPS-SRL, Romano

EVA Free Flyers on the ISS

Higher realism facilities, beyond frictionless table:





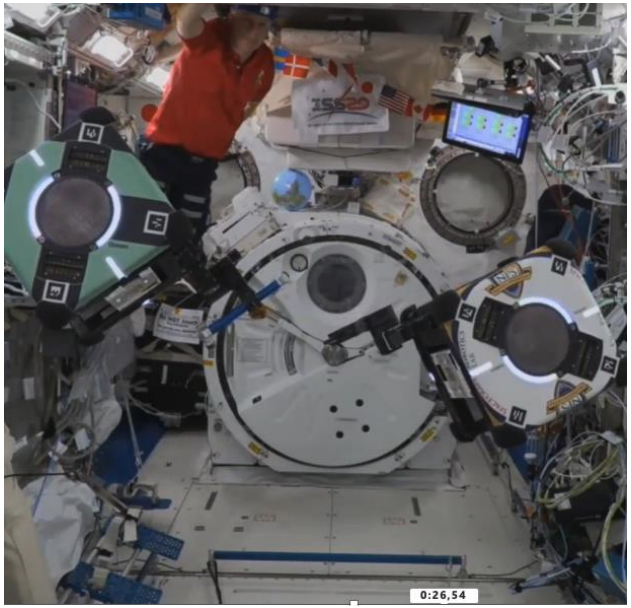


Figure credit: NASA, NPS-SRL, Romano

HIL Dynamic Simulator Testbeds
Benefits for Education & Workforce Development

- **Hands-on SE learning:**
  - Students first design & integrate real hardware spacecraft-like systems,
  - then they test and operate them in a representative dynamic environment
- **Research platform:** autonomous proximity maneuvers, docking, and ISAM
- **Verification & validation of**: multibody dynamics models, AOCS, GN&C
- **From theory to flight-like testing**: algorithms are exercised with real sensors, actuators, contact mechanics, delays and noise

Source: personal experience (25+ years with HIL testbeds at NPS and TUM)

Conclusions

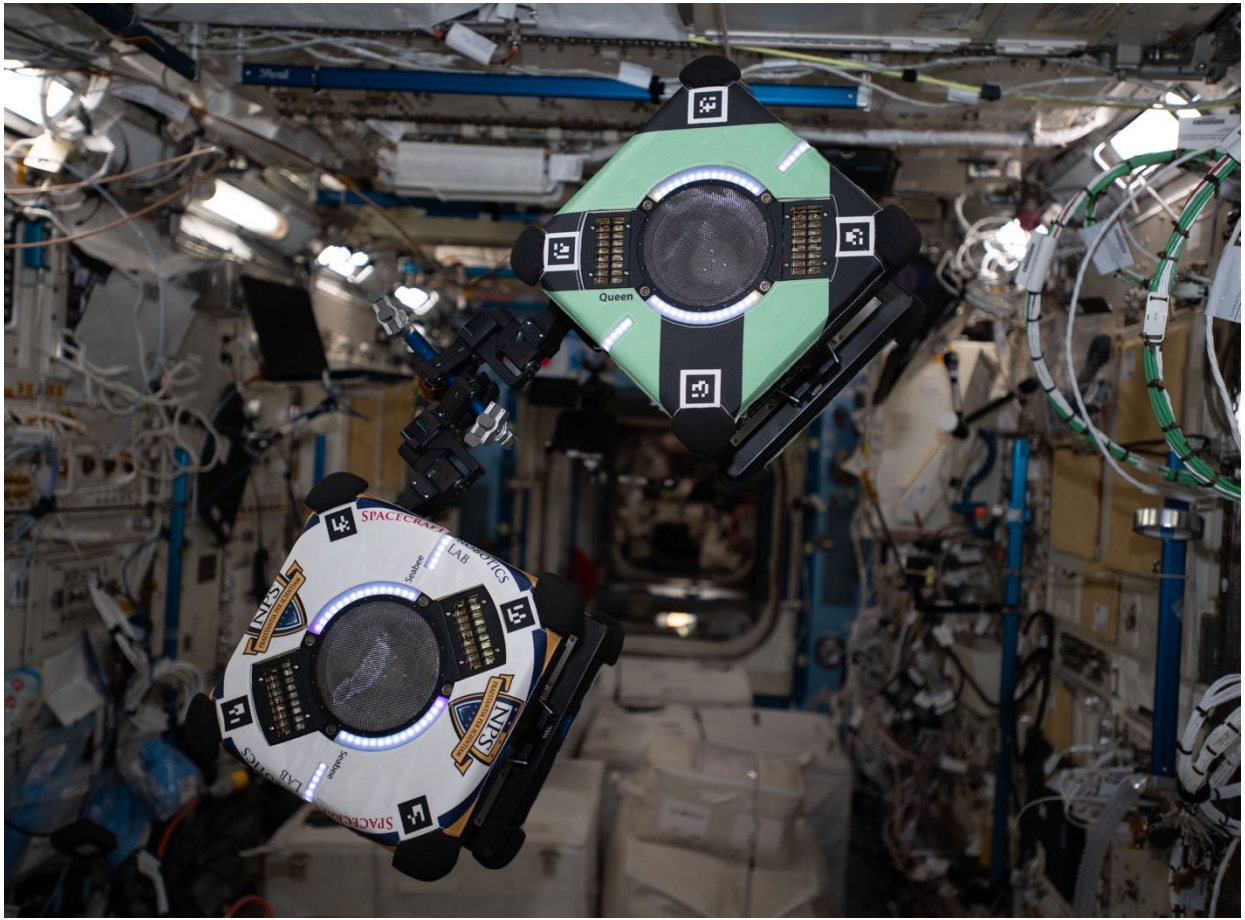
- **HIL dynamic simulators** are essential resources for teaching and research in graduate astronautics programs

- **Open-source hardware and software enable:**
  - Collaboration across different laboratories
  - Reproducibility and independent verification of results
  - Comparative studies on common platforms

- **Testbed development as a capstone project:** design, integration and testing of custom simulator systems and subsystems

- **Workforce outcome:** students and young professionals gain hands-on experience in spacecraft design, system integration, spacecraft operations

Thank you for your attention



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