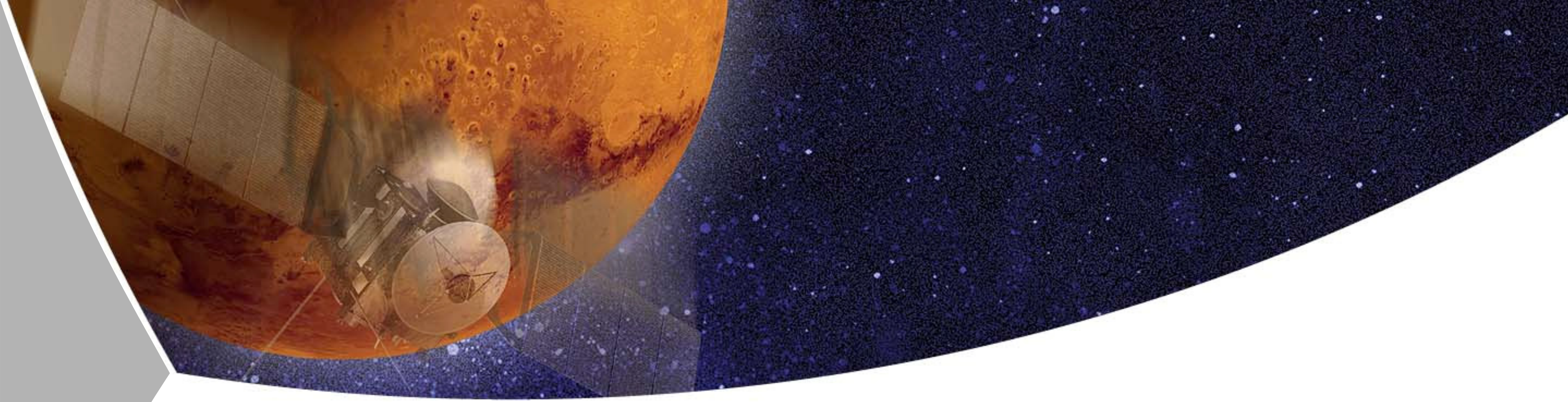

Passivity Control for Hybrid Simulations of Satellite Docking

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ICRA11 Space Robotics Workshop
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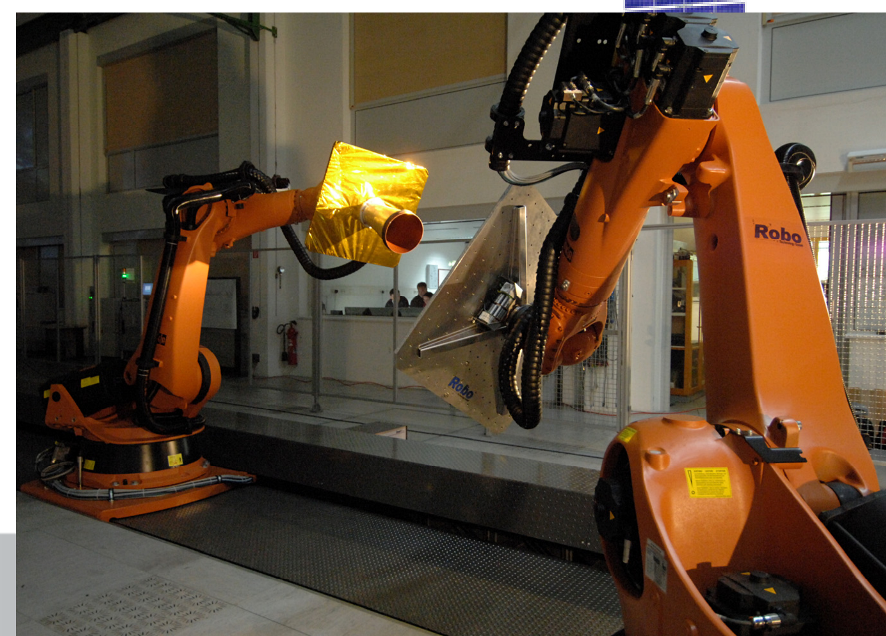
DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Contents of Workshop Contribution

Simulation activities in the context of On-Orbit Servicing

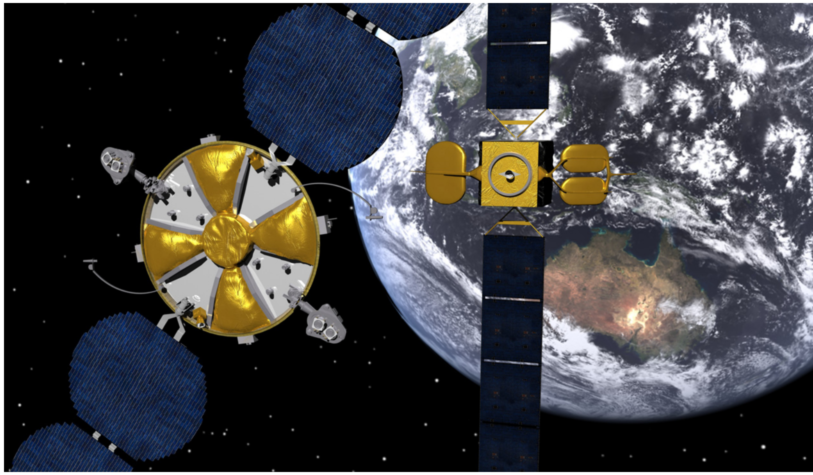
Focus: Contact dynamics simulation

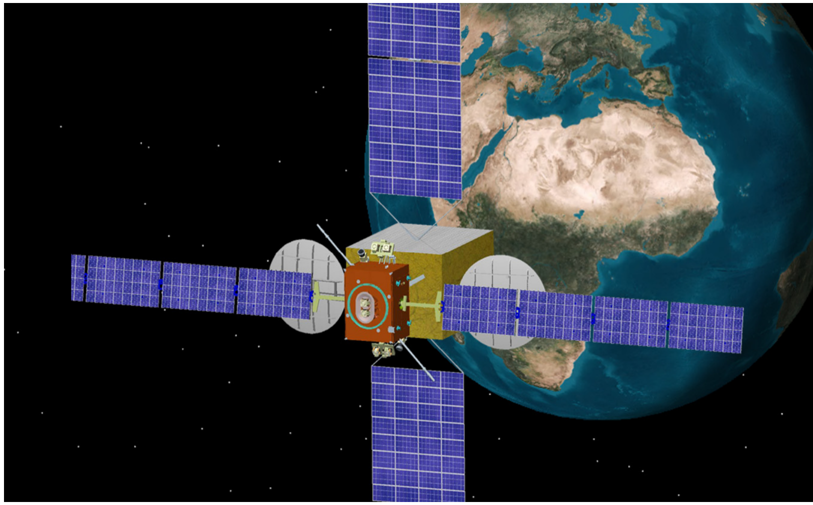
- On-orbit servicing projects and contributions
  - CX-OLEV & Smart-OLEV
- Modeling and simulation in software
  - Contact dynamics modeling
  - Docking simulation results
- Hybrid simulation using EPOS RvD facility
  - Introduction of hybrid simulation method
  - Introduction of EPOS facility
  - Contact dynamics simulation with EPOS
    - Numerical stability aspects
    - Passivity control



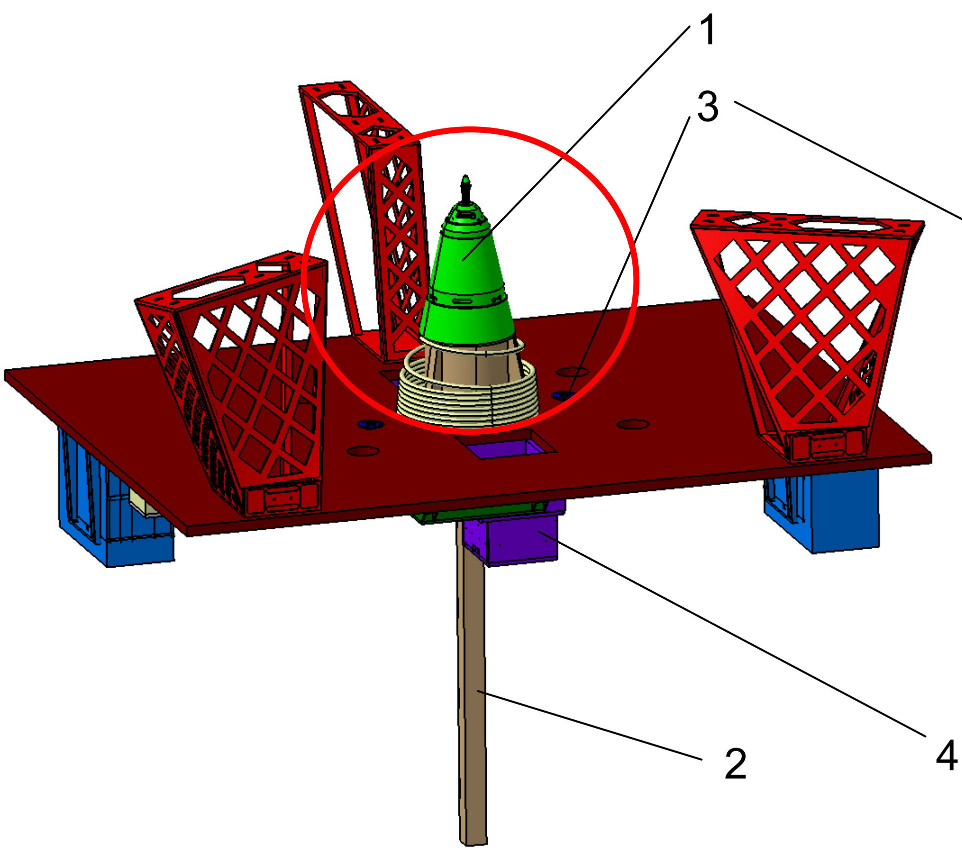
On-Orbit Servicing Projects – OLEV Type Missions (Orbital Live Extension Vehicle)

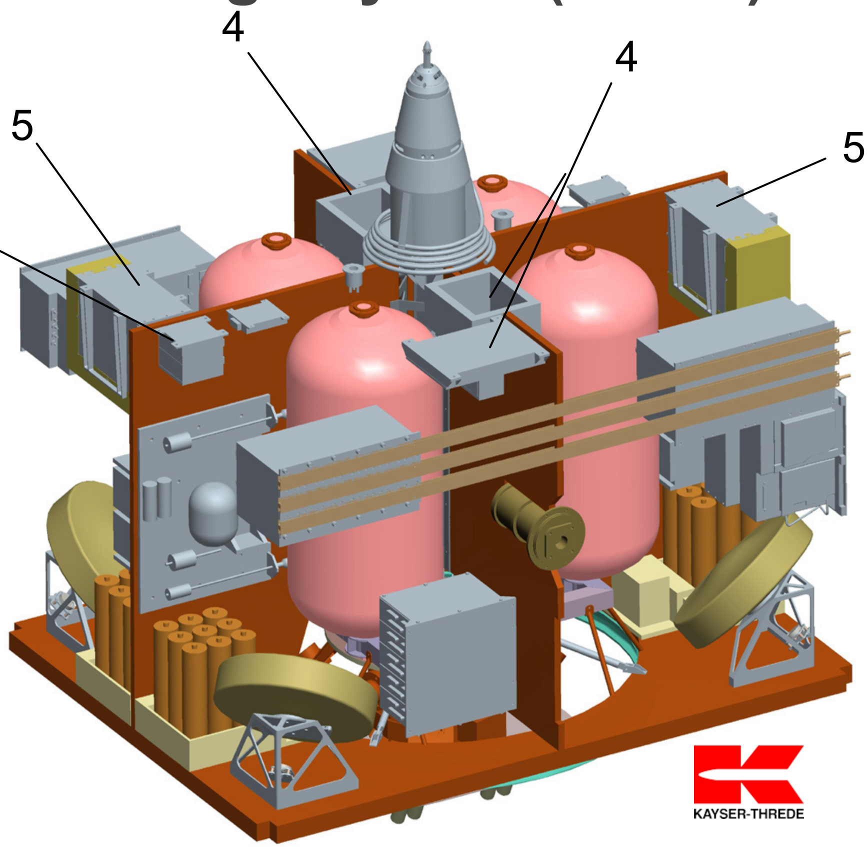
- Projects involved:
  - CX-OLEV (ESA, Dutch Space & contractors)
  - Smart-OLEV (Kayser-Threde, SSC, Senser & contractors)
- Clients: Telecom satellites in GEO
- Objectives: Offer commercial services
  - Satellite operators (Eutelsat, Optus)
  - Satellite live extension
  - Fleet management
- DLR contributions
  - Robotic docking tool (Capture Tool)
  - Rendezvous and docking control algorithms (image processing)
  - Docking simulations (S/W)





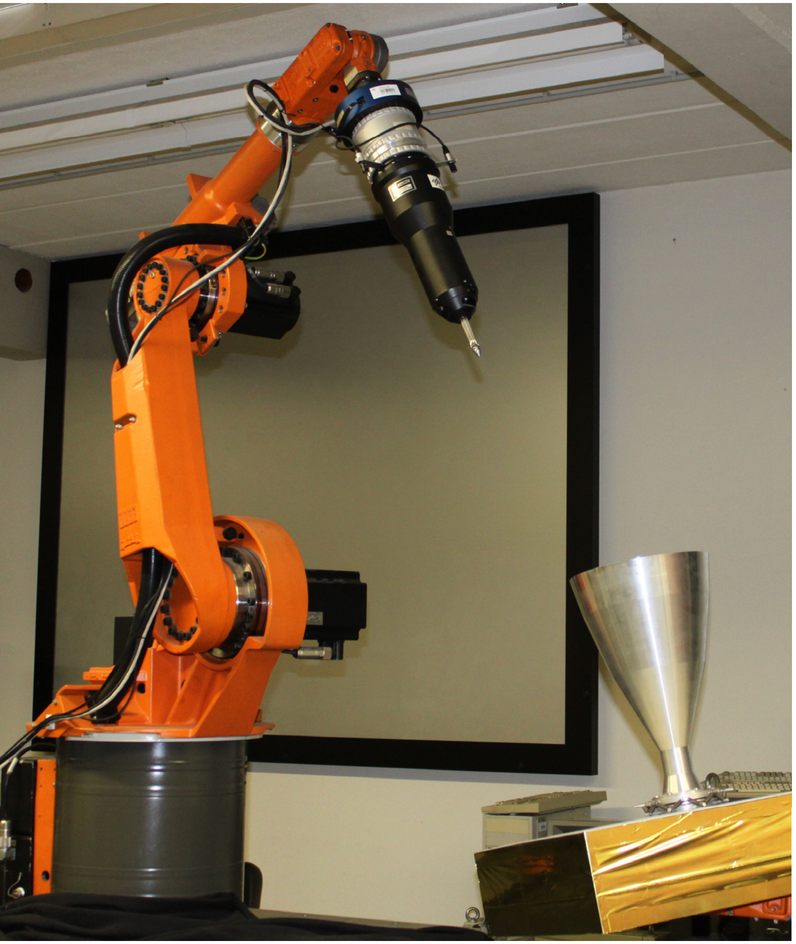
OLEV Servicing Satellite & Docking Payload (Smart)

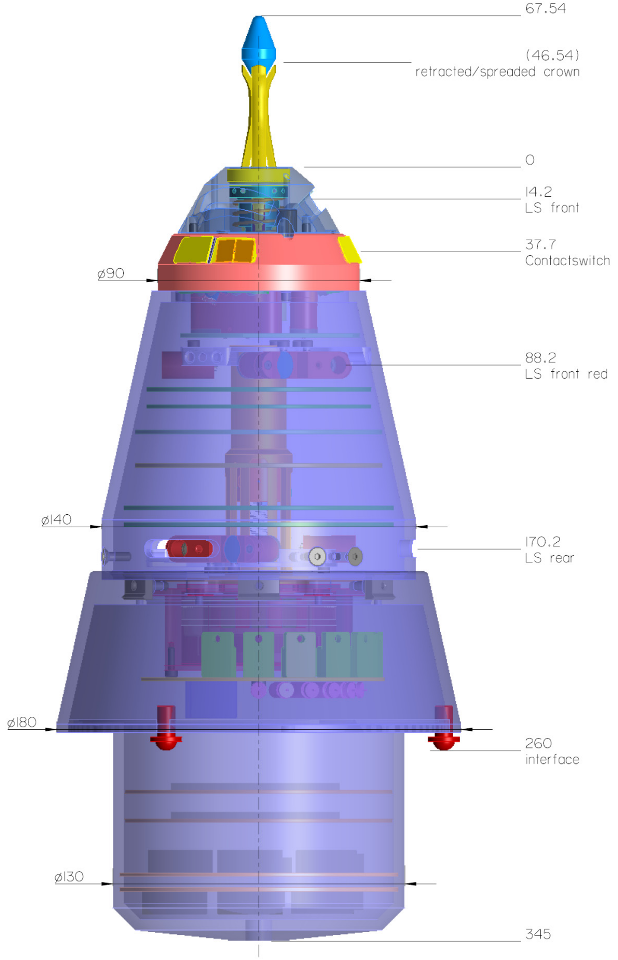


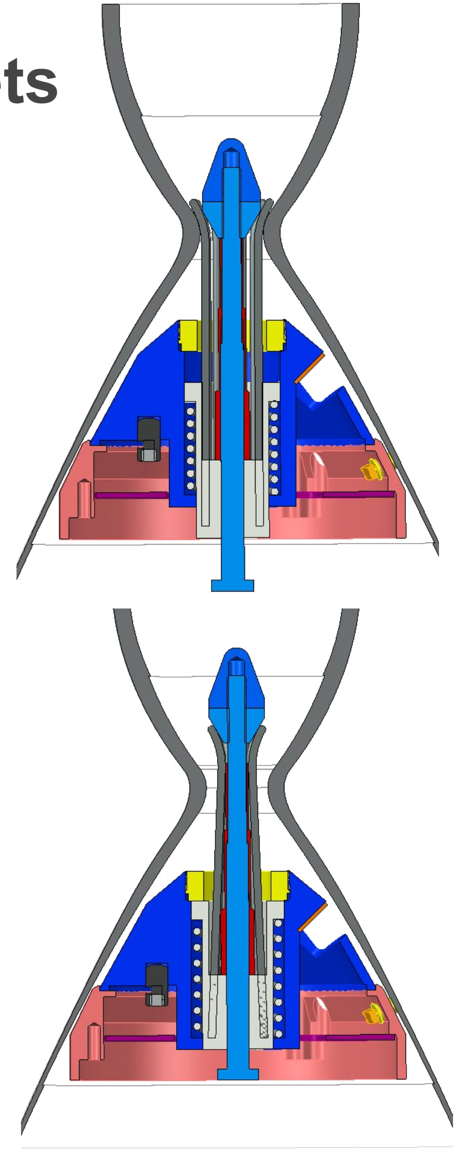


1) Capture Tool (CT)
2) CT Deployment Mechanism (CDM)
3) Target Illumination System (TIS) (2x)
4) Camera System (Far-, Mid-, Near-Range Cameras with Electronics) (2x)
5) Docking Payload Control Unit (2x)

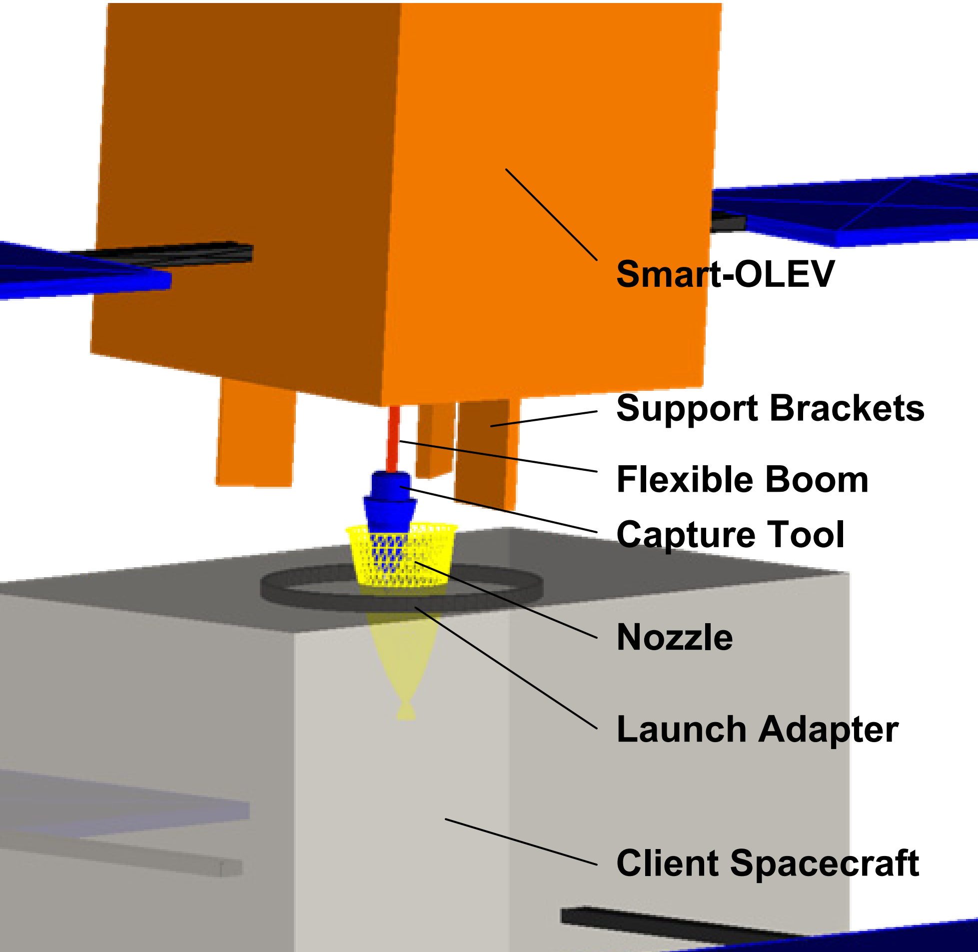
Capture Tool for Non-Cooperative Targets





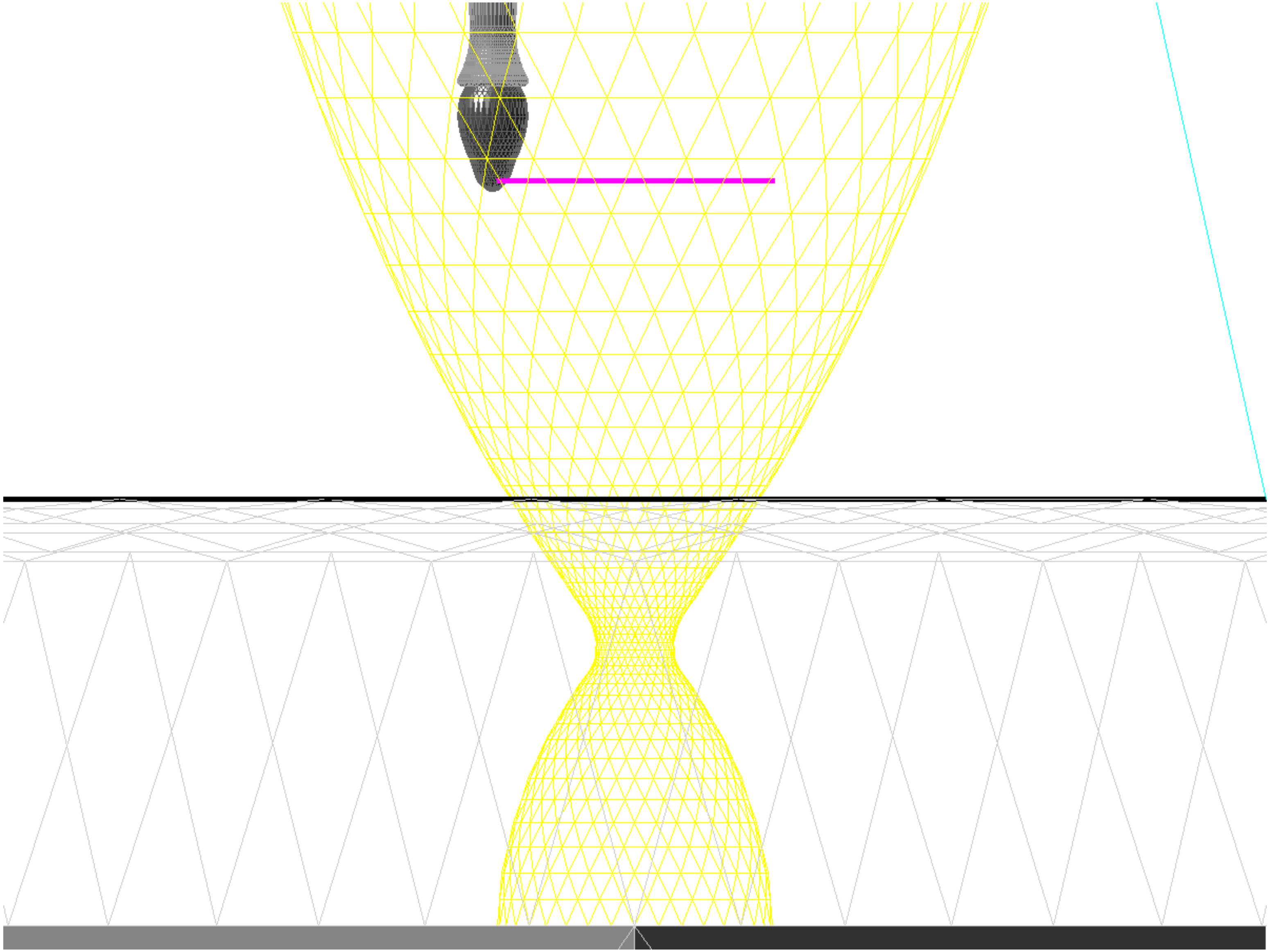


Docking Scenario for Multi-Body System Simulation

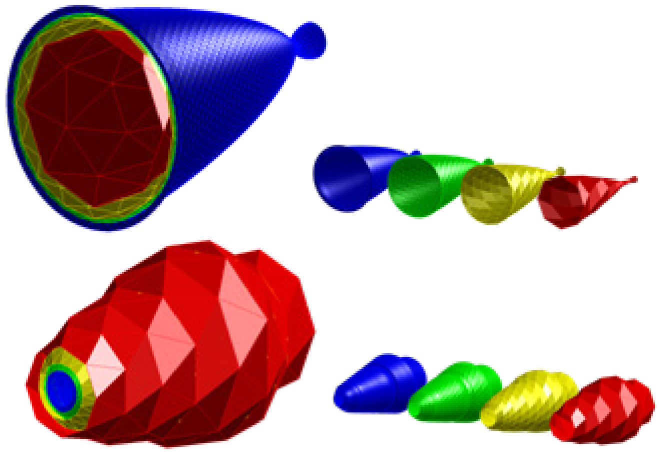


- Client
  - Hot Bird series, with flexible solar wings
  - Orbit: GEO
  - AOCS deactivated, momentum wheels loaded
  - Aerojet/Marquardt R4D nozzle, **slightly tilted**
  - 1194 mm launch adapter
- Smart-OLEV
  - Orbit: GEO + 2.178 m (R-bar)
  - AOCS active
  - 75 mm **lateral misalignment**, 2° **attitude error** in all axes
- Flexible Capture Tool deployment mechanism
  - $|v| \leq 4$ mm/s deployment/retraction velocity
- Capture Tool
  - Radial laser distance sensor
  - Contact switches
  - Operational Locking Crown
- Contact sensitive bodies:
  - Nozzle vs. Capture Tool + Locking Crown
  - Launch adapter vs. Client Support Brackets

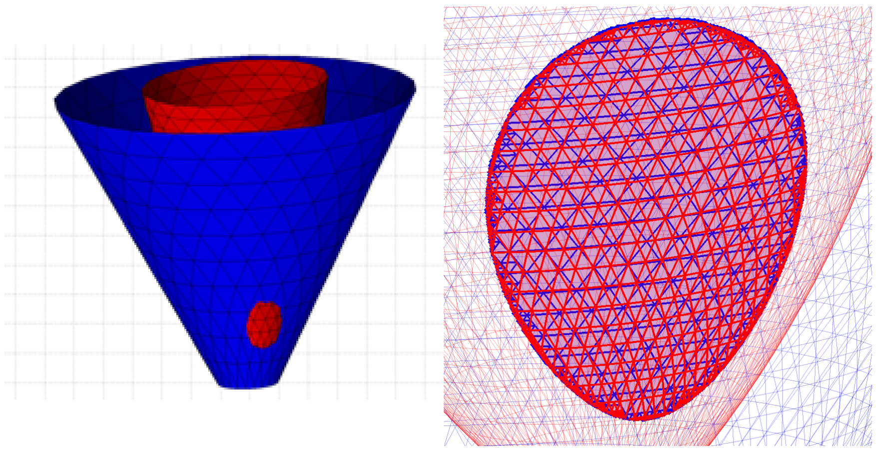
DLR · Kayser-Threde · Swedish Space Corporation · SENER



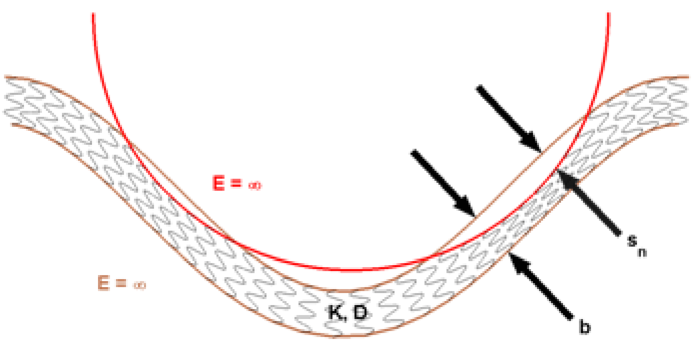
Contact Dynamics Model (3D, Multi-Point)



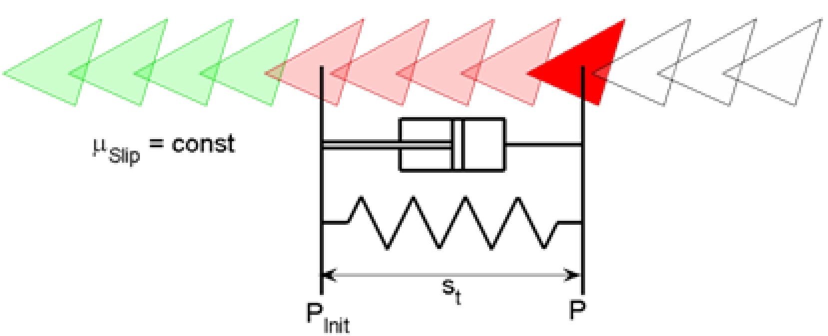
- Surface meshing
- Bounding volume tree generation



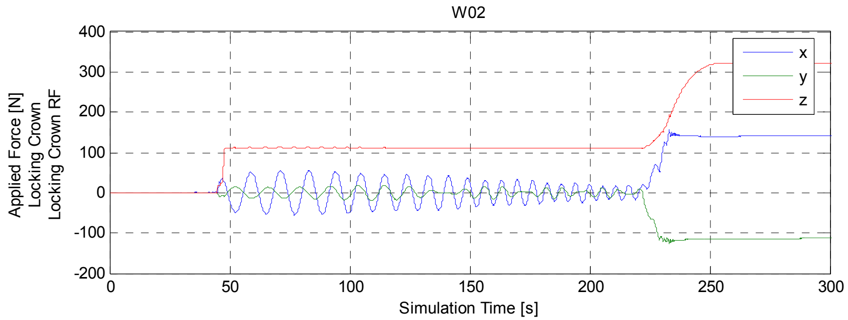
- Contact area detection algorithm

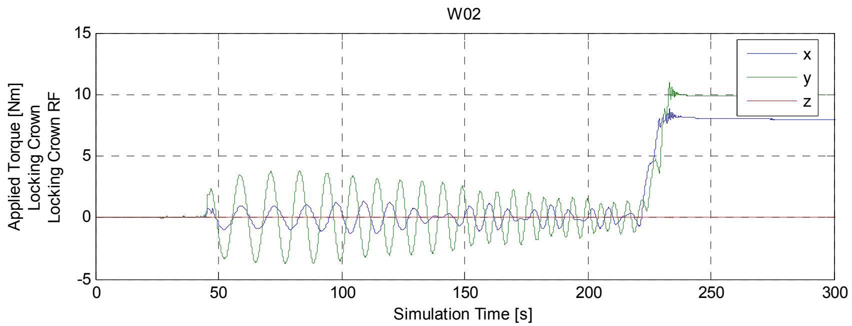


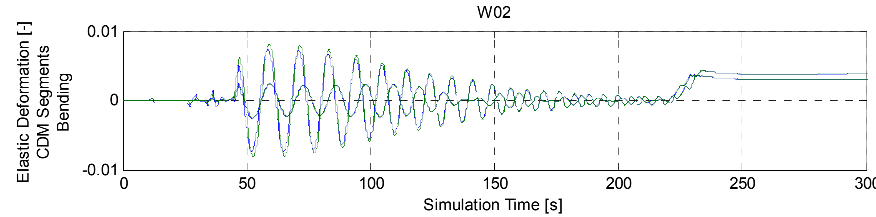
- Elastic foundation model for contact force computation

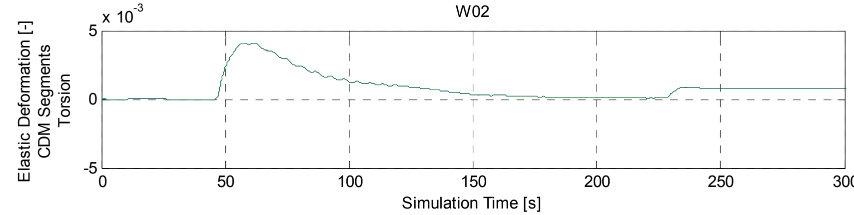


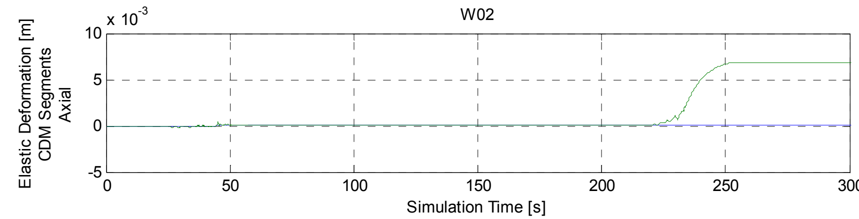
- Friction model with stick-slip

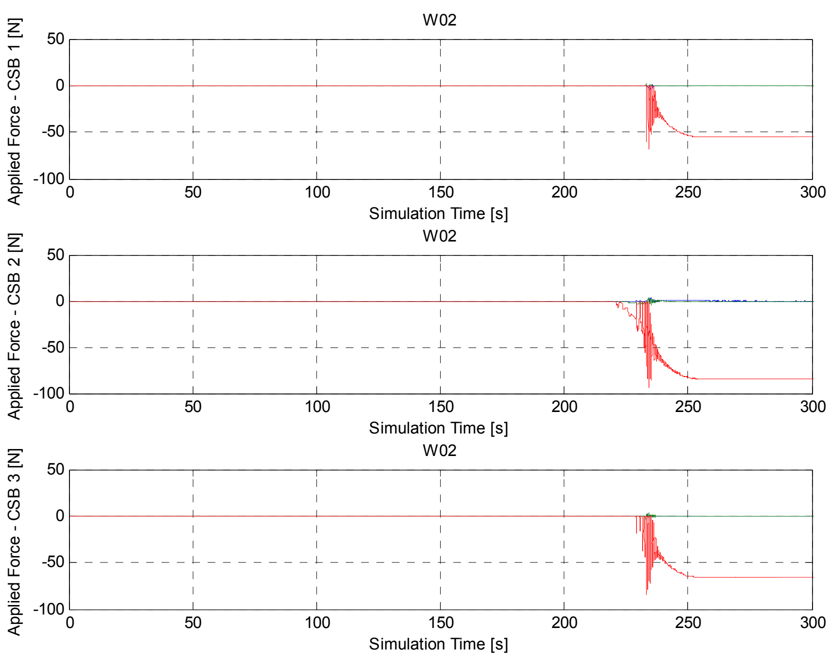

W02
Applied Force [N]
Locking Crown
Locking Crown RF
Simulation Time [s]
x
y
z

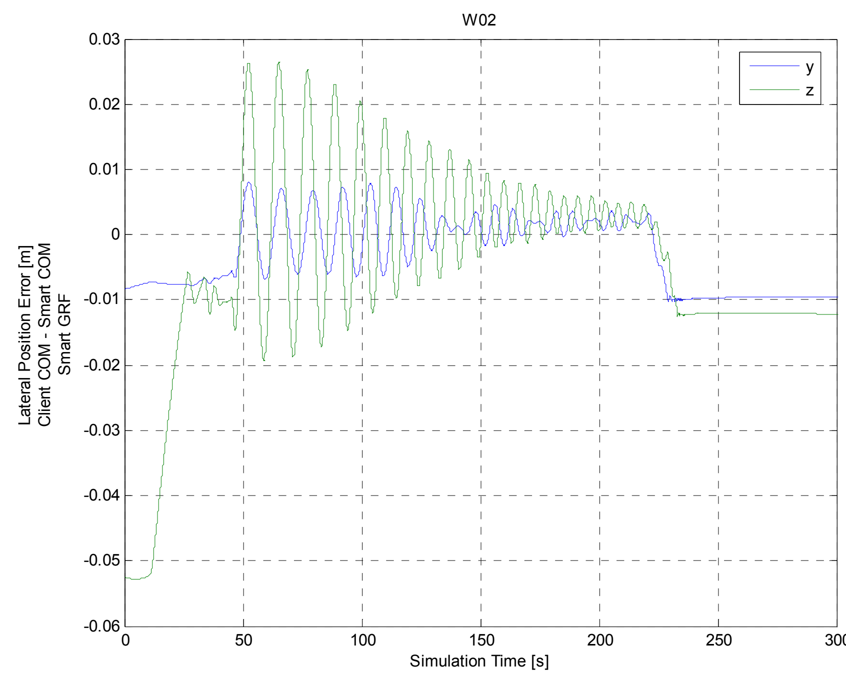

W02
Applied Torque [Nm]
Locking Crown
Locking Crown RF
Simulation Time [s]
x
y
z


W02
Elastic Deformation [-]
CDM Segments
Bending
Simulation Time [s]


W02
x 10^-3
Elastic Deformation [-]
CDM Segments
Torsion
Simulation Time [s]

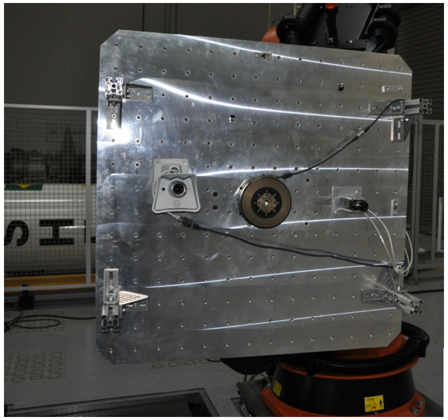

W02
x 10^-3
Elastic Deformation [m]
CDM Segments
Axial
Simulation Time [s]


W02
Applied Force - CSB 1 [N]
Simulation Time [s]
W02
Applied Force - CSB 2 [N]
Simulation Time [s]
W02
Applied Force - CSB 3 [N]
Simulation Time [s]


W02
Lateral Position Error [m]
Client COM - Smart COM
Smart GRF
Simulation Time [s]
y
z

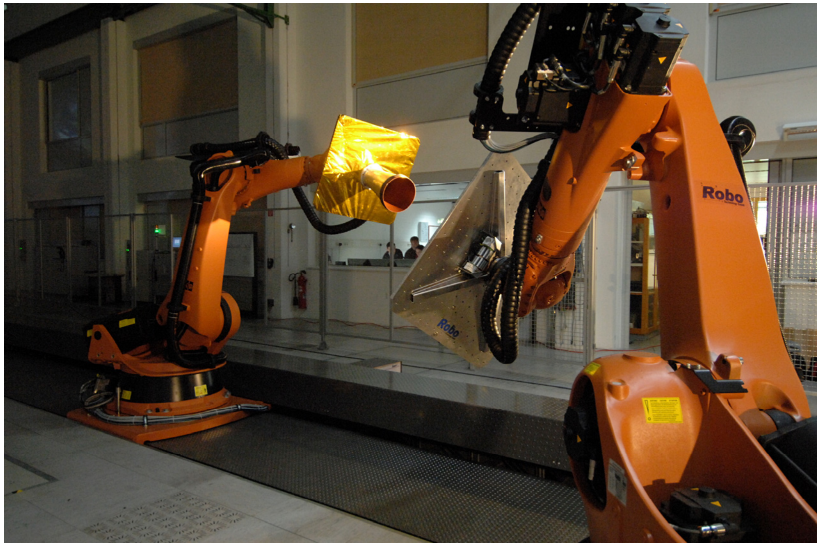
Hybrid Simulation Method

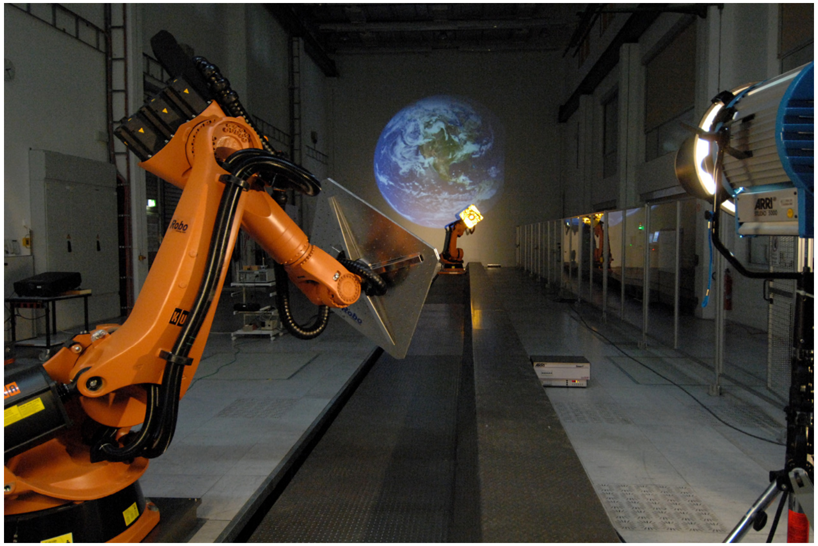
1. Numerical simulation of satellite trajectory (S/W)
   - Free floating dynamics of satellites, 6 DOF
   - Micro-gravity / 0-gravity conditions
   - Large flexible structures, solar panels
   - Momentum wheels, reaction wheels, thrusters
2. Physical-mechanical display of computed trajectory using industrial robots
   - Attachment of satellite mockups
   - Perform physical contact (capture tool, nozzle)
   - Use of missions specific mechanisms, actuators and sensors (capture tool, GNC-sensors)
3. Sensor data feedback from facility specific sensors
   - Robot joint sensors → actual trajectory
   - Force torque sensors → contact dynamics purposes



Hybrid Simulation Facility
EPOS (European Proximity Operations Simulator)

1. Development system for dynamics models: Matlab/Simulink
   Real-time target for numerical simulation: VxWorks
2. Robotic system for trajectory emulation: (Kuka, RSI, position controlled)
3. Force/torque sensor feedback: Schunk/DLR FTS (“Compliance”)

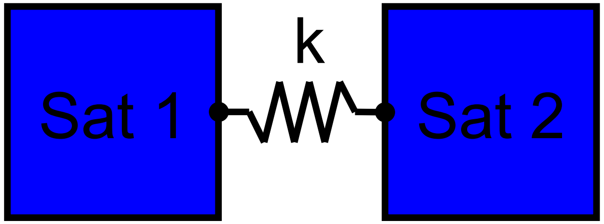




EPOS has a long history as open-loop satellite rendezvous simulator (ATV sensor verification).

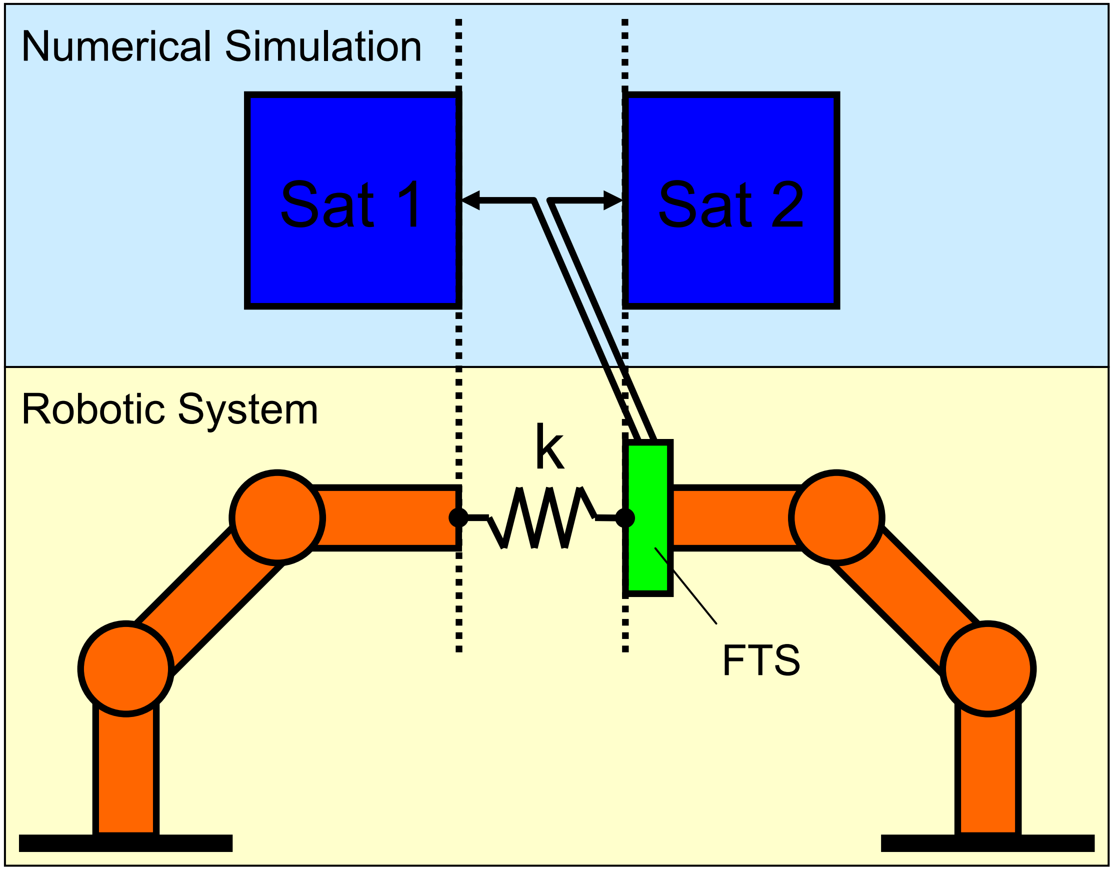
But: Is EPOS applicable for closed-loop contact dynamics simulations?

Hybrid Simulation of Docked Configuration



System to be simulated
"Ideal System"

- Free floating rigid bodies
- Spring at natural length
- v = 0

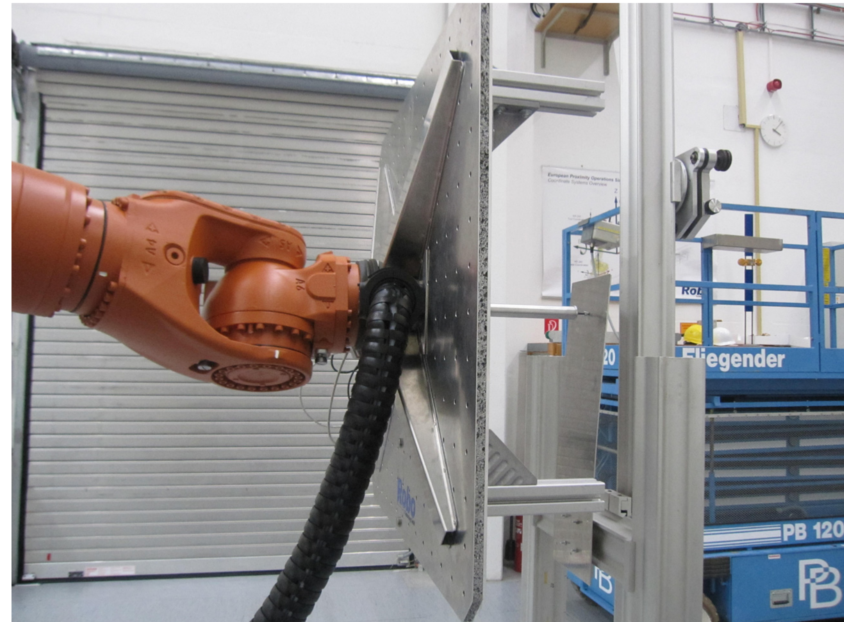


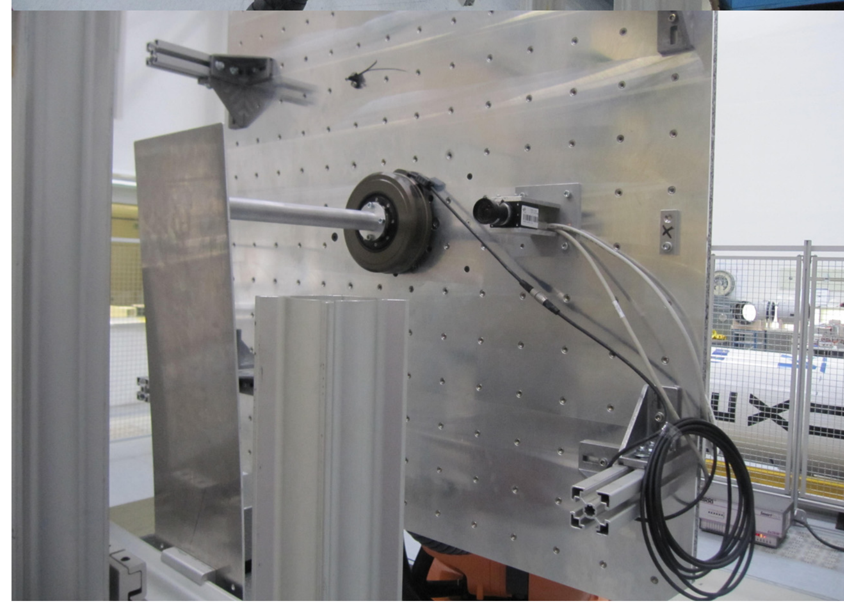
Hybrid simulation setup

Experimental Setup
“Docked Configuration”

- Simulating the elastically fixed configuration (1 DOF) using single robot and one-end supported aluminum sheet metal
    1. Open hybrid simulation loop
    2. Initial robot/satellite position with bent beam
    3. Sensor calibration/reset (F = 0)
    4. Close hybrid simulation loop again

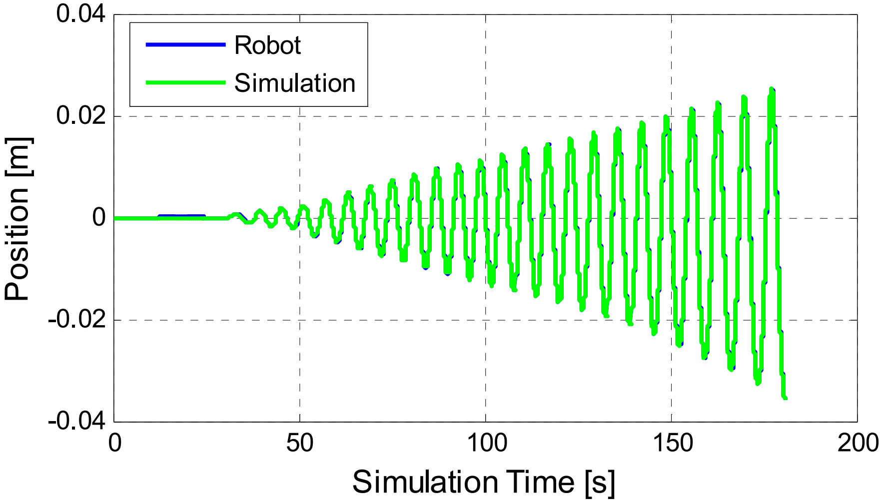
- Easy mechanical setup
- Nearly linear stiffness and low damping
- Easy stiffness adaptation by changing contact point distance from support point
 (1500 N/m … 3000 N/m)
- Low risk of mechanical damage during experiment

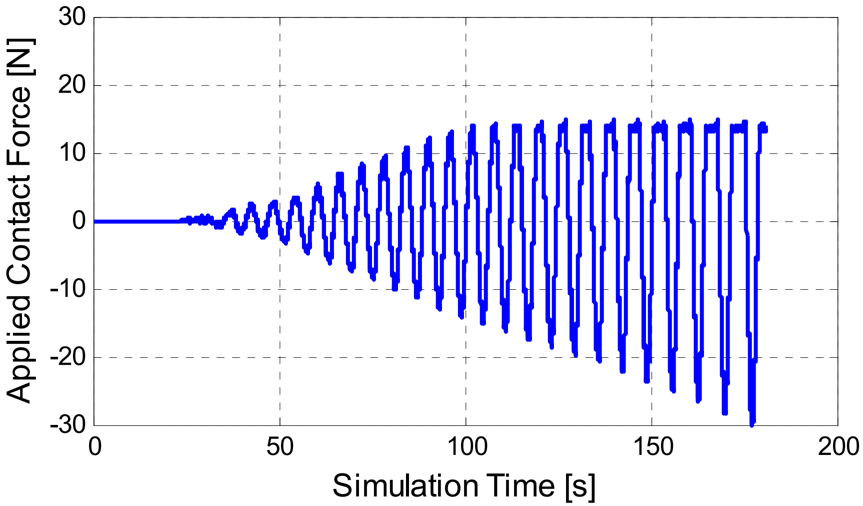


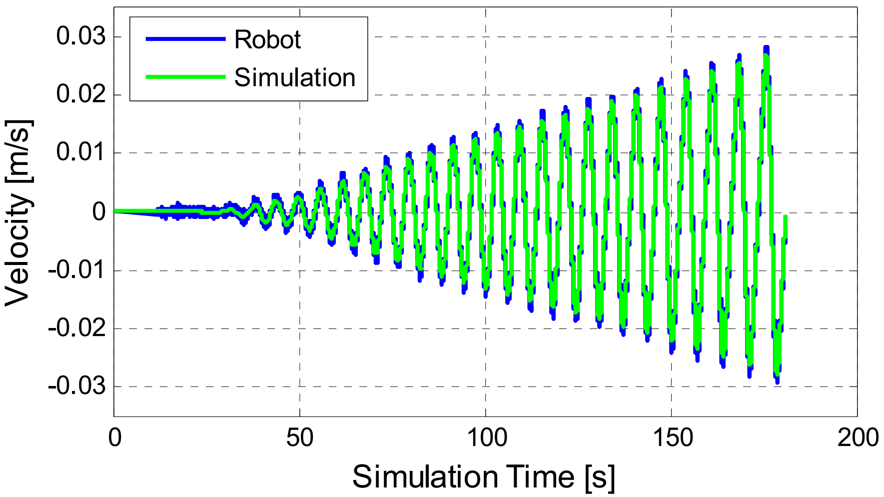


Observations

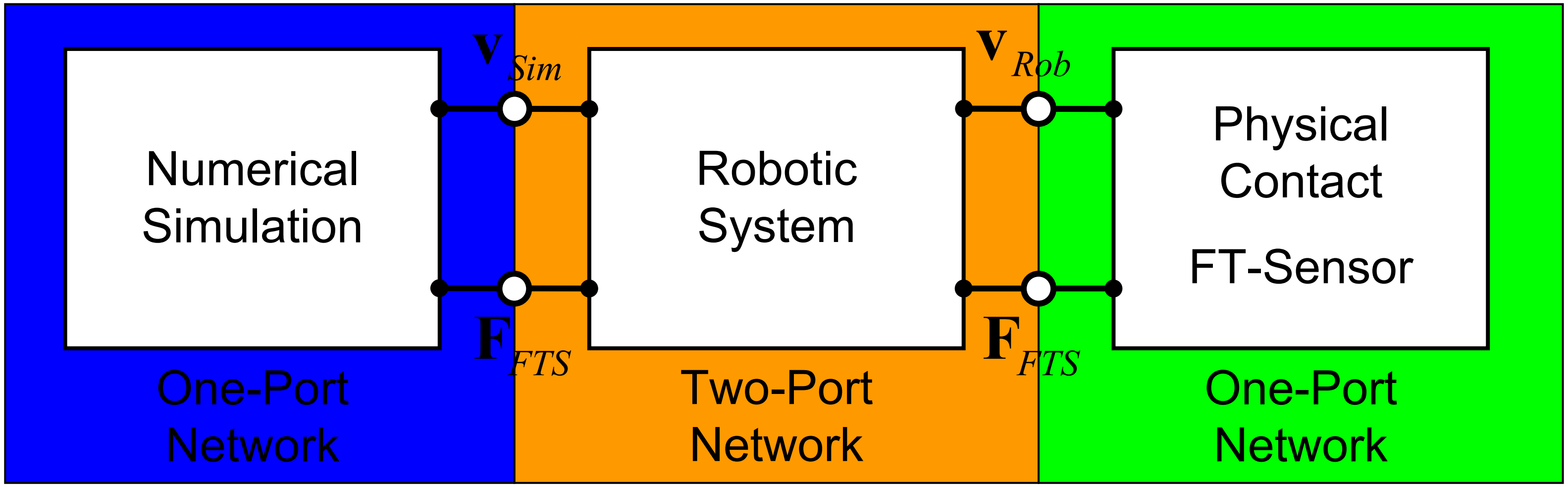
- Expected: Stationary system at rest
- Observed: Unstable system
  - Oscillating system
  - Increasing amplitudes





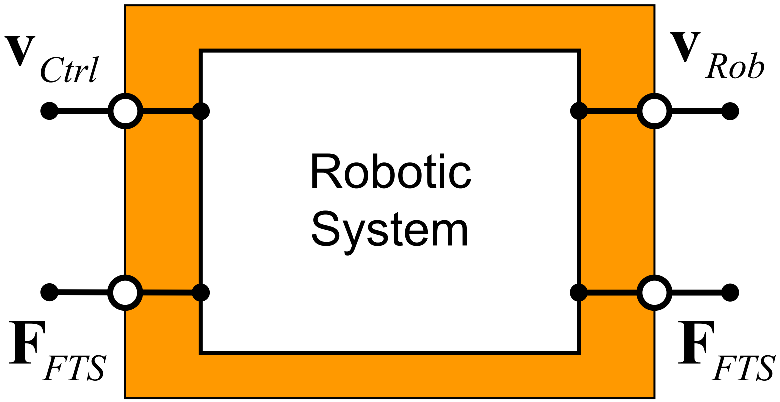


Sources of Excitation? --- Active Elements?

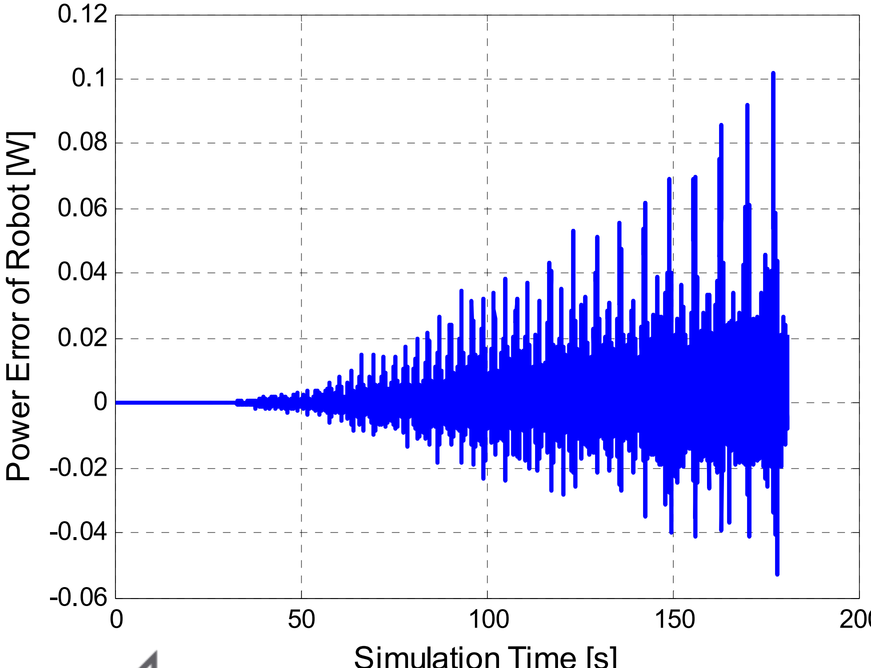


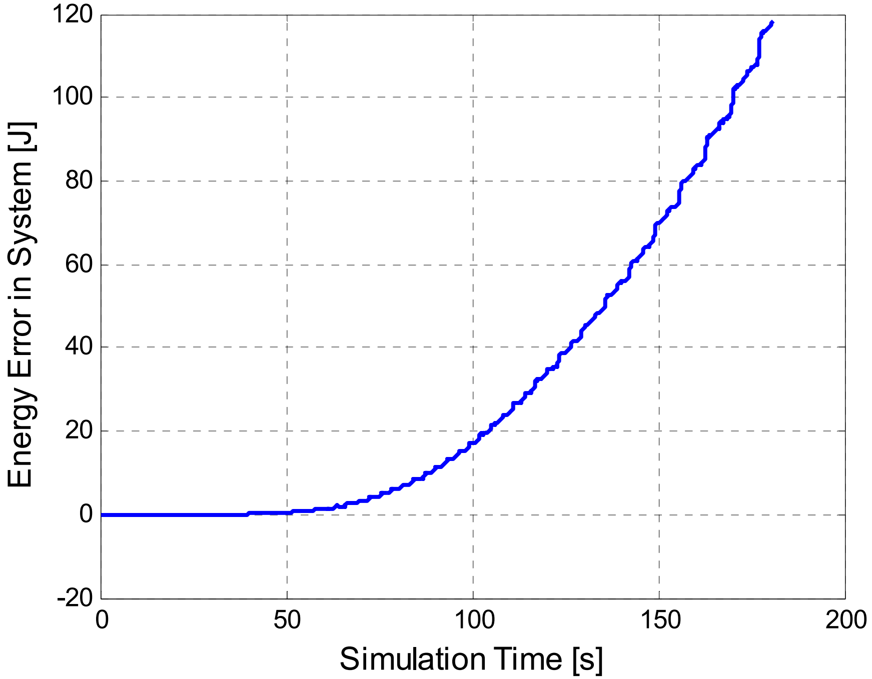
- Simulation sampling rate not adequate for system dynamics?
  - 250 Hz >> eigen-frequency of contact dynamics problem
- Force-Torque sensor errors and noise?
  - Calibration error may cause change of static equilibrium position
  - Mean of noise is zero
  - But: May initiate system instability if active elements are in the loop
- Passivity of robot system to be investigated

Observed Energy Error



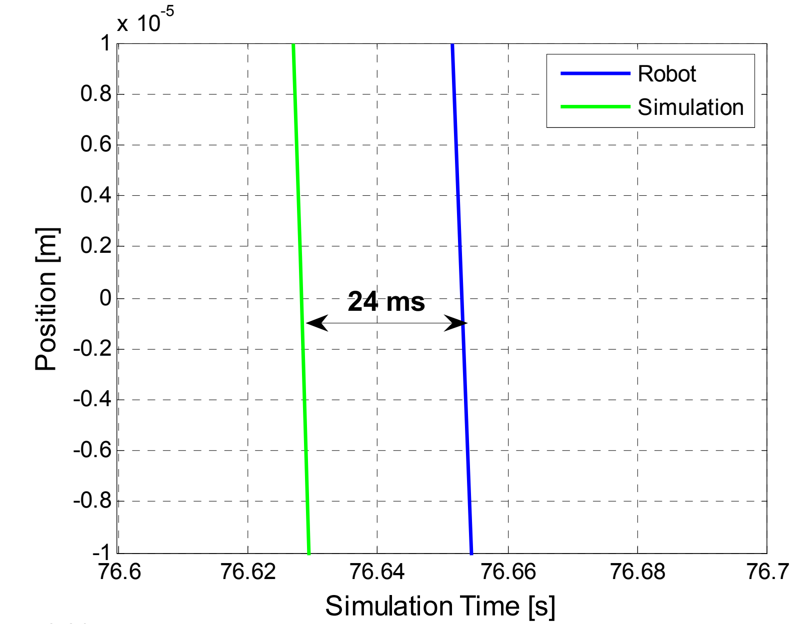
$$
\begin{aligned}
E_{Error} &= dt \sum_{i=0}^{k} P_{out}(t_i) - P_{in}(t_i) \\
&= dt \sum_{i=0}^{k} F_{FTS}(t_i)\left(v_{Rob}(t_i) - v_{Ctrl}(t_i)\right)
\end{aligned}
$$

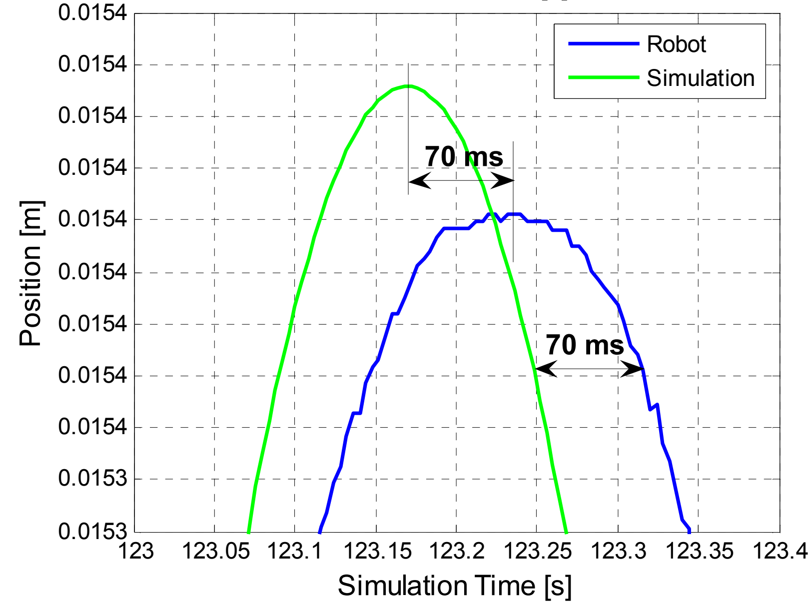




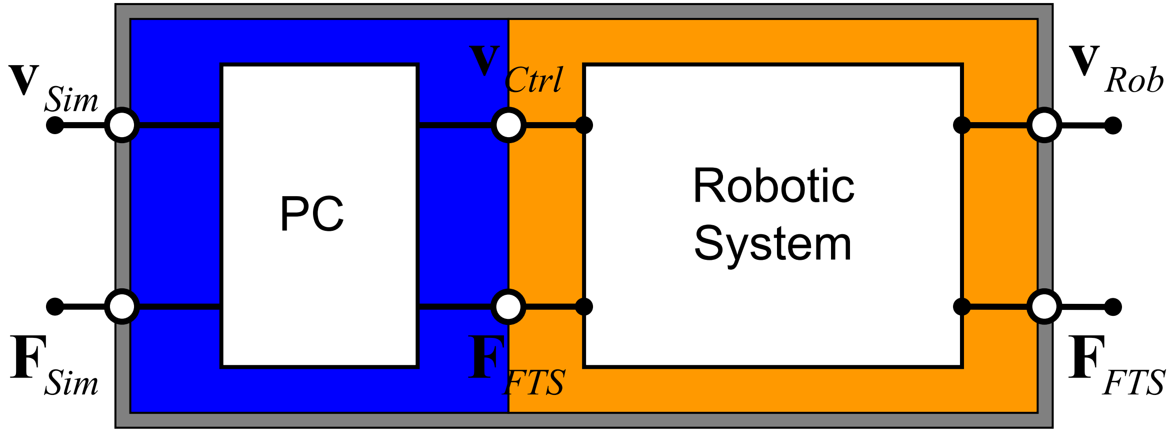
Transfer Function of Robot System

- Electro-mechanical system
  - Amplitude response of robot arm
  - Phase response of robot arm
- Robot control system with preprocessing of external commands
  - Latency
  - Smoothing of input signals





Passivity Control



- Dissipate energy error
- Maintain system dynamics

Impedance causality:

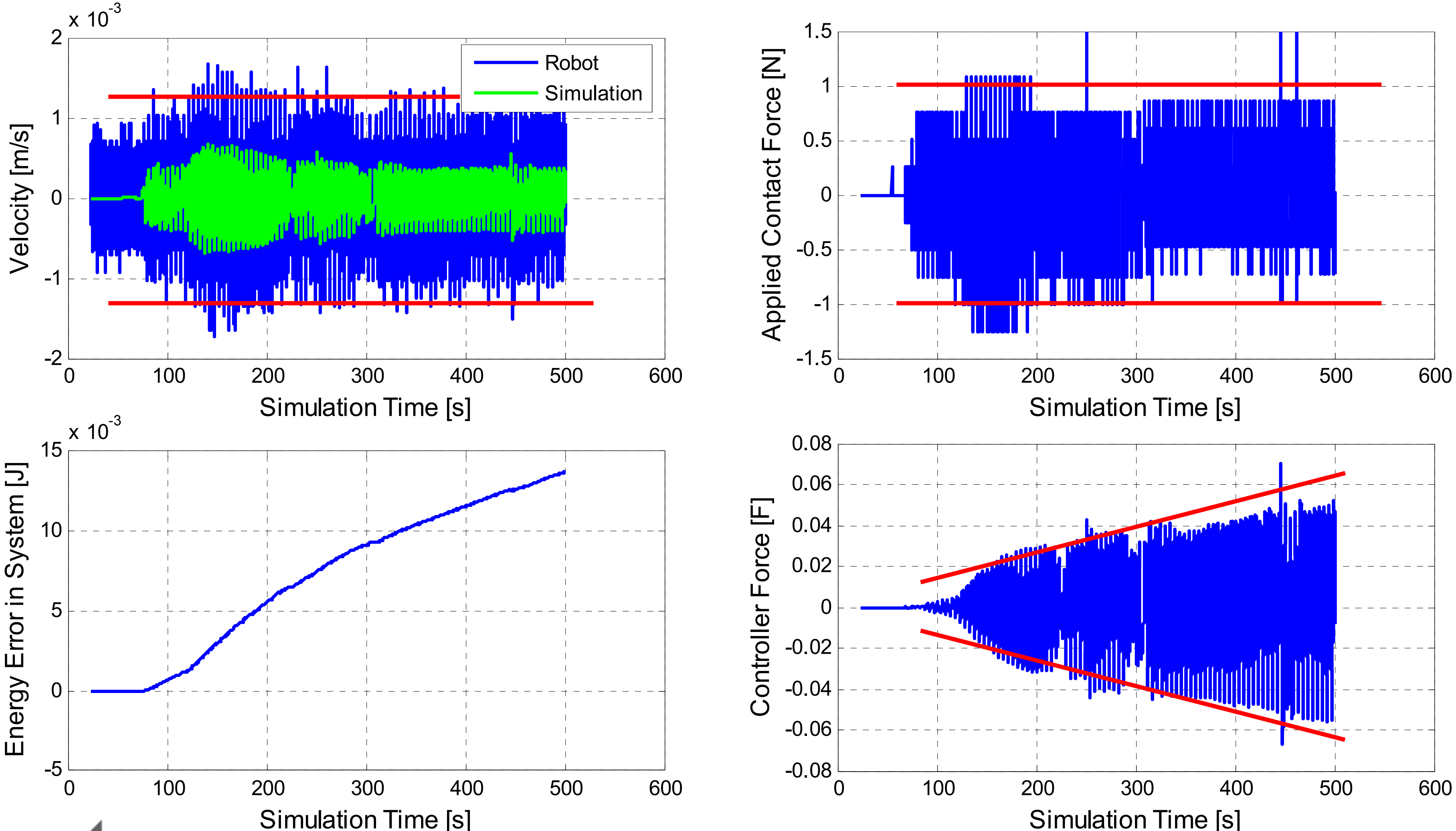
$$F_{Sim}(t_i) = F_{FTS}(t_i) - \alpha(t_i)\, v_{Sim}(t_{i-1}); \quad \alpha(t_i) = \begin{cases} k_v E_{Error}(t_{i-1}); & \dfrac{E_{Error}(t_{i-1})}{dt \cdot v_{Sim}^2(t_{i-1})}; & E_{Error}(t_{i-1}) > 0 \\ 0; & 0; & E_{Error}(t_{i-1}) \le 0 \end{cases}$$

Admittance causality:

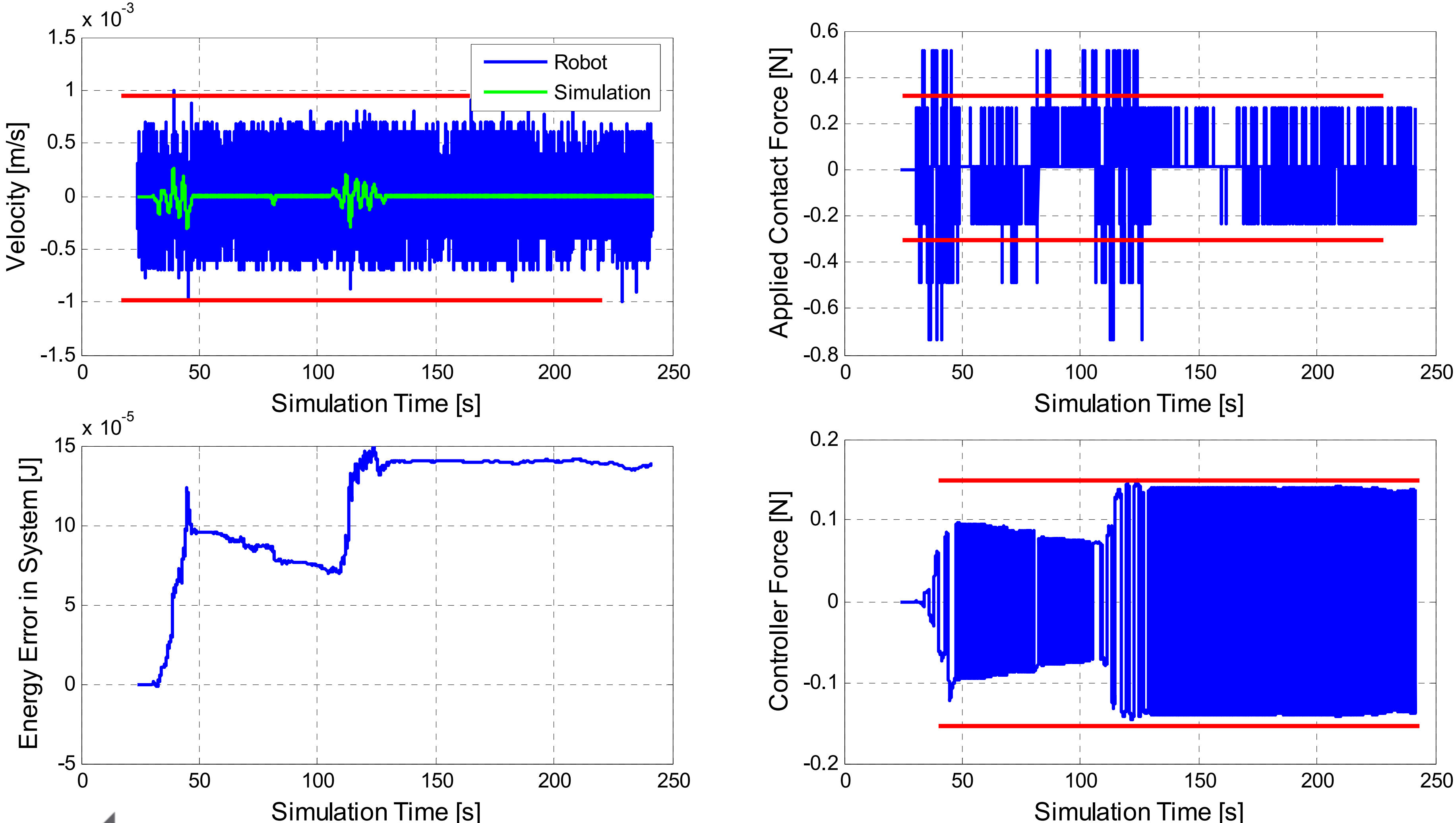
$$v_{Ctrl}(t_i) = v_{Sim}(t_i) - \beta(t_i)\, F_{FTS}(t_{i-1}); \quad \beta(t_i) = \begin{cases} k_F E_{Error}(t_{i-1}); & \dfrac{E_{Error}(t_{i-1})}{dt \cdot F_{FTS}^2(t_{i-1})}; & E_{Error}(t_{i-1}) > 0 \\ 0; & 0; & E_{Error}(t_{i-1}) \le 0 \end{cases}$$

PID type Energy Control	Time Domain Passivity Control
Hybrid simulation of space robot applications	Haptic devices
[Krenn, Schäfer, AIAA GNC 1999]	[Hannaford, Ryu, ICRA 2001]

Experiment Results Using PID Type Energy Control



Experiment Results Using Time Domain Passivity Control



Conclusion & Future Work

- Meaningful results for design phases A/B using software simulation.
- Hybrid simulation required for phases C/D/E
  - Real-time simulation requirement
  - Hardware-in-the-loop simulation requirements
- Robotic systems are not passive → Numerical instabilities of closed-loop simulation
- Passivity control solutions successfully implemented and tested at EPOS
  - PID energy control approach
  - Time domain passivity control

- Future work:
  - Passivity tests at higher contact stiffness
  - Test of system transparency (accuracy of contact dynamics simulation)