Workshop on Gravity Offload Testbed for Space Robotic Mission Simulation
September 24, 2017

The DLR On-Orbit Servicing Simulator: Reproducing Free-Floating Dynamics with Robotic Facilities

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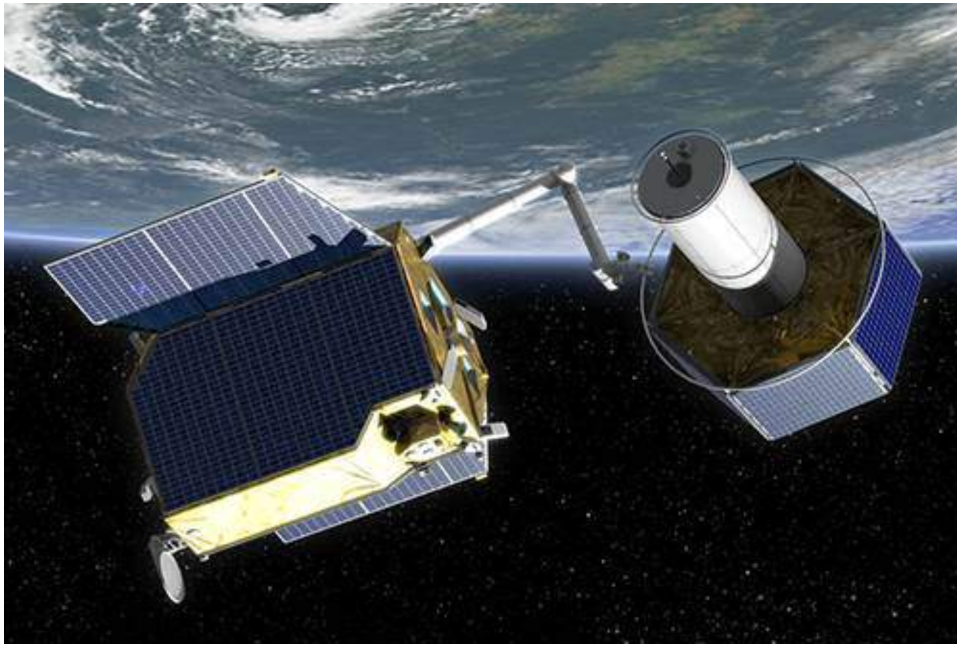
Contents

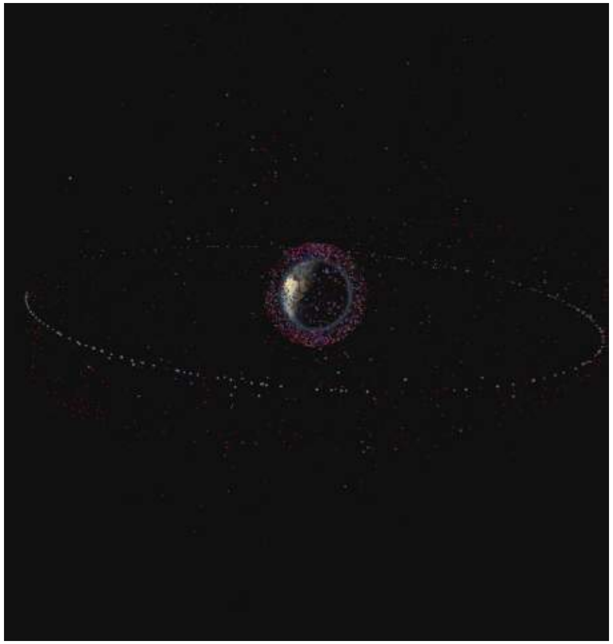
Contents

On-Orbit Servicing

- Maintenance and life extension of existing satellite
- Active space debris removal



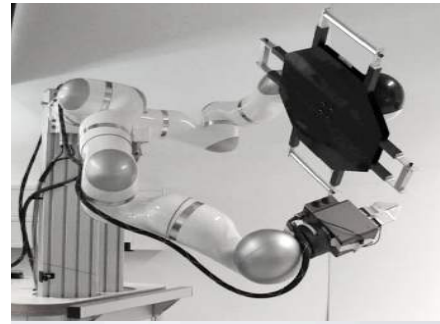
Servicer satellite *equipped with a robotic arm (left) approaching a* ***client satellite*** *(right)*

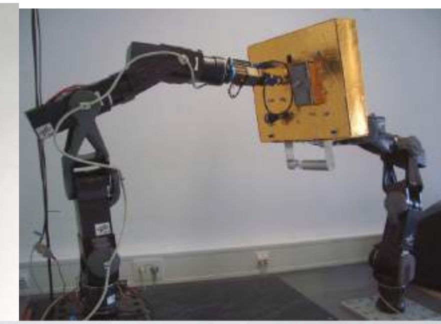


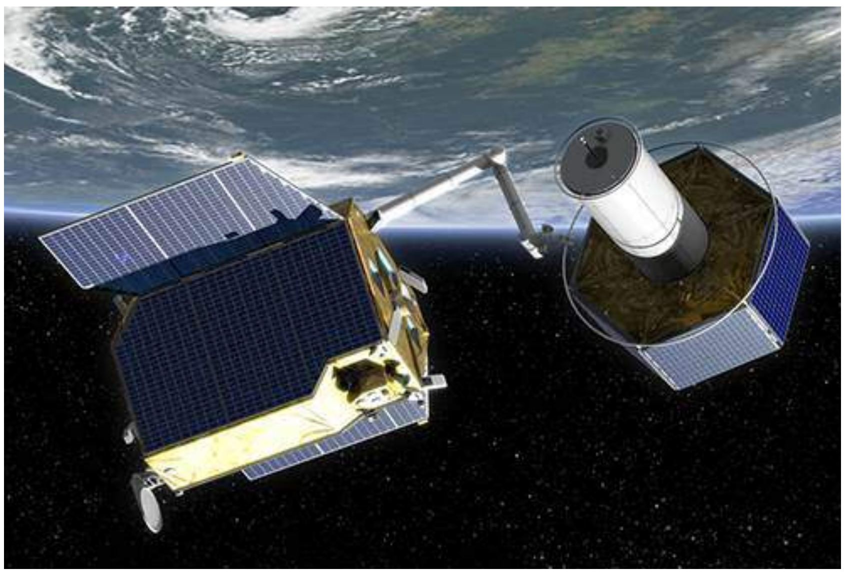
Density of Space Debris in LEO and GEO orbit

Why Robotic Facilities?

- 6 dof dynamics simulation
- Mass/inertia pars. can be easily changed
- Reproduction of microgravity
- Large workspace







Space Scenario:

Servicer satellite with manipulation arm and client satellite

On-ground scenario:

The robot simulates the dynamics of the satellite

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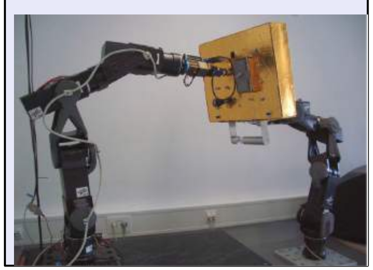
On-ground Robotic Simulator in DLR-RM

LWR-2 based

Servicer LWR-2
Client LWR-2

Fixed-base
No free-floating

2008

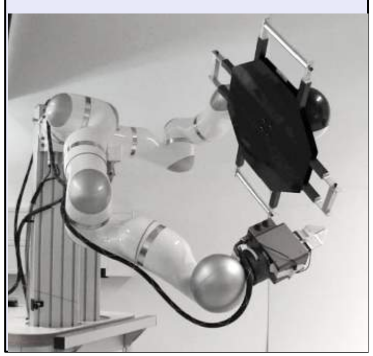


LWR-3 based

Servicer LWR-3
Client LWR-3

Fixed-base
Free-floating em

2011



OOS-SIM

Servicer KR-120
Client KR-120
Arm LWR4+

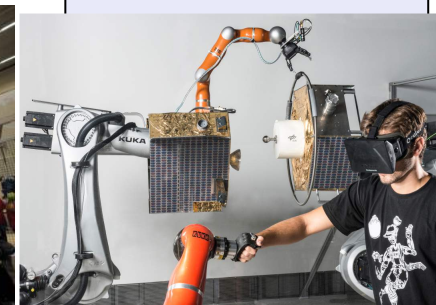
Free-floating
dynamics

2013

OOS-SIM+

Servicer KR-120
Client KR-120
Arm LWR4+
Stereocamera
Haptics interface
End2End

2015 -2018



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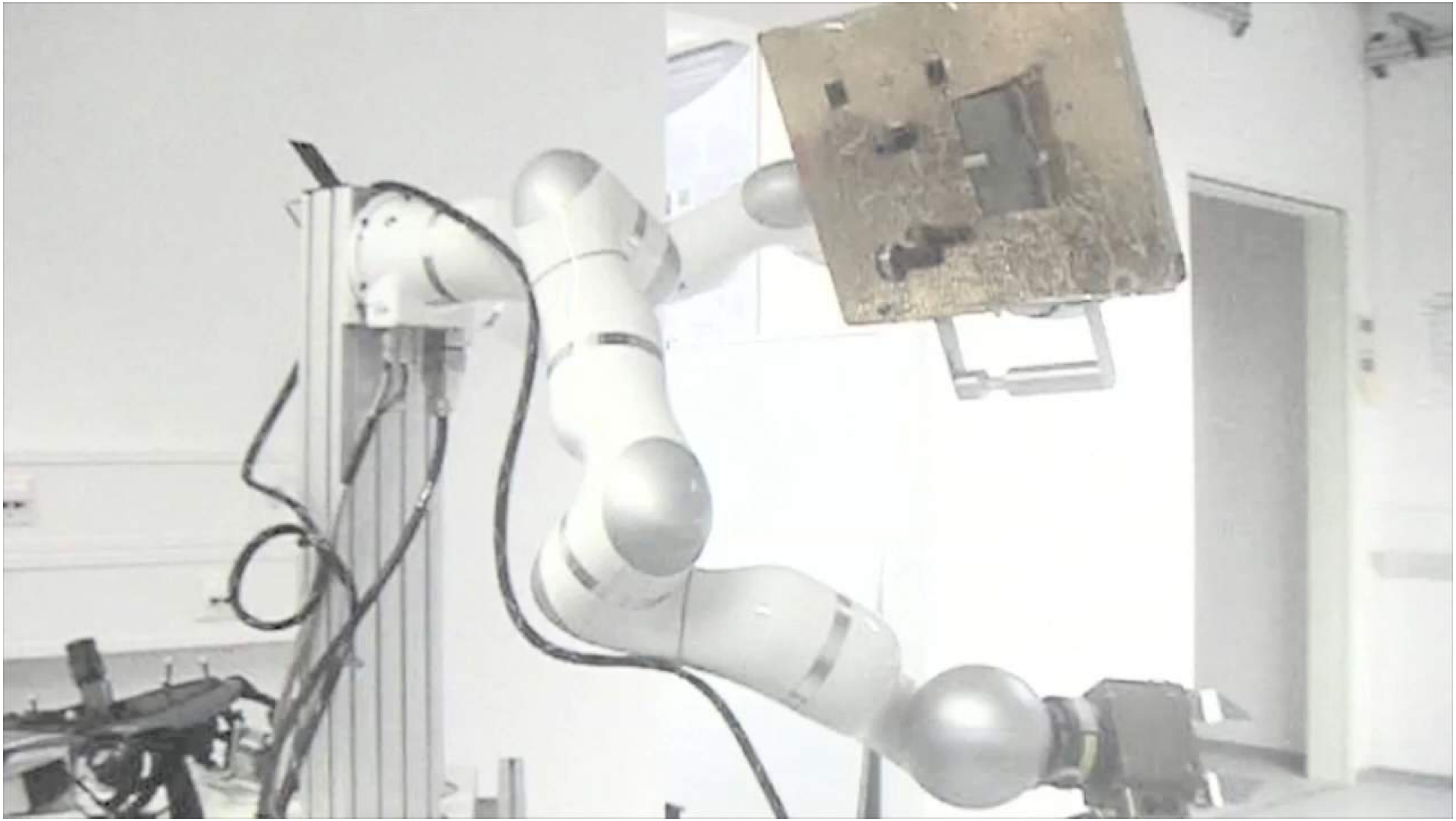
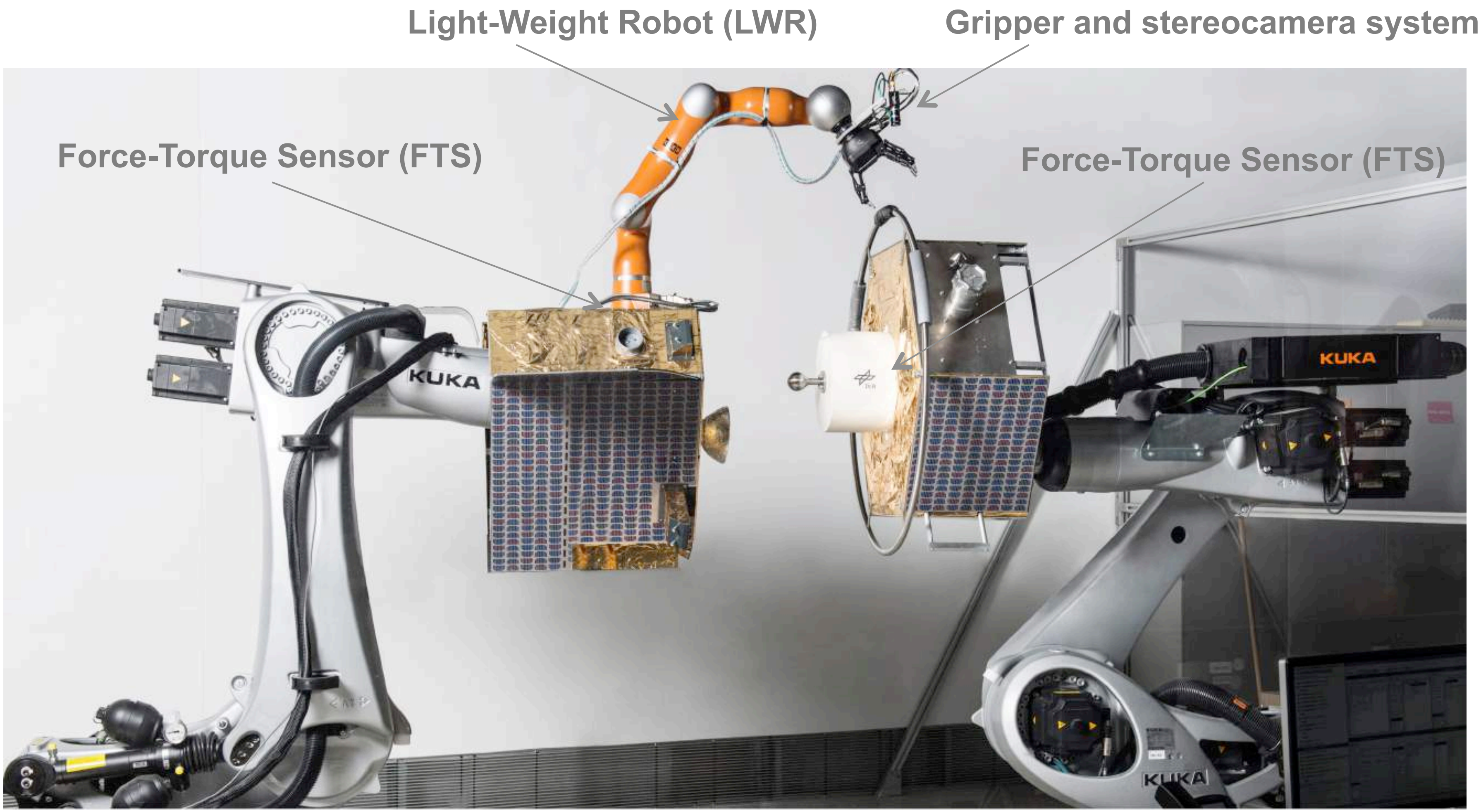
On-ground Robotic Simulator in DLR (2011)



On-ground Robotic Simulator in DLR-RM: the OOS-SIM



Servicer satellite: KUKA KR-120

Client satellite: KUKA KR-120

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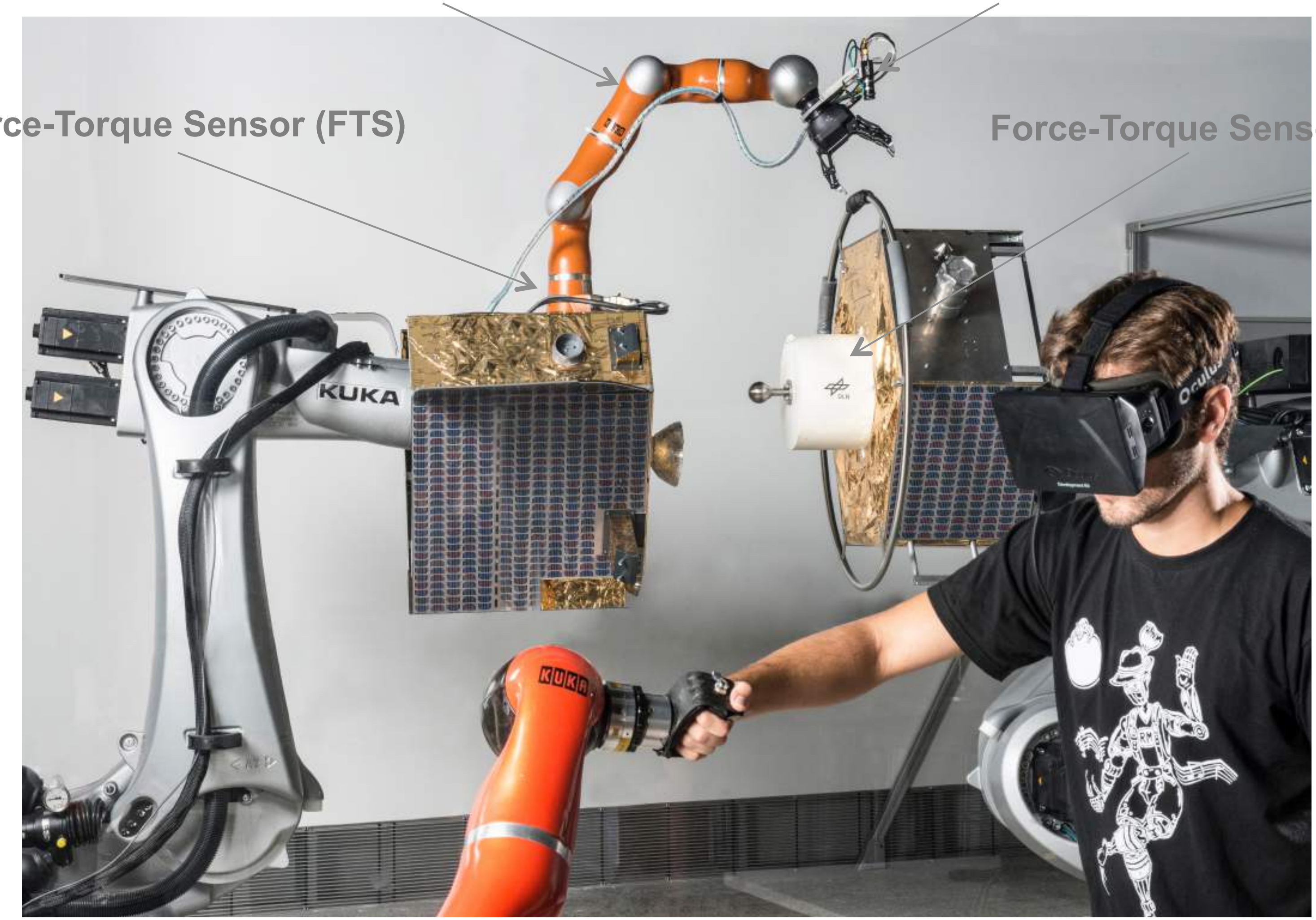
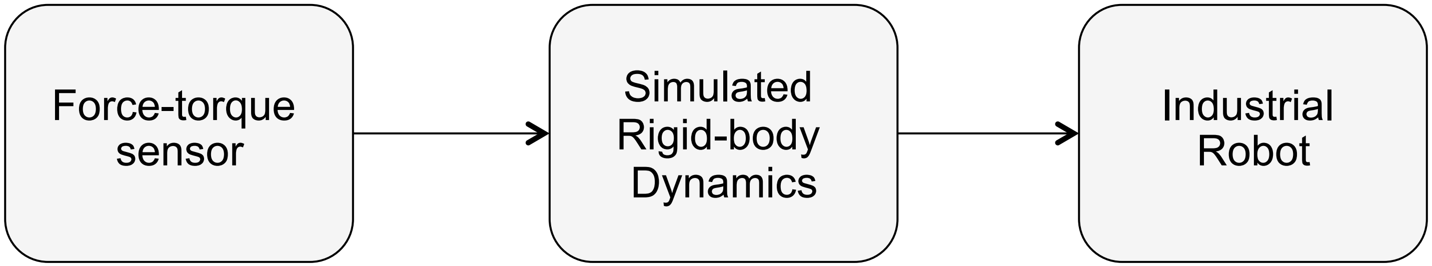
On-ground Robotic Simulator in DLR-RM: the OOS-SIM

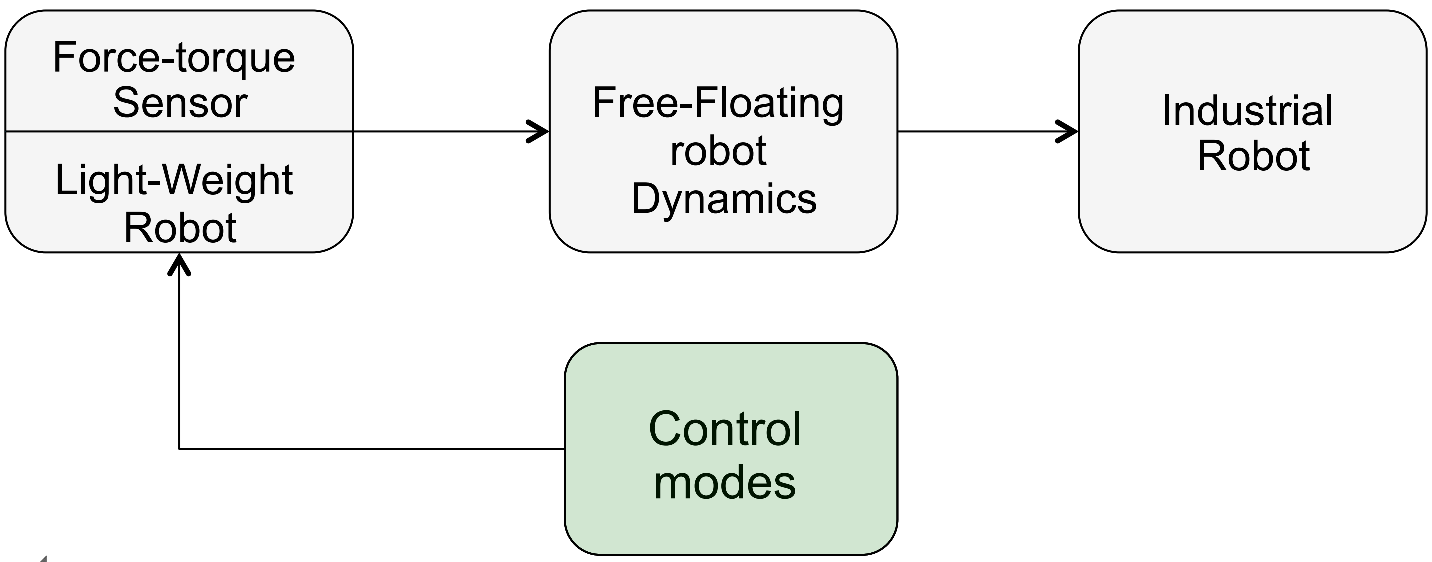


The DLR OOS-SIM

- **Data flow of the target simulator**



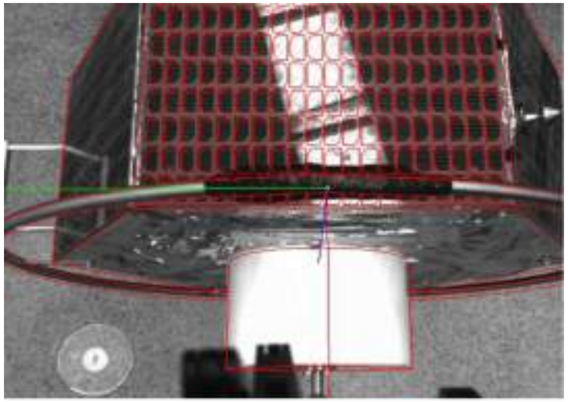
- **Data flow of the free-floating robot simulator**

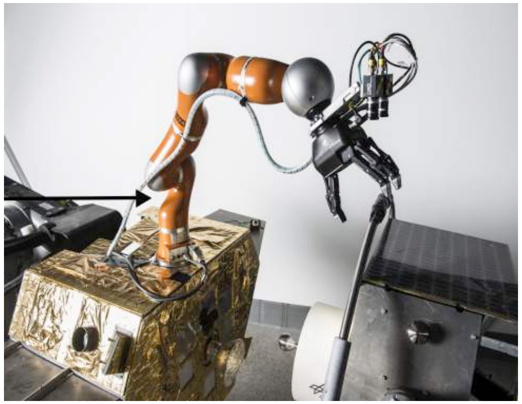


Control modes

The LWR can be controller in position or torque mode for different operations:

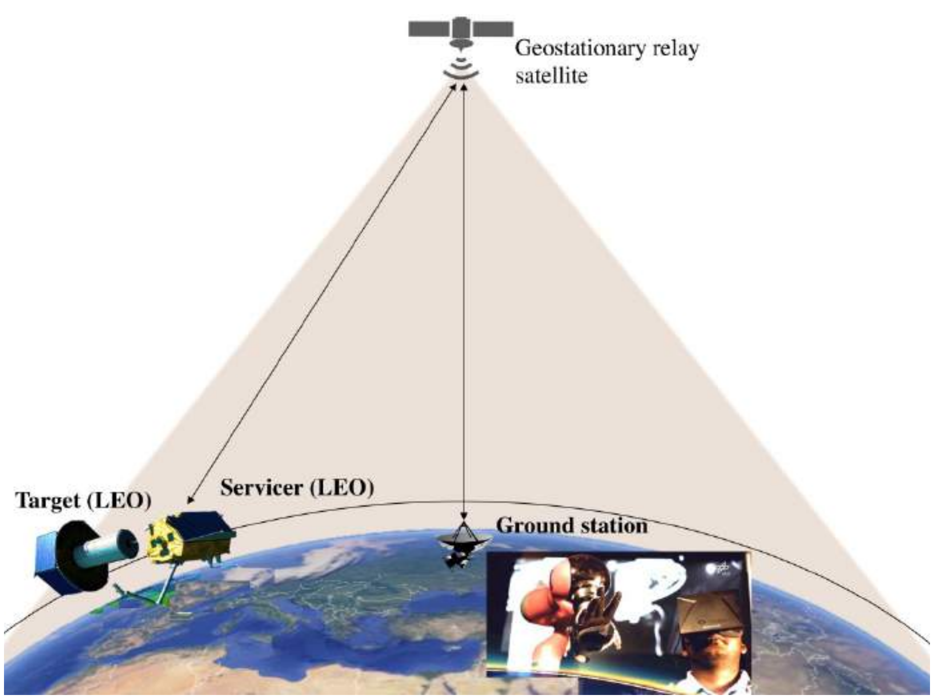
- **Semi-autonomy**
  - Stereo camera at the end-effector
  - Visual servoing
- **Telepresence**
  - Remote human operator with haptic interface
  - Teleoperation with force-feedback
- **Shared control**
  - torque input from the visual-servoing and telepresence



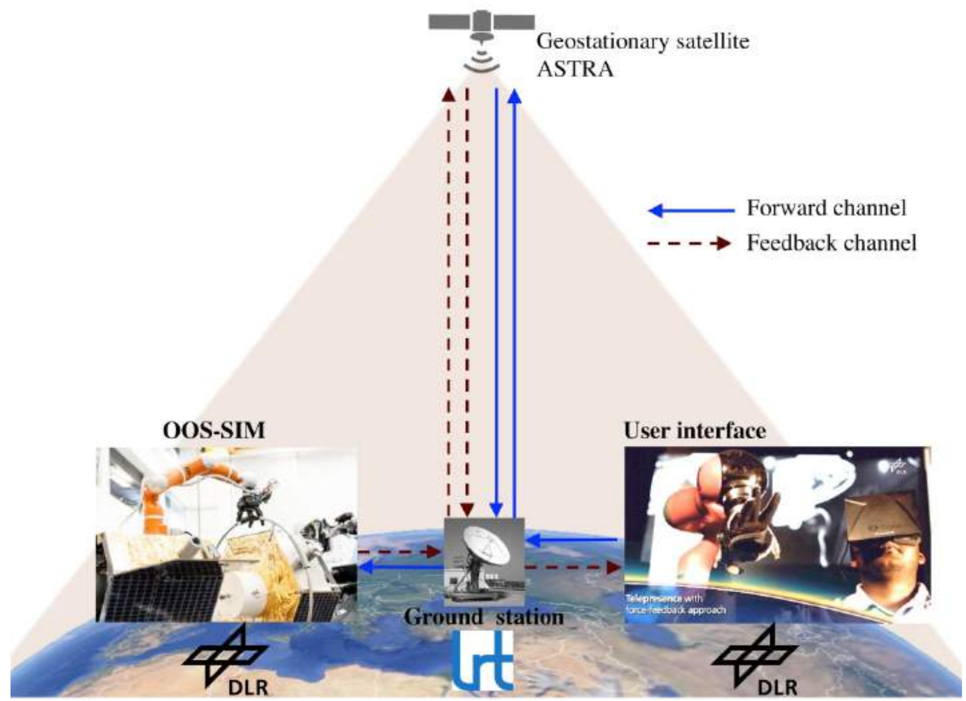


Space link experiment

- Passive bilateral controllers have been developed to cope with time delay and was tested on a space link infrastructure



Targeted scenario



Implemented scenario

The OOS-Sim facility

Contents

1. Motivation: On-orbit servicing

2. DLR On-ground facilities for simulating free-floating dynamics
   - Light-weight-robots based
   - OOS-SIM facility
   - Main control modes

3. Factors that affect the free-floating dynamics simulation with a robot
   - Time delay
   - Discretization

4. Reproducing free-floating dynamics: An Energy-based approach

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Reproducing free-floating dynamics with Robotic Facilities

3. Factor that affect the free-floating dynamics simulation on a robot

4. Reproducing free-floating dynamics: An Energy-based approach

Time delay

- Time delay between measured force-torque and command to the robot causes system instability
- Virtual energy is generated due to intrinsic latencies

Discretization

- Standard Euler Integrator leads to generation of energy and position drifts
- Implicit integration methods require a numerical and iterative solution,
- Iterative solutions can be prohibitive for real-time determinism.

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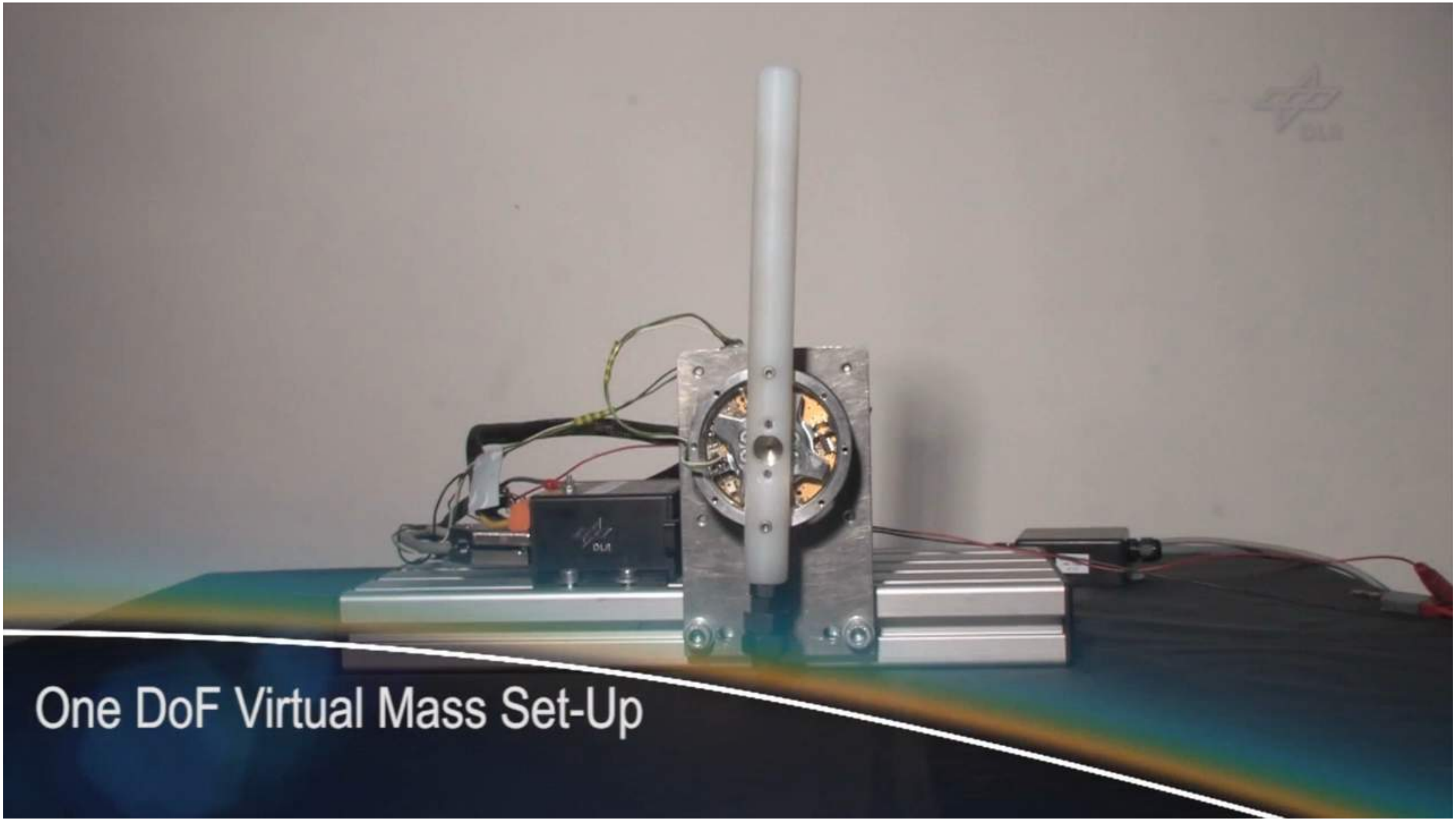
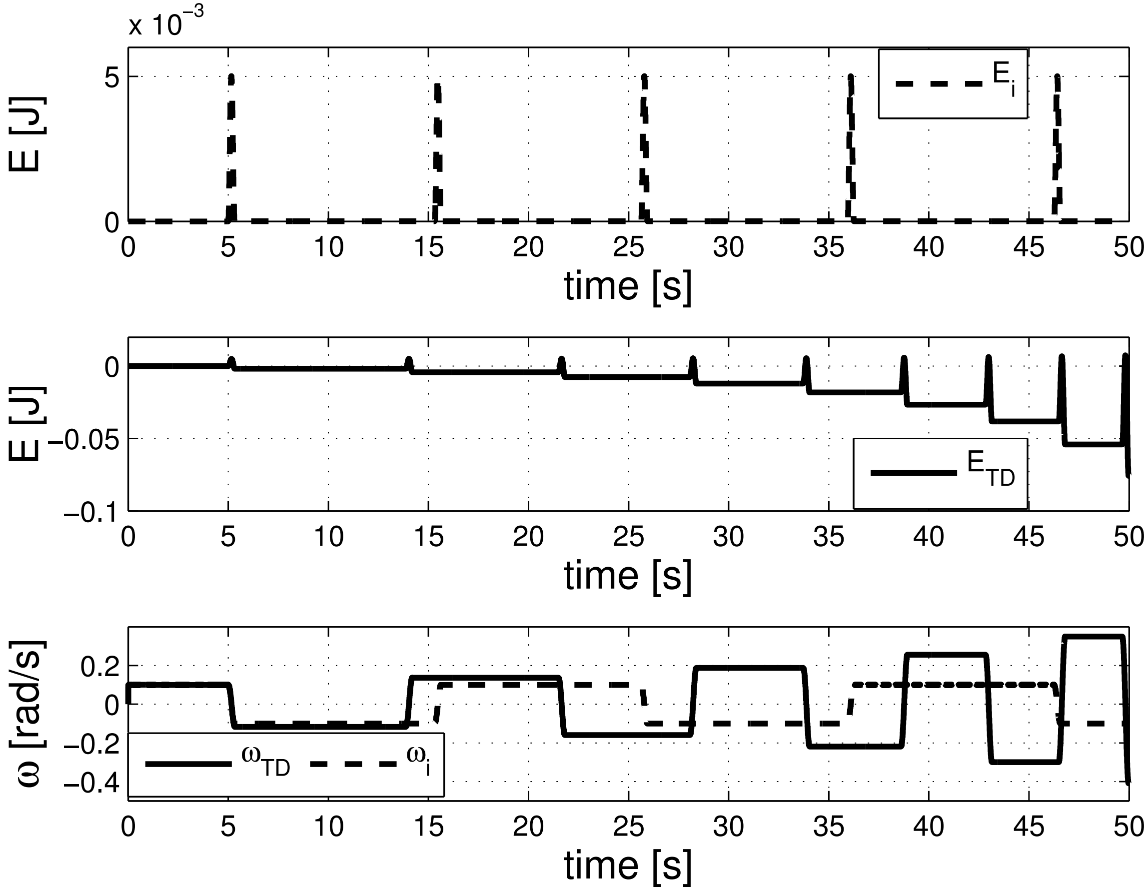
Time Delay: Problem Statement



Time Delay: Problem Statement



Energy without time delay, with time delay and angular velocity comparison

Time Delay: Proposed Approach

Control goals

1. **Ensure a stable system with the passivity condition**
2. Guarantee the performance of the simulated dynamics on a robot

Passivity Condition:

$$E(m) = E(0) + \sum_{k=0}^{m} F^T(k) v(k) \Delta T \quad \geq \quad 0.$$

If *E(m)* < 0, then the system is producing energy and such a regenerative effect can destabilize the system

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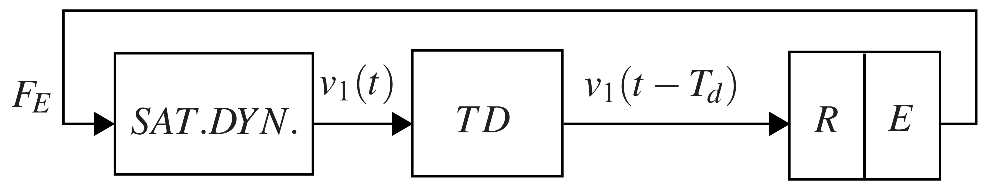
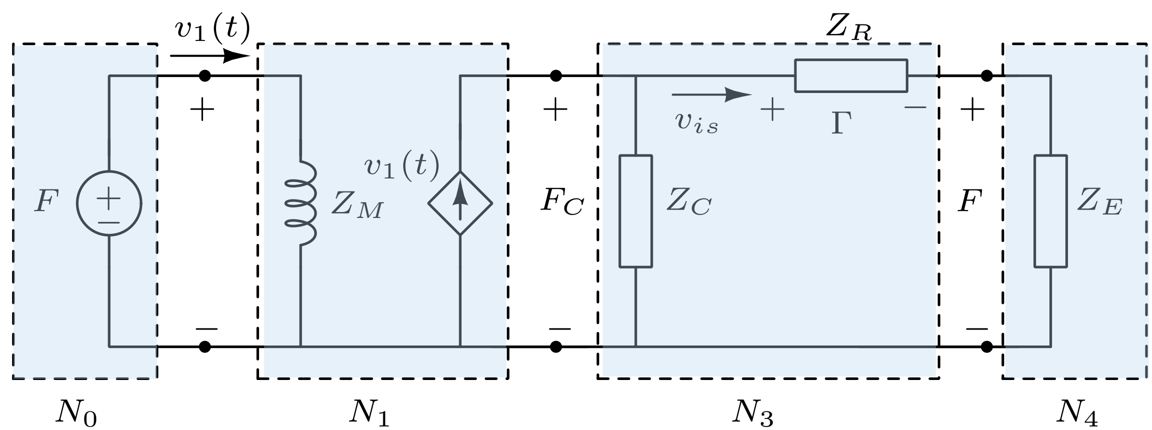
Modeling: Making the system passive

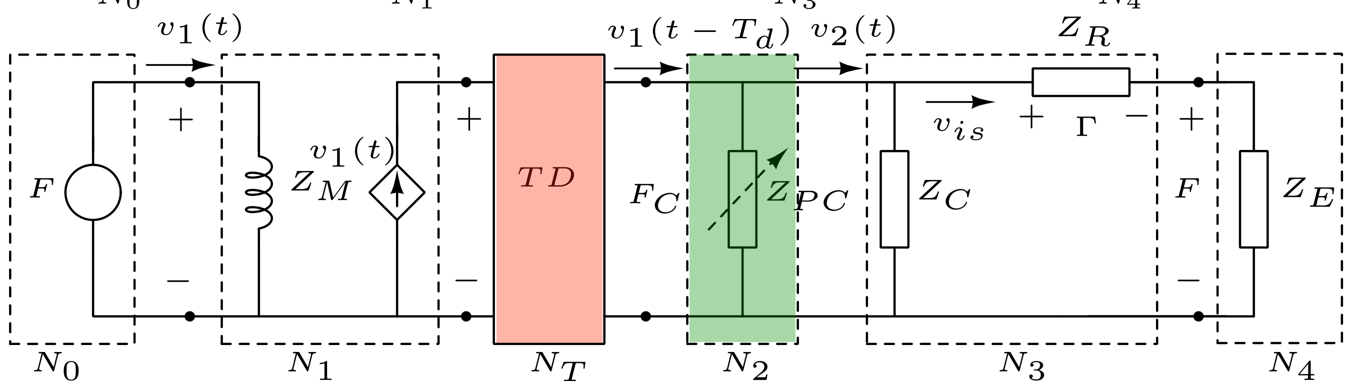
1. Block diagram



2. Electrical and Network scheme



3. Energy leaks can be seen in electrical network



Ensure the stability of the robot with the passivity criteria

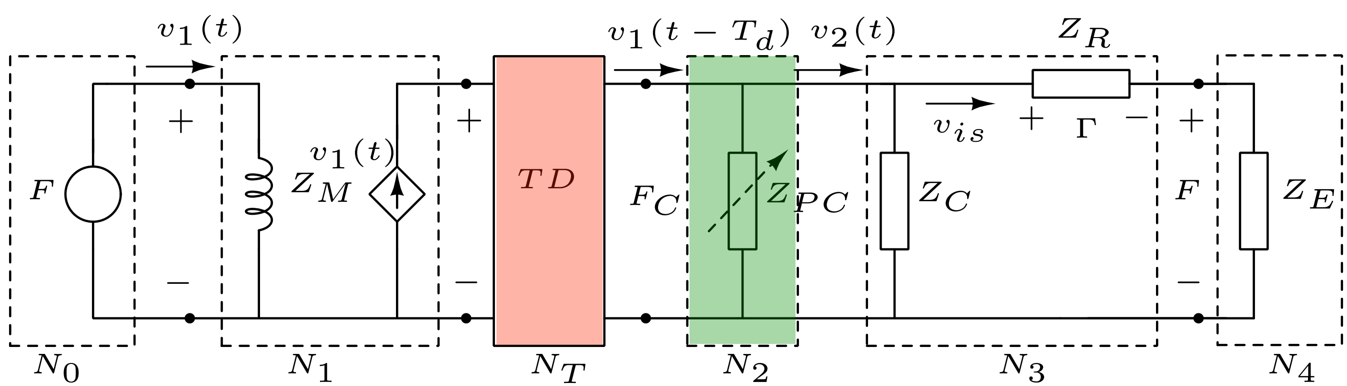
- **Passivity Controller (PC)** acts if passivity condition is violated

$$v_2(k) = v_1(k-\mu) - \beta(k)F_c(k)$$

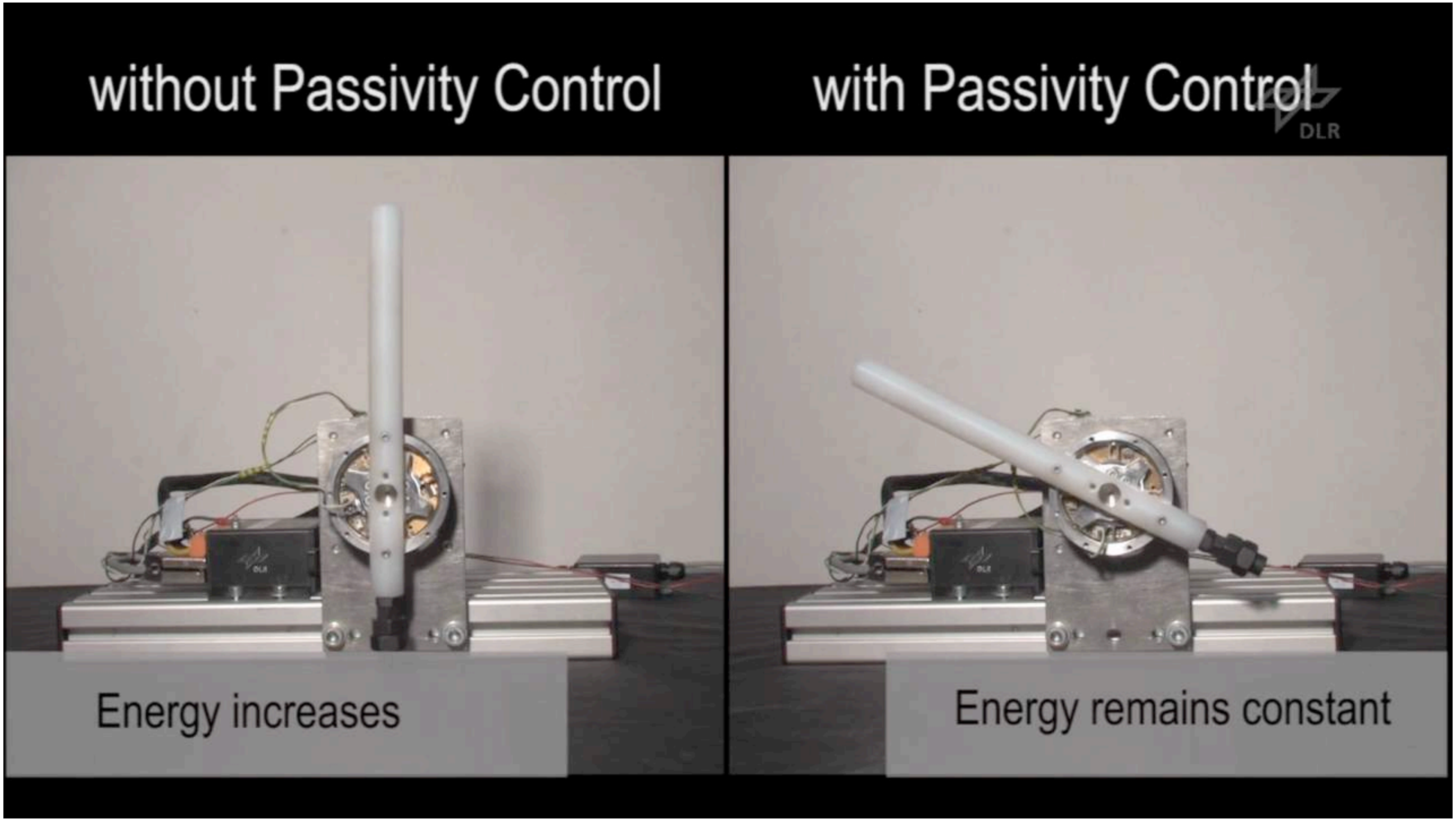
- **Passivity Observer (PO)**

$$E_{obs}(m) = \sum_{k=0}^{m} F_c^T(k)(v_1(k) - v_1(k-\mu))\Delta T$$

3. Energy leaks can be seen in electrical network



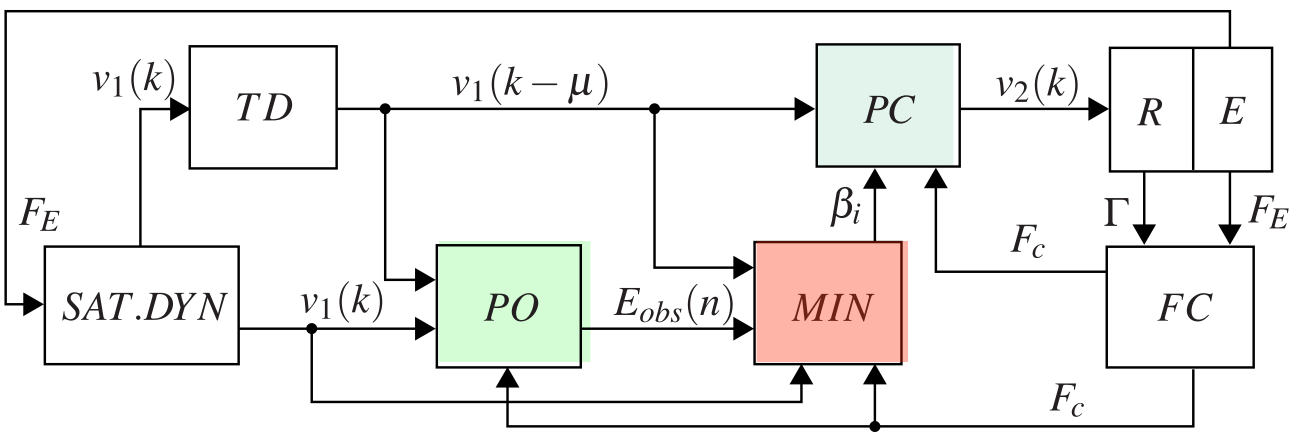
Ensure the stability of the robot with the Passivity criteria



Time Delay: Proposed Approach

Control goals

1. Ensure a stable system with the passivity condition
2. **Guarantee the performance of the simulated dynamics on a robot**



Guarantee performance with a designed optimization problem

- Performance is guaranteed through a multidimensional optimal damping as a result of a minimization problem:

$$\min_{\beta(k)} \|v_1(k-\mu) - \beta(k) F_c(k) - v_1(k)\|^2$$

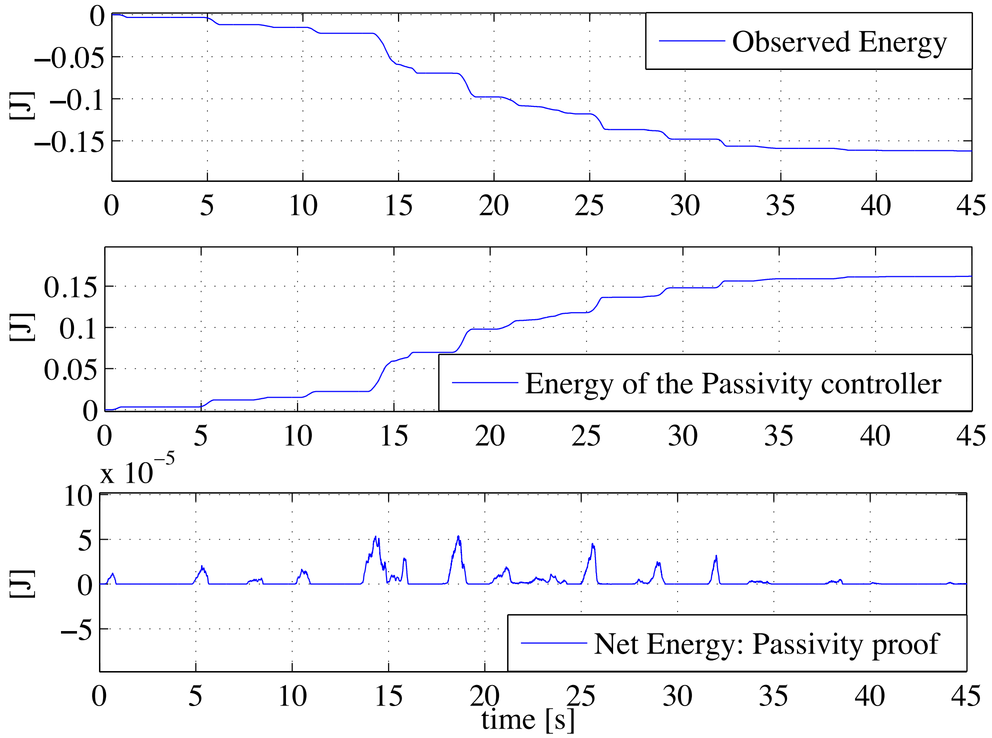
- The minimization problem will force the velocity to stay as close as possible to the ideal value. The constraints to satisfy are:

$$\sum_{k=0}^{m} F_c(k)^T \beta(k) F_c(k) \Delta T = \begin{cases} 0 & \text{if } E_{obs}(m) \geq 0 \\ -E_{obs}(m) & \text{if } E_{obs}(m) < 0 \end{cases}$$

- The minimization problem generates a $\beta(k)$ such that **the active energy (produced by the delay) is dissipated** and the velocity transmitted to the robot is as close as possible to the ideal target velocity.

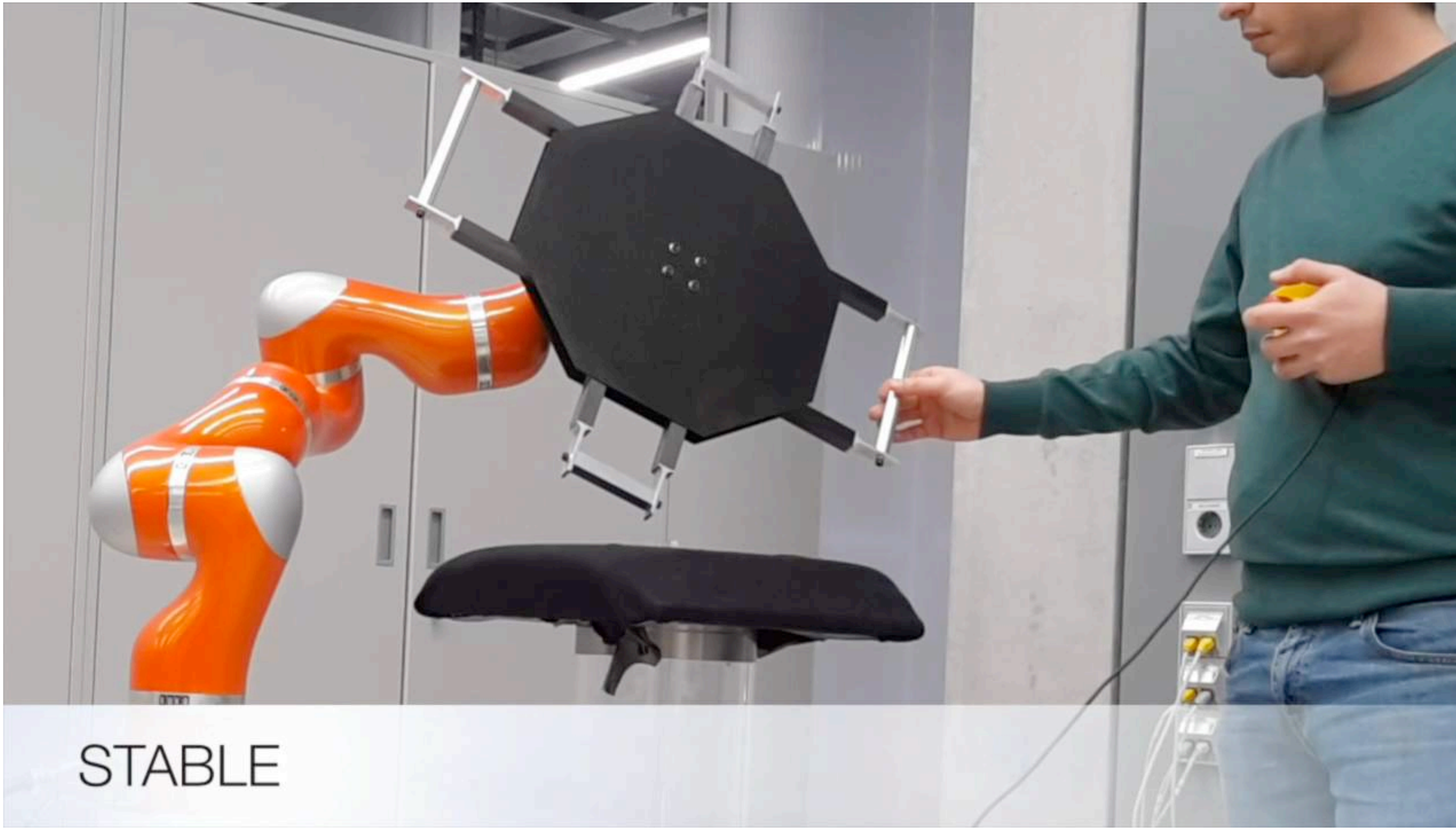
Time Delay: Experiment Results

- The observed active energy is dissipated with the optimal damping and the system results to be stable.



Observed Energy, Energy of the passivity controller and Passivity proof

Time Delay: Experiment



Reproducing free-floating dynamics with Robotic Facilities

3. Factor that affect the free-floating dynamics simulation on a robot

4. Reproducing free-floating dynamics: An Energy-based approach

Time delay

- Time delay between measured force-torque and command to the robot causes system instability
- Virtual energy is generated due to intrinsic latencies

Discretization

- Standard Euler Integrator leads to generation of energy and position drifts
- Implicit integration methods require a numerical and iterative solution,
- Iterative solutions can be prohibitive for real-time determinism.

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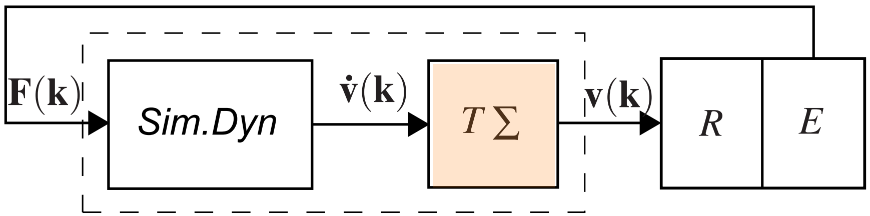
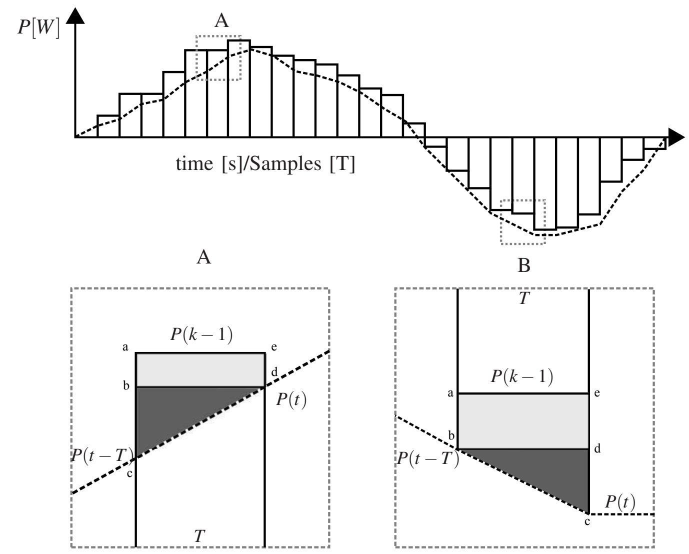
Discretization

- Admittance architecture of the robot simulator:





- The desired dynamics is subjected to external forces,

- **Explicit and Discrete Integrator strategy by modifying the output of the Euler integrator.**

Discretization

- Standard Euler Integrator leads to generation of energy and position drifts
- Implicit integration methods require a numerical and iterative solution,
- Iterative solutions can be prohibitive for real-time determinism.

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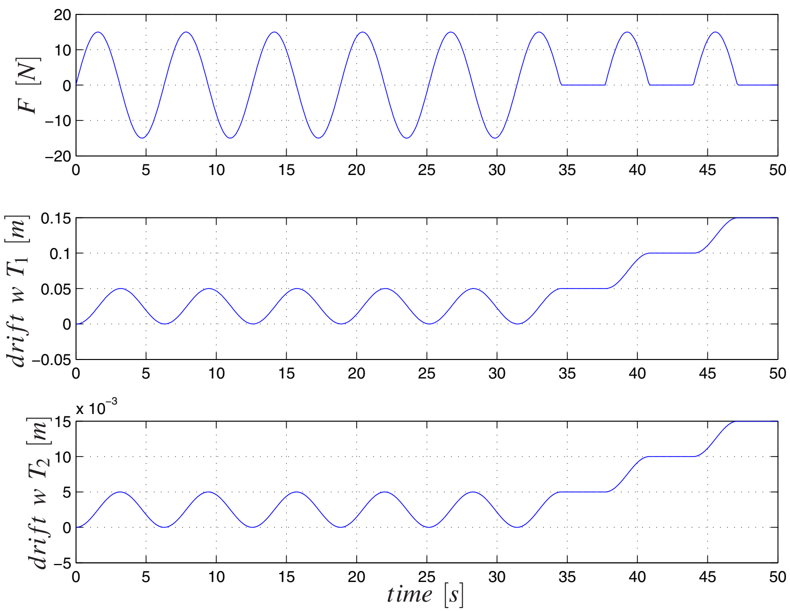
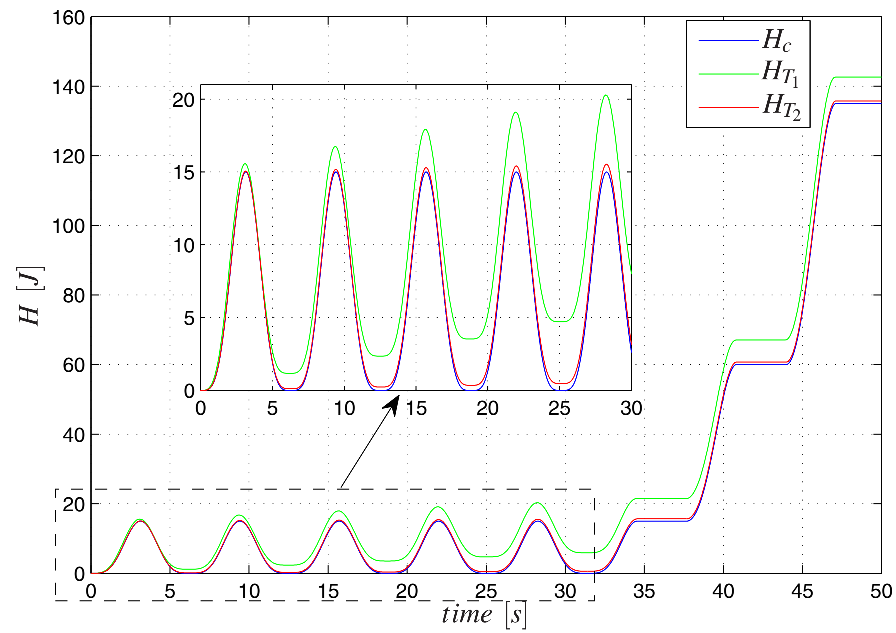
Discretization: Problem Statement

- Considering the Hamiltonian system: $\dot{H} = \mathbf{F}^T \mathbf{M}^{-1} \mathbf{p} = \mathbf{F}^T \mathbf{v}$

- Standard Euler method causes **drift in position and energy inconsistency**



*Force profile, **drift in position** due to the discretization with different sampling time*



***Energy drift** for different sampling time and comparison with the continuous case H_c.*

Energy produced by the Euler Integrator

- The energy variation should be due only to the energy provided through the port (F,v),

- The Energy due to Euler method is:

$$H(k) = H(k-1) + T\mathbf{v}(\mathbf{k}-\mathbf{1})^T \mathbf{F}(\mathbf{k}-\mathbf{1}) + \underbrace{\frac{1}{2} T^2 \mathbf{F}(\mathbf{k}-\mathbf{1})^T \mathbf{M}^{-1} \mathbf{F}(\mathbf{k}-\mathbf{1})}_{\Delta \mathbf{H}}$$

- $\Delta \mathbf{H}$ is the active energy introduced at each time step T,

- The active energy will cause a non-physical and a non-passive behaviour.

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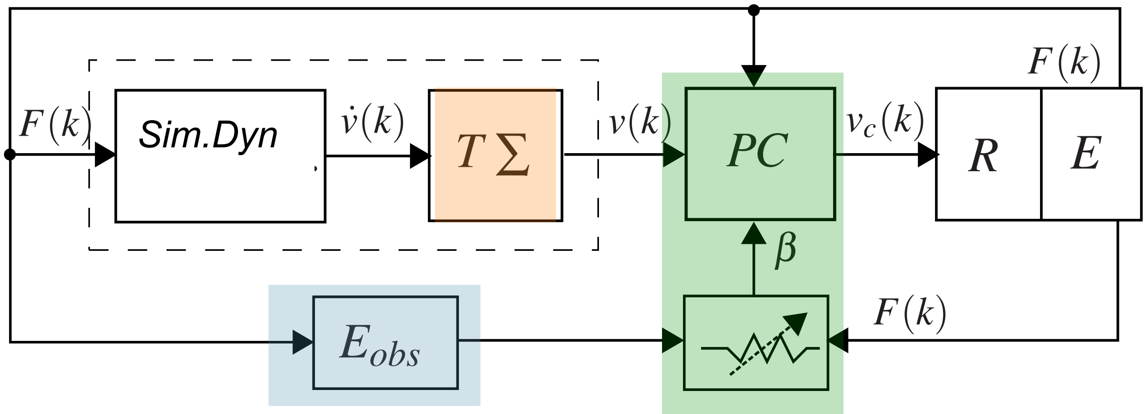
Passivity-based integration scheme

- The energy observer checks the energy flows:

$$E_{obs}(k) = E_{obs}(k-1) - \Delta H(k) + \beta(k-1)F(k-1)^2 T$$

- The passivity controller acts in admittance configuration:

$$v_c(k) = \begin{cases} v(k) - \beta(k)F(k) & E_{obs} < 0 \\ v(k) & else. \end{cases} \qquad \beta(k) = \begin{cases} -\frac{E_{obs}(k)}{F(k)^2 T} & E_{obs}(k) < 0 \\ 0 & else. \end{cases}$$

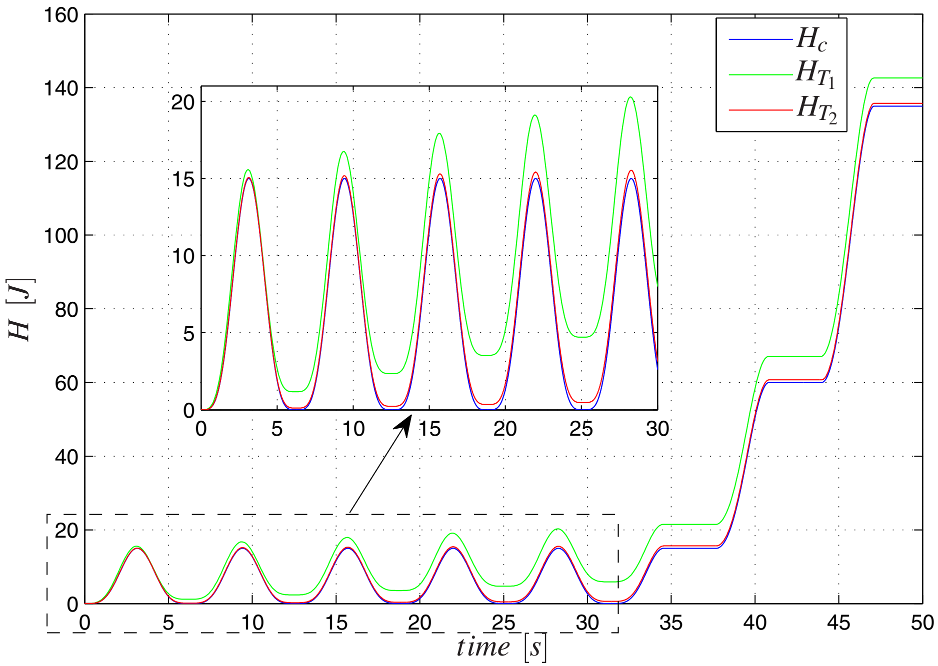


The passivity-based integration scheme

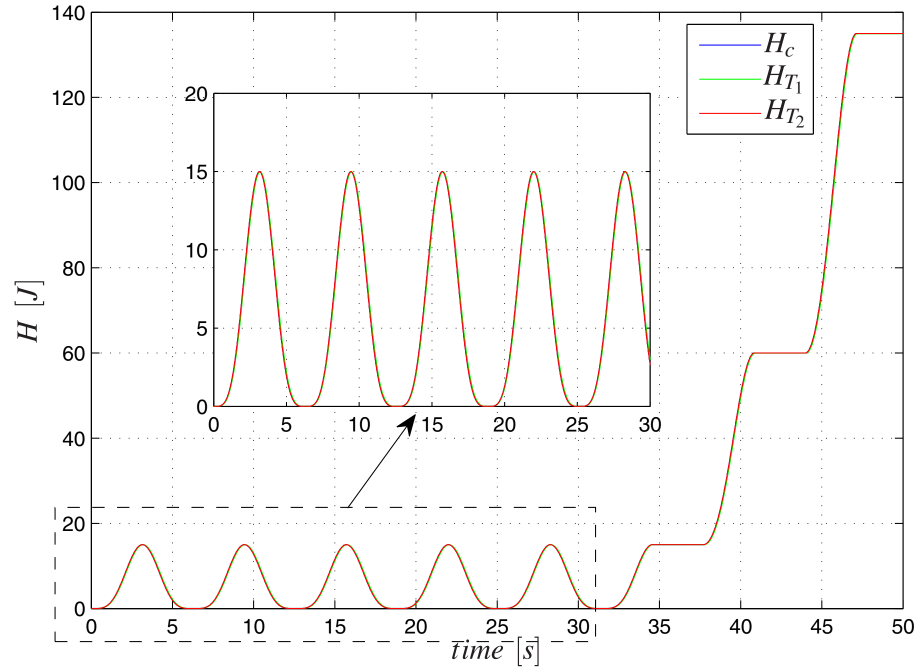
- The passivity control (PC) corrects the velocity with a variable damper β
- The energy observer (E_{obs}) measures the active energy

Results: Energy comparison

The energy is preserved for the simulated rigid body



***Energy drift** considering different sampling time:*
before applying the method



Energy considering different sampling time:
with the proposed method

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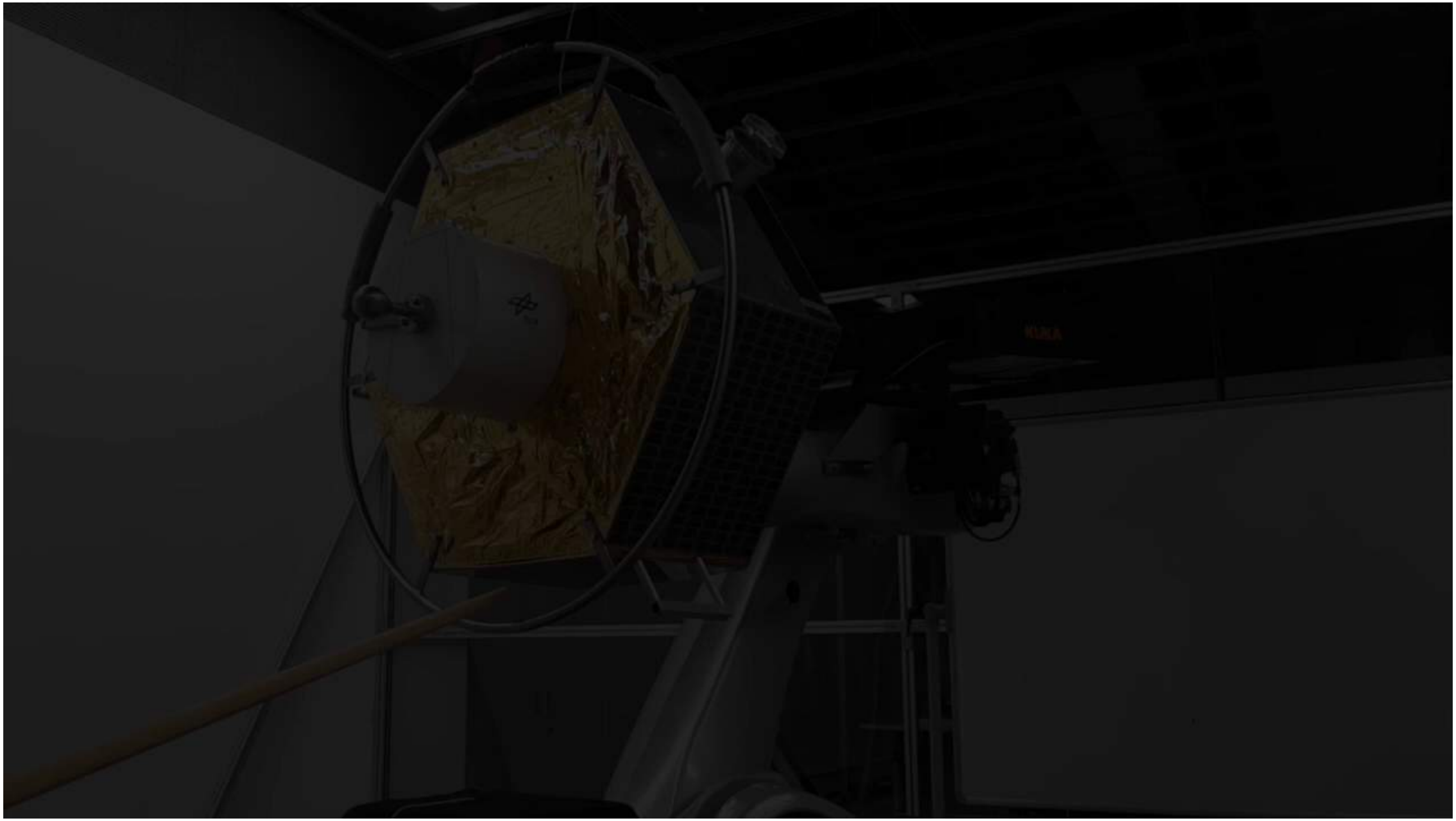
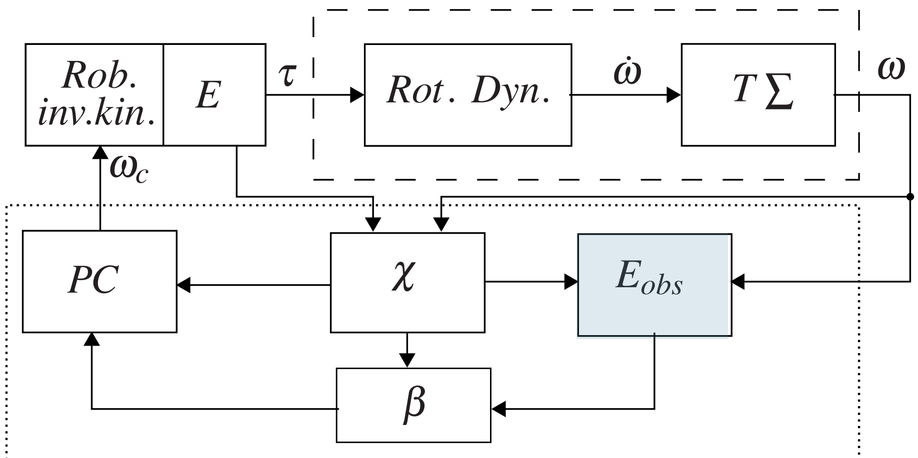
Experiments on the robot simulator



Passive integrator: extention to coupled dynamics

Energy generated by the Euler integrator:

$$H(k) = H(k-1) + T\omega(k-1)^T \tau(k-1) \underbrace{+\frac{1}{2}T^2\omega(k-1)^T S(I\omega(k-1))^T I^{-1} S(I\omega(k-1))\omega(k-1)}_{\Delta H_1} \underbrace{+\frac{1}{2}T^2\tau(k-1)^T I^{-1}\tau(k-1)}_{\Delta H_2}.$$



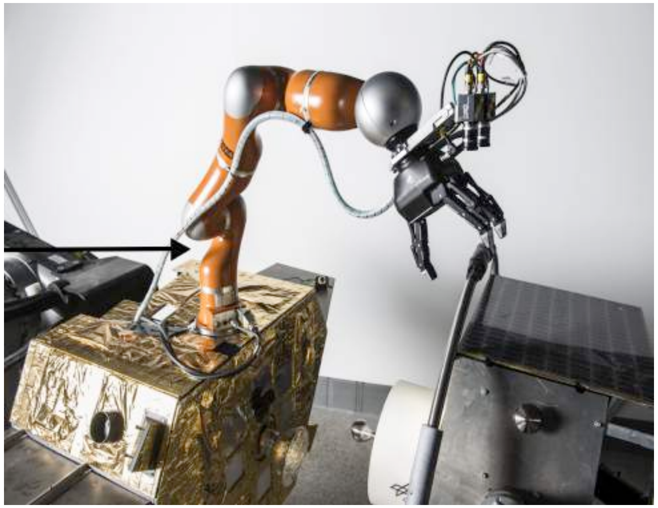
M. De Stefano, J. Artigas, C. Secchi, " A passive Integration Strategy for Rendering Rotational Dynamics on a Robotic Simulator" , IROS 2017 - **TuAT12, Room 208**

Passive integrator extended to coupled dynamics

Method extended for rotational dynamics

M. De Stefano, J. Artigas, C. Secchi, " A passive Integration Strategy for Rendering Rotational Dynamics on a Robotic Simulator" , IROS 2017 - **TuAT12, Room 208**

Summary

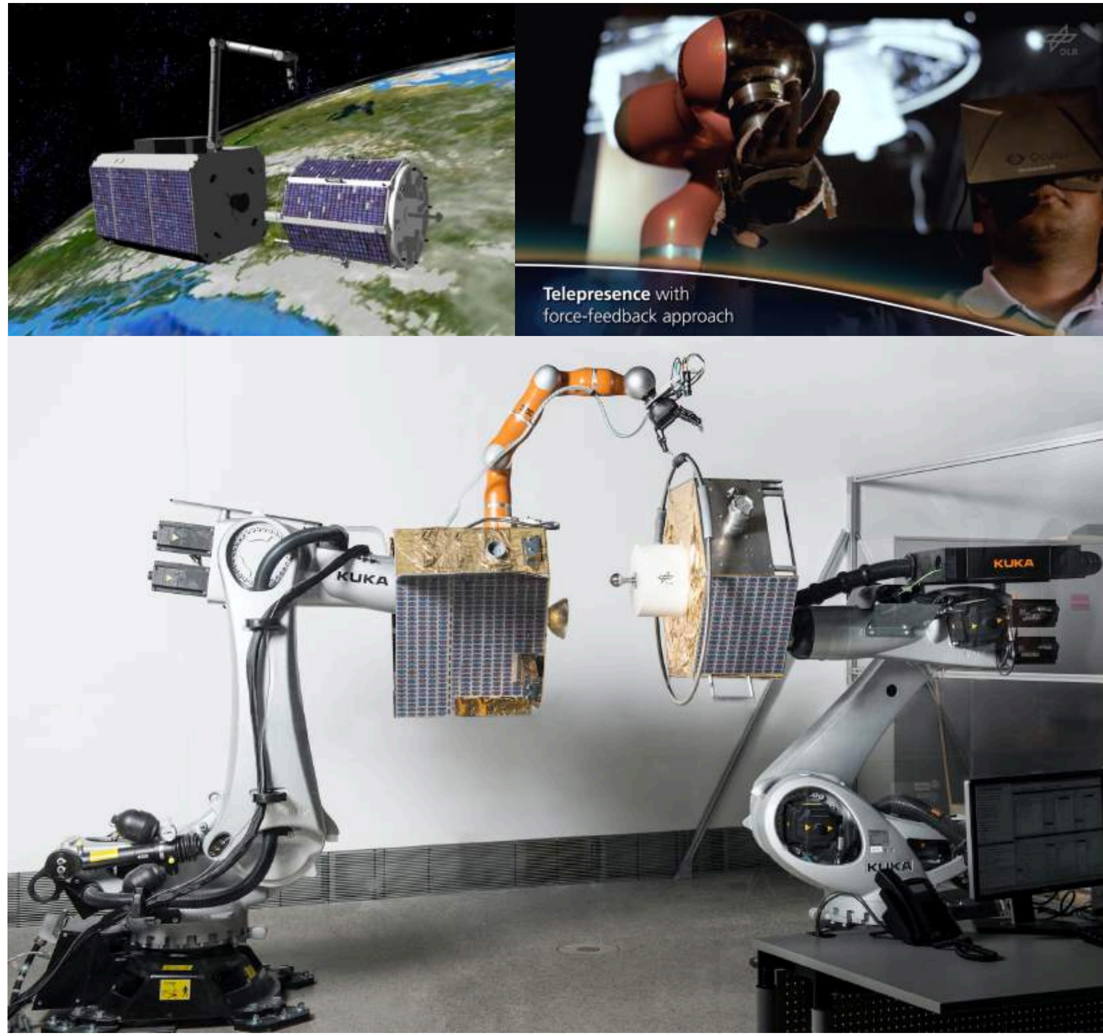


- The OOS-SIM was presented as an on-ground facility for testing on-orbit servicing tasks
- Autonomy, Telepresence and Shared-control algorithms can be tested
- Main issues in rendering passive free-floating dynamics are addressed
- Time delay and discretization can lead to a non-physical behaviour of the simulated dynamics
- Energy-based methods have been develop to realistically simulate physical dynamics

Acknowledgment

The researchers made this possible!

- Roberto Lampariello
- Ribin Balachandran
- Wolfgang Rackl
- Phillip Schmidt
- Giorgio Panin
- Alessandro Giordano
- Michael Panzirsch
- Martin Stelzer
- Bernhard Brunner
- Robert Burger
- Florian Schmidt
- Wieland Bertleff
- Cristian Secchi
- Christian Ott
- Alin Albu-Schaeffer



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