The DLR On-Orbit Servicing Simulator: OOS-SIM

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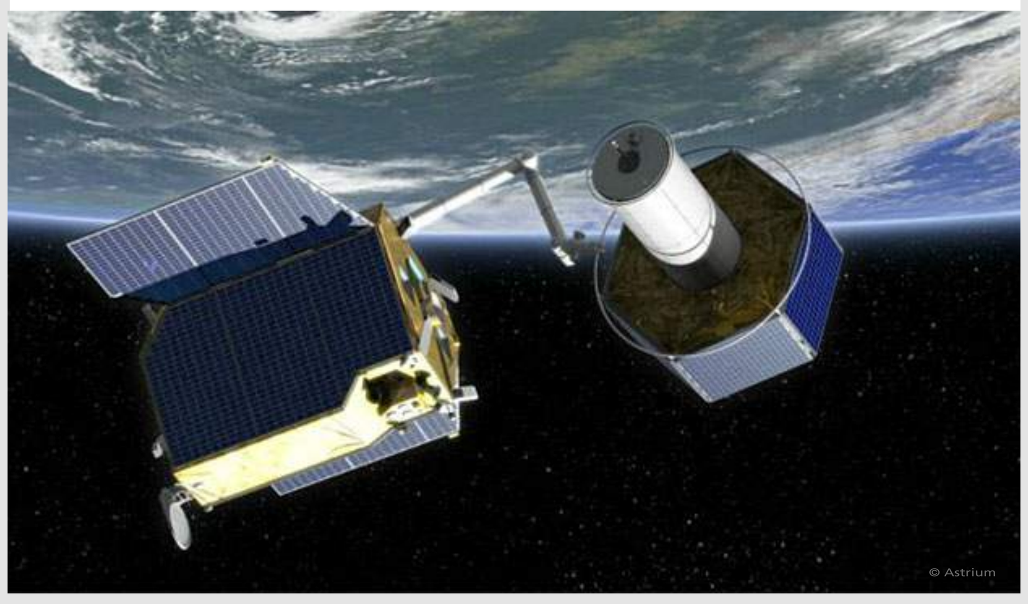
Objective

On Orbit-Servicing (OOS) missions stand for a new class of complex space mission in which a servicer satellite is launched into the orbit of a target object. The servicer satellite is equipped with a robotic arm, a gripper and cameras. OOS missions are envised for:

- **maintenace and life extension of existing satellites**
- **de-orbiting**
- **active debris removal**

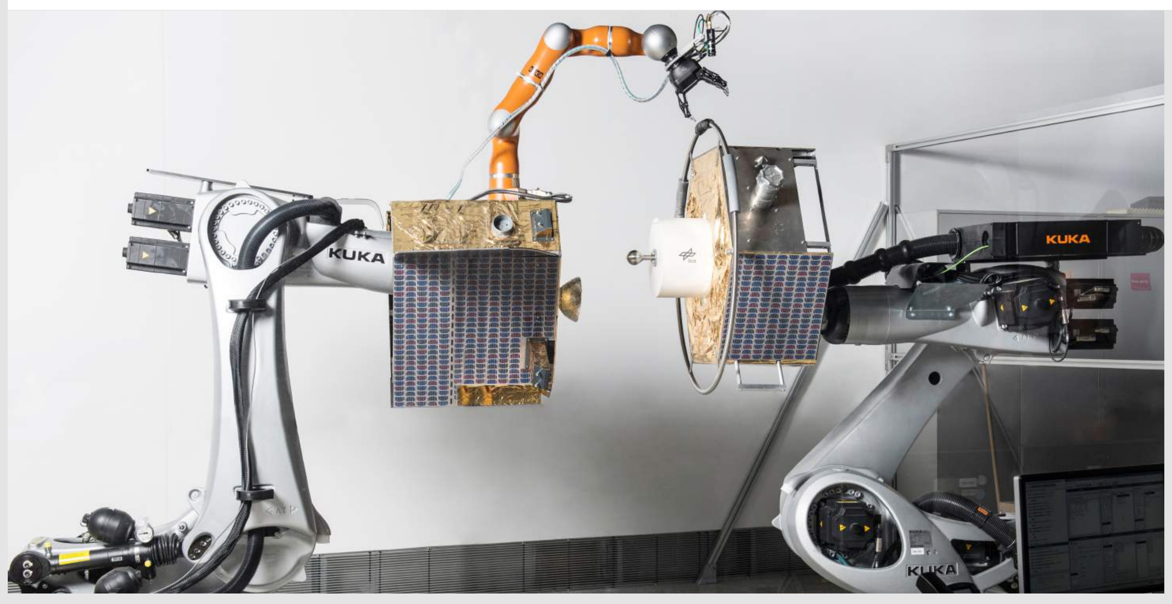


On-orbit scenario: servicer satellite (left), client satellite (right)

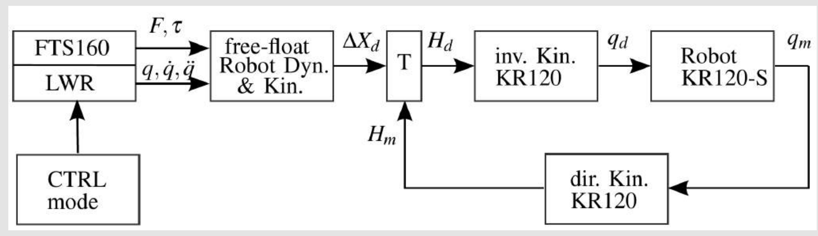
The DLR OOS-SIM

The DLR OOS-SIM is an on-ground robotic facility for simulating and validating on-orbit servicing operations [1], [2].
The facility is composed of:

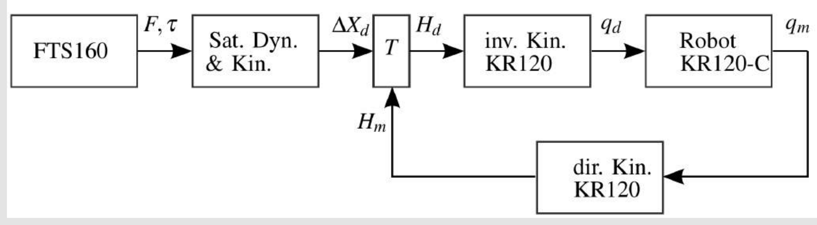
- **Servicer satellite with manipulator arm:** a 6 Dof industrial robot (KR-120) performs the simulation of a floating satellite. The robot is equipped with a force-torque sensor. The manipulation task is performed by a light-weight robot (LWR) mounted on its end-effector. The LWR is equipped with stereocamera and a 3-fingers gripper
- **Client satellite:** a second 6 Dof industrial robot (KR-120) equipped with a force-torque sensor at the end-effector simulates the dynamics of a floating body.



The OOS-Sim: on-ground servicer satellite (left) and client satellite (right)



Data flow for the servicer robot



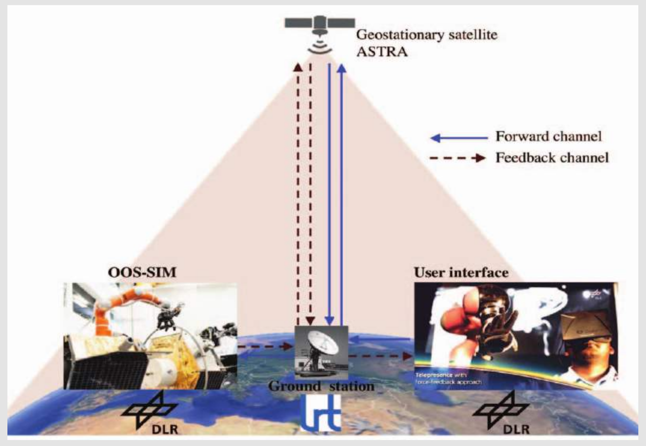
Data flow for the client robot

Control modes

The servicer manipulator can be controlled in position or torque mode. Three main operational modes are possible [3], [4]:

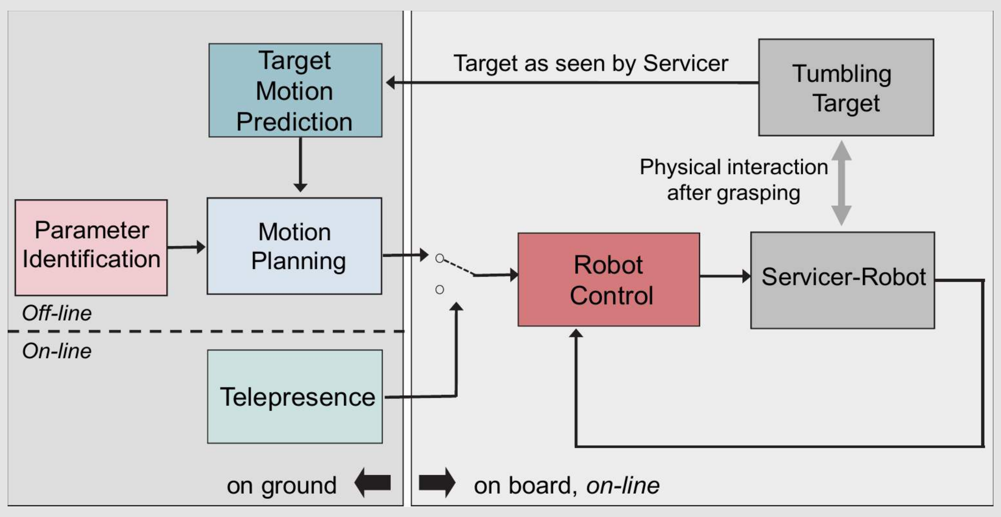
1. Telepresence:

- the servicer manipulator arm can be controlled remotely with an haptic interface
- the operator receives visual and haptic feedback
- control methods have been developed to remove the destabilizing effects of the time delay and tested on a space link infrastructure:



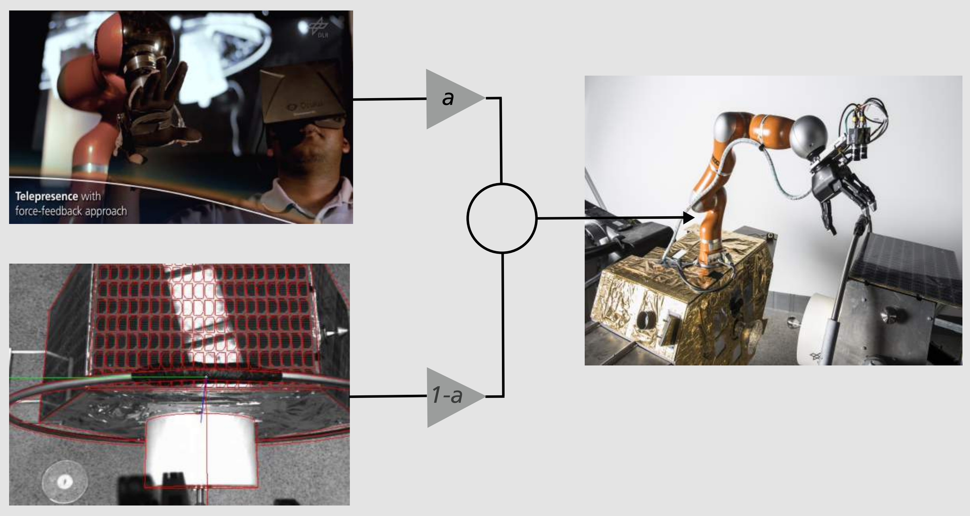
2. Semi-autonomy:

- provides extra operational safety, with respect to motion contraints
- reference trajectory is planned based on the motion of the target satellite derived from the estimeted target pose



3. Shared-control:

- torque input from the visual servoing component and from the telepresence component
- weight allocation (*a*) can be set either by autonomy or the operator



Energy-based methods for simulating free-floating dynamics

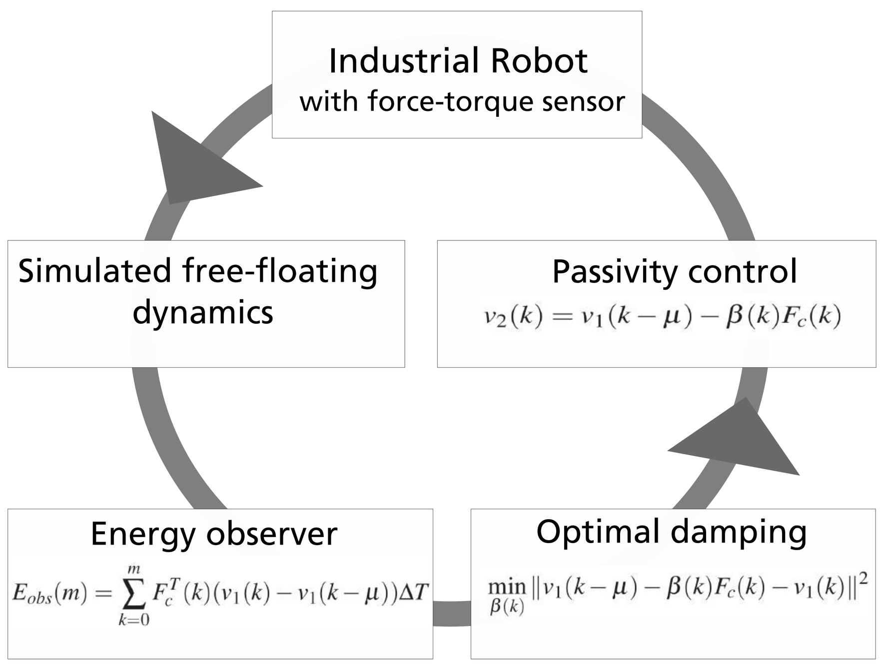
The satellite dynamics simulated by the robot is affected by time-delay and discretization effects [2], [5], [6], [7].

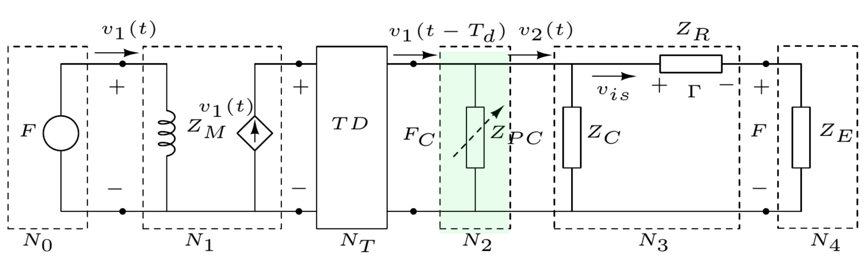
1. Time Delay: causes system instability.

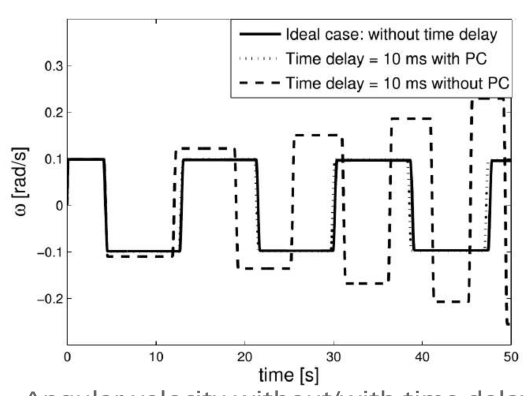
Approach:

I. Ensure the **stability** with the passivity criteria: $E(m) = E(0) + \sum_{k=0}^{m} F^T(k)v(k)\Delta T \geq 0$

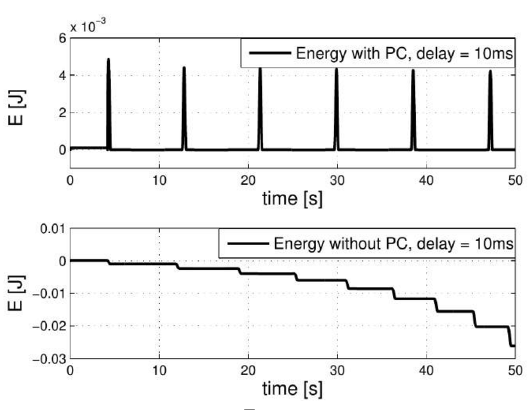
II. Guarantee the **performance** of the simulated dynamics with an optimal damper.







Angular velocity without/with time delay and delayed velocity with PC



Energy

2. Discretization: causes activity and position drift

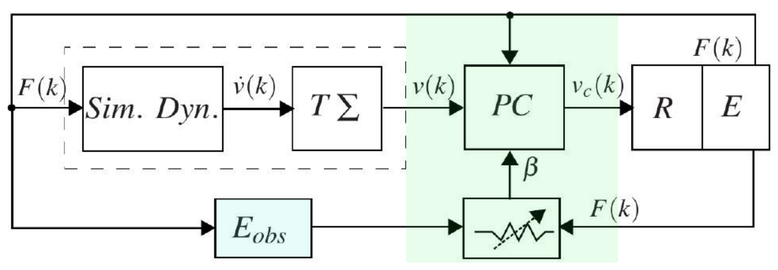
Approach:

I. Identify the energy generated by the integrator

II. Render the integrator passive

Energy generated by the Euler integrator

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

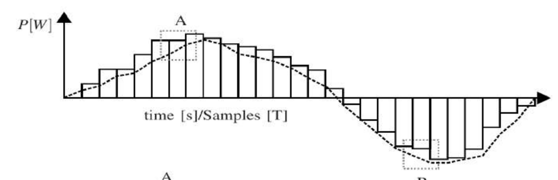


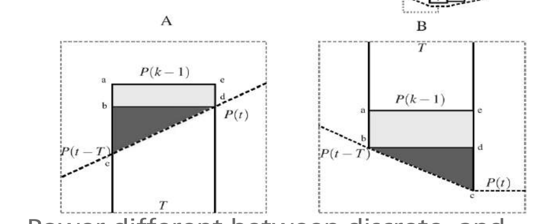
The energy observer:

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

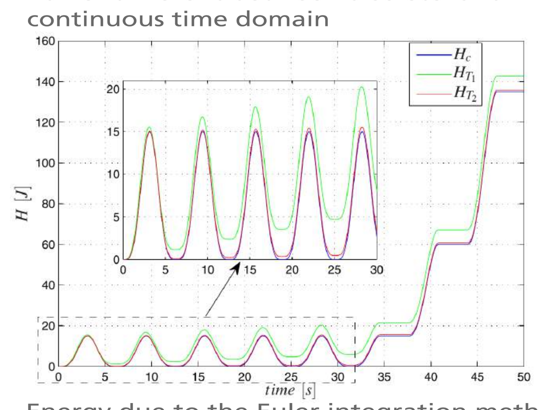
The passivity controller:

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

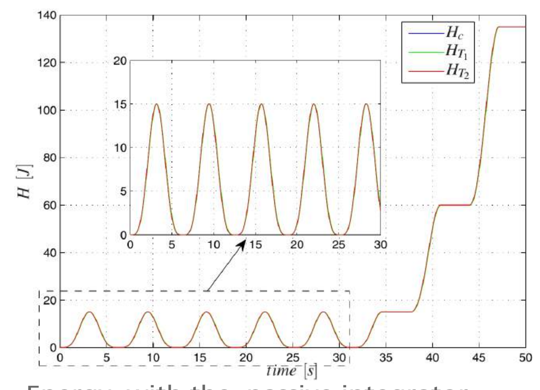




Power different between discrete and continuous time domain



Energy due to the Euler integration method



Energy with the passive integrator

References

[1] J. Artigas, M. De Stefano, W. Rackl, R. Lampariello, B. Brunner, W. Bertleff, R. Burger, O. Porges, A. Giordano, C. Borst and A. Albu-Schäffer, " The OOS-SIM: An On-ground Simulation Facility For On-Orbit Servicing Robotic Operations", in IEEE International Conference on Robotics and Automation (ICRA), Seattle, USA, pp.2854-2860, May 2015.
[2] M. De Stefano, J. Artigas, W. Rackl and A. Albu-Schäffer, " Passivity of Virtual Free-Floating Dynamics Rendered on Robotic Facilities", in IEEE International Conference on Robotics and Automation (ICRA), Seattle, USA, pp.781-788, May 2015.
[3] J. Artigas, R. Balachandran, M. De Stefano, M. Panzirsch, J. Harder, J. Letschnik, R. Lampariello, A.. Albu-Schaeffer, "Teleoperation for On-Orbit Servicing Missions through the ASTRA Geostationary Satellite", in IEEE Aerospace Conference, Big Sky, Montana, USA, pp. 1-12, March 2016.
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[5] M. De Stefano, J. Artigas, C. Secchi, " An optimized passivity-based method for simulating satellite dynamics on a position controlled robot in presence of latencies", in IEEE/RSJ International Conference on Intelligent Robot and System. (IROS), Daejeon, Korea, pp.5419-5426, October 2016
[6] M. De Stefano, R. Balachandran, J. Artigas, C. Secchi "Reproducing Physical Dynamics with Hardware-in-the-loop Simulators: A Passive and Explicit Discrete Integrator", in IEEE International Conference on Robotics and Automation (ICRA), Singapore, pp. 5899-5906, May 2017.
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