

Passivity Control for Hybride Simulations of Satellite Docking

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In the recent years a couple of scientific and commercially oriented spacecraft projects were initiated in Europe, which are involved in On-Orbit Servicing (OOS) business and related activities. Typically the term On-Orbit Servicing implies approaching a client satellite with a servicing satellite (e.g. Fig. 1), docking on it (e.g. Fig. 2) and performing any kind of servicing and repair procedures (e.g. Fig. 3). Moreover, space debris removal is also included according to the latest use of the expression OOS.

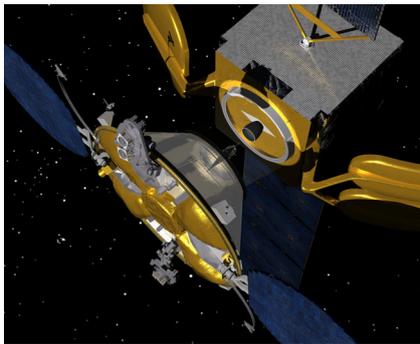


Fig. 1: ConeXpress-OLEV (ESA) Rendezvous Phase

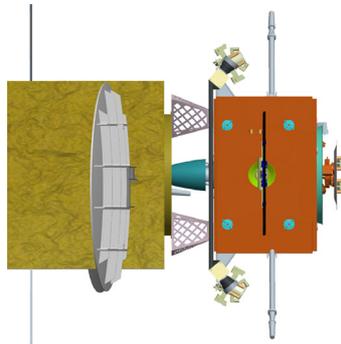


Fig. 2: Smart-OLEV (Kayser-Threde, SSC, Sener) Docked Configuration

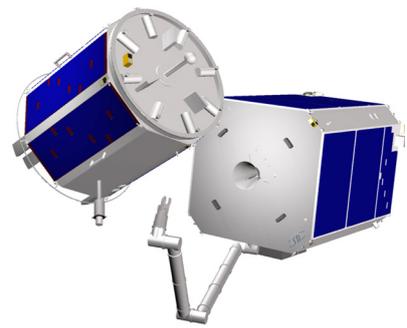


Fig. 3: DEOS (DLR): Robotics Based Satellite Servicing

A specific type of OOS applications in GEO are Orbital Life Extension Vehicle (OLEV) related missions (see Fig. 1, Fig. 2 and [1]). They are based on a tug boat like servicing satellite that docks at a client, which is running out of fuel, and takes over the entire AOCS tasks of the mated configuration in order to perform both, extending the operational life time of the client and transferring it to the graveyard orbit after end of life. A key component of OLEV is the docking payload with the docking mechanism. It is a specific capture tool, which is mounted on an extendable and retractable boom and which is dedicated for grasping and locking the apogee kick motor nozzle of the client satellite (see Fig. 4 and Fig. 5).

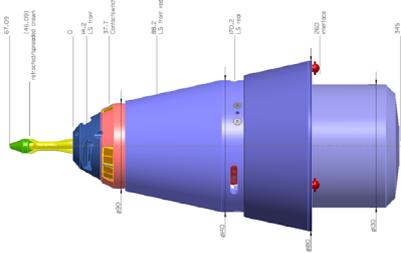


Fig. 4: Capture Tool Design

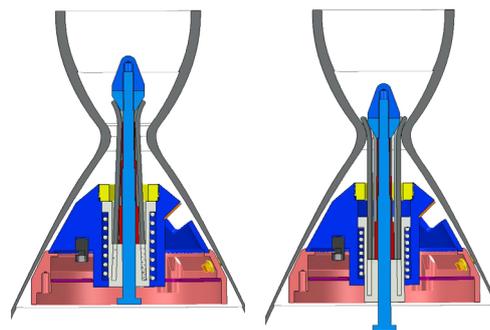


Fig. 5: Capture Tool Working Principle Passing the Nozzle Throat (left) and Locking (right)

For verification purposes of the proposed docking maneuver, which seems to be one of the most critical phases in OLEV type missions, extensive software simulations were performed in the past at DLR's Institute of Robotics and Mechatronics. In order to further improve the accuracy and fidelity of the simulations and to be able to include flight hardware like sensors, actuators and mechanisms in the simulation setup a dedicated hardware-in-the-loop (HIL) simulation facility, namely the second version of the European Proximity Operations Simulator (EPOS) was recently built at the German Space Operations Center premises [2].

EPOS is designed as a robotics based hybrid simulation facility, which splits the closed-loop simulation in a numerical part and a physical-mechanical part (see Fig. 8). Inside the numerical simulation the satellite dynamics and related effects are being calculated. The computed trajectories of the satellites are physically displayed by

two robotic systems carrying mockups of the spacecrafts and the docking payload (Fig. 6 and Fig. 7). One of the robots is mounted on a rail system such that EPOS is able to display the entire satellite rendezvous and docking procedure starting at a distance of about 25 m. In the docking case force-torque sensors feed back the physical contact forces in form of measurement data into the numerical simulation, where the satellite dynamics is affected accordingly.



Fig. 6: Robotics Part of EPOS

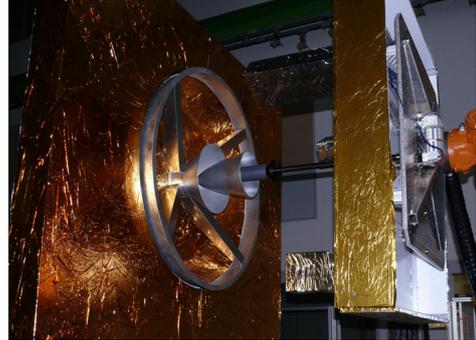


Fig. 7: OLEV Simulation Scenario in EPOS

In terms of passivity of the simulation facility, respectively numerical stability of the simulation loop we have to consider that a) system is a time-discrete one working at an overall sampling rate of 250 Hz and b) the robotic systems have a transfer behavior with a small time delays of about 30 ms required to execute the trajectory commands.

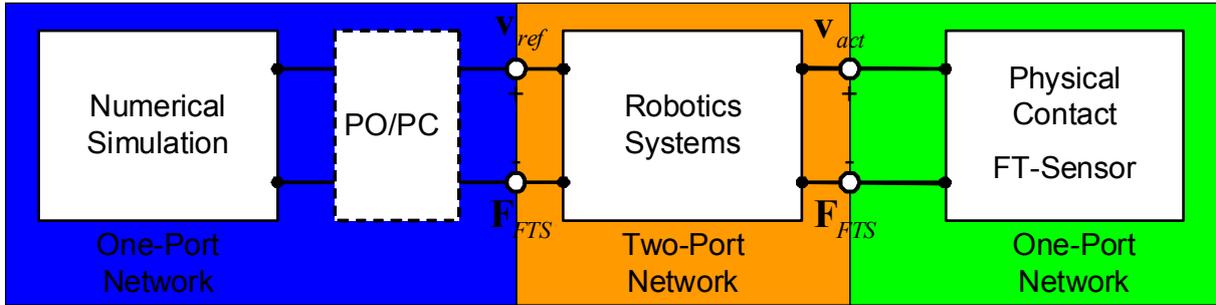


Fig. 8: Network System of Hybrid Simulation Loop

By means of network theory it can be proven that the robot systems behave potentially like active network elements, in particular if the force feedback is non-zero. In order to guarantee for system passivity in any simulation state a passivity observer (PO) and the corresponding passivity controllers (PC) are integrated in the hybrid simulation loop (Fig. 8) according to the following equations:

$$\text{Observer: } E_{PO} = dt \sum_{i=0}^k F_{FTS}(t_i) v_{ref}(t_i) - F_{FTS}(t_i) v_{act}(t_i) - E(t_0)$$

$$\text{Controller: (impedance causality) } F_{PC}(t_i) = F_{FTS}(t_i) + \alpha(t_i) v_{ref}(t_i); \quad \alpha(t_i) = \begin{cases} \frac{E_{PO}(t_i)}{dt \cdot v_{ref}^2(t_i)}; & E_{PO}(t_i) > 0 \\ 0; & E_{PO}(t_i) \leq 0 \end{cases}$$

$$\text{Controller: (admittance causality) } v_{PC}(t_i) = v_{ref}(t_i) + \frac{F_{FTS}(t_i)}{\beta(t_i)}; \quad \beta(t_i) = \begin{cases} \frac{dt \cdot F_{FTS}^2(t_i)}{E_{PO}(t_i)}; & E_{PO}(t_i) > 0 \\ 0; & E_{PO}(t_i) \leq 0 \end{cases}$$

The time domain passivity controllers work in parallel with the numerical simulation and are able to compensate for observed energy errors (E_{PO}) instantaneously within one sampling step (dt) by interference either with the sensor force feedback or with the robot motion control. The method is well known from teleoperation systems with haptic interfaces [3]. However, in the hybrid simulation case the compliant human operator in the loop who is controlling the haptic device is replaced by the dynamically incorruptible numerical simulation, which makes the system much stronger coupled.

In the presentation the implementation of the PO/PC will be introduced in detail. The experiences and results recorded during performance tests in EPOS will be presented and discussed. Critical issues like control performance at low velocities and low force signals as well as sensor signal constraints like noise and resolution will be considered.

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