EPOS−A Robotics-Based Hardware-in-the-Loop Simulator for Simulating Satellite RvD Operations

T. Boge, T.Wimmer, O.Ma, M.Zebenay

Germany Aerospace Operations Center, DLR, 82234 Wessling, Germany
e-mails: Toralf.Boge@dlr.de, Tilman.Wimmer@dlr.de, Ou.Ma@dlr.de, Melak.Zebenay@dlr.de

Abstract

Increasing complexity and costs of satellite missions promote the idea of extending the operational lifetime or improving functionalities/performance of a satellite in orbit instead of simply replacing it by a new one. Further, satellites in orbit can severely be affected by aging or degradation of their components and systems as well as by consumption of available resources. These problems may be solved by satellite on-orbit servicing missions. One of the critical issues of such a mission is to ensure a safe and reliable Rendezvous and Docking (RvD) operation performed autonomously in space. Due to the high risk associated with an RvD operation, it must be carefully analyzed, simulated and verified in detail before the real space mission can be launched. This paper describes a ground-based hardware-in-the-loop RvD simulation facility. Designed and built on 2-decade experience of RvD experiment and testing, this unique, high-fidelity simulation facility is capable of physically simulating the final approach within 25-meter range and the docking/capture process of an on-orbital servicing mission.

1 Introduction

With the increasing activities for planetary exploration and satellite on-orbit servicing, space missions requiring physical contact (including low relative-speed impact) become more common than ever. A critical step for a satellite on-orbit service mission is to successfully rendezvous, dock to, and capture the target satellite in orbit. Autonomous capture or docking in space is a very difficult and risky operation and therefore, the docking/capture system of a servicing spacecraft has to be thoroughly tested and verified before a real space mission can be launched. Ground-based test and verification of contact-dynamics responses of a spacecraft to a general 3-D physical contact in space environment is very difficult. The existing test technologies have difficulties in testing full 6-DOF contact-dynamics of large and complex space systems. For examples, the parabolic flight can only mimic 20~30 seconds of flight time inside a limited cargo space, which is insufficient for a complete docking test; the counterweight-balance technology suffers extra inertia effects which becomes significant during impact-contact motion due to large accelerations; the air-bearing based

floating test method is only a 2-D or pseudo 3-D system and also subjects to extra inertial burden due to the needed massive supporting frame/structure; the water-based neutral buoyancy technique alters the dynamic characteristics of the tested system because of the water drag. It cannot be used to test real space hardware, especially electronic hardware, too due to water environment. Only does a robotics-based active gravity compensation system have no limits on the complexity of the space system to be simulated or tested while still retaining a full 6-DOF motion condition. Plus, it can use real physical contact interfaces to generate contact forces and thus it is more accurate than any mathematical contact-dynamics model used in computer-based simulation. The concept of such a general robotics-based, contact-dynamics test facility is illustrated by the diagram shown in Fig. 1. It consists of three basic parts or subsystems:

1) A real-time computer simulator used to predict the dynamic response of the target and servicing satellites based on a high-fidelity multi-body dynamics model of the satellite system.
2) A 6-DOF robotics system used to physically deliver the computer-generated 3D dynamic motion of the two-satellite system.
3) A hardware mockup of the docking mechanism of the satellites, which will make physical contact operations (for docking and capturing).
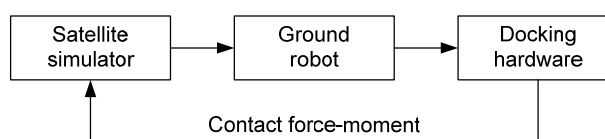

Figure 1. Three primary parts of an HIL contact-dynamics simulator

.In the concept of this hardware-in-the-loop (HIL) simulation system, the dynamics of a spacecraft including the microgravity condition is predicted by a mathematical model of the dynamical system, because it is very difficult to physically produce a full 6-DOF on-orbit dynamic motion of the satellites on the ground but it is rather easier to accurately model and simulate such dynamics on a computer. On the other hand, contact dynamics is represented by the real hardware contact because such contact action is very difficult to accurately model and simulate on a computer. Therefore, the HIL

simulation concept is a combination of both math-model based software simulation and hardware based physical test. The combined simulation process is intended to take advantages of both.

In fact, there have been several examples of HIL simulators for simulating contact-dynamics operations of space systems. German Space Center (DLR) developed an HIL simulation facility called European Proximity Operations Simulator (an early version of EPOS) a decade ago to simulate satellite rendezvous operations [1]. The facility has been used to support the testing of ATV and HTV rendezvous sensors. NASA/MSF developed an HIL simulator using a 6-DOF Stewart platform for simulating the Space Shuttle berthing to the International Space Station (ISS) [2-3]. The Canadian Space Agency also built a SPDM Task Verification Facility (STVF) using a giant 6-DOF customer-built, hydraulic robot to simulate SPDM performing contact tasks on ISS [4-5]. US Naval Research Lab used two 6-DOF robotic arms to simulate satellite rendezvous for HIL testing rendezvous sensors [6]. China is also developing a dual-robot facility to simulate satellite on orbit servicing operations [7]. The unique features of the new EPOS facility, in comparison with those existing systems, are that it uses two heavy-payload robots which can handle a payload up to 250 kg and it allows one robot to approach the other from 25-meter distance away until zero distance.

2   EPOS Facility

2.1 Overview

DLR has more than two decades of experience in the field of simulating RvD maneuvers. The previous EPOS facility was a test bed jointly developed by ESA and DLR for the simulation of spacecraft maneuvers notably over the last few critical meters of the rendezvous phase (prior to physical docking). As shown in Fig.2, the facility consists of a large mobile platform used to hold the RvD hardware interface. The platform can provide 6-DOF translational and rotational motion to the RvD interface. The last intensive utilization of the facility was the test and verification of the ATV RvD sensors and systems which are used for the approach to ISS. It was also used for testing RvD sensors of the Japanese HTV.

Future applications for satellite on-orbit servicing missions require the EPOS facility to be able to provide the following test and simulation capabilities:

(A) the 6-DOF relative dynamic motion of two satellites in the final approaching phase from 25 meters to 0 meters.

(B) the 6-DOF contact dynamic behavior during the entire docking process including the initial impact,

soft docking, and hard docking (final rigidization).

(C) the space-representative lighting and background conditions

Since the old EPOS facility apparently cannot provide all of these capabilities, especially the capability for contact dynamics simulation, it was replaced completely by a new EPOS system. The design and construction work of the new facility began in 2008. The development work is a joint effort of two institutions of DLR at Oberpfaffenhofen. The first institution is the German Space Operations Center (GSOC), which provides the major resources for the project and is responsible for the overall design, construction, and operation of the facility. The second contributing institution is the DLR's Robotics and Mechatronics Institute, which provided expertise in space robotics technology and some HIL simulation experience.
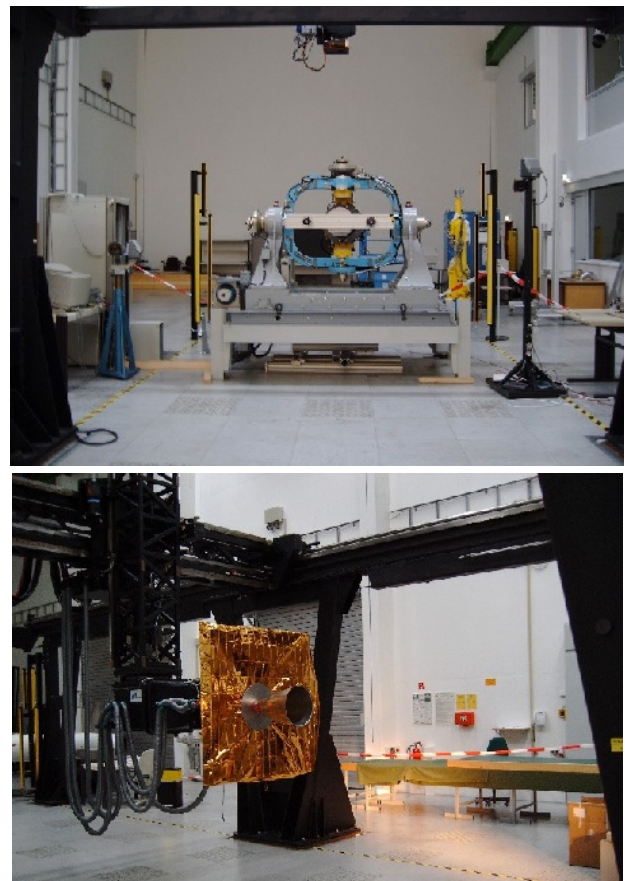

Figure 2. Old EPOS facility: the fixed part of the testbed (top view) and the mobile part (bottom view)

The new EPOS facility is aimed at providing test and verification capabilities for complete RvD processes of on-orbit servicing missions will be provided. The facility comprises a hardware-in-the-loop simulator based on two industrial robots (of which one is mounted on a 25m rail system) for physical real-time simulations of rendezvous and docking maneuvers. This test bed will

allow simulation of the last critical phase (separation ranging from 25m to 0m) of the approach process including the contact dynamics simulation of the docking process.

Moreover, its main advances are:

- It is a highly accurate test bed. The measurement and positioning performance will be increased by factor 10 compared to the former EPOS facility.
- Dynamical capabilities will allow for high commanding rates and the capability of force and torque measurements.
- The simulations of sunlight illumination conditions as well as the compensation of Earth-gravity force are both part of the assembly to generate an utmost realistic simulation of the real rendezvous and docking process.
- The utilization of standard industrial robotics H/W allows a very high flexibility related to different application scenarios.
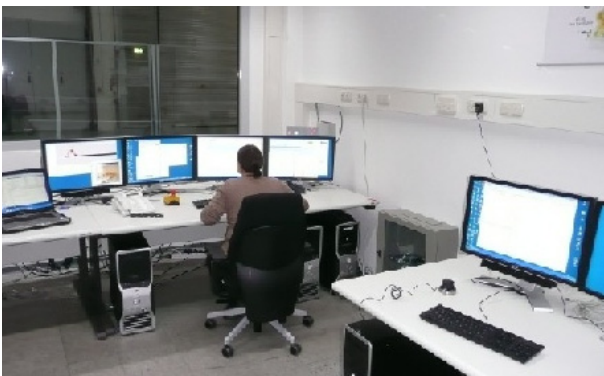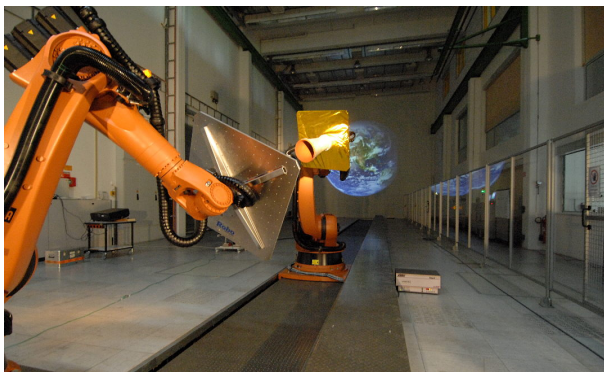 \end{itemize}

Figure 3 The new EPOS facility: robotics-based testbed (top view) and operation station (bottom view)

The new facility consists of the following components (for details, see dglr09):

- A rail system mounted on the floor to move an industrial robot up to a distance of 25m,
- A KUKA KR240 robot (robot 1) mounted at the end of the rail system for simulating the 6 degree of freedom of the second spacecraft.
- A KUKA KR100HA robot (robot 2) mounted on the

rail system for simulating the 6 degree of freedom of one spacecraft.
- A PC-based monitoring and control system to monitor and control the RvD simulation on the facility. In can be divided into three levels.
  - The local robot control where all axes of the robots are separately controlled.
  - The facility monitoring and control system (FMC) where the entire facility is controlled in real time.
  - The application control system where the actual RvD-simulation application is running

2.2 A typical RvD Simulation Scenario

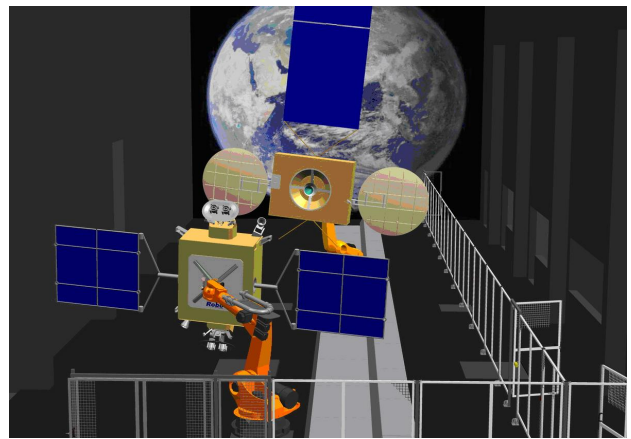.A typical set up of the EPOS facility for an RvD simulation scenario is shown in figure 4.

Figure 4. EPOS set up for SMART-OLEV [8]

For "hardware in the loop" scenarios such as these, the RvD sensors and the robotic manipulator arm are mounted on one robot and a typical satellite mock-up of the client satellite is mounted on the other robot. The RvD sensors can measure the relative position and attitude of the client satellite. On this basis, the on-board computer calculates the necessary thrusters or reaction wheel commands. These are put into the real time simulator. For the next sample, this dynamic simulator computes an update of the state vector (position attitude of the spacecrafts) based on all relevant environmental and control forces and torques. Then, the state vector for the new sample will be commanded to the facility.

2.3 Facility Performance Specifications

Table 1 specifies the EPOS motion simulation capabilities [9].

Table 1 EPOS motion capabilities

Parameter	Robot 1	Robot 2
Position:		
X [m]	-2,5 -+2,5	-2,5 -+24,5
Y [m]	-1,0 -+4,0	-2,5 -+2,5
Z [m]	-0,5 -+1,5	-0,5 -+1,2
Roll [deg]	-300 -+300	-300 -+300
Pitch [deg]	-90 -+90	-90 -+90
Yaw [deg]	-90 -+90	-90 -+90
Max. tip velocity:		
Translational [m/s]	2	2
Rotational [deg/s]	180	180
Command IF		
Command rate [Hz]	250	250

Because EPOS will also be used for RvD sensor verification purpose, the facility was extensively calibrated after its installation. With a laser tracker device an overall positioning accuracy of the facility of better than 2 mm (3D 3σ) and an orientation acuracy of 0.2° (3D 3σ) have been verified. In addition it is planned to develop a online measurement system which measures the relative position between both robots and commands corrections to the robots. So the achieved position accuracy will be in sub millimeter range.

3 Contact dynamics simulation

A critical requirement for the control of this HIL simulator is that the 6-DOF robot in the loop has to exactly mimic the dynamic response of the space system to be simulated during a contact operation. In other words, the dynamics of the 6-DOF robot should not alter the dynamics characteristics of the simulated satellite system as they exhibited at contact interfaces. This requirement will be met by applying advanced robotics control technologies. The major aspects of the system are described in the following subsections.

3.1 Control Architecture and requirements

The architecture of the high-level EPOS control system is illustrated in the diagram shown in Fig.5. From the figure, one can see that the two active robots (KUKA industrial robots in this case) are controlled to strictly track the satellite simulation output. When a physical contact happens, the contact force and moment generated by the docking hardware will be fed back into the satellite simulator and, as a result, the simulated satellite motion output will be changed (with a time delay) by the contact forces. For such a HIL simulation system to have high simulation fidelity, it is required that the simulated

docking behavior (which is measured by the resulting motion state and contact force-mention) must be the same as that from the real satellite docking operation. Based on the common sense in engineering, one can easily understand that such a fundamental requirement can be achieved in the following two conditions:

1) The active robots used to deliver the simulated satellite motion must be able to respond the HIL control command fast.
2) When reacting to a physical contact during a docking operation, the active robots must dynamically behave like the on-orbit satellites being simulated.

The first condition requires the active robots to have fast response to its control system and the second condition requires the robots to exhibit the very similar dynamics characteristics as the satellites to be simulated.

3.2 Control Challenges and Solution Strategies

Although the necessity of the first condition stated in Section 3.1 is not difficult to understand, it is not easy to meet for the EPOS robotic system because the two KUKA robots are industrial robots with massive bodies (thus large inertias). They are made for usual industrial applications, such as working in a automobile assembly line, the robots do not have very fast responding speed. The known responding time of the robots is about 8 command cycles and each command cycle takes 4 milliseconds [11]. In other words, the duration from the time when the EPOS control system issues a control command to the time when the robot physically reacts to the command can be up to 8 command cycles or 32 ms. This is a large time delay for controlling a robot to perform contact motions. Moreover, the maximum sampling rate of the robots is the same as their commanding rate, 250 Hz. This rate has been quite high for a usual industrial robot but it is not considered high for a robot to be used to perform HIL contact dynamics simulations. Since the robots must be used as is in the HIL system, advanced process control system must be developed to resolve this time delay problem. The Robotics and Mechatronics Institute of DLR is currently developing technology to practically solve this problem. Their intended approach is based on the principle of actively balancing the energy inputting to and outputting from the robotic system. In other words, the method is trying to achieve a passivity behavior of the industrial robots in the HIL simulation process, so that the risk of simulation instability due to the large time delay will not happen. A primary concept of the said technology is reported in [12].
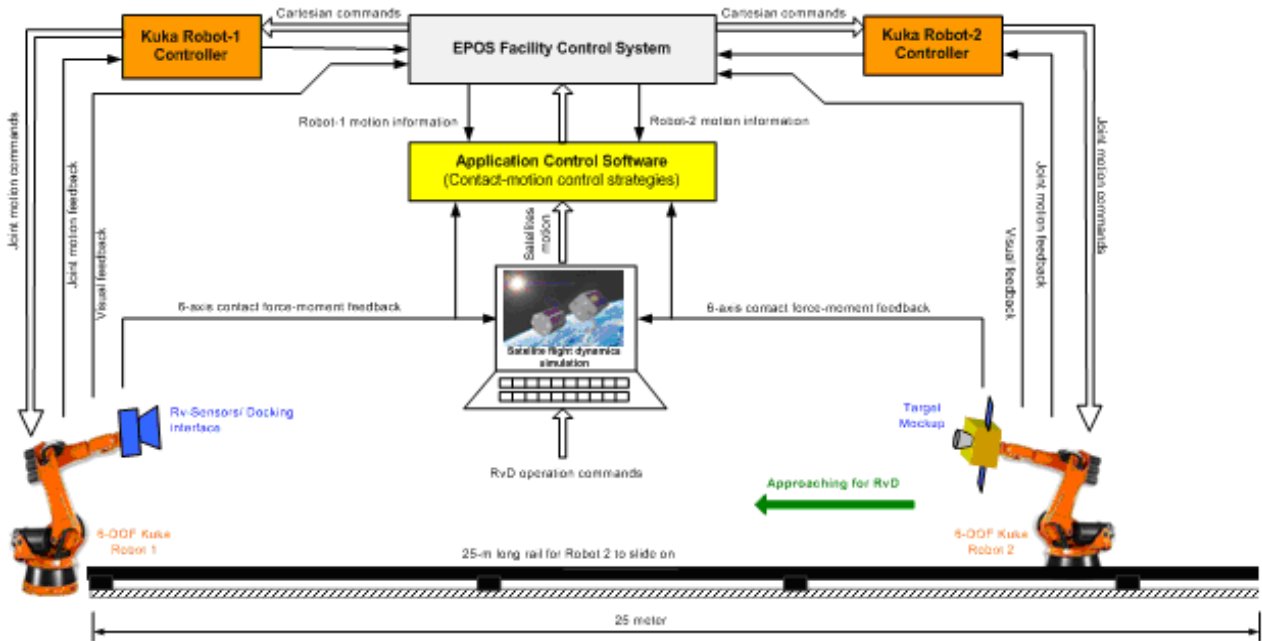
Figure 5 Control system of the EPOS facility

Obviously, the second condition described in Section 3.1 cannot be met by the industrial robots either because the robots are basically positioning machines with high stiffness. Therefore, when the robot tip is in physical contact or being pushed by an object (e.g., the docking hardware), it will not comply as a free-floating satellite would. The robot may even encounter instability in a stiff contact case. Note that whether a contact operation to be simulated is stiff or not depends on the satellites and their docking interfaces and it cannot be chosen by the EPOS system. Therefore, another control loop outside the industrial robot needs to be implemented to solve this problem (since no inner control loops of the industrial robots can be modified). An end-effort contact force control method cannot be implemented either because the reference contact force profile for a proper docking operation can never be known. An ideal approach would be to apply an impedance control strategy such as the one described in [13]. However, an impedance control requires torque control capability at the joint level. This is not available in the KUKA robots. All we have from the robots is an end-effector position or rate control capability. Similarly, many other advanced and proven robot control strategies, such as the computed torque control [14], passivity-based control [15], etc. cannot be implemented in EPOS either because we either do not have a joint torque control capability or do not have an inverse dynamics model of the robots. Instead, an end-effector admittance control strategy is proposed to deal with the problem because such a control method does not need a joint torque control capability or a dynamics mode of the robot to implement.

As seen in the block diagram shown in Fig.6, the admittance control will adjust the commanded end-effector trajectory (generated by the satellite simulator) such that the robot will exhibit similar impedance as the docking satellites during a docking operation. The input to the admittance control will be the real contact force and moment which are measured from the physical contact between the two parts of the docking hardware. The admittance control law may be expressed at high level as follows:

$$\Delta \mathbf{x} = \left[\mathbf{M}s^2 + \mathbf{C}s + \mathbf{K} \right]^{-1} \mathbf{f}_c$$

where vector $\Delta \mathbf{x}$ is the adjustment to the end-effector's reference motion command; $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ are the parameter matrices of the impedance model of the docking satellites; and $\mathbf{f}_c$ is the vector of the contact force and moment measured by the 6-axis force-moment sensors.
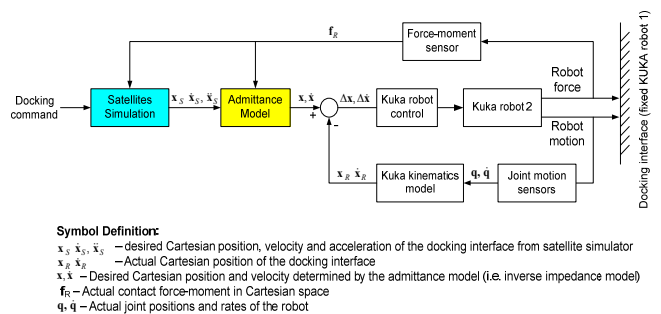

Symbol Definition:
$\mathbf{x}_S$ $\dot{\mathbf{x}}_S$, $\ddot{\mathbf{x}}_S$ − desired Cartesian position, velocity and acceleration of the docking interface from satellite simulator
$\mathbf{x}_R$ $\dot{\mathbf{x}}_R$ − Actual Cartesian position of the docking interface
$\mathbf{x}$, $\dot{\mathbf{x}}$ − Desired Cartesian position and velocity determined by the admittance model (i.e. inverse impedance model)
$\mathbf{f}_R$ − Actual contact force-moment in Cartesian space
$\mathbf{q}$, $\dot{\mathbf{q}}$ − Actual joint positions and rates of the robot

Figure 6 Admittance control strategy for EPOS robot

.It should be emphasized that the impedance model used in the admittance control algorithm needs to be carefully selected based on the dynamics properties of the involved satellites. This should not be very difficult if the dynamics properties of the two involved satellites are known. The application of the admittance control

technology in the Canadian HIL simulator STVF has showed robust performance against the variations of some parameters of the its robotics system as well as possible external disturbances [16].

3.3 Measuring contact force and moment

In order to implement the HIL contact dynamics simulation capability, the facility should be able to properly measure the contact force and moment during simulation. Due to the complicated geometries of the docking hardware interfaces, a measurement of all the local contact forces (from multiple contacts) is impossible. Hence, a 6-axis force-moment sensor is installed at the base of the docking interface hardware. In the case shown in Fig.7, the force-moment sensor is installed right behind the docking nozzle. As a result, the sensor will measure the resultant contact force and moment as applied to the end of the nozzle which is also the tip of the robot. The selected force-moment sensor has built-in compliance avoiding hard impact which may not only be inconsistent with the impedance of the satellite docking system but also damage the force sensor and robot equipment. This additional compliance in the loop is justified as long as the added compliance is compatible with that of the real docking system of the satellites. The sensor is capable of collect force data every 3 ms, a rate much faster than the robot's commanding rate. Before being sent to the admittance controller and the satellite simulator, the raw contact force data from the force-moment sensor will be processed by the EPOS operation system to compensate the partial weight of the docking hardware and to be transformed to the proper coordinate frames.
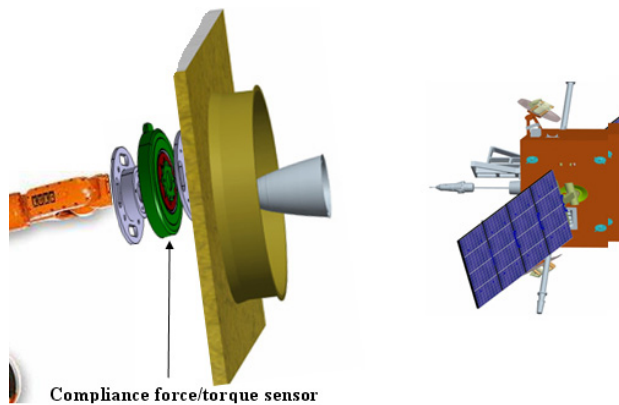

Figure 7 Compliance force/torque sensor configuration

4   Applications

As a generic RvD simulation facility, EPOS is not designed for a specific mission-related application. However, potential future missions did provide the momentum for the development of the facility. Recently,

several satellite programs have proposed on-orbit servicing (OOS) capabilities in the near future. The scenarios involve an on-orbit servicing satellite approaching and docking to a client satellite. Described in this section are the two future missions, for which EPOS can play a critical role in the test and verification of the involved RvD operations.

4.1 SMART-OLEV

The objective is the orbital lifetime extension for commercial Geo-stationary satellites (OLEV- Orbital Lifetime Extension Vehicle). A service satellite shall approach to a client satellite, dock on it and take over the attitude and orbit control of the client. This scenario is shown in Fig.7.
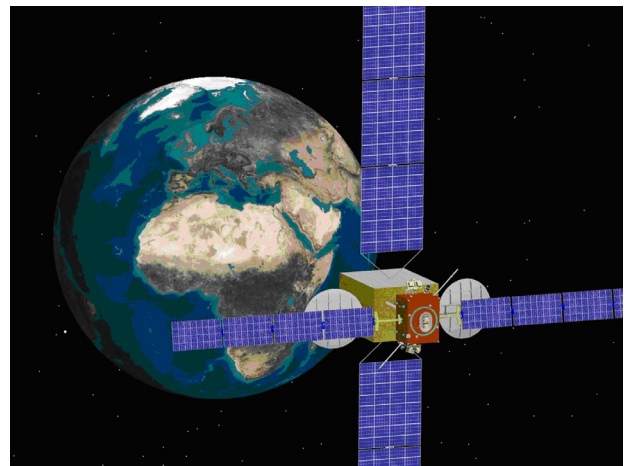

Figure 7   SMART-OLEV docked at a Geostationary satellite

4.2 DEOS (**DE**utsche **O**rbitale **S**ervicing mission)

DEOS is a technology demonstration mission in low Earth orbit where various scenarios in the area of rendezvous and docking as well as re-entry capabilities will be considered. According to the current Phase A study DEOS will consist of both a servicing and a dedicated client spacecraft, which will be launched together into an initial orbit. Primary mission goal is the capturing of a tumbling and non-cooperative client satellite with a manipulator on the servicing spacecraft and the re-entry (de-orbit) of the rigidly coupled configuration within a pre-defined orbit corridor. To achieve the envisaged goal a dedicated set of experiments have to be conducted in which the complexity will be stepwise increased over the mission period. The two spacecrafts are depicted in Fig. 8.
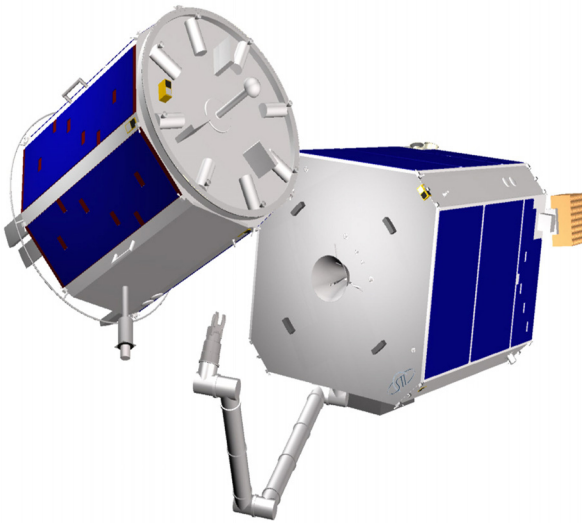
Fig. 8 Servicer and client satellite of DEOS [10]

5 Conclusions

An advanced hardware-in-the-loop (HIL) simulation facility is currently being developed by DLR to support future development and operation of satellite on-orbit servicing missions. The facility is capable of simulating a complete rendezvous and docking (RvD) process in a final approaching phase from 25 meters to 0 meters including the soft docking and capturing operations. Two specially ordered KUKA robots are used to maneuver the RvD hardware interfaces in full 6-DOF Cartesian space. One of the robots can slide on a pair of rails to provide the approaching motion. Lighting equipment is available to provide space lighting condition and background image. The hardware construction of the facility has been completed and the software development and integration work is still underway. The facility is currently available to simulate rendezvous operations. It is anticipated that the facility will be fully operational by the end of 2010.

References

[1] R. Krenn and B. Schaefer, "Limitations of hardware-in-the-loop simulations of space robotics dynamics using industrial robots", *European Space Agency*, ESA SP-440, Aug. 1999, pp. 681-686.

[2] S. Ananthakrishnan, R. Teders, and K. Alder, "Role of estimation in real-time contact dynamics enhancement of space station engineering facility", *IEEE Robotics and Automation Magazine*, Vol. 3, No. 3, 1996, pp. 20-28.

[3] F.D. Roe, R.T. Howard, and L. Murphy, "Automated rendezvous and capture system development and simulation for NASA", *Proc. SPIE*, Vol. 5420, 118 (2004); doi:10.1117/12.542529.

[4] J.-C. Piedboeuf, J. De Carufel, F. Aghili, and E. Dupuis, Task verification facility for the Canadian special purpose dextrous manipulator, Proc IEEE Int Conf on Robotics and Automation Detroit, 1999, Vol. 3, pp. 1077–1083.

[5] O. Ma, J. Wang, S. Misra, and M. Liu, "On the validation of SPDM task verification facility", *Journal of Robotic Systems*, Vol.21, No.5, 2004, pp. 219-235.

[6] R. Bell et al., "Hardware-in-the-loop tests of an autonomous gn&c system for on-orbit servicing", AIAA-LA Section/SSTC Responsive Space Conference 2003.

[7] W. F. Xu, B. Liang, Y. S. Xu, C. Li and W. Y. Qiang, "A Ground Experiment System of Free-floating Space Robot for Capturing Space Target", Journal of Intelligent and Robotic Systems, vol.48, no.2, pp. 187-208, 2007.

[8] T. Tzschichholz and T. Boge; GNC Systems Development in Conjunction with a RVD Hardware-in-the-loop Simulator; 4th International Conference on Astrodynamics Tools and Techniques; Madrid, 3-6 May 2010

[9] T. Boge et. al. Hardware-In-The-Loop Simulator für Rendezvous- und Dockingmanöver. In Proceedings of DGLR-conference, 2009.

[10] T. Rupp, T. Boge, R. Kiehling, and F. Sellmaier. Flight dynamics challenges of the german on-orbit servicing mission DEOS. In 21th International Symposium on Space Flight Dynamics, 2009.

[11] KUKA Robot manual or a RoboTech Document.

[12] B. Shaefer, R. Krenn, M. Loesch, and W. Rulka, "Space robotics dynamics simulation performance in real-time environments", *Adances in Computational Multibody Dynamics*, Lisbon, Portugal, Sept.20-23, 1999.

[13] N. Hogan and S.P. Buerger, "Impedance and Interaction Control", Chapter 19 of ????.

[14] R. H. Middleton and G. C. Goodwin, "Adaptive

computed torque control for rigid link manipulations", Systems & Control Letters, Vol. 10, Issue 1, January 1988, pp.9-16.R.

[15] Ortega, A.J. van der Schaft, I. Mareels, and B. Maschke, "Putting energy back in control", IEEE Control Systems Magazine, February 2001.

[16] AGHILI, E, DUPUIS, E., PIEDBaeUF, J.-C., and DE CARUFEL, J.:PERRY, M. Hardware-in-the-loop simulations of robots performing contact tasks'. Proceedings of fifth intemational symposium on Artificial intelligence, robotics and automation in space, 1999, Noordwijk, The Netherlands, ESA,.Publication Division, pp. 583-588