VISUAL NAVIGATION FOR ON-ORBIT SERVICING MISSIONS

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Abstract: *Increasing complexity and costs of satellite missions promote the idea of looking for opportunities to extend the operational lifetime or to improve the performance of a satellite instead of simply replacing it by a new one. Satellites in orbit can severely be affected by ageing, limited fuel source, or degradation of their hardware components. Also the disposal of spacecraft after the end of lifetime will play a more and more important role in the future, especially, if the involved orbits are of strategic importance. Therefore, satellite on-orbit servicing (OOS) has increasingly caught the interests of both satellite developers and users. One of the critical issues of a satellite on-orbit servicing mission is to ensure a safe and reliable Rendezvous and Docking (RvD) process. DLR is developing new navigation algorithms using standard camera systems and advanced 3D sensor systems like PMD (Photonic Mixing Device). Furthermore DLR has built a new and more advanced RvD simulation facility called EPOS 2.0 (European Proximity Operations Simulator). The facility uses robotic manipulators to generate the relative motion between two satellites and allows full RvD test and simulation capabilities for OOS missions up to a range of 25m.*

Keywords: *Rendezvous and Docking, Hardware in the Loop, Visual navigation, On-Orbit Servicing*

1. Introduction

Meanwhile, OOS has become part of the space programs of the US, Japan, Canada and Germany. A milestone was set with the successful completion of DARPA's Orbital Express (OE) mission in 2007 [5]. The goal of OE was to demonstrate the ability to autonomously perform Rendezvous & Docking (RvD) operations including maintenance activities like refuelling. In contrast to the goals of OE, the focus of DLR is to capture non-cooperative and/or not specially prepared client spacecraft. "Non-cooperative" is understood as there is no cooperation with respect to attitude and orbit control of the client, e.g. when the client is out of operation. "Not specially prepared" means that the client satellite does not have a special docking port or retro reflectors used for vision based navigation.

1.1. OOS missions

Recently, several satellite projects focuses on providing on-orbit servicing (OOS) capabilities in the near future. The scenarios involve a service spacecraft approaching and docking to a client satellite. The paper is based on research work performed by DLR which can be used for the following two mission scenarios.

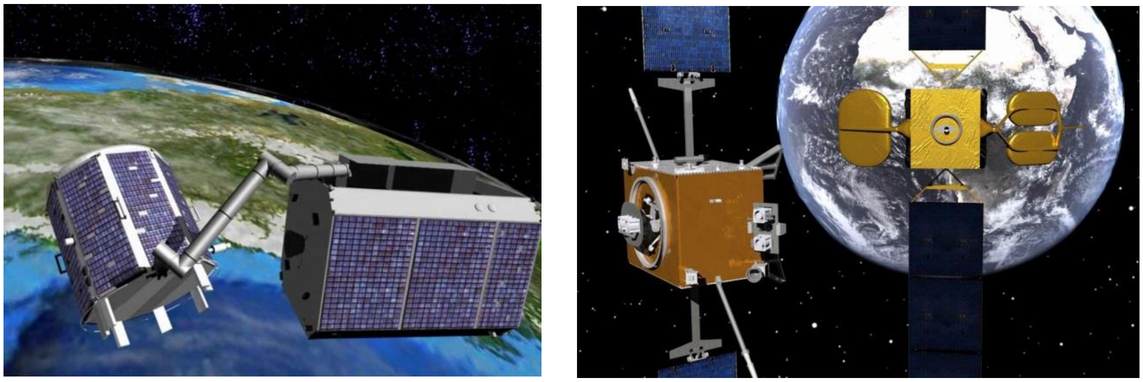

Figure 1. DEOS servicer capture the client satellite (left) and OLEV approaching a ComSat (right) [8]

1.1.1. OLEV

OLEV is a purely commercial project managed by a European consortium including a strong DLR participation [7]. The business case of OLEV is to build an orbital servicer which is able to dock on high value, geostationary communication satellites and to take over attitude and orbit control in order to extend the clients' lifetime after their fuel has been depleted. Beside life extension OLEV can be used for fleet management purposes like relocation to other GEO positions or disposal to graveyard orbit.
The OLEV project has finished a delta phase B study in 2008, the present focus lies on financial engineering and development of key technologies like GNC systems.

1.1.2. DEOS

DEOS is a robotic technology demonstration mission [6]. Its primary goals are to capture a tumbling non-cooperative client satellite with a service spacecraft and to de-orbit the coupled configuration within a pre-defined orbit corridor at end of mission. Secondary goals are to perform several rendezvous, capture and docking scenarios as well as orbit maneuvers with the mated configuration.
The DEOS project has finished a delta phase B1 study in 2011. Currently, a Phase B2 study is on-going.

1.2. Technological Challenges for OOS-Missions

Rendezvous and Docking is state of the art for manned spaceflight missions today. In addition to the new OOS applications, new technological requirements can be found for:

- the rendezvous phase
- the docking phase
- the degree of on-board autonomy

Typically, the target satellites have not been built for rendezvous and docking tasks. Therefore the rendezvous sensors and systems have to cope with completely

uncooperative targets. The robotic based mechanisms have to ensure a safe and reliable gripping or docking at a target without any foreseen docking mechanisms. For missions without continuous contact to ground (typically LEO missions), the on-board autonomy plays an important role.
In addition to these specific design requirements for the space segment an extensive validation and verification program has to be performed during the various development steps on ground. Because the rendezvous and docking processes are the most critical mission phases the corresponding maneuvers have to be analysed, simulated and tested extensively. DLR has built up a simulation facility, called EPOS 2.0, to provide test and verification capabilities for rendezvous and docking processes of on-orbit servicing missions. It is a hardware-in-the-loop simulator for physical real-time simulations of rendezvous and docking maneuvers. This testbed allows the simulation of the last critical phase of the approach process, 25 meters to 0 meters, including the contact dynamics simulation of the docking and berthing processes.
This paper provides an overview about the on-going developments at DLR for the rendezvous navigation process using only uncooperative targets. Additionally it presents the advanced test facility EPOS 2.0 for simulation of rendezvous and docking processes on ground.

2. Rendezvous Navigation

2.1. Overview

The rendezvous phase starts at a distance where the navigation process switches from absolute navigation to relative navigation (see Fig. 2). The absolute navigation uses onboard GPS measurements or ground station tracking data for the determination of servicer and target orbit [7]. The relative navigation process needs sensors onboard the servicer to determine the relative position of the target w.r.t. the servicer. This rendezvous process can be split into the following sub-phases [6]:

Far Range Rendezvous:
During the far range rendezvous phase the servicer is transferred from the rendezvous entry gate to a safe point which is in the vicinity of the client. This is also the starting condition for the close range rendezvous approach. However, if the relative navigation process needs more than one sensor (e.g. far and mid range camera), at least one intermediate hold point is required which allows a controlled switch-over from one sensor to another.

Close Range Rendezvous:
A first target pose estimation is conducted at the safe point followed by a fly around. This is necessary before the docking or berthing procedure with respect to a more or less unknown target can be performed. Afterwards the close range rendezvous process is started with an orbit maneuver from the safe point to the close hold point. Arrived at the close hold point the navigation cameras have to be switched from mid-range to close range mode. From the close hold point the final approach to the docking or berthing box is performed via a straight line trajectory (v-bar maneuver). During the final

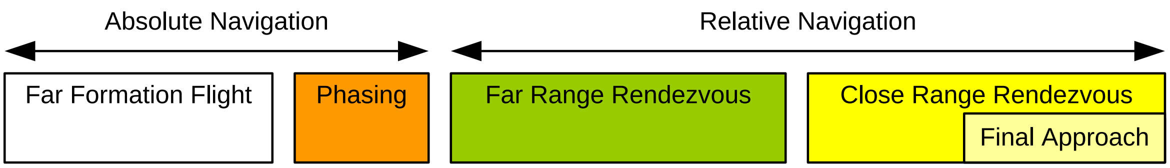

Figure 2. Rendezvous sub-phases [6]

approach the servicer has to be kept within a corresponding pre-defined corridor in an onboard automated way. If the approach corridor is violated a collision avoidance maneuver has to be initiated autonomously onboard. The close range rendezvous terminates at the hold point at the berthing / docking box denoted as mating position.

2.2. Far Range Navigation

The far range rendezvous, starting from large distances (up to 30 km) and ending at a few hundred meters, is of high importance in the first phases of the approach to the target spacecraft. A robust and reliable estimation of the relative position with respect to the target has to be provided by a navigation system. For estimation of the relative position, the concept of angles-only navigation [10] can be employed by using a monocular camera as rendezvous sensor. In this method, the direction to the target (line-of-sight, LOS) is extracted from camera images and serves as measurement for a navigation filter.

DLR developed an algorithm to detect the target in images for large distances to the target object [1]. Due to the large distance, the object will only cover a few pixels in the camera image which makes it impossible to extract the whole pose of the object. However, it is still sufficient to determine the bearing of the object. The algorithm does not require any a priori information about the target object. By using sophisticated high-level processing such as cluster analysis, the target is isolated from other objects and stars. Finally, the image position of the target is provided with subpixel precision.

Figure 3 presents the single components of the algorithm and their interactions. The far range image processing system sequentially processes the images. Inputs to the system are the current image and the attitude of the service spacecraft. Outputs are the target’s position in 2D image coordinates and the line-of-sight vector as well as the camera’s attitude. At first the image processing method for far range navigation consists of the detection of objects of interests (=clusters) which could be stars in the background, the target S/C and hotspots of the camera CCD-chip. In a second step the target has to be identified by the determination of certain cluster properties. This can be done by identifying stars using a star catalog. Furthermore the different motion of stars and target in the image are identified by motion segmentation. If the target identified the line-of-sight vector of the target in J2000 coordinate system are computed.

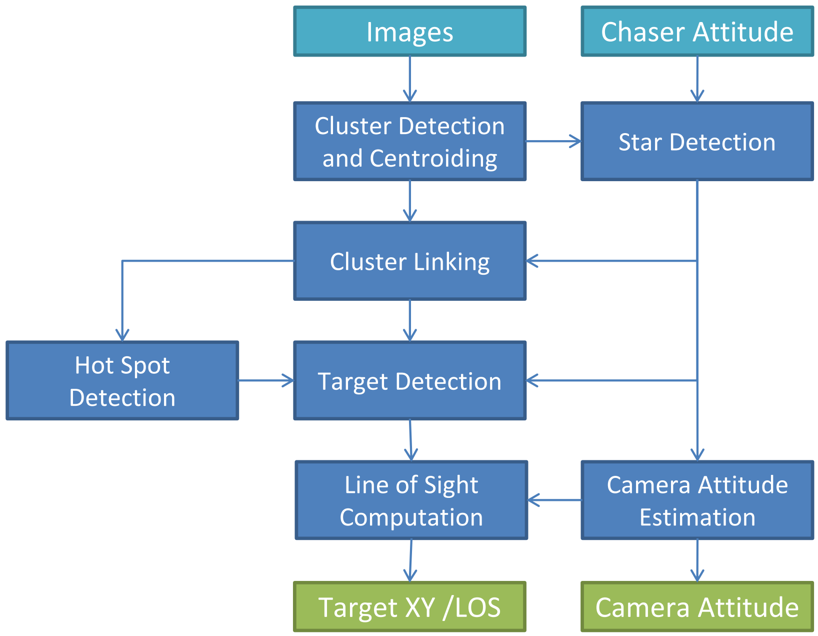

Figure 3. Overview on the Algorithm for Far Range Image Processing [1]

The image processing algorithm has been tested in a rendezvous experiment called ARGON (Advanced Rendezvous demonstration using GPS and Optical Navigation) [4]. It was conducted by DLR-GSOC in the extended phase of the PRISMA mission. DLR/GSOC could demonstrate far range rendezvous technology based on angles-only navigation and successfully performed an approach from 30 km to 3 km. Figure 4 shows an overlapping of sample images captured at ~ 5km distance between chaser and target. In the right sub-figure the 2D (x,y) position of the target in image coordinates is plotted. The image processing system could provide the LOS to the target with an accuracy of better than one pixel; refer the more detailed presentation of accuracy results in [1].

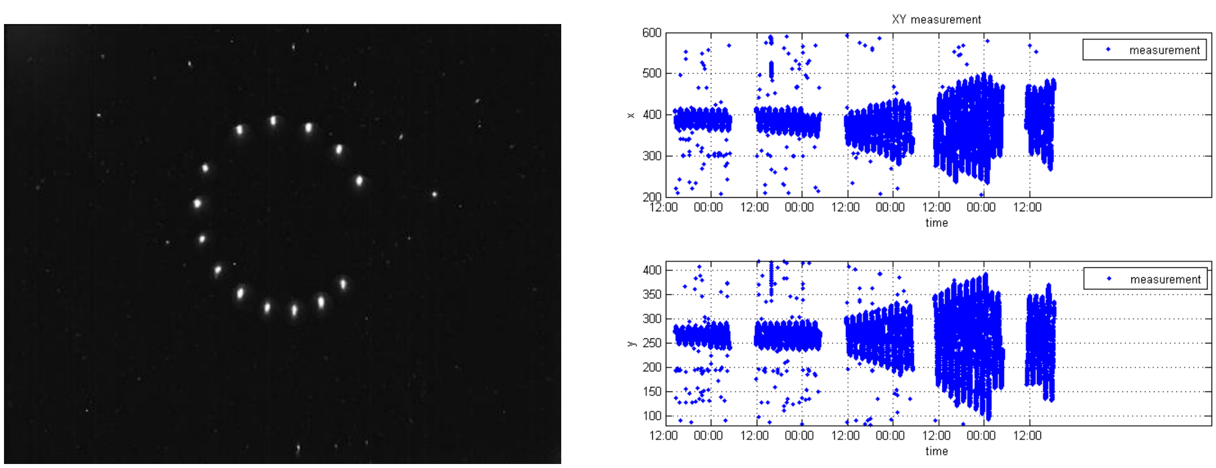

Figure 4. Overlapping of images captured with the far range camera (left, [4]) and 2D measurement of the target position in the image in pixel coordinates (right, [1])

2.3. Close Range Navigation

2.3.1. Navigation Using a Monocular Camera Sensor

In this section, we present a new developed algorithm to track a target satellite at close distances [9]. The goal is to track the pose of a known object under changing lighting conditions. As a result, the object will remain in sight, however, the background and all surrounding lighting can change in direction and intensity significantly.
The object is known by a surface of specific shape. The shape is a polygon and may have an arbitrary number of edges, as long as they can be modeled appropriately. In our case, we restrict ourselves to the rear part of a satellite, which usually contains the apogee motor and maybe some sensors.
The tracker has two parts. The first part is the texture segmenter, which does most of the work, tracking the outer edges of the satellite. Once the edges are known, the lines obtained can be intersected to give the corner points. These corner points assign 3D direction vectors. Up to this point, all that can be done without knowing anything of the target object in terms of size or dimensions is actually done.
The remaining part (estimating full 6 DOF) requires information about the target object, since the problem cannot be solved otherwise due to underdetermined equation systems (missing information). In this article, the target is assumed to be of rectangular shape and the both side lengths of the target object are known. This is sufficient information to calculate the complete 6 DOF.
Figure 5 shows an illustration of how the algorithm works.

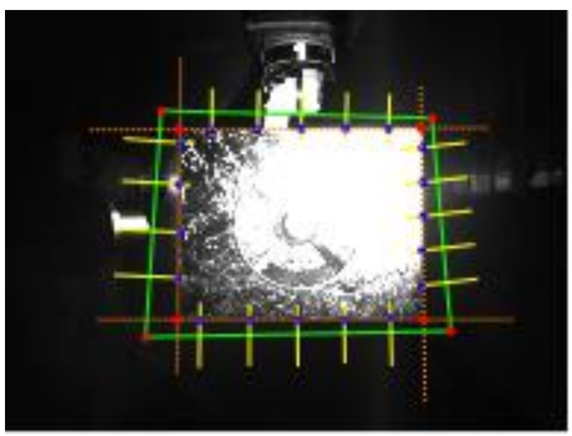

Figure 5. Tracking the outer edges of the OLEV mockup using texture segmentation [9]

For the performance analysis, images have been generated on the EPOS facility (see chapter 3). Here, a linear movement was performed ranging from a distance of 25m down to 4m. The tracked model is a real-size (2.3 x 1.8m) aluminum part. It includes an apogee motor, as most geostationary satellites have at the rear. The mockup is wrapped in gold-colored foil to achieve utmost realistic images. A 5kW theatre lamp was used to simulate the sun. Figure 6 shows the obtained accuracy measurements.

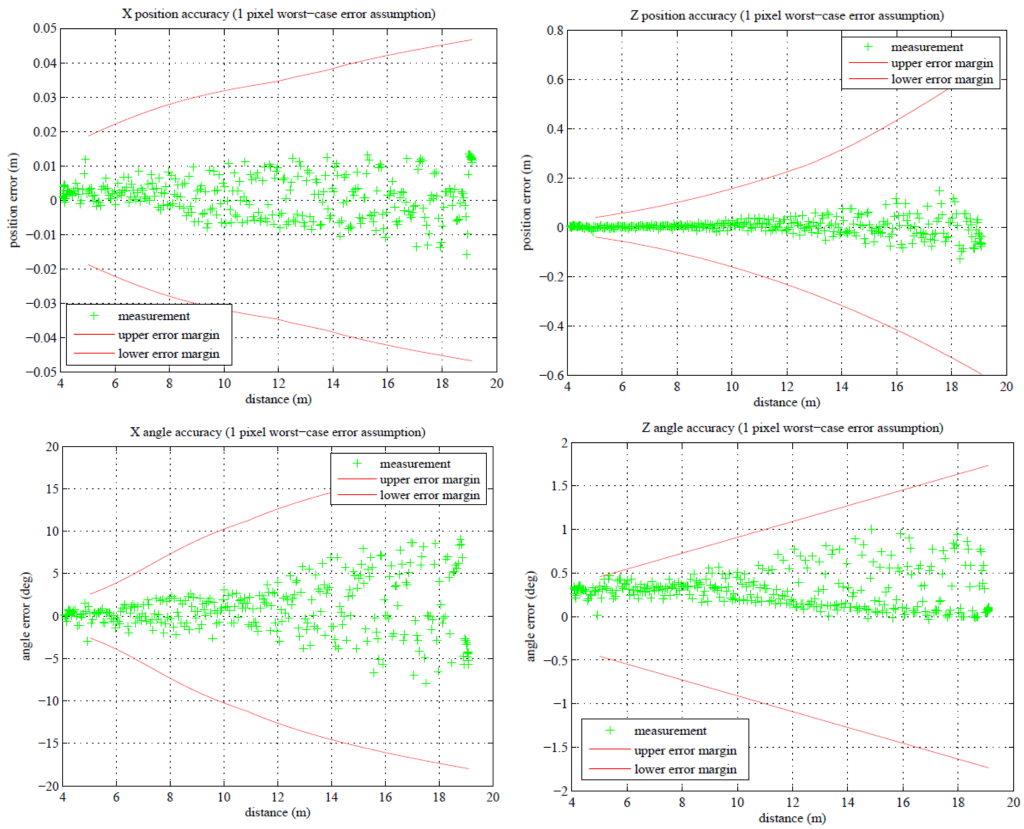

Figure 6. Results of the target moving away from the chaser experiment [9]

2.3.2. Navigation Using Time of Flight Sensors

A Time-of-Flight sensor (ToF) is a range imaging system that resolves distances based on the known speed of light, measuring the time-of-flight of a light signal between the sensor and the subject for each point of the image. In contrast to a simple 2D camera sensor it can provide instantaneous 3D information about the target pose (position and attitude) without a priori information of the target geometry.
Today two types can be distinguished:

- chip based camera like sensors using an illumination system with modulated light (PMD, Flash LIDAR)
- mirror based scanning systems using a modulated or pulsed laser beam

DLR uses the first type of sensor to develop navigation algorithms for such type of sensors. A good candidate is a Photonic Mixer Device also called PMD camera. It is an active optical sensor, which can measure the distance to an object for each pixel of its imaging area.
In principle, the distance measurement works by emitting a modulated infrared signal. When receiving the signal, the waveform will be shifted depending on the distance to the target object, which has reflected the light. By correlating the received signal with the reference signal, the phase shift can be measured. The phase shift directly

corresponds to the distance. Due to the relatively small wavelength, only very short distances can be measured (~5-10 meters at maximum). Therefore, more elaborate approaches are necessary to measure even farther. One typical approach is to use two different modulation frequencies in such a way that the two measurements retrieved from every single pixel are unique in a large range (~60 meters or more).
Once an object has been measured, its distance and pose can be calculated from the 3D point cloud produced by the PMD sensor. Drawbacks of current implementations are imaging errors due to high movement speeds, very limited dynamic range and low image resolution.
Figure 7 shows a today available PMD sensor for industrial applications. Additionally it presents a typical 3D image which shows directly the distances to the target by different colours.

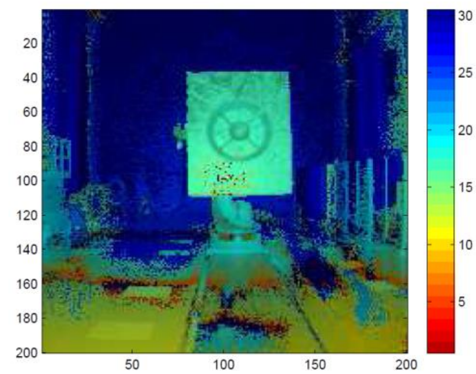

Figure 7. The CamCube provided by PMD-Technologies GmbH and a typical 3D image showing a satellite mockup in EPOS-laboratory (right)

3. Verification of the Rendezvous and Docking Process

One of the critical phases of an on-orbit servicing mission is to ensure a safe and reliable rendezvous and docking (RvD) process. Especially this phase has to be analyzed, simulated and verified in detail. Classical approaches, e.g. numerical simulations, deliver only limited results. Therefore tests or test facilities have to be defined where the entire RvD process including real flight hardware components of the guidance, navigation and control (GNC) system can be simulated and evaluated under utmost realistic conditions with respect to the space environment.
The former EPOS facility (European Proximity Operations Simulator) was a test bed jointly developed by ESA and DLR for laboratory simulation of rendezvous maneuvers of spacecraft over the last 12 meters of the rendezvous phase (without docking simulation) [6]. It consisted of a six degree of freedom gantry robot for simulating the chaser motion, a three axis servo table for simulating the attitude motion of the target and a sun simulator to generate utmost realistic illumination conditions. The last intensive utilization was the test and verification of RvD sensors and systems for the European Automated Transfer Vehicle (ATV).

Because the former EPOS facility was outdated, now DLR has built up a completely new simulation facility to provide test and verification capabilities for RvD processes of future on-orbit servicing missions.

3.1. The new EPOS 2.0 facility

After dismantling the former EPOS facility DLR was building up a completely new simulation facility called EPOS 2.0 [3]. It is shown in Fig 8.
The new RvD simulation facility is a hardware-in-the-loop simulator which comprises two industrial robots for physical real-time simulations of rendezvous and docking maneuvers. EPOS 2.0 allows for the simulation of the approach process up to 25 including the contact dynamics simulation of the docking process.

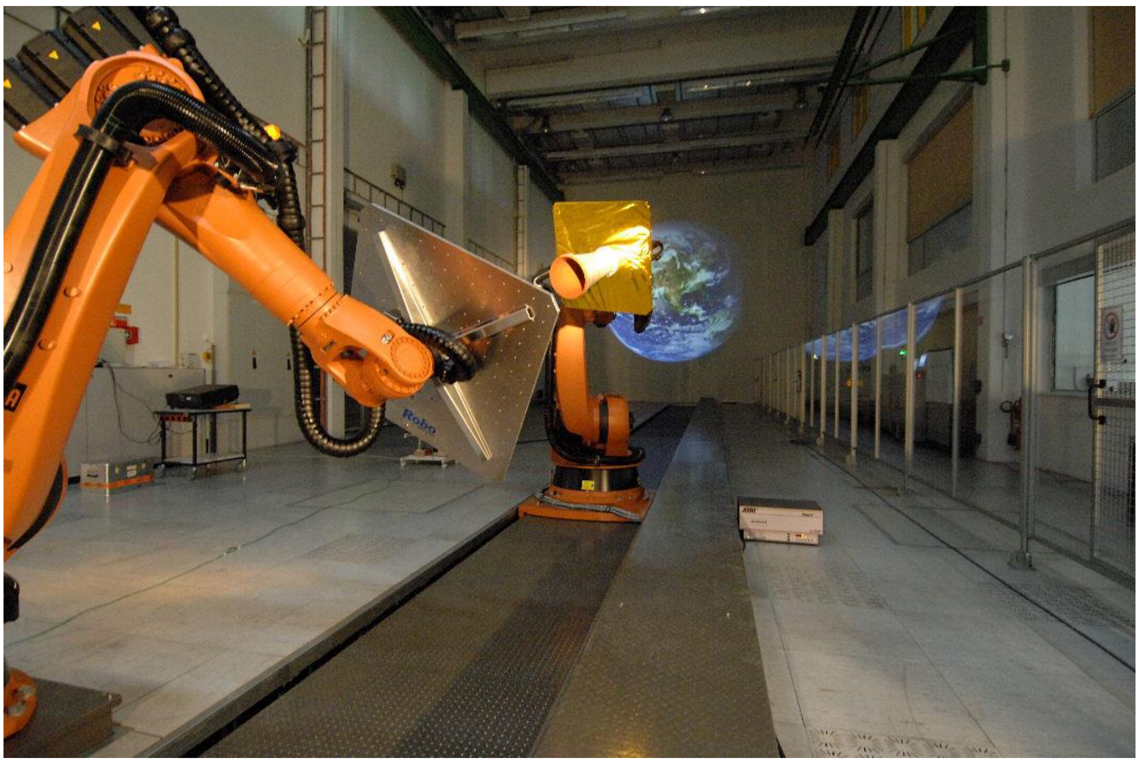

Figure 8. The new EPOS 2.0 facility

The new simulation facility can be characterized by the following:

- It is a highly accurate test bed. The measurement and positioning performance is increased by factor 10 compared to the former EPOS facility,
- Dynamical capabilities allows for high commanding rates and the capability of force and torque measurements.
- The simulation of sunlight illumination conditions can be used to generate a realistic simulation environment of the real rendezvous and docking process.
- The utilization of standard industrial robotics hardware allows a very high flexibility with respect to different application scenarios.

3.2. Hardware-in-the-Loop Simulation using optical sensors

Hardware-in-the-loop simulation is a very effective way to perform verification and testing of complex real-time embedded systems like rendezvous sensors. Inputs and outputs of an embedded system (here: a mono, CCD camera) are connected to a correspondent counterpart - the so-called HIL-simulator - that simulates the real environment of the system.
For such "hardware in the loop" scenario the RvD sensors and the robotic manipulator arm are mounted on one robot and a typical satellite mockup of the client satellite is mounted on the other robot. The RvD sensors can measure the relative position and attitude of the client satellite and the onboard computer calculates on this basis the necessary thrusters or reaction wheel commands. These will feed in a real time simulator. This dynamic simulator computes for the next sample an update of the state vector (position attitude of the spacecraft) based on all relevant environmental and control forces and torques. Then the state vector for the new sample will be commanded to the facility. This scenario is depicted in Fig. 9.
A controlled approach from a distance of 20m to a distance of 3m between chaser and target has been simulated. Figure 9 shows the x-coordinate of the resulting measurement and filter output as well as the real position.

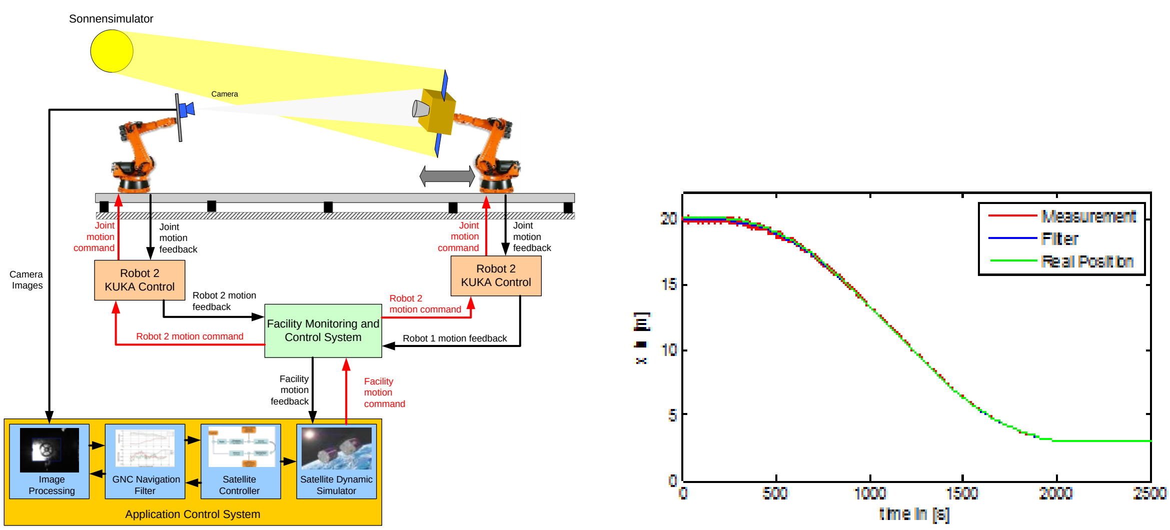

Figure 9. Control loop for rendezvous and a typical simulation result [2]

4. Conclusion

The presented paper reflects the results of the developments at DLR/GSOC for future On-Orbit Servicing missions. It presents the achieved performance for far range navigation as well as for close range navigation. With the EPOS 2.0 facility DLR/GSOC is able to provide the means for verification and testing of the servicer's rendezvous and docking-payload.

Future work will focus mainly on the development of more advanced navigation sensors for the rendezvous process and will be described in future presentations.

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