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ON-ORBIT SERVICING MISSIONS AT DLR / GSOC

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The German Space Operation Centre (GSOC) is presently involved in the preparation of two On-Orbit Servicing Missions DEOS and OLEV which are presented in this paper. Additionally, we describe potential applications for this mission including space debris removal. Since there are many new challenges in the context of Rendezvous & Docking manoeuvres the ground segment design requires new concepts. We present our solutions in the field of Approach Navigation and Teleoperation. Finally, an integrated system test including GSOC's new European Proximity Operations Simulator (EPOS) facility is described.

I. INTRODUCTION

Many new developments are triggered by a failure which is also true for the history of On-Orbit Servicing (OOS) technologies at DLR: shortly after the launch of TV-Sat1 in 1987 the mission turned out to be a loss since one of the solar panels could not be deployed. As a consequence the main antenna could not swing out either and the payload could not be activated. After many attempts of DLR / GSOC to repair the spacecraft from ground it was finally moved to the graveyard orbit in 1989. However, this failure triggered the idea to build a rescue satellite which is able to capture and repair TV-Sat1. SETTELMEYER et al. [1] presented the concept of an Experimental Servicing Satellite ESS in 1998 (Fig. 1).

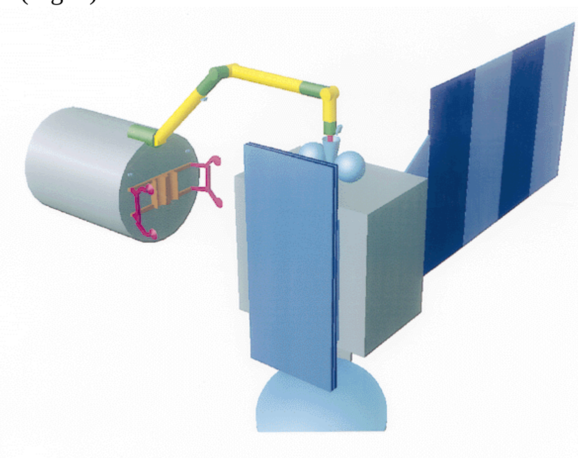

Fig. 1: ESS captures TV-Sat1 **[1]**

A result of the ESS study was the development of space robotic technologies like the design of a capturing tool which enables the Servicer to capture most geostationary satellites at their apogee engine. Other developments in the field of space robotic like the ROKVISS [2] experiment on the ISS followed (see also LANDZETTEL et al. [3] and references within).

Meanwhile OOS technologies are investigated by a number of national space agencies. In the US DARPA's Orbital Express [4] mission e.g. demonstrated the ability to autonomously perform Rendezvous and Docking (RvD) operations including maintenance activities like refuelling. Another, recent OOS technology demonstration is the Swedish mission PRISMA [5] which has been launched in June 2010. The goal of PRISMA is to demonstrate autonomous formation flying and RvD manoeuvres.

In contrast to the mission objectives of Orbital Express and PRISMA the focus of DLR is to capture un-supportive and not specially prepared client spacecrafts. By "non-supportive" we mean that there is no support with respect to attitude and orbit control of the client, e.g. when the client is non-operational. "Not specially prepared" means that the client satellite does not have a special docking port or retro reflectors used for vision based navigation. This is pursued with DLR's involvement in the two OOS projects DEOS (DEutsche Orbitale Servicing Mission) and OLEV (Orbital Life Extension Vehicle). The goals of DEOS are to demonstrate the capture of a tumbling and non-supportive client satellite in low earth orbit and a controlled de-orbiting of the mated system. OLEV is a commercial project with the goal to extend the lifetime of geostationary communication satellites whose fuel has been depleted. A brief description of DEOS and OLEV is given in section II.

The techniques and concepts developed in the context of these two projects open a wide field of applications like space debris removal and fleet management (section III).

However, the OOS mission DEOS and OLEV also pose several challenges to spacecraft operations: (1) the approach navigation has to cope with limited mass and power budgets due to a reduced financial budget compared to manned missions. Therefore intelligent methods have to be used for the approach navigation. (2) Capturing a tumbling client as well as RvD operations set requirements far beyond the capabilities of standard communication architecture: Delay Time and Jitter of the signal have to be minimized. (3) Approach navigation, capture and docking algorithms should be thoroughly tested on ground first. A sophisticated test facility including gravity compensation and contact dynamics is necessary. The concepts and solutions to the above listed challenges will be discussed in section IV. Aspects regarding the Flight Operation System (FOS) of DEOS and OLEV are discussed in EBERLE et al. [6].

II. PRESENT ON-ORBIT SERVICING PROJECTS AT GSOC

II.I Technology Mission DEOS

The primary goals of the technology demonstrator DEOS are (1) to capture a tumbling non-supportive client satellite with a servicer spacecraft and (2) to de-orbit the coupled configuration within a pre-defined orbit corridor at end of mission. Secondary goals are to perform several Rendezvous, Berthing and Docking scenarios as well as orbit maneuvers with the mated configuration. Therefore the Servicer is equipped with an active Attitude and Orbit Control System (AOCS) and both a manipulator arm and a docking port (Fig. 2).

Fig. 2: DEOS Client and Servicer

Since the initial experiment conditions like tumbling rate of the client have to be set several times, the client is provided with an active Attitude Control System (ACS).

Similar to Orbital Express the mission philosophy is to subsequently “crawl, walk and run”: Both spacecraft, client and servicer, will be injected together in an initial low earth orbit (LEO). Starting with the mated configuration the complexity of the experiments is stepwise increased over mission period.

The DEOS project is presently in a phase B study financed by the German Space Agency. More details can be found in [7].

II.II Commercial Mission OLEV

OLEV is a purely commercial project managed by a European consortium including a strong DLR participation. The primary goal of OLEV is to build an orbital “tug boat” 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 its fuel has been depleted (Fig. 3).

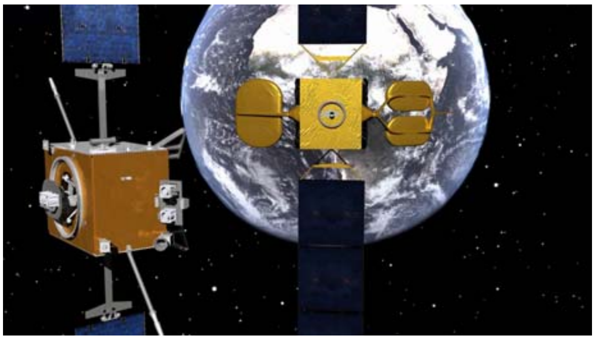

Fig. 3: OLEV approaching a ComSat

The core element of OLEV is the capturing tool (patented by DLR) which enables OLEV to dock on the apogee engine of the majority of the existing geostationary communication satellites. The capturing tool is designed to allow OLEV to dock / undock several times. The OLEV platform is equipped with six “Hall Effect Thrusters” (HET): Two of them are used for the transfer from the Geostationary Transfer Orbit (GTO) to the Geostationary Orbit (GEO), the other four (2x2) are dedicated for the station keeping. The electric propulsion system enables OLEV to perform station keeping of the mated configuration for approx. twelve years depending on the client mass.

The OLEV project has finished a delta phase B study; the present focus lies on financial engineering.

III APPLICATIONS FOR THE ON-ORBIT SERVICING CONCEPT OF DEOS AND OLEV

III.I Removal of space debris in LEO

Originally the DEOS concept was developed to de-orbit in-operative satellites which might be hazardous on earth while de-orbiting in an uncontrolled way. With the 2009 satellite collision between the operational Iridium 33 satellite and the in-operative Cosmos 2251 satellite it became obvious that there are also other reasons why we should be able to remove in-operative and un-supportive satellites from the low earth orbit (LEO).

The low earth orbit is in principle “self cleaning” since the rest atmosphere drags all satellites and debris particle in a way that they will finally de-orbit. However, in heights above 600 km the time frame for such a drag induced de-orbiting becomes substantially longer than a typical lifetime of LEO satellites. Therefore these heights become more and more populated by inoperative satellites and other kind of space debris. Additionally, orbit heights between 600 and 1000 km are very popular for Earth Observation satellites since they guaranty an optimum between swath width and resolution. Hence, space debris became more and more problematic over the past decades. As a consequence ESA published its “European code of conduct for space debris mitigation” with the goal to limit the presence of in-operative satellites in the protected regions (LEO up to 2000 km and GEO +/- 200 km) to a maximum of 25 years.

According to KLINKRAD [8] the most problematic orbits are located between 800 and 1000 km height in high inclination circular orbits. **Fig. 4** shows that the density of particles > 10 cm peaks in altitudes between 800 and 1000 km. **Fig. 5** confirms that the highest density can be found at the sun synchronous orbit at 98°.

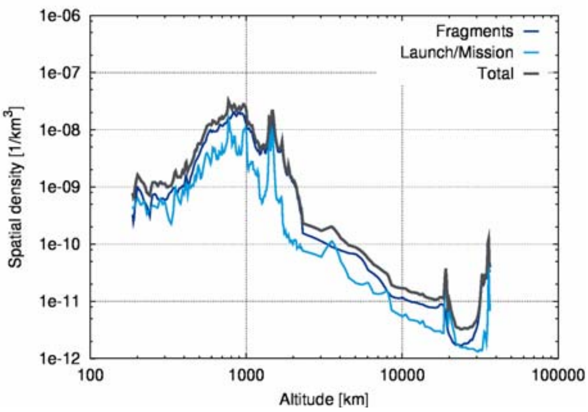

Fig. 4: Spatial density of debris particles larger 10 cm vs. altitude as a result of both observations and simulations (KLINKRAD [8])

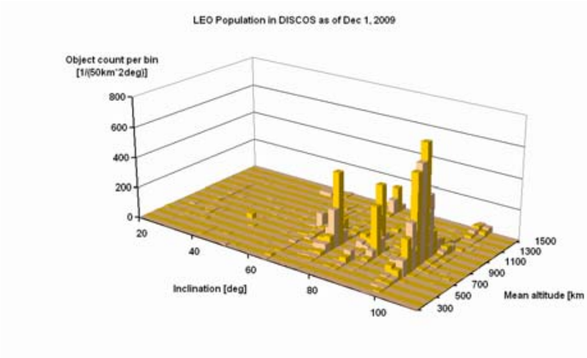

Fig. 5: Density of particles larger 10 cm vs. inclination vs. mean altitude (KLINKRAD [8])

Coming from spatial to time dimension forecasts indicate that the problem will become even worse in the future. **Fig.6** shows that even without any more launches the number of effective LEO objects > 10 cm will increase over the next 200 years. The forecast shows a decrease within the next 20 years due to the unrealistic assumption that there are no further launches (which would be the best method of prevention). However, within these 20 years a cascade of collisions starts which substantially enhances the number of collision fragments and therefore the total number of debris particle in LEO (KLINKRAD [9]). This shows that abatement measures only are not sufficient enough. The only method to limit the further increase of debris particles in LEO is to actively remove objects in the most populated region around 900 km altitude and high inclination orbits.

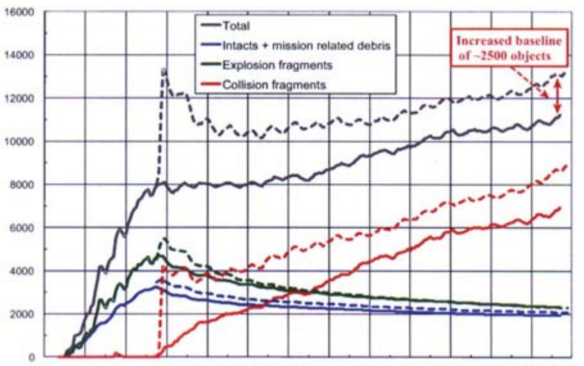

Fig.6: 200 years forecast for effective LEO objects >10cm before (solid) & after the 2009 satellite collision (dashed) under the assumption that there are no more launches (source: NASA).

Many methods to de-orbit LEO satellites have been discussed so far: from tug boats over the application of ropes to the client to the use of solid rocket engines. However, most of the methods need a servicer spacecraft which approaches and captures the client objects. Therefore – no matter which de-orbit method is preferred – the DEOS mission is an excellent preparation to actively de-orbit major debris objects in LEO.

III.II Fleet Management and Disposal in GEO

The Orbital Life Extension Vehicle OLEV was designed to dock on operative GEO satellites and extend their life time. Additionally, OLEV can be used for general fleet management purposes. Therefore OLEV was designed to dock and undock for several times enabling the customers to use OLEV for life extension, relocation and disposal to the graveyard orbit.

However, docking to operational Communication Satellites is not the only application for the OLEV concept. There have been quite a number of problems due to satellites which were drifting uncontrolled through the geostationary belt. One recent example is the Galaxy 15 satellite to which Intelsat lost contact in April 2010. Unfortunately, the transmitter of Galaxy 15 was still functioning while it started drifting through the geostationary belt forcing other satellite service provider to react. An extended version of OLEV – including the results gained from the technology mission DEOS – will be able to inspect and eventually capture uncontrolled drifting GEO satellites in order to remove them to the graveyard orbit.

A good description of the commercial business models including the use of OLEV for space debris mitigation can be found in [10].

IV. CHALLENGES OPERATING THE OOS MISSIONS DEOS AND OLEV

There are three major challenges for the ground segment of the missions DEOS and OLEV:

1. Navigation concept for the approach of the servicer to the client
2. Guaranty teleoperation conditions during the robotic phase (capture, berthing or docking)
3. Test the Rendezvous & Docking maneuvers on ground first within an integrated system test.

Solutions to the above challenges are briefly described in the sections below. A more detailed discussion is given in [11].

IV.I. Navigation

The major design driver for the navigation system of a spacecraft performing RvD operations is the duration of autonomous operation. For the presented LEO mission the requirement is to achieve one orbit of autonomous operation. Due to orbital propagation of uncertainties this requirement yields a measurement accuracy of one percent of the range between target and servicer for the navigation sensors [12], the so-called “1% rule”. However, for missions in GEO this requirement can be slightly relaxed as there is a permanent communication link and the orbital period is much longer. Hence, adjustments can be performed much quicker. Having identified the design driver navigation sensors can now be selected for each mission phase (Fig. 7).

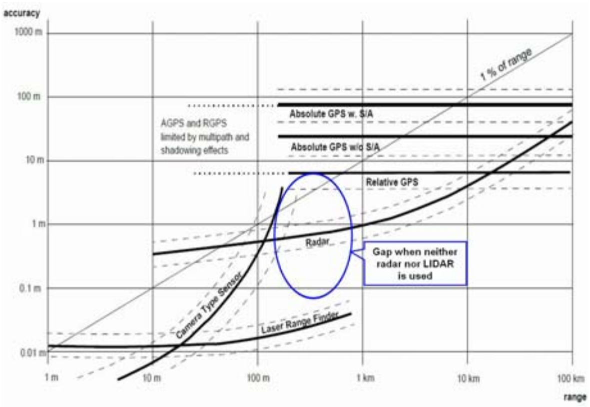

Fig. 7: Typical operational ranges of rendezvous sensors; the diagonal indicates the “1% rule” (diagram from FEHSE [10])

Far Range Approach

Approaching the client spacecraft during phasing and far range approach the preferable method of navigation in LEO is to use GPS on both spacecraft (Fig. 7, range > 1km). However, in the case the client is inactive or does not have an active GPS receiver on board the best solution is to use radar tracking from ground, allowing orbit determination accuracies in the same order of magnitude [13]. As a result, absolute navigation using GPS or radar tracking can be used in LEO down to distances in the order of 1 km.

Since GPS is not available during far rage approach in GEO, orbit determination has to be performed on the basis of ranging measurements. The accuracies lie between 300m in radial, 600m in along-track and 2500m in cross-track direction. Due to better communication conditions and hence a relaxed “1% rule” also in GEO absolute navigation can be used down to distances of about 1km.

Close Range Approach

At very short distances camera type sensors yield the best accuracies (Fig. 7, range < 20m). Additionally, the optical images are helpful during the docking or berthing maneuver. Therefore camera type sensors have been selected for the mission DEOS and OLEV. Using camera type sensors the relative distance is calculated either by using stereo cameras or by resolving the outline of a known object. If we obey the 1% rule camera type sensors can be used for distances smaller a few hundred meter.

Angles Only Navigation

If neither radar nor LIDAR is used there is a gap of accurate navigation data in the range between ~ 1km and a few hundred meter (Fig. 7, blue ellipse). The option to avoid LIDAR or radar sensors is quite attractive for DEOS and OLEV since it will substantially decrease the power and mass budget.

However, a method called angles-only can bridge this gap. The method is well known and widely applied in naval applications, orbit determination, target tracking, lunar and interplanetary optical navigation [14]. The principle of angles-only navigation is to substitute the baseline of purely geometric navigation, e.g. the distance between two stereo cameras or the size of a known image, with a known or estimated part of the relative path (Fig. 8). Since much larger baselines can be used now the method of angles-only navigation can be extended to much larger distances. A more detailed description of the potentials of angles-only navigation can be found in [11].

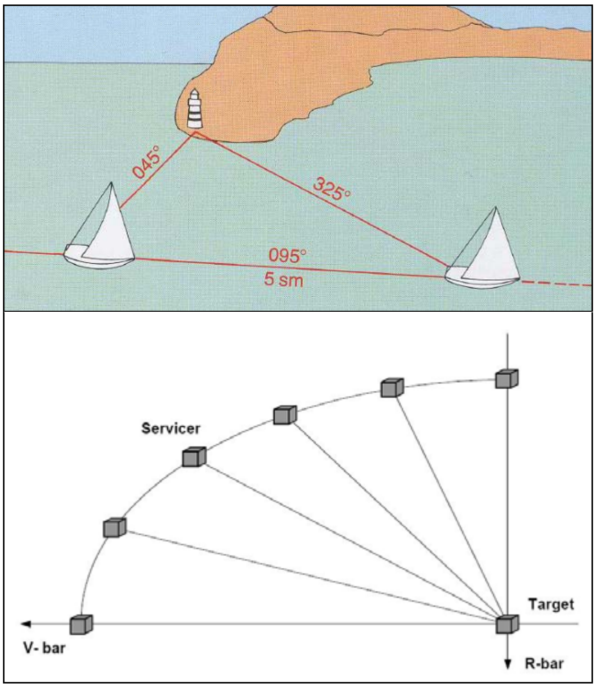

Fig. 8: Principle of angles-only measurements during fly around

As a result, angles-only navigation is able to fill the mentioned gap in the navigation method on condition that the maneuvers before or during fly around are calibrated with an adequate accuracy.

IV.II Teleoperation

The requirement to minimize delay time and jitter is driven by the robotic operations in the final Rendezvous and Docking / Berthing phase. The payload control system (PCS) of DEOS requires a delay time of less than 500 msec (round trip) during the robotic phase, i.e. the capture of the tumbling client. For OLEV the requirements are less stringent since the approach velocities in GEO are much smaller and, additionally, the client is not tumbling but 3-axis stabilized. However, a delay time smaller than one second (round trip) is recommended. The problem is that the standard communication architecture introduces a delay time of typically 2-5 sec, mainly due to the signal path through electronic components on ground. Additionally, automatic switching of redundant lines may cause unpredictable jitter.

A solution to both problems is to connect the PCS directly with the cortex (CTX) of the teleoperation antenna with a dedicated non-redundant high rate TM/TC link (Fig. 9: dashed lines). The 34 Mbps line introduces a very small delay time of 2,5msec round trip. This solution is used for ROKVISS [2] operation since several years. Hence, the over all delay time can be reduced to less than 500 msec round trip (including image processing).

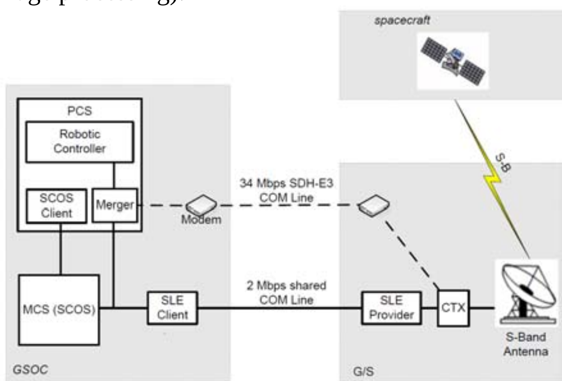

Fig. 9: Communication architecture to minimize delay time and jitter

IV.III Verification

The critical phase of OOS missions, the Rendezvous and Docking (RvD) of two spacecraft is a very complex maneuver which requires relative position accuracy of a few mm. Additionally, this is connected with difficult communication conditions in low earth orbit (see section III), or with a high risk in case of failure in the (near) geostationary orbit. In consideration of these circumstances an RvD maneuver shouldn't be performed in space for the first time. All RvD maneuvers have to be analyzed, simulated and verified on ground 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 the flight HW of GNC components and systems can be simulated and tested under utmost realistic conditions of the space environment.

The requirements on testing the missions OLEV and DEOS can be summarized in following three categories:

Approach: A test facility should be appropriate to verify sensors and systems within the entire range of vision based relative navigation, i.e. from several km down to contact (see section IV). For camera based sensors this can be realized in a combination of scaled models and a sufficient range of the test facility. Additionally, the facility shall provide utmost realistic environmental conditions, i.e. the simulation of the sun illumination effect under all angles of incidence and the simulation of the reduced gravity force in orbit.

Capture: In order to verify the final "robotic phase" of the RvD maneuver, i.e. the capture of the client satellite, contact dynamics has to be included. This implies a sensor to measure the contact forces and torques and a dynamic model of both satellites (client and servicer) to simulate the reaction on the contact during the capture process. Furthermore, the requirement to verify spacecraft position accuracy in the range of mm the test bed has to guarantee accuracy in the sub-millimeter range.

Integration: The facility shall be able to support an integrated system test including RvD system hardware-in-the-loop. It should further be connected to the control center infrastructure including the mission control system (MCS) and the payload control system (PCS) as well as a realistic ground data infrastructure with respect to delay time and jitter. Finally, the facility shall be used for operator training and mission support.

The new European Proximity Operations Simulator (EPOS 2.0) facility comprises a hardware-in-the-loop simulator based on two industrial robots for physical real-time simulations of rendezvous and docking maneuvers (**Fig. 10**). One of the industrial robots is mounted on a 25m rail system to simulate the 6 degree of freedom (DOF) of the first spacecraft; the other industrial robot is mounted at the end of the rail to carry the second spacecraft (6 DOF).

Fig. 10: The new EPOS 2.0 facility at GSOC

The utilization of standard industrial robotics H/W allows a very high flexibility related to different application scenarios. The robots are capable of carrying up to 200kg payload. It should be mentioned that both, client and servicer model can be either mounted on robot 1 or 2 (compare **Fig. 11**) - there are pros and cons for both scenarios. All necessary cables for sensors etc. are also available on the rail mounted robot.

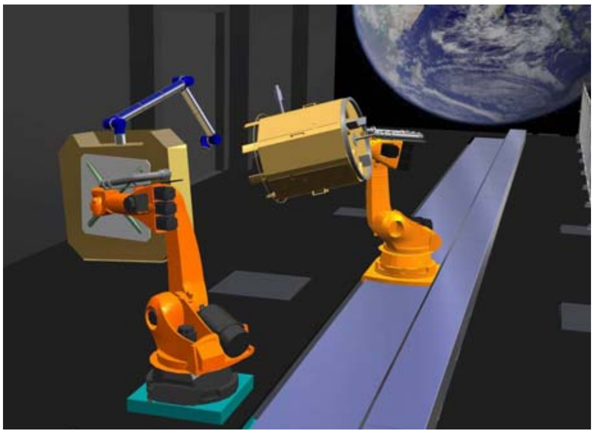

Fig. 11: EPOS simulation set up for DEOS [16]

To achieve best simulation and verification results the accuracy of the entire facility was extensively evaluated. Additionally, an optical high-accuracy measurement-device will guarantee position accuracy in sub-millimeter level. Furthermore, a lot of effort was made to increase the command frequency to 250 Hz which is an important precondition to simulate real time contact dynamics. Further details can be found in BOGE et al. [15].

V CONCLUSION

The developments so far have shown that On-Orbit Servicing Missions are technical feasible with an adequate effort.

Furthermore, the technology of OOS offers a wide field of applications from purely commercial approaches as life extension and fleet management of geostationary communication satellites to systematic removal of space debris in problematic zones like high inclination orbits between 800 and 1000 km.

DLR/GSOC is prepared to operate OOS missions within the next few years: A concept has been developed to reduce the delay time of the signal to smaller 500msec (round trip including image processing). We found a navigation method based on angles-only measurements in combination with calibrated maneuvers to bridge the gap between the hand over from absolute navigation (ranging and/or GPS) to purely geometric relative navigation (stereo camera or image resolution) without the use of LIDAR or radar. Finally, we described the requirements for a realistic hardware in the loop test and the specification of the new EPOS facility built at DLR as well as an integrated test set up for the missions DEOS and OLEV.

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REFERENCES

[1] Settelmeyer, E., Lehrl, E., Oesterlin, W., Hartmann, R., Landzettel, K., "The Experimental Servicing Satellite – ESS", *IARP 98-c-14*, 1998

[2] Landzettel, K., Albu-Schäffer, A., Brunner, B., Beyer, A., Gruber, R., Krämer, E., Preusche, C., Reintsema, D., Schott, J., Steinmetz, H.-J., Hirzinger, G., "ROKVISS: Verification of Advanced Light Weight Robotic Joints and Tele-Presence Concepts for Future Space Missions", *ASTRA 2006 – the 9th ESA Workshop on Advanced Space Technologies for Robotics and Automation*, ESA's research and technology centre, ESTEC, Noordwijk, Netherlands, 28-30 November 2006

[3] Landzettel, K., Preusche, C., Albu-Schäffer, A., Reintsema, D., Rebele, B., Hirzinger, G., "Robotic On-Orbit Servicing - DLR's Experience and Perspective", *Proceedings of the 2006 IEEE/RSJ, International Conference on Intelligent Robots and Systems*, October 9 - 15, 2006, Beijing, China

[4] Mulder, T.A., "Orbital Express Autonomous Rendezvous and Capture flight operations", Part 1 of 2 and Part 2 of 2, *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, 18 - 21 August 2008, Honolulu, Hawaii

[5] Persson, S., Bodin, P., Gill, E., Harr, J., Jörgensen, J., „PRISMA – an Autonomous Formation Flying mission", *ESA Small Satellite Systems and Services Symposium (4S)*, 25-29 September 2006, Sardinia, Italy

[6] Eberle, S., Ohndorf, A., Faller, R., „On-Orbit Servicing Mission Operations at GSOC", *SpaceOps 2010 Conference*, Huntsville, Alabama, USA, AIAA 2010-1975

[7] Reintsema, D., Thaeter, J., Rathke, A., Naumann, W., Rank, P., Sommer, J., "DEOS The German Robotics Approach to Secure and De-Orbit Malfunctioned Satellites from Low Earth Orbit", *iSAIRAS* 2010

[8] Klinkrad, H.: *Private communication*, 2010

[9] Klinkrad, H.: *Space Debris: Models and Risk Analysis*, Springer-Praxis Books, Springer-Verlag, 2006

[10] Kaiser, C., Bellido, E., Hofmann, P., "Space Debris Mitigation using On-Orbit Servicing Solutions", *IAC 2010 conference*, IAC-10.A6.4.6 (submitted)

[11] Sellmaier, F., Boge, T., Spurmann, J., Gully, S., Rupp, T., Huber, F., „On-Orbit Servicing Missions: Challenges and solutions for Spacecraft Operations", *AIAA SpaceOps 2010 Conference*, Huntsville, Alabama, USA, 2010-2159

[12] Fehse, W.: *Automated Rendezvous and Docking of Spacecraft*, Cambridge Aerospace Series 16, Cambridge University Press, 2003

[13] Aida, S., Patzelt, T., Leushacke, L., Kirschner, M., Kiehling, R., "Monitoring and Mitigation of Close Proximities in Low Earth Orbit", *21st International Symposium on Space Flight Dynamics, Toulouse, France*, 2009

[14] Woffinden, D.C., and Geller, D.K., "Relative Angles-Only Navigation and Pose Estimation For Autonomous Orbital Rendezvous", *Journal of Guidance, Control and Dynamics*, Vol. 30, No. 5, 2007, pp. 1455

[15] Boge, T., et al.: "Hardware in the Loop Simulator von Rendezvous und Docking Manövern", *German Aerospace Congress of DGLR*, Aachen, Germany, 8-10 September, 2009

[16] Rupp, T., Boge, T., Kiehling, R., Sellmaier, F.: "Flight Dynamics Challenges of the German On-Orbit Servicing Mission DEOS", *21st International Symposium on Space Flight Dynamics*, Toulouse, France, September/October, 2009