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RENDEZVOUS GNC-SYSTEM FOR AUTONOMOUS ORBITAL SERVICING OF UNCOOPERATIVE TARGETS

F. Rems[(1)], **E.-A. Risse**[(1)], **H. Benninghoff**[(1)]

[(1)] *German Aerospace Center (DLR)/German Space Operations Center (GSOC), 82234, Weßling, Germany, florian.rems@dlr.de, eicke-alexander.risse@dlr.de, heike.benninghoff@dlr.de*

ABSTRACT

The immediate future holds new challenges for spaceflight in general, and rendezvous GNC systems in particular. Space debris removal, in-orbit satellite maintenance and repair, or in-orbit assembly - all these On-Orbit Servicing (OOS) scenarios demand a reliable and safe relative approach to a so called uncooperative target object. There is no communications with this target, no precise information about its position or status and no attitude stabilization. Rendezvous is possible only by using visual relative navigation based on optical sensors.

GSOC's OOS group is developing an advanced rendezvous GNC system as a research platform, for coping with these challenges. This paper describes the rendezvous GNC system and its interacting components. This includes sensors, pose estimation algorithms, navigation filter, guidance and control functions. The system's operation within the EPOS simulation environment is shown. This environment provides a high fidelity robotic Hardware-in-the-Loop simulator for the final 20 meters of rendezvous manoeuvres. With the GNC system, it carries real sensor hardware and a true-to-scale target mockup with realistic surface materials. Finally, the paper outlines the GNC system's role in the current DLR project "On-Orbit Servicing End-to-End Simulation", and concludes with the GNC system's current status and future work.

1 INTRODUCTION

On-Orbit Servicing (OOS) is a key capability for spaceflight in the 21st century [1]. It is an enabling technology for actively removing hazardous debris objects from orbit [2, 3], which threaten future manned and unmanned spaceflight. The number of debris objects in orbit around Earth has increased considerably since the first missions into space. Collision avoidance manoeuvres are executed daily. The collision of Iridium 33 and Cosmos 2251 in 2009 has demonstrated impressiveley, that satellite collisions in orbit can happen, and will happen! [4] It has shown the severe consequences of such a collision [5]. Further, OOS has the potential to change the way money is made in the satellite market [6]. Expensive communication satellites in GEO may be short on fuel, yet still operational. The transceiver hardware could be outdated or even defective, but the rest of the satellite fulfils its duty just fine [7]. In such cases, orbital servicing can re-fuel the satellite or replace individual components [8]. By repairing, upgrading and/or re-fuelling the satellite automatically in orbit, its operational lifetime is prolonged considerably. Finally, OOS can be the answer to assembly of large structures in space, like large aperture observatories [9, 10] and spacecraft [11] heading for other planets.

In almost any OOS mission, the servicing spacecraft, the chaser, has to approach closely some target object, may it be some satellite to be serviced or a piece of space debris. This final approach is a critical phase [12]. The rendezvous GNC system has to guarantee a high level of reliability. A collision between chaser and target has to be avoided at all cost, lest the very mission dedicated to e.g. remove space debris fails and generates even more.

Manned rendezvous in space has a long, successful history [13]. And unmanned, automated rendezvous and docking has become state of the art (ATV) [14]. Rendezvous is carried out with a cooperative target, meaning that the target spacecraft is active in some way. Communications is working properly, the targets location and status are roughly known. The target spacecraft may have optical devices mounted onto its outside to aid the approaching chaser spacecraft with optical navigation. Examples are passive retro-reflectors or actively illuminated markers.

However, with general orbital servicing, a rendezvous GNC system has to cope with more serious conditions. The target object, assuming a non-operational satellite or some piece of space debris, is uncooperative. It is just a passive object in space. Its orbit and position therin can be known from ground-based radar tracking, but its precise location has to be determined by the servicer spacecraft in space. There are no active lights or passive retro-reflectors to aid the approaching chaser spacecraft navigating. The target may be tumbling. Its surface may consist of a mixture of reflecting and diffuse materials. Depending on the individual situation, there may be sharp shadows on the target object, or even total darkness during eclipse. Visual navigation has to take place autonomously onboard. The GNC systems sensors and processing algorithms have to deal with a wide variety of illumination conditions, possible target geometries and surface materials. What's more, the GNC system has to be capable of a high level of autonomy. One cannot expect permanent ground station contact. At least, transition between ground stations is not seamless. More likely, only for a small fraction of an orbit, direct contact to a ground station is guaranteed. In-between, the GNC system has to act autonomously. Contact times are to brief, to have approach operations take place only during contact.

This paper presents a laboratory prototype of a rendezvous GNC system dedicated to coping with these demanding challenges. The system is tested in a very special simulation environment: The European Proximity Operations Simulator (EPOS), a robotic Hardware-in-the-Loop simulator for the final 20 meters of rendezvous manoeuvres. The GNC-system's first employment takes place in a large, distributed simulation experiment: DLRs On-Orbit-Servicing End-2-End simulation project. The paper gives a brief overview of the project and the GNC system's role.

In the following, the term chaser is used for the spacecraft carrying out a servicing operation. The object or satellite the chasers servicing mission is aimed at, is denoted target. The combination of a rigid object's (e.g. a satellites) position and orientation is called pose. The combination of position, velocity, orientation and angular velocity is called state. In this paper, GNC-system denotes a rendezvous GNC-system, i.e. a system that is responsible only for relative guidance, navigation and control with respect to some target. So, in a real mission, the GNC-system, as presented in this paper, builds upon a classical attitude determination and control system.

2 GNC-SYSTEM REQUIREMENTS

2.1 General Task

The GNC-systems principle purpose is to control the approach of the chaser towards the target object based on visual navigation. The main navigation loop gets information about the current absolute position and attitude of the chaser from the satellite's attitude and orbit control system. It uses this information along with the estimated relative target pose from visual sensor data and calculates control forces and desired chaser attitude depending on the current guidance mode. While the GNC system incorporates a position controller, the attitude controller is considered part of the satellite's AOCS. When the GNC system is active, the AOCS receives desired attitude values and feeds them to the attitude controller.

2.2 Design Requirements and Boundary Conditions

The following boundary conditions serve as basis for rendezvous GNC-system design.

- Contact times: Contact times between ground station, i.e. control centre and chaser spacecraft are limited to a couple of minutes a time. In theory, ground stations could be chained together to realize contact over a period of time. But even if such a chain could be arranged, transition between the individual ground stations most likely would not be seamless. More likely, there would be considerable gaps between successive stations. Therefore, it is much safer and realistic to assume that contact is restricted to a couple of minutes at a time, with long gaps between passages.

- Communications quality: Ground stations are connected to the control centre via dedicated, but COTS-based network technology. There are many network devices (switches, routers, firewalls...) involved. As a consequence, a certain amount of jitter and delay cannot be avoided. Without further information, it is difficult to ascertain the specific extent of these effects. For the design of the GNC system, values are assumed, that have a considerable impact on a ground-based real-time control loop of the chaser. Bandwidth is strongly limited. Telemetry (downlink) provides few megabits per second.

- Target: The target object is considered dead in space. No matter if it is a non-operational but otherwise complete satellite, an upper rocket stage or some unspecific piece of space debris, the target will be uncooperative. This means it doesn't provide any information about its state in general, or its position and attitude in particular. It has no aids attached to its surface that could support visual navigation, like actively illuminated markers or passive retro-reflectors. What's more, it is not stabilized and could be tumbling. The target's surface is composed of different materials, strongly reflecting solar panels and MLI on the one hand, diffuse materials and surface properties on the other hand.

- Illumination conditions: The GNC system has to navigate visually under different kinds of illumination conditions. On the one extreme the target can be completely dark and on the other, it can be in full sunlight. The sun can be located behind the chaser or behind the target. It can hit the target from the side, leading to sharp shadows, leaving a part of the target in darkness. The illumination conditions will change during the rendezvous manoeuvre considerably.

- Reliability: The most important, obvious boundary condition is clear. There must not be a collision between chaser spacecraft and target object. This sounds silly as a requirement, but it cannot be overestimated. The mission as a whole, and consequently its individual parts and components like the GNC system, must ensure the highest reliability possible. It is not simply about creating new space debris. It is about the mission to launch at all. If the reliability cannot be convincingly ensured, an OOS mission would have no chance to be realized in the first place. No investor can risk such a mission, that, instead of reducing the space debris in orbit, might generate even more.

2.3 Typical Approach Scenario

The target is considered to be in a slowly tumbling state with a spin rate of about $4°/s$. Navigation takes place with respect to the targets body frames origin only, i.e. the chasers attitude is independent of the targets orientation.
Close approach starts at 15 m. It is a requirement at this point, that the target is in sensor view. Mid-range rendezvous is responsible for this task. For this scenario, the rendezvous GNC-system focuses on close range rendezvous, which is very well suited for HiL simulation with EPOS. At this Pose Initialization point (PI), the pose tracking algorithms are initialized and their proper function is verified.
As soon as tracking is stable, a command has the chaser hold position, and fine-orient itself such that the sensors point directly at the target. It follows a straight line approach towards the target with a velocity of 5 cm/s. The next hold point is at 8 m. Here, any robotics arm or some similiar mechanism, that could be part of a real servicing satellite, is moved from a passive to an active stand-by configuration. Now a fly-around phase has the chaser inspect the target from different perspectives, keeping distance constant. The GNC-system realizes this phase with its fly-around modes. As soon as a good angle for the final approach phase is identified, the GNC-system has the chaser near its target at a velocity of 1 cm/s.
The final hold point, called Mating Point (MP), is located at a mere distance of about 3 m. Any grasping, docking or other activity starts here. This is an especially critical situation, not only for a real mission, but for a HiL simulation as well. The sensors field of views are employed to their limits. Any closer, and the pose estimation algorithms may have problems keeping tracking stable.
After servicing operations have finished, the GNC system withdraws to a distance of 8 m.

3 RENDEZVOUS GNC-SYSTEM

3.1 General Design Decisions

As already outlined in the requirements, it has to be expected that short contact times and low communication bandwidth make ground-based processing of rendezvous sensor data, a so called ground-in-the-loop approach, very difficult. This approach depends on many yet uncertain parameters. Therefore, the GNC-system is designed as a widely autonomous system. Processing is carried out on-board. During the approach relative sub-trajectories are followed automatically without any need for control centre contact.
Navigating visually with respect to an uncooperative target under varying illumination conditions with high reliability is a very demanding task. The authors strongly believe, that no single sensor type with a single pose estimation algorithm can cope. The GNC-system is equipped with a multi-type sensor suite, incorporating classical passive 2D sensors as well as active 3D sensors. The pose estimation algorithms associated with each sensor differ radically in concept and principle. The GNC-system

uses the pose estimates simultaneously by fusing them to obtain a high quality pose estimate. The sensors complement one another and compensate their individual weaknesses.
Since automated rendezvous with an uncooperative target is not state of the art, the authors consider the rendezvous GNC-system a payload or an experiment, that is closely connected to the satellites AOCS. The GNC-system presented here is not intended to serve as a fully integrated, stand-alone flight control system. Rather, it focuses on the actual approach using relative visual navigation.

3.2 Architecture

Fig. 1 depicts a schematic overview of the GNC-system, focusing on the data flow. It consists mainly of visual sensors, pose estimation algorithms, navigation filter, guidance function and position controller.
The GNC-system uses three distinct sensors: a classical CCD camera, a Time-of-Flight camera based on PMD technology, and a scanning LiDAR. These sensors provide a two-dimensional image, a three-dimensional image and an unstructured point cloud of the target in real-time.
The individual pose estimation algorithms, specific to each sensor, use these data to calculate an estimate of the targets relative pose with respect to the chaser spacecraft. The AOCS provides the absolute pose of the chaser with respect to some inertial reference frame like ECI. The navigation filter, an Extended Kalman filter, takes this pose along with the relative pose estimates from sensor data, and calculates a high quality estimate of the targets pose.
Depending on the actual guidance mode, the guidance function provides a desired chaser pose relative to the target, at each time step.
The AOCS receives the desired attitude directly. The position controller calculates control forces. The AOCS is provided with these forces and controls the chasers actuators accordingly.

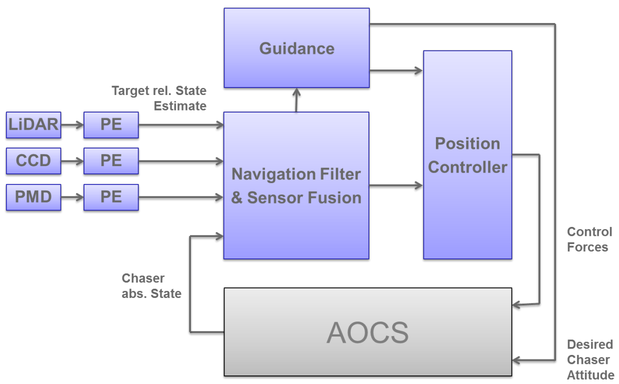

Figure 1: Basic gnc system architecture.

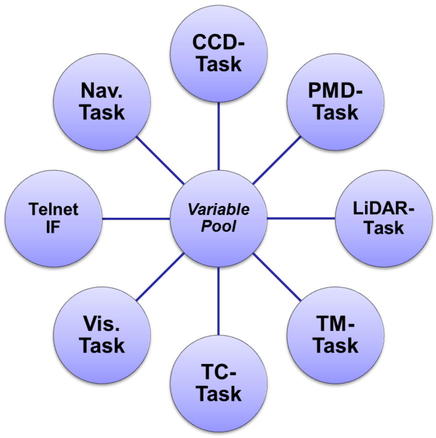

Figure 2: Overview of gnc system software structure.

3.3 Implementation Overview

Fig. 8 shows the sensor assembly on the left, a breadboard on which the GNC-system's sensors are mounted along with power supply and communication infrastructure. Typically, the sensor assembly

is mounted onto one of the EPOS simulator's robots.
GNC-system software, i.e. communication interfaces, pose estimation, navigation filter, guidance etc., is implemented on a dedicated GNC-PC in modern C++ (C++11) running Linux. Fig. 2 gives an overview of GNC-system software architecture. At the centre the thread-safe variable pool is located. This pool encompasses all telemetry and telecommand variables. Commanding the system takes place exclusively by setting telecommand variables. Various (mostly) periodic tasks execute GNC-system functionalities. The tasks communicate with one another exclusively by writing to and reading from the variable pool. In that way, coupling between tasks is minimal. Non-deterministic long period tasks (pose estimation algorithms) can run along deterministic short period tasks (navigation filter loop) without impeding one another.
The navigation task runs navigation filter, guidance function and position controller. The AOCS drives the navigation task by periodically providing the chasers motion state and receiving control forces and desired attitude. With each sensor a dedicated task is associated. These tasks receive the sensor data and execute pose estimation. A few other tasks handle communications with the ground console, as well as other supporting tasks like logging or local visualization of sensor data.

3.4 Visual Navigation Sensors

The GNC system doesn't rely on one sensor or even one type of sensor. Every sensor type has its very specific characteristics, advantages and weaknesses. In some situations, one sensor type works well, in different situations, others do. It is the authors' conviction that only a suite of sensors of different types working together, thereby complementing one another and compensating each other's weaknesses, is capable of providing the high reliability and safety necessary.
The GNC-system employs simultaneously three sensors for visual navigation (Fig. 3): A classical, industrial CCD camera, a Time of Flight (ToF) camera based on PMD technology and a scanning LiDAR sensor developed by GSOC's OOS team based on COTS components [15].

Figure 3: Gnc system sensor suite. From left to right: CCD camera, PMD camera, scanning LIDAR

CCD (Charge Coupled Device) camera technology has a long flight heritage. It is a visual sensor technology with a high TRL level. Therefore, a CCD camera is included into the sensor suite as the primary sensor. It is a Prosilica Gigabit Ethernet monochromatic camera GC-655, with a resolution of 640x480 pixels. A CCD camera is a passive sensor, of course, and can therefore only operate if the target object is sufficiently illuminated. This discourages its use during an eclipse. What's more, in space there may be sharp shadows on the target, most likely due to its own shape being illuminated

from the side or from behind. In that case only the illuminated parts of the target are visible in the CCD images. On that basis, pose estimation is difficult, if not impossible. However, pose estimation greatly benefits from the cameras high resolution and reliability.
The GNC system incorporates a Bluetechnix Argos3D-P320 PMD (Photonic Mixer Device) camera, with a field of view of 30° and a resolution of 352x287. A Time-of-Flight camera is very similar to a CCD camera, insofar as it captures images on a two dimensional matrix-like chip. However, a ToF camera takes three-dimensional images, that is each pixel has a range information associated with it. ToF means, that the distance information is obtained by exploiting the speed of light, i.e. the time it takes the light emitted by the illumination unit of the camera to travel to the target and for the backscattered light to reach the camera sensor. In case of the PMD camera, this is done by emitting modulated light and evaluating the phase difference between transmitted and received modulated light. Consequently, the camera has a low unambiguous range. At longer distances the phase shift and therefore the range measurements repeat cyclically. This drawback can be handled by using different modulation frequencies at the same time. Another drawback is the high sensitivity to ambient light. On the positive side: The camera provides a three-dimensional image, all pixels at the same time in contrast to a scanning LiDAR. What's more, the camera is capable of providing these images with a reasonable high frame rate. The greatest advantage compared to the passive CCD camera is, that the PMD sensor does not depend on proper illumination of the target by the sun or some other natural source.
The third sensor is a scanning LiDAR (Light Detection and Ranging, or Light RADAR). Just like the PMD camera, a LiDAR exploits the time it takes actively emitted light to return to the sensor by backscattering. But the LiDAR has only a single photo detector, that is to say only a single pixel. It uses a narrow laser beam to illuminate the target only at a small spot and uses the single detector to determine the range. A deflection system consisting of one or two mirrors has the laser beam and detector scan across the target to create a three-dimensional point cloud. For the rendezvous GNC-System a custom LiDAR scanner is developed by GSOC's OOS group [15]. This is a sensor build from COTS components, intended as a laboratory sensor for rendezvous navigation experiments. The advantage of a scanning LiDAR is the high immunity to varying illumination conditions, an efficient exploitation of the illumination power and consequently high range as well as the independence from any other illuminaton source. Drawbacks are the complexity of the sensor due to the need for a deflection mechanism, the power demand of this mechanism, the deformation of the point cloud when the target is moving and a low frame rate, if the analogy to the PMD camera is allowed.

3.5 Pose Estimation Software

Details about pose estimation for the rendezvous GNC-System are beyond the scope of this paper. In the following, only a rough sketch of the algorithms is provided.

3.5.1 2D Pose Estimation

The main idea of the 2D tracking algorithm is to estimate the pose based on 2D gray-scaled images showing the target, an initial guess of the pose from the previous execution of the pose estimator (tracking principle) and the 3D geometric model of the target. The target model is divided in a few geometric sub-bodies. In our case the target mockup consists mainly of a hexagonal prism, a cylinder

Figure 4: 2D Pose Tracking: exemplary image with projected geometric model (magenta lines): Initial guess (left) and result of 2D pose estimation (right)

and an octagonal prism at its end. The image is divided in four regions: the three sub-bodies, and the background.
The tracking algorithm uses as initial guess the result of the last execution of the pose estimation. The 2D image coordinates can be computed for each of the 3D vertices using the 3D geometric model, the pose and sensor properties like calibration data (focal length, principal point, etc.). The edges of the model (each connecting two vertices) can then be projected to the 2D image plane. In the tracking mode, the edges of the model corresponding to the previous pose are close to the true edges of the image. The main idea is to slightly change the model edges such that they best match with the edges of the object in the image. This is done by finding the best pose, i.e. by finding a pose which locally minimizes a certain energy functional.
Since the initial guess is close to the actual pose, we evaluate the image only in a small bandwidth around the model edges. We consider a small band around each edge and assign each pixel to one of the four regions: background region (1), hexagonal prism (2), cylinder (3) or octagonal prism (4).
For each region, the mean value of the image intensity is calculated. Then the image intensity of the pixels of the small band are compared to the mean value. The squared difference is then added to a sum, which results in the energy functional to be minimized. It is a region based method which uses directly the image intensity, not its gradient. Therefore it is very robust with respect to noise. The squared differences are small, if a pixel's gray value is close to the mean value of the region.
The minimum of the energy is finally found by using the line search algorithm, a standard minimization algorithm in numerical optimization, see [16].
Figure 4 shows for an exemplary image the initial pose guess (left sub-figure) and the result of the pose estimation (right sub-figure). The initial 3D pose is projected to the 2D images and the edges of the model are drawn. We observe that the initial guess has a slightly wrong orientation by some degrees. After eight iteration steps of the line search, the pose as shown in the right sub-figure match well with the target shown in the image.
We also observe, that there are parts of the hexagon which are in the shadow of the cylinder (the tower of the mockup). However the algorithm is robust with respect to a few shadowed regions. There is

enough contribution by the other, non-shadowed parts of the model.

3.5.2 3D Pose Estimation

The principles of pose estimation from 3D data are very similar, regardless of the specific type of 3D data (unstructured point clouds or matrix like data from ToF cameras). Therefore, 3D Pose Estimation for the rendezvous GNC-System is described here briefly in a general way.
Tracking is based on the Iterative Closest Point (ICP) principle. This is a model based technique that minimizes the summed-up squared distance error between the target model surface and the three-dimensional point cloud provided by the 3D sensors. A variety of algorithms exist [17]. In general, ICP algorithms follow six stages: Selection of points, matching of measured points to target surface points, weighting of point pairs, rejection of point pairs, assignment of an error metric, minimizing the error metric. Specific GNC algorithms may use different techniques and criteria for each of these stages. As a research platform, the rendezvous GNC system is intended to allow for testing of a variety of tequniques for these stages, and the suitability for spacecraft relative navigation.
For initial pose estimation, that is to say for the very first pose estimate before actual tracking starts, a RANSAC-based algorithm will be used, presented in [18]. Later, other algorithms and algorithm varieties will be evaluated with the rendezvous GNC system.

3.6 Navigation Filter

The navigation filter provides an estimate of the state of the target, i.e. of position, velocity, attitude quaternion and attitude rate (in ECI coordinates). The estimation is based on prior knowledge of the state of the target combined with measurements of the optical sensors (CCD camera, PMD camera, LiDAR, cf. Section 3.4).
The filter is an Extended Kalman filter [19] which can handle delayed measurements. Details on the filter algorithm and how delayed measurements are integrated are described in [20]. The term ”delayed measurements” means that, at the time of the filter execution, a measurement corresponding to the current time is not yet available. A measurement corresponding to a state in the past is available. For example, the image processing and such the 2D pose estimation as described in Section 3.5.1 has a typical runtime between 0.1s and 0.2s. Therefore, measurements based on the CCD camera have a typical measurement delay of 0.2s. It is very important to consider such delays because the satellite’s velocity is in the magnitude of 7 km/s in our scenario. By neglecting a delay of a magnitude of 0.2s, an error of 1 km-2 km in the position estimation would occur! Therefore we need to use an adaptation of the standard Kalman filter as proposed in [20].
Figure 5 visualizes the delayed filter problem: The figure shows a time line and two chronological lines: the upper line is the continuous true world, the lower line is the filter estimation. The vertical lines mark the execution of the filter at discrete times. At time t, an estimation of the true state $\mathbf{x}(t)$ should be performed. A measurement of the current state is however not available. The green line illustrates the most recent measurement, a measurement of the state at time t_{meas}.
The navigation filter is executed with a frequency of about 10 Hz. Due to the processing time of the image processing, there are steps of the filter execution where no new measurement is available. In such time steps, the filter propagates only, i.e. only the prediction step of the filter is executed, not the correction step.

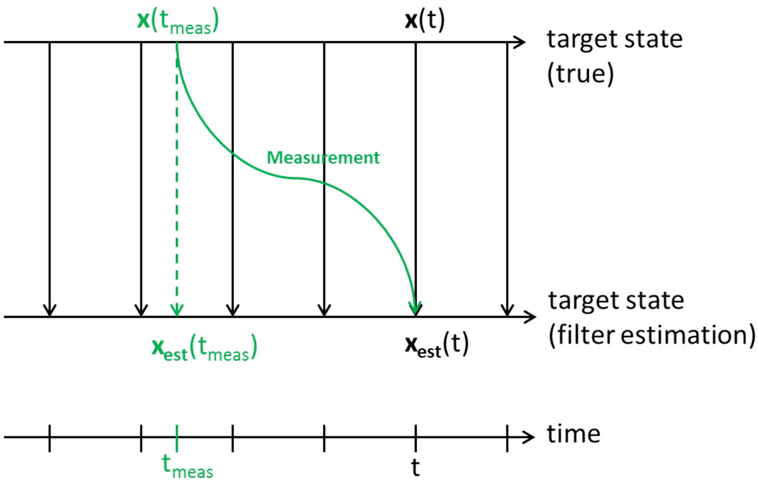

Figure 5: Delayed filter problem: At the time of the filter execution, the available measurement corresponds to a state of the past.

When a new measurement is finished, the measurement is integrated in the correction step of the filter the next time the filter is executed. A certain history of the state estimates of the filter is stored using ringbuffers. Since the measurements are delayed and since the time of the image capturing may not be synchronized with the execution time of the filter (see Figure 5), the state of the filter is interpolated in order to compare the current measurement with a so-called predicted measurement. For details on the Kalman filter with delay, we refer to [20].

In contrast to [20], we do not only estimate the position and velocity, but also the attitude and attitude rate. Further the prediction step of the filter uses Newton's law of gravity to propagate the position and velocity of the target in an Earth orbit. The quaternion differential equation [21] is solved for the attitude propagation.

In the update step, the delayed measurements are handled. It is possible to include different sensors, i.e. CCD camera and PMD camera and LiDAR. The dimensions of the measurement vector and of the gain matrix of the Kalman filter can be adapted accordingly. For example, if the position (3D) and the attitude quaternion (4D) are measured by three sensors, the measurement vector is a 21D vector. The state to be estimated is a 13D vector (3D position, 3D velocity, 4D quaternion, 3D attitude rate). The gain matrix is then a 13 times 21 matrix. The matrix entries can be considered as weighting parameters. It is possible to weight certain components of CCD measurement, PMD measurement and LiDAR measurement differently. This concept can be easily adapted to any arbitrary number of sensors.

3.7 Guidance

The guidance function produces approach trajectories between the different hold points. The Local Vertical Local Horizontal (LVLH) coordinate system is always used as the reference for the guidance function. Its origin is similar to the targets location. The frames orientation is determined by the

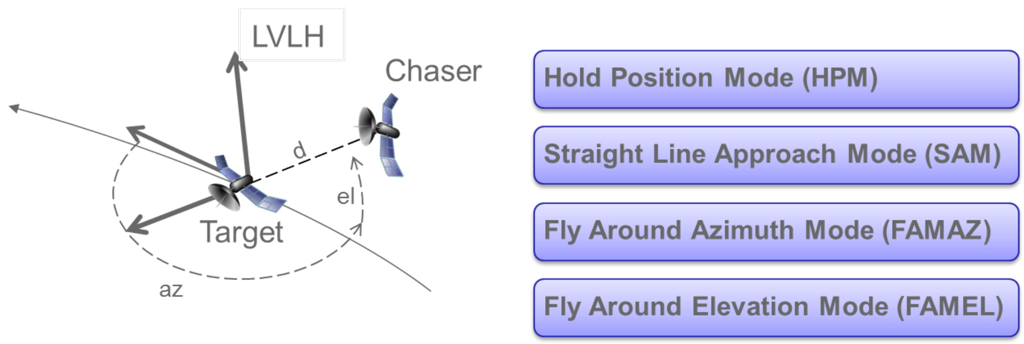

Figure 6: Guidance trajectory parameterization (left) and major guidance modes (right)

targets velocity vector. For easy chaser position description from an operational point of view, the guidance function uses spherical coordinates (Fig. 6). Looking at the reference approach profile, the partial trajectories between hold points can be categorized in a small number of principal trajectory types and associated guidance modes.

- The current position relative to the target is held: Hold Position Mode (HPM)
- The chaser advances the target in a straight line: Straight Line Approach Mode (SAM)
- The chaser circles the target changing the azimuth angle only, thereby keeping distance and elevation constant: Fly Around Mode Azimuth (FAMAZ)
- The chaser circles the target changing the elevation angle only, thereby keeping distance and azimuth constant: Fly Around Mode Elevation (FAMEL)

From this portfolio of sub-trajectory types, a large variety of close range approach and inspection manoeuvrers can be realized, even on-the-fly, reacting to the individual situation.
Note that the approach trajectories are independent from the actual orientation of the target object. The guidance function keeps the chaser steadily pointed towards the target object's origin, such that it stays within sensor field of view.

4 HARDWARE-IN-THE-LOOP TESTING OF THE GNC-SYSTEM

Hardware-in-the-Loop testing is carried out in a very special simulation environment: The European Proximity Operations Simulator (EPOS). It is a Hardware-in-the-Loop simulator for the last phase of rendezvous and docking maneuvres. The EPOS facility is part of GSOC, located in Oberpfaffenhofen, near Munich. It consists of two industrial robots with 6 DoF each. One of the robots is fixed to the laboratory floor, the other moves on a linear rail 25 meters long (see Fig. 7). For testing the GNC-system, the sensor assembly is mounted to the robot moving on the linear rail, as depicted in Fig. 8 on the left side. This robot represents the chaser spacecraft. The other robot carries a true-to-scale satellite mockup, serving as the target object, as shown on the right side of Fig. 8. The mockup is build from realistic surface materials, incorporating MLI foil and real solar cells. A 12 KW daylight

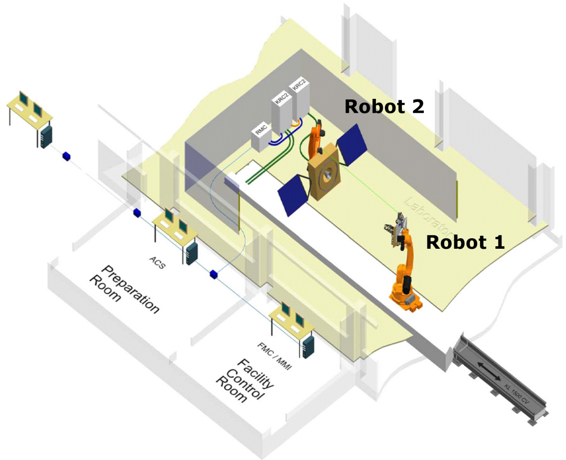

Figure 7: EPOS facility layout. Linear rail is 25m long.

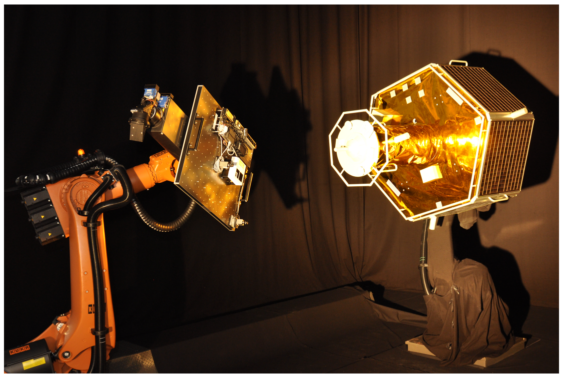

Figure 8: Chaser and target robots at close range before background curtain.

spotlight provides illumination with a spectrum widely similar to the suns and power density like in LEO. Behind the target robot, a deep black theatre curtain simulates the space background in orbit. The robot itself is covered with the same fabric. Fig. 4 illustrates impressively the curtain's effect. For more details on the EPOS facility, please refer to [22, 23, 24, 25].

5 RENDEZVOUS GNC IN DLR'S ON-ORBIT-SERVICING END-TO-END SIMULATION PROJECT

The rendezvous GNC-system plays an important role in the current DLR project On-Orbit Servicing End-to-End Simulation, E2E for short. It is a combined effort of three DLR institutes (Space Operations and Astronaut Training/GSOC, Institute of Robotics and Mechatronics as well as Institute of System Dynamics and Control) with the aim of developing a distributed simulation environment for OOS missions.

In a E2E simulation, a number of components at different locations work together: A high fidelity satellite simulator mimics a satellite bus and provides chaser and target states with orbit and attitude danymics. The EPOS facility serves as a platform for the rendezvous GNC-system, including real sensor and true-to-scale target mockup. The OOS-Sim, a robotic Hardware-in-the-Loop environment for simulating contact dynamics, carries the robotics payload, including a 7 degree of freedom robotic arm for grasping the target. GNC, robotics and general satellite consoles, located in a real multi-mission control room at GSOC, allow controlling the chaser satellite, as well as GNC and robotics payload, via space communication standards ECSS and CCSDS. Finally, a sophisticated communication system, using real control center network infrastructure, connects consoles and chaser satellite, while simulating communication jitter, delay and realistic Up- and Downlink bandwidths.

A typical scenario that can be simulated, starts with a visually guided approach to the target with EPOS at GSOC. In the middle of the approach, a fly-around is carried out to inspect the target and to find a suitable spot for grasping. At the mating point, very close to the target, attitude and position control are switched off (rendezvous GNC passive) and the actual grasping and berthing of the target

is carried out with the OOS-Sim facility, part of DLR's Robotics and Mechatronics Institute.
This can be but a very brief overview of the E2E project. Benninghoff et al. give a considerably more detailed description of the E2E project in [26].

6 CONCLUSION

Future OOS missions have the potential to change spaceflight as known today. However, OOS holds numerous challenges rendezvous GNC has to cope with. GSOC's OOS group is developing a rendezvous GNC system as a research and development platform to handle these challenges. The GNC system uses several types of sensors simultaneously to realize high reliability of the visually controlled approach to an uncooperative target object. The system is tested with the robotic Hardware-in-the-Loop simulator EPOS, including real sensors, true-to-scale target mockup and realistic illumination conditions. Further, it is part of a larger distributed end-to-end simulation project, incorporating real control center network infrastructure and a console in a multi-mission control room.
Concerning the GNC-system's current status, visual navigation is working in closed loop with the CCD camera sensor. The next steps involve tuning of the system to optimize performance and robustness, as well as integrating PMD sensor and LIDAR scanner with the associated pose estimation algorithms.

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