# Robotics Rendezvous&Capture Test Facility "Inveritas"

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## Abstract

This paper describes the Inveritas hardware-in-the-loop (HIL) movement simulator for rendezvous maneuvers between two objects in space and how it was used by EADS Astrium to test a functional mock-up of a semi-autonomous satellite (Servicer) for satellite servicing in closed-loop. Its unique construction makes this HIL simulator very flexible and adaptable. It is explained how the usage of the limited available space and the limited degrees of freedom of the movement system were optimized to allow large approach distances and long real-time simulation times and how the accuracy of the simulator was increased using online and offline tracking mechanisms. Additionally, results from testing the Servicer's sensors, sensory data processing and GNC (guidance, navigation and control) in the HIL simulator are presented. Finally, the paper also includes future plans of how the HIL simulator can be improved in accuracy and flexibility.

## 1 Introduction

Space debris is an increasing threat for manned and unmanned space flight. As a result, de-orbiting existing space debris or preventing still operational satellites from becoming space debris are important future tasks for ensuring the safety of space missions. Most possible missions with these goals have a rendezvous and capturing phase between a target object and a Servicer satellite in common. Possible target objects can range from cooperative satellites (e.g. equipped with optical markers) to space debris of unknown shape. Developing and testing semi-autonomous Servicer satellites for such missions needs test facilities capable of including as much of the real hardware as possible into a mission simulation as "Hardware in the Loop" (HIL). Only this way the real sensor setups can be tested on earth under realistic lighting conditions and with realistic sensory data acquired from realistic target object materials. This sensory data can be transferred back into the simulation in real-time, so that the autonomous behaviors of the Servicer can be tested in "closed-loop".

The Inveritas project, which involved EADS Astrium as principal technical investigator and project coordinator, Jena-Optronik GmbH and DFKI RIC as project partners, had the goal of developing technologies for the rendezvous with an uncooperative target and a related HIL test facility for testing the Servicer GNC system under conditions close to reality. In addition to this, technologies for a semi-autonomous on orbit servicing were envisaged to be verified using the HIL simulator. The project was funded by the Space Agency (DLR Agentur), acting on a mandate from the Federal Government, grants no. 50RA0908 and 50RA0910.

The Inveritas facility uses a cable robot system that can move a Servicer platform in three dimensions inside a large workspace in combination with one industrial robotic arm that moves a target, the so called Client satellite. Both systems move the Servicer and the Client according to a software simulation of orbital dynamics, so that the relative movement of both objects inside the facility matches the movements that would occur in orbit.

These HIL capabilities enable a software simulation to get very close to the real situation in orbit in a test bed on earth and sensors as well as sensory data processing algorithms can be tested under realistic conditions. However, aside from being real-time capable, this needs a very accurate reproduction of the relative movements, positions and rotations between both objects with the real mockups, otherwise for example errors in sensor based pose estimations could not clearly be blamed on the sensor hardware or the sensory data processing algorithms, as the error could also be the result of an inaccurate placing of the mockups by the HIL system. The Servicer GNC itself was mainly developed by EADS Astrium supported by Jena-Optronik GmbH for the LIDAR sensor. The design driver for the navigation system was the uncooperativeness of the Client, i.e. no markers or RF links were present. However, since the Client can be assumed to be known, its geometry can be exploited for the onboard image processing.

Section 2 describes the HIL simulator itself, including a summary of similar installations, an overview over the hard- and software setup, how the accuracy of the HIL simulator was measured and improved, and how third parties and future projects can use the system. Section 3 gives an overview of the design of the tested Servicer's GNC system with focus on the close range navigation in the vicinity of an uncooperative target, and the rendezvous sensors. Section 4 summarizes concepts that were developed for improving the HIL simulator in the future. Section 5 gives a conclusion for this paper.

## 2 Hardware in the Loop simulation facility

This section describes the Inveritas hardware-in-the-Loop simulator that can be used to simulate rendezvous maneuvers between two objects, for example between two satellites in space. First, an overview over the hard- and software setup is given. Then, this section describes how the accuracy of the HIL simulator was measured and improved followed by a summary of similar installations and a description of how third parties and future projects can use the system.

### 2.1 Hardware Setup

The central parts of the Inveritas HIL simulation system are the cable robot, which is carrying the Servicer satellite, and the KUKA robotic arm moving the Client satellite. Both systems must move the mock-ups in real-time according to the software simulation with low latency and high positioning accuracy. The relative positions between both objects must match the simulated relative positions.

Figures 1 and 2 show the 24m long, 12m wide and 10m high Space Exploration Hall of the Robotics Innovation Center (RIC), which has additional test setups for robotic extraterrestrial exploration missions [1] like the moon crater mock-up shown in those figures.

The cable robot can move freely in 3d space and thus use a diagonal approach of up to 16.5m inside the available operation space, which increases the maximum distance to the Client. The cable robot is a special design by spidercam, a modification of their systems normally used to move cameras over large areas using a mount attached to four cables that are controlled by four winches. For Inveritas, spidercam changed the design of the system to use eight wires, still controlled by four winches. This increases the maximum weight (150kg) and the stability of the mount in movement. As the Servicer containing sensors and data processing hardware is attached to the mount of the cable robot, power and data connections need to be connected to the mount. Voltage of 230V AC at up to 1kW is transferred through two of the wires moving the cable robot and data is bidirectionally transferred using a 10 Gbit/s optical fiber inside a third wire.

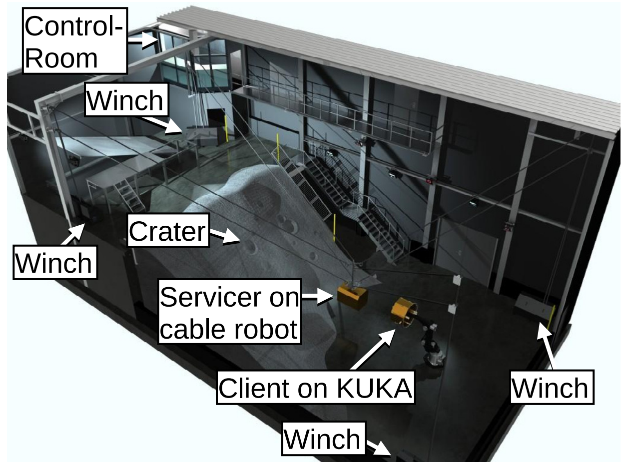


**Figure 1: Overview: cable robot, KUKA, Servicer and Client**

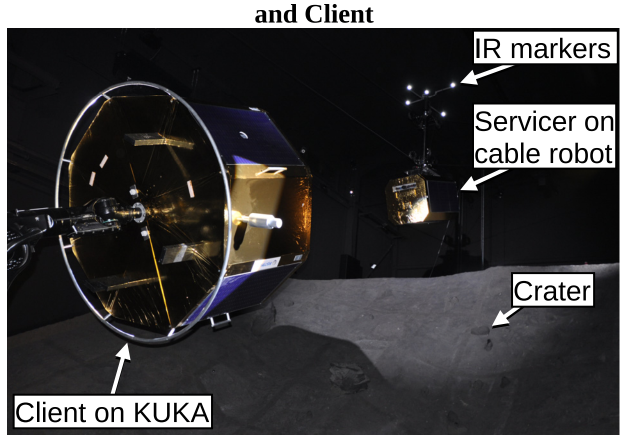


**Figure 2: Real image: cable robot, KUKA, Servicer and Client**

To increase the possible approach directions and the flexibility of the system, a controllable vertical rotational z-axis has been added to the mount, giving it 4 DOF (degrees of freedom). This axis and the cable robot itself can be controlled at 250Hz, providing a low control latency.

The robotic arm used to manipulate the Client mock-up is a KUKA-KR-60. It has six rotational joints and is capable of moving up to 60kg at the tool center point (TCP). The Client had no data or power connections in Inveritas, however, the KUKA generally allows wired connections to a Client mock-up through a flexible tube. The KUKA is controlled at 83.33 Hz, which is still providing a low control latency.

A motion tracking system (MTS) by Vicon based on seven infrared cameras is used to track the position of the cable robot mount. This is used offline to correct systematic errors in the internal position measurements of the cable robot (explained in Section 2.4) and online to correct non-systematic errors. The mount is tracked using a non-symmetric setup of passive IR markers (visible in Figure 2).

The lighting system consists of six light sources with pan-tilt units and lifts. The lifts can move the lights from 1m to 6m height, and the 800W lamps produce light with a color temperature of 3200K and a maximal light intensity of 3900 Lux at 5m distance. Hard shadows from parallel light and effects like flares occur in camera images, so that the resulting input from the real Servicer cameras comes close to camera images from a real orbital mission. Light absorbing paint has additionally been applied to the walls, so that the Space Hall is almost not visible behind the target in camera images (see Figure 3).

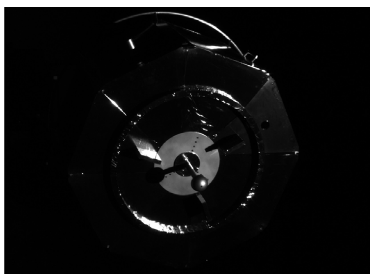

**Figure 3: Real Servicer image of the Client mock-up**

## 2.2 Software Architecture

The HIL simulator is controlled by a dSPACE real-time system with a quad-core architecture. Each of the first three cores can run a separate Matlab/Simulink model. One core runs the control of the movement system and the transformation of 12 DOF (degrees of freedom, here of the Client and Servicer) to the 10 DOF of the HIL simulator (explained in detail in Section 2.3). Two cores are available for end-users of the facility and have to provide the 12 DOF trajectories of the two simulated objects in real-time to the system. In Inveritas these two cores were used by Astrium for the GNC and the orbital dynamics providing the aforementioned trajectories. The fourth core runs Linux and handles all Ethernet communications.

## 2.3 Mapping the satellites' 12 DOF to the system

One of the main challenges for the Inveritas HIL simulator is reducing the 12 unlimited DOF of both satellites to the in total 10 limited DOF of the movement system (6 DOF for the KUKA arm and 4 DOF (translational movements + z-axis) for the cable robot). Two solutions were developed. The first solution keeps the Client, attached to the KUKA arm, fixed to its center of mass and the KUKA only rotates it around this point. Then, all relative translations between the two objects are only done by the cable robot and the relative rotations only by the KUKA arm. While this is a very clean solution, it turned out that in certain configurations the weaker wrist joints of the KUKA cannot safely move the Client, so that the KUKA stops its movement.

This is why a second solution was developed, where the KUKA uses only 3 joints to rotate the Client while the problematic wrist joints rest in positions where almost no force is applied to them. This has the disadvantage that every rotation done by the KUKA arm also results in translational movements of the Client, which have to be compensated by inverse translational movements of the cable robot carrying the Servicer.

The z-axis of the cable robot is used to compensate its own unwanted rotations that occur during translational movements and to extend the possible approach distance by using the diagonal of the available space.

## 2.4 Accuracy Measurement and Improvement

The accuracy of the movement system is very important, since it is meant to be used for testing visual navigation algorithms and sensors. For testing algorithms in closed loop, positioning accuracies around a few centimeters and degrees are enough, but if the accuracy of sensors and pose estimation algorithms is to be measured, the facility needs a tenth of their accuracy. For the pose estimation using the LIDAR in Inveritas this would be 1 mm.

The accuracies of the cable robot, the KUKA arm and the MTS were measured using a very precise laser tracker according to test methods defined in [11]. The unwanted rotations of the cable robot during translational movements were measured using the MTS, as the laser tracker could only track one point. It turned out that the KUKA is already very precise (1.6mm absolute accuracy and 0.01mm repeatability), the MTS had a precision of 8.9mm but the cable robot was clearly the biggest source of inaccuracy with only 267.4mm, not taking into account the errors in rotation. So the main effort was taken to increase the accuracy of the cable robot, and as a second priority the MTS itself was improved. As the repeatabilities of the cable robot (1.1mm) and the MTS (0.6mm) are quite good, it was decided to use offline tracking to determine the systematic errors of both systems and compensate them at runtime. The results were approximated by a third order 3D polynomial function, which can then be used during a HIL simulation to correct the systematic errors. This increased the positioning accuracies of the cable robot to 6.6mm and of the MTS to 5.3mm. This is not yet taking into account the visual positioning error, which results from rotational errors of the cable robot, which make the Client appear at a wrong position in the sensor images of the Servicer. This error was originally around 70cm at a distance of 8m to the target. After the improvements to the accuracies this error was decreased to 21mm. A rotational error of the cable robot that cannot be compensated by its own z-axis can be corrected by inverse rotations of the KUKA. The MTS is additionally used online to correct non-systematic errors of the cable robot. Errors in numerical calculations, mock-up

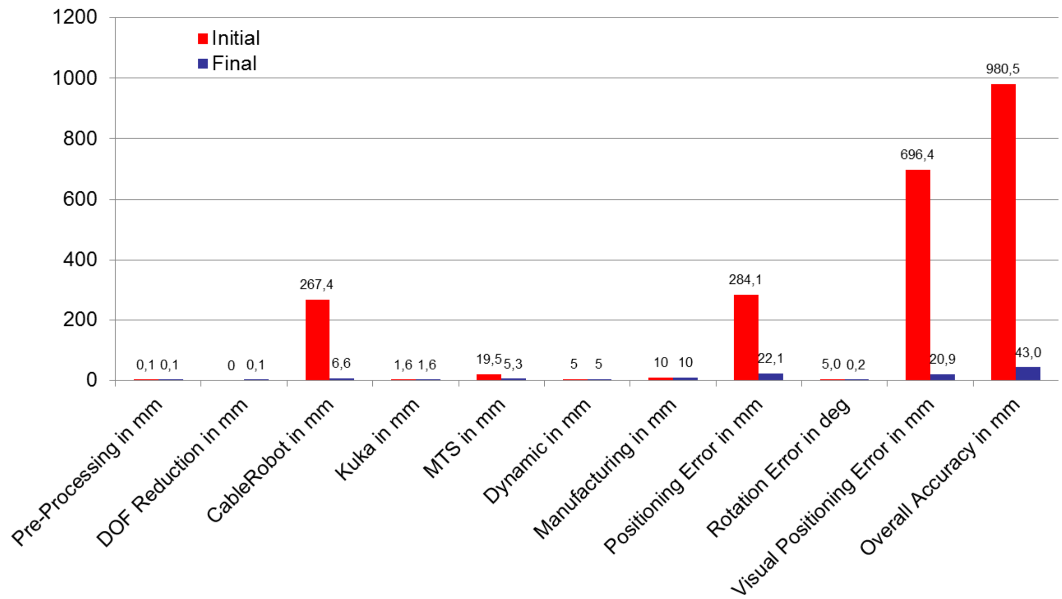


**Figure 4: Accuracies before and after calibration**

manufacturing and dynamic behaviors turned out to be almost negligible. Taking all reduced errors into account we reach an overall accuracy of 43mm (see Figure 4), which is enough for stable closed loop tests, but would not be sufficient for measuring the accuracy of sensors and pose estimation algorithms.

### 2.5 Summary of similar Facilities

The Inveritas simulator differs in some features from most comparable systems. The system was designed to be flexible and not restricted to one class of experiments. Instead of just using a one dimensional movement system for the approach distance, the three degrees of freedom (DOF) of the cable robot would also allow approach maneuvers towards an immovable target like a (e.g. lunar) surface mockup for the simulation of landing maneuvers. Using the 4 DOF cable robot combined with the 6 DOF robotic arm gives the whole movement system 10 DOF. It can simulate approaches from a distance of up to 16.5m. The light simulation is improved by light absorbing paint.

The comparable HIL simulator EPOS [6] uses two robotic arms holding the two approaching objects in combination with a linear rail, giving the system 13 DOF. It is able to simulate approaches of up to 20m with a high accuracy. No light absorbing paint is used. The SOSC [7] uses three 6 DOF motion systems of different sizes and two of them are mounted on rails. The systems are used and combined according to the mission that is to be simulated, also including large static targets. Lama [8] can simulate landing maneuvers and rover mobility, using a robotic arm on a rail. The system is used to compensate earth gravitation to the gravitations of extraterrestrial bodies for full size and weight objects of up to 500kg. TRON [9] uses a 6 DOF robotic arm on a rail to simulate approaches to the moon's surface. Unlike the 1:1 Client model used in Inveritas, the surface models of TRON are scaled, enabling very large simulated distances at the expense of higher necessary system precision. RACOON [10] is limited to movements in a 2D plane and simulates scaled close proximity operations. The target can be moved in the 2D plane and rotated around the axis perpendicular to that plane. The chaser is not movable, but can be rotated around two axes. EPOS, TRON, SOSC, and RACOON have lighting systems similar to the one used in the Inveritas simulator.

### 2.6 General Usability for Rendezvous Tests

The Inveritas HIL simulator is intended to be flexible and adaptable in use, enabling a wide range of possible HIL rendezvous maneuvers. Planned future improvements to the facility are covered in Section 4. An end user of the facility should provide the mock-up to be picked up by sensors, the sensor hardware and (at least binary) Matlab/Simulink models for the behaviors of the objects. As only binaries have to be provided, the end-user does not have to disclose the Matlab/Simulink models. The cable robot mount provides 230V AC at 1kW and 24V DC as well as a data connection of 10 Gbit/s via optical fiber, which can both be used for the sensor hardware.

## 3 Servicer GNC

The following section gives a brief overview of the design of the Servicer GNC system that was used in Inveritas with focus on the close range navigation in the vicinity of an uncooperative target, and the rendezvous sensors, which were the first test subject of the Inveritas robotic test facility.

### 3.1 Outline of the GNC System

The GNC system comprises sensors, actuators and the software controlling the vehicle position and attitude in space and relative to an uncooperative, potentially tumbling target. The software is in charge of the processing of the sensor measurements, the computation of the flight trajectory, the navigation, the attitude and position control as well as the flight control and safety monitoring of the Servicer space-craft. Compared to existing rendezvous and docking systems as applied for ATV, the new system is able to perform relative position and attitude control with respect to a passive and tumbling target on the basis of optical measurements. Hereafter the basic ideas and the preliminary performance of the major modules are presented.

### 3.2 Guidance

For the tests in the Inveritas facility, only the last meters approach was investigated due to the limitations of the size of the facility. Therefore, the guidance started at a distance of approximately 10m, where usually an inspection flight had been performed before in order to determine the target spacecraft integrity.

After the inspection a hold point on the V-Bar about 10m behind the target is acquired. In this point the navigation sensor is switched to a mode, where initial pose estimation is performed. Based on the inspection results the approach direction towards the target is defined. Since the V-Bar approach is advantageous in terms of complexity, flexibility (easy introduction of further hold point) and fuel consumption this is selected whenever possible.

### 3.3 Control

The control relies on proven methods from the ATV design. The attitude control is performed with a configurable PID controller. The same principle holds for the position control in close range. H∞ control may be applied if stronger robust performance requirements arise from the manipulator system. Recent studies (e.g. [5]) propose an MPC (model predictive control) controller also for rendezvous, however at the cost of very high CPU load. The resulting force/torque command vector is processed by a thruster management function to find the best (fuel minimizing) combination of thruster firing for its realization.

### 3.4 Primary Navigation Sensor

The navigation for the close-range was mainly based on the measurements of a 3D-LIDAR sensor, which is able to provide a 3D representation of the object in front of the chaser. For this experiment, a prototypic 3D-LIDAR developed by Jena-Optronik GmbH, was used.

Typical scans had a number of 5000 scan points distributed over a field of view of 20°x20° along a sinusoidal scan pattern, which is the result of the motion of a gimbal mounted mirror, which performs oscillations in azimuth and elevation directions.

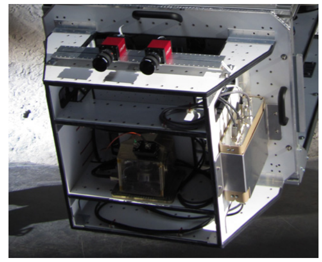

**Figure 5: Servicer support structure carrying cameras and the 3D-LIDAR.**

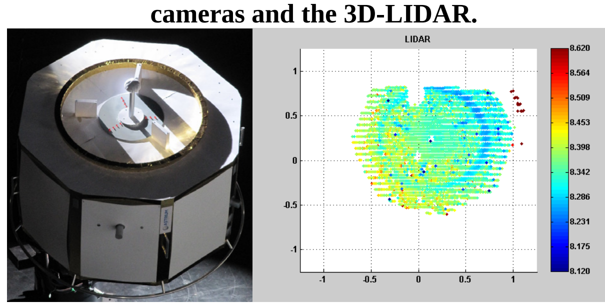


**Figure 6: Left: Mock-up of target satellite covered with diffusive reflective material. Right: Range data acquired by the 3D-LIDAR.**

### 3.5 Vision-Based Navigation

The vision-based navigation is one of the core-elements of the close-range rendezvous due to the fact that a high precision of the target position and attitude is required to perform rendezvous but also to enable following robotic manipulations like capturing. For this purpose, the position of the center of mass of the target is required and not only the centroid of all 3D-LIDAR measurements, which might be several tens of centimeters or even meters away from the center of mass. The vision-based navigation, which was tested in the Inveritas test facility, was based on measurements provided by the 3D-LIDAR as described in the previous section. Since the target had to be assumed to be non-cooperative (i.e. no visual markers and no attitude control) but not as unknown, it was allowed to use the geometric appearance of the target as the essential feature that bears the position and attitude of the object. Therefore a model-based approach was chosen to estimate the pose of the target object. The 3D-LIDAR based pose-estimation is divided into two main stages: The pose-initialization and the pose-tracking.

#### 3.5.1 Pose-Tracking

Assumed that an initial pose of the target is known, the pose can be tracked over time very robustly by application of the iterative closest point algorithm (ICP) [2]. For this purpose, a model of the target object is used to be registered with the 3D point cloud acquired by the 3D-LIDAR. We use a specific version of the ICP algorithm that matches 3D points of the 3D-LIDAR with a model consisting of planar patches, lines and points [3]. Especially the usage of planar patches provides better accuracies compared to the point-to-point ICP due to the avoidance of a discretization of the model, which imposes additional errors.

A critical aspect was the limited field of view of the 3D-LIDAR, which was used for the experiments. Since the geometric structure of the object is the only relevant pose-bearing feature, very close distances in connection with a small field of view can lead to single planes in the field of view, which can no longer define all degrees of freedom of the relative pose. However, the exploitation of the knowledge of boundary points could solve most of the cases where only small portions of the boundary of the objects were visible. The increase of the field of view of the 3D-LIDAR would dramatically reduce this difficulty. In order to survive situations where only few geometric structures are available in the field of view, a Kalman filter had been introduced that models the system dynamics of a free-tumbling target object. The Euler-equations describe the rotational movement of the object. A sufficiently long observation of the object with larger distances between sensor and target enables the convergence of the Kalman filter. Once the filter converged, phases with limited view of the object and less geometric structures help surviving critical situations.

#### **3.5.2** Pose-Initialization

Before starting with the pose-tracking, a rough initial pose-estimation is essential for the convergence of the following tracking by means of the ICP algorithm. Therefore, a pose-initialization from scratch is necessary. Again, the 3D measurements of the 3D-LIDAR were used to solve this task. This choice has the advantage of being independent from illumination conditions. The proposed method applies a view-based approach. For this purpose, similar to well-known correlation techniques from 2D template matching, a method has been developed for 3D templates.

The proposed method exploits specific properties of the pose-initialization task:

1. The object is known and can be represented as a model consisting of patches, lines and points.
2. The object consists only of a single object in the field of view. At least in 3D-data the object-background separation is already solved.
3. The 3D-sensor provides spatial measurements, which especially contains depth information.

All three properties can be exploited for an algorithmic search of the target pose, which we call 3D-Template-Matching. While 2D-template matching methods [4] suffer from the lack of rotation and scale invariance and the lack of sufficient robustness against changing illumination conditions, the 3D-Template-Matching does not show these drawbacks and thus can be used quite efficiently. The 3D-LIDAR provides 3D point clouds, which are independent from illumination conditions. The missing scale invariance of 2D template matching can be compensated by using the knowledge about the range values measured by the 3D-LIDAR. In case of complete view of the target object, even the full 3D-position of the object can be defined by the position of the centroid of the 3D point cloud (at least for a specific attitude). Thus, only 3 degrees of freedom (i.e. the three angles of the attitude) are subject to a search in the search space.

The 3D template matching consists of the following main steps:

1. The 3D-point cloud is converted into a small matrix representing a depth image for a specific object attitude.
2. For many different attitudes, similar views are represented in a model database.
3. For every template of the database, the centroid of the 3D point cloud and its offset to the center of mass of the objects are stored.
4. An orthographic projection of a view into a matrix of fixed size and discretization enables scale invariance.
5. The storage of the offset between center of mass and the 3D-point cloud's centroid provides translation invariance.

Thus, the search of three of six degrees of freedom can be avoided. The search for the remaining 3 rotational degrees of freedom can be solved by storing many different reference views in a database of small reference templates. The templates do not have to be very large and detailed. For the experiments with the satellite mock-up of the Inveritas facility, small reference views of 30x30 pixels were used.

If the object shows further symmetries, the number of different attitudes can be further reduced.

Two of the three attitude angles can be represented as points on a unit sphere whereas the third attitude angle is a rotation around the direction given by the spherical point.

The initial search of the target attitude and position can now be performed by comparing all reference views of the model database with the small template generated from the most recent 3D-LIDAR point cloud.

The first criterion for comparison between templates is the size of the bounding boxes of the 3D point clouds. This trick allows pruning of the search space with dramatic consequences for the computational loads. If the current view has a larger bounding box than the one stored in the database, the two cannot be matching. If the sizes correspond to each other, a sum of squared differences cost function can be computed. If it shall be possible to work on partial views of the object, the bounding box of the current view can also be smaller than the one stored in the database. This is the most time consuming step and does not need only the computation of the sum of squared differences of two templates but also requires the computation of the correct offset, i.e. 2D correlation is needed. The views of the model database always contain complete views. In this case, the best correlation value (or the minimum of the sum of squared differences) is regarded as the result of the comparison between the two templates. Finally, the best matching result gives a rough estimate of the attitude of the object and thanks to the known offsets between the center of mass and the centroids for every reference view also the initial position can be obtained. The resolution of the viewing angles represented in the template database depends on the required accuracy that assures convergence of the ICP algorithm. For the experiments shown in the next paragraph, an angular step width of 10° was sufficient.

### 3.6 Experiments and Results

The flight system consisting of guidance and control and vision based navigation based on 3D-LIDAR measurements was implemented on the dSPACE real-time system in combination with a C/C++ implementation of the vision-based navigation hosted on a standard PC running a non-realtime OS. This setup enabled a closed-loop simulation of the close-range rendezvous phase including real 3D-LIDAR measurements and on-line vision-based navigation and the control of the chaser spacecraft based on a computed guidance and the navigation data. The following Figure **7** shows the results of the closed-loop experiments.

The three diagrams show the results of the position estimation. The blue line (marked as ideal) depicts the positions as computed by the guidance function and thus represents the ideal position. The red lines represent the state of the space-craft (i.e. positions) as estimated by the GNC system based on ideal measurements of a behavior model of the navigation. The estimated states of the GNC system based on real measurements of the vision-based navigation (VN) are depicted by the green lines.

It could be demonstrated that the implemented system was able to successfully perform the close-range rendezvous maneuver based on the real sensor measurements of the 3D-LIDAR although the results were significantly worse than predicted by an ideal sensor model. The errors of the VN system were in the order of several centimeters and the errors of the attitude angles (not shown here) were in the order of ~1° for roll and pitch angles and <5° for the yaw angle (with the z-axis being the bore-sight direction). However, the measurement results also include some inaccuracies of the test facility itself. It has been observed that the accuracy of the VN system and the ground-truth measurements of the facility were in the same order of magnitude. Increasing the ground-truth accuracy of the facility is therefore one of the future goals of the Inveritas team, as detailed in Section 4.

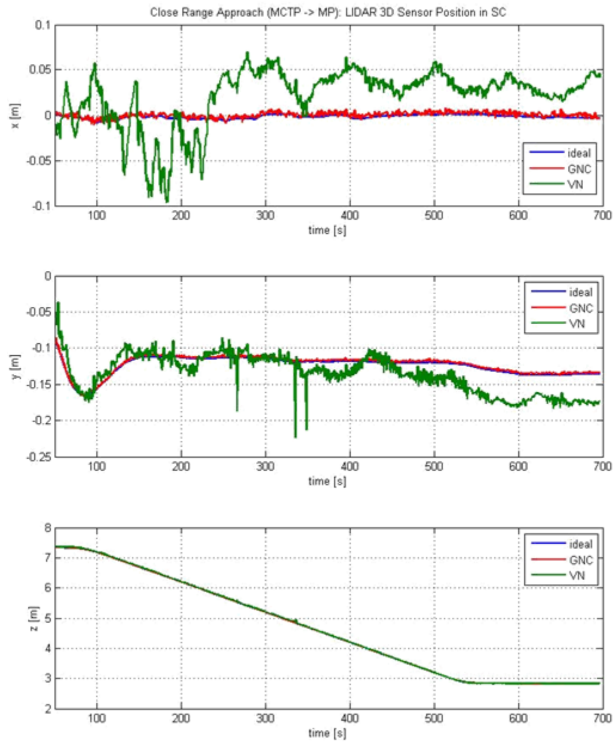


**Figure 7: Results of the closed-loop experiments for close-range rendezvous in the test-facility.**

## 4 Concepts for improving the HIL Simulator in the future

Although the performance of the HIL simulator was satisfactory for the Inveritas project, improvements to some aspects of the system would be very beneficial for future projects. Being able to use heavier mock-ups for the Client and the Servicer with realistic (probably heavier) materials is desirable. Some possible uses also need to simulate three objects in space. Being able to adapt the direction of the light sources during a simulation would also be an advantage. However, when measuring the performance of sensors and navigation algorithms, the accuracy of the mock-up and sensor positions should be around 1mm, so improving the accuracy is the most important goal for the future.

After researching the possibilities it was concluded that increasing the accuracy could best be achieved by using 6D laser trackers that directly track the positions and rotations of the mock-ups online, requiring one tracker per moved object. Control loops can then compensate possible inaccuracies so that the desired positions of all objects are reached precisely. This solution also has the potential to interfere less with other sensors than for example infrared marker based trackers.

An inverse setup has already successfully been tested where the Client is attached to the cable robot and the Servicer (only its Sensors) was attached to the KUKA arm. This allows heavier Client mock-ups, giving more freedom to the choice of materials.

Using an optimized position of the KUKA arm, up to two linear rails and up to two additional robotic arms would allow moving up to three objects and an online controllable light source on a pan-tilt unit on the cable robot as a fourth object. Moving three objects would be possible in the current facility, however moving four objects in a reasonable setup would need a bigger environment, which would also allow longer approach distances.

## 5 Conclusions

The HIL rendezvous simulator developed for the Inveritas project proved to be sufficient for closed-loop tests and has many possible uses for future projects due to the flexibility of the concept.

The experiments successfully demonstrated the close-range rendezvous based on real 3D-LIDAR measurements with a prototype of a scanning LIDAR. The obtained accuracy of the pose estimation was sufficient to enable a safe and accurate close-range-rendezvous between two space-crafts. This was mainly achieved by applying a quite robust version of the established ICP algorithm and by introducing a simple but highly effective pose-initialization technique called 3D-Template-Matching.

Future improvement especially concerns the development of the 3D-LIDAR by Jena-Optronik GmbH. The sensor used was not designed to meet the special requirements of the described experiments. Therefore, current developments of new LIDAR technology aim at improving the scan-speed and increasing the field of view and the sensitivity of the 3D-LIDAR such that more realistic materials of the target object can be used.

For the HIL simulator the accuracy especially of the cable robot was dramatically improved using offline calibration, but as stated in Section 4, the overall accuracy should still be improved in the future to go beyond stable closed-loop tests and also be able to measure the accuracy of sensors and algorithms in the future. Using more and heavier mock-ups is also a desirable goal for the future.

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