A VIRTUAL TESTBED FOR OPTICAL SENSORS IN ROBOTIC SPACE SYSTEMS – VITOS

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ABSTRACT

Virtual testbeds are used for the comprehensive development and testing of complex systems even before building the first hardware prototype. In this paper, we present a virtual testbed for optical sensors in robotic space systems. It comprises configurable simulation models for cameras and laser scanners, interfaces to real sensors, error models, environment models, and analysis tools. The simulation models are calibrated and validated using reference experiments executed in parallel in real and virtual test setups. From these test setups, we extrapolate to the application scenario of an orbital rendezvous with the full cycle of optical sensors, pose estimation, and dynamic spacecraft control. An analysis toolbox allows the engineer to explore the parameters of the system and answer critical design questions.

1. INTRODUCTION

Optical sensors are essential in almost every space application. With a growing degree of automation and autonomy, the requirements for an accurate and reliable environment perception with such sensors increases as well. The sensor data processing algorithms rely on the accuracy of the sensor data as they provide the foundation for an automated control or they integrate into closed loop systems for fully automated control. Those complex systems cannot be developed component-by-component, but require a comprehensive development approach, which considers the performance features of every component as well as their mutual interaction under varying constraints and applications. Therefore, the use of Virtual Testbeds (VTBs) is a good choice, because they rely on modern simulation-based methods providing an inevitable basis for cost-efficient solutions of many problem statements. This allows comprehensive virtual testing of products even before building a first prototype giving the opportunity for parallelized development of hardware and its utilizing software respectively. Thus, VTBs enable cost-efficient engineering over the entire product lifecycle of robotic aerospace systems in an arbitrary detail and for different application scenarios.

This paper presents the contribution of the ViTOS project by providing a Virtual Testbed for Optical Sensors to enhance the Testbed technology with simulation algorithms and new processes for the development of robotic aerospace systems in an overall "Virtual Space Robotics Testbed".

2. FLEXIBLE SETUP FOR FAR-RANGE REFERENCE TESTS

One of the main topics in ViTOS was the automated calibration of optical sensor systems. We achieve automated calibration by setting up situations equivalent in simulation and reality, which are used to deduce parameters of optical sensor systems by comparing the results. In the VTB we place the sensor under test, e.g. a space camera, into a virtual environment, where we produce motions as they are expected to occur in a real application. In parallel, we map these motions onto robots which hold the real sensors and objects. Utilizing this setup, we generate sensor data from real sensors that is equivalent to the data coming from the VTB.

Our setup consists of two KUKA lightweight robots (LWR). Each robot is mounted onto a mobile platform, which we place at a suitable distance apart from each other.

In order to examine several sensors, we equipped one robot with an electrical tool changer. The tool changer provides the sensor with supply voltage, Ethernet, and IO feed-through such that several sensors may be used without extra cables, usually causing constraints to the robots motion.

Onto the second robot, we mounted a small manual tool changer, such that heavier objects may be handled.

In Figure 1 one robot is shown holding a scaled model of the Pressurized Mating Adapter (PMA) from the International Space Station (ISS). We use this as a target for the examination of an orbital rendezvous with the full cycle of optical sensors, pose estimation, and dynamic spacecraft control.

Figure 1: Robots holding the target object and the examined sensor, here: Zoom camera prototype [1].
object for camera calibration during a simulated approach of the Automated Transfer Vehicle (ATV) to the ISS. During the approach to the ISS, even in the 1:8 scaled setup, the absolute translational motions of the objects far exceed the workspace of the robots. Therefore, we used both robots as a joined kinematic in order to produce correct relative motions between the objects. We map the translational motion of the ATV during the approach onto a rotation of the PMA. Simultaneously we compensate the rotation of the PMA by a rotation of the ATV. Utilizing the limited workspace of the LWR in this way, the ATV camera gets the same image from the PMA as expected over a wide range around the ISS, since PMA and ATV have the same relative position and orientation.

As sensor, the second robot in Figure 1 holds the zoom camera, which we calibrated using this setup. In the next section, we present the sensor and calibration results in detail.

3. VALIDATION OF SENSOR SIMULATION

The validation of simulated sensors against their physical counterparts is a challenging task. It begins with the identification and parameterization of physical effects and error models to alter the clean simulated sensor data according to the real sensor hardware. Particularly for optical sensors, the environment simulation and visualization affect the sensor data almost to the same extent as the simulation of the sensor hardware itself. Thus, all involved simulation components have to be validated again in their entire integration. In doing so, the utilization of the resulting sensor data has to be kept in main focus.

Therefore, the flexible setup for reference tests introduced before was used to validate the camera simulation in a virtual rendezvous and docking maneuver (Figure 2), as this is the main application for the respective physical camera. As simulation scenario the approach of a transport vehicle (in this case, we used a simulated ATV model) to the PMA module of the ISS was chosen. The performed trajectory was a vertical oscillating movement around the direct approach path.

For the physical mockup, the flexible setup for reference tests, mainly comprising the physical camera, a scaled model of the PMA module and two lightweight robots, were used. The first robot (target) carried the 1:8 scaled model of the PMA module, while the second robot (chaser) was equipped with the prototype of a zoom camera system [1] provided by project partner Jena-Optronik. The individual mobile platforms on which the two robots are mounted allow for arbitrary large displacements, resulting in highly flexible mockups. To benefit from this variability, the rendezvous-scenario was carried out in a long hallway instead of a spatially limited laboratory. To achieve controllable lighting conditions, the entrance and exit of the hallway were shaded using curtains, and a well-positioned spotlight was used as only light source. In Figure 3, the physical mockup (top) and the according virtual testbed (bottom) are depicted.

The necessity of the second robot (target) arises from the circumstance that the movement of the camera is decisively limited due to the small work space of the chaser robot, as described above.

The focus of the scenario mockup was the calibration of the simulated camera sensor according to the sensor data of the physical camera prototype with regard to the image processing algorithms; i.e. the simulated camera is supposed to generate image data, resulting in

![physical mockup](image1.png)

**Figure 2:** Virtual rendezvous scenario of a transport vehicle (front) and the PMA module of the ISS (background).

![Virtual Testbed](image2.png)

**Figure 3:** Physical mockup and Virtual Testbed of the rendezvous scenario.
comparable results in the image processing algorithms used for movement reconstruction during the approach. Figure 4 shows one of the resulting images during the test scenario from the simulated camera (top row) as well as the physical prototype (bottom row). Independent from minor visible differences between simulated and real sensor data, the feature detection and tracking algorithms used to reconstruct the movement of the target according to the chaser, result in exceedingly similar results, as shown in the right side column of Figure 4.

The feature tracking between two consecutive camera shots was respectively used for movement reconstruction using a standard visual odometry approach, as described in [2]. The trajectory was mainly a vertical pendulum motion of the PMA module relative to the camera reference system. The resulting movement reconstruction is depicted in Figure 5 over time. The yellow line describes the vertical movement reconstructed from the simulated sensor data, while the purple line shows the reconstruction based on the real camera data. As can be seen, the reconstruction shows similar behavior with both input data sources.

4. HARDWARE SETUPS AND RELATIVE MOTION TRACKING

Two hardware setups, comprising two KUKA LWRs each, were developed during the project to provide a platform that allows for direct comparison of simulated and physically sampled sensor data. The concept of simulation-based control is used as a basis for both robot work cells to track the relative poses between two objects. The goal is to integrate digital twins of the physical robots in the simulated environment. This allows direct control of these actuators from inside the applications to be inspected in the corresponding Virtual Testbeds.

The first setup was used to track the relative pose in the scenario of an ATV approaching the ISS (see Figure 2) during the high to medium distance phases of the docking maneuver on a pre-planned trajectory.

The design goals of the second setup aim at replicating the close-range phase of a rendezvous and docking maneuver (see Figure 6). In this case, the scenario of a servicing satellite autonomously approaching an uncooperative target was chosen. Instead of a camera, a 3D laser scanner was employed to detect retro-reflecting material mounted on the target (Figure 7). The detection results were fused into pose estimates and fed into a closed control loop reducing the distance between the servicer and target satellites.
A gamepad provided for user input to control the position of a ghost satellite in simulation (see blue model in Figure 8) helps the user for demonstration purposes. The LWRs replicate a controlled approach between the target Galileo OHB model (solid) and the sensor to track the relative pose defined by the user controlled ghost model.

The path planning method for the approach between target and chaser is based on a PID control mechanism and provides a sampled trajectory for both robots. This induces the need for pose measurements of the target in the robot cell. For testing purposes, these measurements were derived from the current robot position resulting in precise values for the current position and orientation. Since the focus of this experiment was the validation of the sensor simulation the pose estimation algorithm depicted in Figure 9 was used to calculate pose estimates from the sensor data acquired by the Velodyne VLP-16 laser scanner.

The retro reflecting material on the satellite model (see Figure 10: Retro reflecting material on the Galileo OHB model.) allows for the utilization of intensity filters in concordance with minimum and maximum distance filters to reduce the amount of data points in the 3D point cloud to be examined (see Figure 9) [7]. In this scheme, the laser scanner generates a set of points \( P \) that is gradually reduced to a set of points \( P_f \). This reduced view of the model can then be used to calculate candidate poses \( P_{obj} \) for the target satellite model (see Figure 11). An additional outlier rejection (e.g. median filter) results in stable estimates applicable to difference calculations for the PID position controller.

Like the case of the flexible setup described in Section 2, an approach of simulation-based control performs actuation of the robots in the work cells. Digital twins of the hardware setups simulate the behavior of the physical counterpart to test the motion tracking and path planning methods. In addition, the physical work cells are directly coupled with the simulation and enable immediate control of the actuators [6]. Thus, combined data acquisition for the validation and verification purposes is possible. This concept is applied to this second hardware setup as shown in Figure 12. It consists of two real time parts (yellow and red) necessary to generate the control output for both robots. The yellow components apply calculations solely for the actuation of both LWRs. The red component implements the controller for the path planning and trajectory sampling for the VLP-16 and Galileo OHB motion. In addition to that, a non-realtime part (green) represents the user interface, allowing user input via gamepad and a visualization to review the current robot and sensor states in the simulated environment.

![Figure 8: Position of ghost satellite (blue) defines target position for actuated Galileo OHB model.](image)

![Figure 9: Estimation of the target pose based on laser scanner data.](image)

![Figure 10: Retro reflecting material on the Galileo OHB model.](image)

![Figure 11: Reduced number of data points observable at the retro reflectors.](image)
5. VIRTUAL DOCKING MISSION

Once we have calibrated the real camera and 3D laser scanner by reference experiments introduced above, we can send their digital twins on various virtual missions. One of the covered applications was the automated docking scenario of ATV on ISS depicted in Figure 13.

For this purpose, a simulated 3D laser scanner with a Lissajous scan pattern and a simulated space camera with three different zoom levels are mounted on the virtual ATV scanning the ISS. During approach, the simulated sensor data of both sensors and further status information of the control loop can be visualized as depicted in Figure 14.

Here, the simulated laser data, visualized as 3D point cloud with color-coded intensity information, clearly shows the position of three retro reflectors (located around the docking port of the ISS) caused by their conspicuously high reflected intensities (white points). This position information is used as input for the data processing system controlling the ATV during the automated approach. To allow for those closed loop scenarios, the whole control loop consisting of 3D laser scanner, laser data accumulator, docking port detection, corridor controller, and thruster system are modeled and simulated in a dynamic space environment (see Figure 15).

By following this holistic approach, all configurations and combinations of system components and environmental influences can be efficiently tested and analyzed to achieve a maximum of robustness and safety. In contrast, real laboratory setups representing such complex scenarios would not even be realizable on earth.

6. ACQUISITION AND ANALYSIS OF SIMULATION RESULTS

Gathering and analyzing data from simulation runs was highly automated using an SQL-based database backend, developed within this project. All state variables of the simulation models, including e.g. sensor data, geometry poses, or joint positions from dynamic multi-body simulation, can be logged with timestamps. In order to get access to the complete simulation state at any time, the Versatile Simulation Database (VSD) was used as central in-memory data store by the simulation system [3]. The VSD is able to notify the logging subsystem whenever a model property (i.e. element of simulation state) changes. The serialized property values are then propagated and logged via callback-events. For more details about our structured data logging method, including the DB schema, see [4].

Simulating the virtual experiments was done by utilizing multi-dimensional parametric sweeps. Any properties or initial state values of all simulation models can be marked as parameters. For each parameter, a numeric range, list of custom values or a statistical distribution can be assigned. We mostly used linear ranges though, as they are intuitively understandable during analysis and visualization. For each desired combination of parameter values, a separate simulation
job is executed. This way, millions of events were recorded and written to SQLite database for each experiment.

For analysis, relevant simulation results are extracted from the database via SQL queries to common data analysis environments such as Python or MATLAB. Analysis components developed to support decision-making in system design and configuration can be reused for different datasets. For more details, see [4] again.

We present a detailed analysis of the virtual docking mission shown in Figure 16 as example of our workflow. As described, during the ATV’s approach towards the ISS, laser scanner data are evaluated to detect retro reflectors mounted on the ISS for pose estimation and corridor control. The simulated 3D laser scanners used in such missions usually contain a mirror to deflect the laser beam, which is rotated around two axes using different possible patterns. The azimuth and elevation frequency of the scan pattern have a great influence on the sensor’s measurements. Depending on the quality of the generated 3D point cloud, detection of the retro reflectors might succeed more frequently. That is why, here we focus on a decision support system which helps to choose the best laser scanner pattern.

We ran 100 simulations, where azimuth frequency was varied from 0.27 to 1.81 Hz and elevation frequency from 35 to 143 Hz, with 10 steps each. The full sweep of 80 seconds simulation time took about 20 hours wall time on a modern 3D workstation, yielding a 1.4 GB sized database containing millions of logged events. For all simulation jobs, i.e. for all parameter tuples of the sweep, we generated the following analytic plots, which are interactively explorable along the given parameter space; the mentioned distances and orientations are relative between ATV and ISS:

A. Estimated distance vs. ground truth over time
B. Errors in distance estimation over time
C. Distribution of errors in distance estimation as histogram
D. Errors in orientation estimation over time
E. Distribution of errors in orientation estimation as histogram
F. Combined distribution of errors in distance and orientation estimation as bivariate histogram
G. Distribution of estimated docking port poses as 3D point cloud
H. Laser scanner hit points on retro reflectors as 3D point cloud over time
I. Number of detected retro reflectors over time

An example for plot-type A is shown in Figure 16. The

Figure 16: Example for plot-type A: Estimated distance between ATV and ISS vs. ground truth for one simulation run.

Figure 17: Example for plot-type F: Distribution of errors in distance and orientation estimations for one simulation run.

Figure 18: Example for plot-type H: Laser scanner hits on the three reflectors (in x-y-plane) over time (z-axis). “Good” scan pattern with many hits.
stairs-shaped trend in distance estimates can be explained with the relatively low azimuth frequency. In the time it takes for a full scanner sweep of the ISS, the ATV moves closer and the measurements quickly become stale. The yellow sections indicate periods where not all three reflectors were detected.

In Figure 17, the error distributions for both distance and orientation estimation are shown for one particular scan pattern. The distributions are highly dependent on the parameters, so the visualization and analysis tool to explore the parameter space interactively, which was developed during the project, is of great use.

To understand the varying error characteristics, we present two examples of plot-type H in Figure 18 and Figure 19. The former one shows a quite evenly distribution of hits on the reflectors over time, which indicates the laser scanner patter was configured “well enough” to provide the docking port pose estimation algorithm with data about all three retro reflectors at all times. In Figure 19 however, we see a degenerate configuration. The zig-zag-pattern is produced by the laser ray sweeping across the reflectors surfaces, which sometimes skips a whole reflector at a time and hence causes a failed detection. This behavior in turn significantly deteriorates the quality of the pose estimation results.

We finalize this short presentation of our analysis by a summary plot shown in Figure 20. It clearly indicates that the quality landscape of the parameter space is not trivially predictable. Other summary plots for RMS of distance error or accumulated visibility of retro reflectors are not shown here, but are integrated with all other plot types into our decision support system. Engineers now have a powerful tool at their hands to design the laser scanner pattern according to their mission’s requirements.

7. SUMMARY, CONCLUSION AND FUTURE WORK

In the course of the work presented here, we developed configurable simulation models for cameras and laser scanners and created an infrastructure for parameter identification, calibration and validation of these models. To this end, we constructed a flexible setup where sensor and target can be mounted on KUKA robots on mobile platforms to allow for a wide range of relative motions. With this infrastructure, we executed reference experiments in reality and simulation in parallel and extrapolated the results to comprehensive mission simulations with closed control loop in the virtual testbed. We complemented the virtual testbed with a data acquisition and analysis toolbox that executes parameter sweeps in the simulation, thus exploring multidimensional parameter spaces, and provides the simulation results in an interactive form. With this virtual testbed, the engineer can answer difficult design questions as demonstrated with the choice of azimuth and elevation frequency of the laser scanner pattern.

Currently, we are working to improve the performance of the laser scanner simulation with raytracing algorithms to increase the efficiency of parameter sweeps and even use the testbed as input source for a real time data processing unit in HiL-setups. Another goal is the use of optimization algorithms to optimize parameters of the system under study w.r.t freely defined quality functions.

Figure 19: Example for plot-type F: Same axes as in Figure 18, but showing a “bad” scan pattern with degenerated results. Yellow circles mark hits on less than three reflectors at a time.

Figure 20: RMS of the orientation error for each simulation run of the parameter space.
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9. REFERENCES


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