GNC 2014: 9th International ESA Conference on Guidance, Navigation & Control Systems
Porto, Portugal | 2 - 6 June 2014
European Space Agency

ON-GROUND TESTING OPTICAL NAVIGATION SYSTEMS FOR EXPLORATION MISSIONS

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ABSTRACT

In response to a growing demand for the test of optical navigation sensors and systems the Institute of Space Systems of the German Aerospace Center (DLR) has developed in the last years the Testbed for Robotic Optical Navigation (TRON). This facility is a special simulator to create realistic scenes which would be encountered by optical sensors during exploration missions. TRON has been applied for breadboard tests of the absolute optical navigation method for ESA's Lunar Lander mission, the EU project Small Integrated Navigator for PLanetary EXploration (SINPLEX) - an integrated miniaturized navigation system [13], and the EU project Flash Optical Sensor for Terrain Relative Navigation (FOSTERNAV) - a flash lidar breadboard [1]. The main elements of the facility are 3D terrain models of celestial bodies and two robots to position the sensor (camera) and a light simulating the sun. Since the tests are carried out with downscaled models special care has to be taken to ensure the accuracy of the ground truth in order to provide a representative test environment. This applies to the manufacturing and verification of the 3D models as well as to the positioning accuracy of the sensor with respect to the target models. Recently DLR also invested in the development of a TRON-complementary test bench offering the possibility of high-speed and long-range tests. The Test Environment for Navigation Systems On airfield Runway (TENSOR) facility was used for testing of the flash lidar developed in the frame of the FOSTERNAV project. This paper shows the layout and operation of the TRON test facility and also gives an introduction to TENSOR. Methods and measures taken to ensure a high accuracy of the ground truth data are presented and discussed.

1. INTRODUCTION

Future space exploration missions envisage precise and safe landing on planetary bodies as well as the performance of rendezvous and docking maneuvers. Such missions will be performed at distances reaching from Earth and Moon out to several astronomical units for targets like Mars or asteroids. For ensuring goals like a precise landing high precision navigation data as well as real-time operation of the spacecraft are required. This stands in contrast to the state-of-the-art of ground-controlled mission operation. Examples for the problems induced by this concept are a decreasing navigation precision with growing distance, latencies due to the signal propagation time and a potential line of sight blocking by the sun or the target body itself. In such cases ground controlled mission operation is not sufficient for achieving future exploration mission goals. An approach for solving this conflict is introducing an autonomous operation of the spacecraft and utilizing the target body as a navigation reference. Among the technologies necessary for autonomous operation is an on-board guidance, navigation and control (GNC) system combining traditional sensors such as an inertial measurement unit (IMU) with novel optical sensors and autonomous data processing.

Due to their promising performance optical navigation systems applicable to exploration missions are in focus of many development projects. These are e.g. efforts for maturing sensor technologies such as scanning lidars [3], flash lidars [1, 15, 16] and cameras [2] and for applying these sensors in optical navigation systems of space exploration missions [4, 11]. The final goal of such developments is a space qualified technology, allowing autonomous operation in the targeted environment. Therefore extensive testing is necessary for achieving an appropriate grade of reliability for an increasing number of candidate optical navigation technologies.

With increasing maturity of the technology the setup for testing requires an increasing complexity, concluding in true scale tests, e.g. on ground [12], on a helicopter [5, 10], or on a sounding rocket [6, 14]. Testing, especially airborne and in true-scale requires a significant amount of resources. Therefore DLR has developed TRON and is developing TENSOR - two complementary test sites - with the motivation of contributing to a path to maturity which allows relying to on-ground testing as long as possible.

2. TESTING APPROACHES FOR OPTICAL NAVIGATION SENSORS AND SYSTEMS

Optical sensors for autonomous navigation for exploration missions can be active like scanning or imaging LIDARS or passive like navigation cameras. Often these sensors are combined with others into navigation systems providing an integrated navigation solution. For all these different versions of navigation sensors and systems for exploration missions the issue exists how their function and performance can be tested and verified on-ground before the launch of the mission. When on-ground testing is considered, many trade-offs have to be made. A major one is between realism and cost. Simulating even parts of the dimensions and dynamics of exploration mission profiles is costly or might not even be possible on Earth. Therefore some sort of scale factor will have to be introduced whenever possible. Another way might be looking at very small, but relevant true-scale sections of a mission.

With respect to that it is appropriate distinguishing between 2D and 3D optical sensors and the integrated navigation systems. A quick look at these three groups tells that all have their specific properties which constrain on-ground testing and verification. The following sections will discuss the peculiarities of the three groups and how representative test setups can be achieved.

2D Cameras take images of target body scenes which are then processed to generate navigation information. A scene is considered to be an illuminated terrain or object. During the real mission a camera is focused on a long distance. The depth of field covers most of the distance at which the objects (e.g. planet surface) will be seen by the camera. In a scaled scene the camera must be focused to a shorter distance where blurring effects might be stronger than in a true-scale environment. Thus the optical setup for the flight cannot be tested in a downscaled scene. But the good news is that apart from focus related effects a 2D camera is not significantly sensitive to scaling. Therefore considering a sharp image which has been taken from a perfectly lighted and modeled downscaled scene, the subsequent image processing techniques will not experience a difference with respect to an image of the true-scale scenario.

Many image processing techniques exploit specific features of the scenes which are based on an illuminated 3D terrain, such as craters or hazards. One possible conclusion from that is creating a scene with scaled 3D landscape models and applying a sun-like lighting. Thus different lighting conditions could be tested and real shadows would be generated avoiding the usual problem of shadows in image rendering techniques. A step further to realism introduced by sun-like lighting is a high dynamic lighting range which cannot be generated by screens or projectors. Of course minor effects remain such as only non-parallel lighting can be achieved or the impossibility to prevent all stray or ambient light due to reflection of other surfaces in a closed area like a lab.

Besides the camera imaging also other aspects of the test environment are affected by the scaling:

- Resolution of object: If a high accuracy in the object's topography is needed, with increasing scale factor the manufacturing accuracy of the scene becomes more and more the driver. E.g. if a scene is scaled by 1:100000 then one millimeter in the test setup corresponds to 100 meters in the real environment.
- Positioning accuracy of sensor: In the same way the scene is scaled also the motion of the sensor within the environment needs to be scaled. When the sensor shall assume a real world position with an accuracy of 100 m, then it must be positioned with a an accuracy of 1 mm in the lab at a scaling of 1:100000.
- Ground truth accuracy: In order to verify a sensor to a certain accuracy the reference measurement should be about one order of magnitude more accurate. For example if a navigation camera shall be tested to an accuracy of 100 meters then a ground truth accuracy of 0.1 millimeter is needed at a scaling of 1:100000.

The analysis above implies that a scene intended for testing 2D cameras can be build much smaller than the expected environment during the mission - as long as the mentioned issues can be overcome, e.g. with precise terrain model manufacturing and precise positioning systems. Therefore the potential is there for trying to get near to such perfect conditions by investing into creating scenes for testing and verification by using scaled 3D terrain models, a sun-like lighting source and actuators capable for positioning the sensor within this scene.

3D sensors provide complete 3D information of the measured surface in the form of points or point clouds. Such sensors could be scanning or imaging LIDARs, or stereo cameras. For this type of sensors a scaling of the scene would affect the measurements significantly especially the distance between object and sensor. If these kind of sensors are operated in a scaled scene, the following effects can be seen:

- Unscaled distance: The distance measured by the sensors is not scaled due to the measurement principle. Although a correction of the measurements with the inverse scaling factor is possible the noise on the measurements would be also scaled. Thus after surpassing a certain scale factor, which is dependent on the magnitude of the noise, the measurement will be useless.
- Unscaled baseline: For stereo cameras the baseline length in relation to the distance to the objects determines the depth resolution. If the scene is scaled then also the baseline length needs to be scaled. For small scales and long baselines it would be possible, a hardware change might be needed. For larger scales it becomes impossible due to the fact the the baseline length between the cameras becomes much smaller than the physical size of the single cameras.

The conclusion is that an operational testing within a realistic and downscaled scene is not very useful for verification. However, a defined lab environment can still be exploited for a characterization of 3D sensors. For that purpose the target for measurements can be made of primitives with a depth variation higher than a scaled scene and higher than the distance measurement noise of the tested sensor. An example for such a target is shown in figure 6. With this kind of setup a sensor characterization can be performed which determines e.g. resolution, noise as well as distance and velocity dependencies.

Integrated navigation systems combine optical sensors with other sensors e.g. inertial sensors. An exemplary integrated optical navigation contains an IMU, a camera, a star tracker and an altimeter or LIDAR. With this combination all the limitations for testing are also combined. Consequently, an integrated system as described above can be fully tested only in true-scale. The measurements of gyros and accelerometers will be according to the motion in the lab. An emulation of a flight in space or a landing on a celestial body is not possible unless the IMU sensor hardware is replaced by a simulated sensor package. In this way at least a part of the integrated navigation system could be tested. The conclusion is that integrated navigation systems can be tested on-ground:

- By stimulating only one sensor type at a time and emulating the other sensors measurements. E.g. when testing the camera part, down-scaled flights on trajectories according to the mission can be tested.
- By navigating in the terrestrial environment. This means that the gravity field model of the navigation filter must be adapted to the Earth gravity model for testing. In this way the whole navigation system can be tested and all sensors can be stimulated. Of course the resulting navigation accuracy must be translated to the mission scenario.

3. TRON - TESTBED FOR ROBOTIC OPTICAL NAVIGATION

There are many on-going developments which aim to apply optical navigation techniques during landing for different kinds of missions. The main goal of TRON is supporting the development of optical navigation technology, and to qualify hardware and software to TRL of up to 6. To test a substantial part of these targeted technologies a representative simulation environment for the phases of landing on bodies similar to the Moon and on Asteroids is required. These considerations led to the design decision of providing a hardware-in-the-loop testbed which simulates the mission dynamics via a robot system, the terrain geometry via scaled 3D terrain models and the optical environment via a black out system, an anti-reflection system and a lighting system. An overview of the concept, layout and first implementation is given in [7]. This section will shortly summarize facts from that publication and mainly focus on the update to the current state of implementation, which is illustrated in figure 1.

A. CONCEPT AND LAYOUT

TRON has the following dimensions: 15 m in length, 5.10 m in width and 3.00 m in height. The lab is divided in two main sections - the operators section and the simulations section (see figure 1). Dividing the lab allows an isolation of the simulation area, for excluding any external light sources, but also to prevent any dangerous radiation, such as laser radiation, to leave the lab. Another important reason is ensuring safety of the operator during dynamic simulations.

The operators section serves as the control center, containing all elements necessary for controlling and observing a simulation, assuring safety and managing data. The operators section is separated from the simulations section by a wall integrating a wide window. For further visual inspection, e.g. in case of closed curtains, a surveillance camera offers an overview of the simulations section. The key elements of operators section are:

- dSPACE real-time simulation and controlling system
- Host-PC for managing the real-time system and other hardware
- Manual controls for robot and gantry
- Safety-system interfaces

The simulations section contains the elements necessary for realizing the simulation and for ensuring safety:

- 7-degree of freedom (DOF) robot system providing all interfaces to the candidate sensor
- 2-DOF motorized spot light lamp
- 3-DOF gantry for moving the spot light within the lab
- 3 terrain models
- EROS asteroid model
- Plane target equipped with primitives
- laser metrology equipment
- anti-reflection system
- black-out system
- laser safety curtains for lasers up to class 4
- surveillance camera

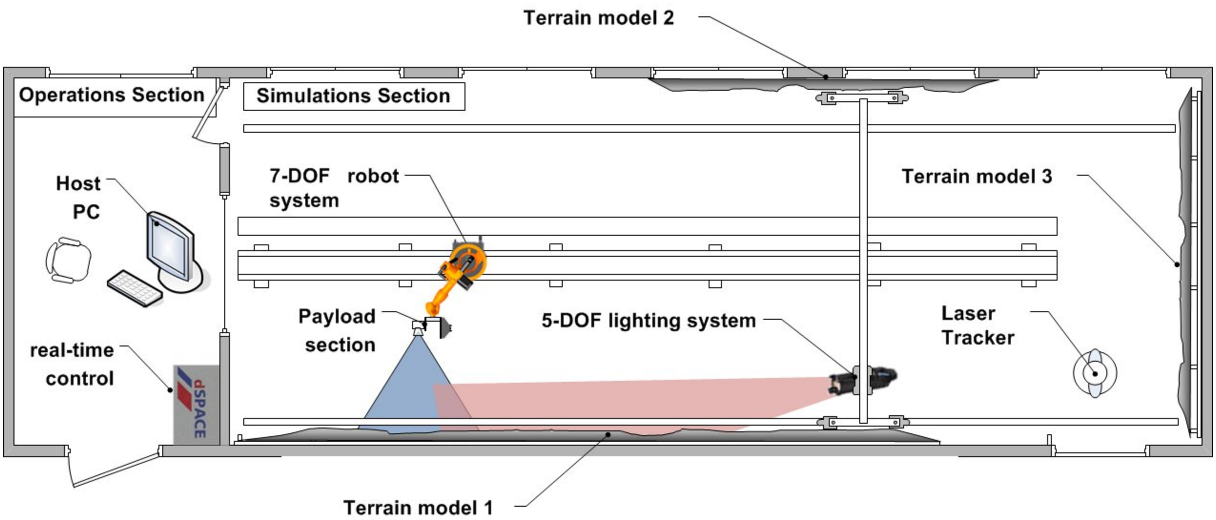


***Fig. 1:** Layout of TRON facility*

B. DESCRIPTION OF LAB ELEMENTS

Dynamics The simulation of the dynamics is realized via a 7-DOF system comprising a 6-DOF KUKA KR 16 industrial robot on a linear rail which points along the long axis of the room. The payload of the robot's hand, the tool center point (TCP), is 16 kg. The static repeatability of the robot is ± 0.1 mm, the maximum TCP traverse velocity is 1.47 m/s. The robot is controlled either manually, or by programs written in a robot script language or by the dSPACE real-time system. The dSPACE system can also be used for potential real world simulations of the spacecraft. Per default the sensor to be qualified will be installed at the robots tool center point (TCP). Should the candidate technology exceed the payload mass of the TCP, the robot's arm and base allow placing additional mass for a total payload of 40 kg. This approach of distributing the payload was successfully performed for the flash lidar prototype of the FOSTERNAV project.

Terrain models During the design process it has been found suitable installing 3D terrain models at three walls of the room for simulating relevant parts of a typical mission profile of a full lunar landing trajectory. Furthermore it was planned illuminating the 3D models with a suitable lighting system for achieving high quality shadows in real time. This approach was successfully realized during the execution of two test campaigns, the testing of the absolute navigation camera of the European Space Agency (ESA) Lunar Lander Phase B1 study and the optical navigation camera for an autonomous, safe and precise lunar landing software developed within the DLR's ATON project (Autonomous Terrain-based Optical Navigation). Three terrain models had been designed, manufactured and installed and will be explained in the following.

Terrain model 1 (following numbering scheme in figure 1) is installed at the long windowless side of the simulations section. It measures 9.80 m x 1.96 m. The terrain dynamics, being the range between the lowest and the highest part, is about 6.2 cm. The model has been milled to an accuracy of 1 mm. Its reference data was software generated for being representative for the lunar surface. Due to the self-similarity of the crater size distribution and its definition in the cross-range, down-range, altitude system it can represent a lunar surface at different scales. As an exemplary use case the robot's TCP could be moved along the entire terrain model placed at wall 1, with a variable distance between approximately 0.2 m and 3 m. Considering terrain model 1 at a scale of 1:10000, the spacecraft (SC) position could be simulated over a downrange distance of 100 km and altitudes between 2 km and 30 km. Consequently this model served as the terrain model for the breadboard tests of the ESA Lunar Lander project and is currently used for the Autonomous Terrain based Optical Navigation (ATON) project. These two projects used scales between 1:10000 and 1:50000 for the simulation of the Descent Orbit (DO) phase and also the Powered Descent (PD) phase of a lunar landing.

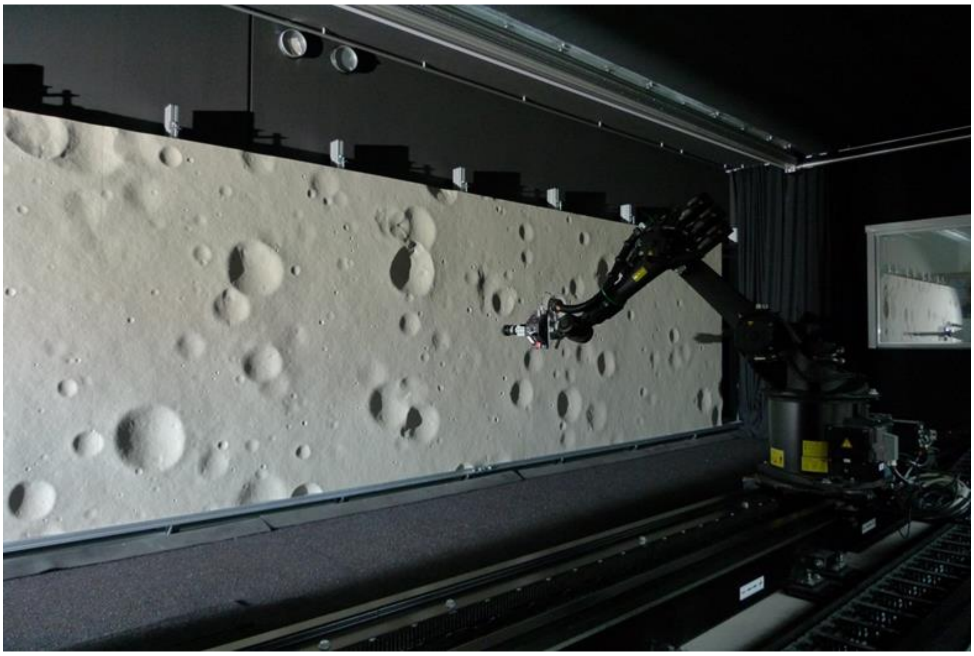


Fig. 2: *Photo of terrain model 1*

Terrain model 2 has been installed opposite to the first model (see figure 1). The model has the size of 3.92 m by 1.96 m and represents a part of the Moon in a scale of 1:125000 (see figure 3). The terrain dynamics is about 20 cm. The model has been milled to an accuracy of 1 mm. The model reference data have been derived from Kaguya 3D data. Using this model high altitude orbits like the parking orbit as well as the first part of the DO can be simulated. In contrast to terrain model 1 this one is truly Cartesian, therefore including the natural curvature of the terrain on the spherical lunar surface. It is used for simulating parts of the DO within the ATON project, but also for DLR's research efforts in the field of landmark based absolute optical navigation [9].

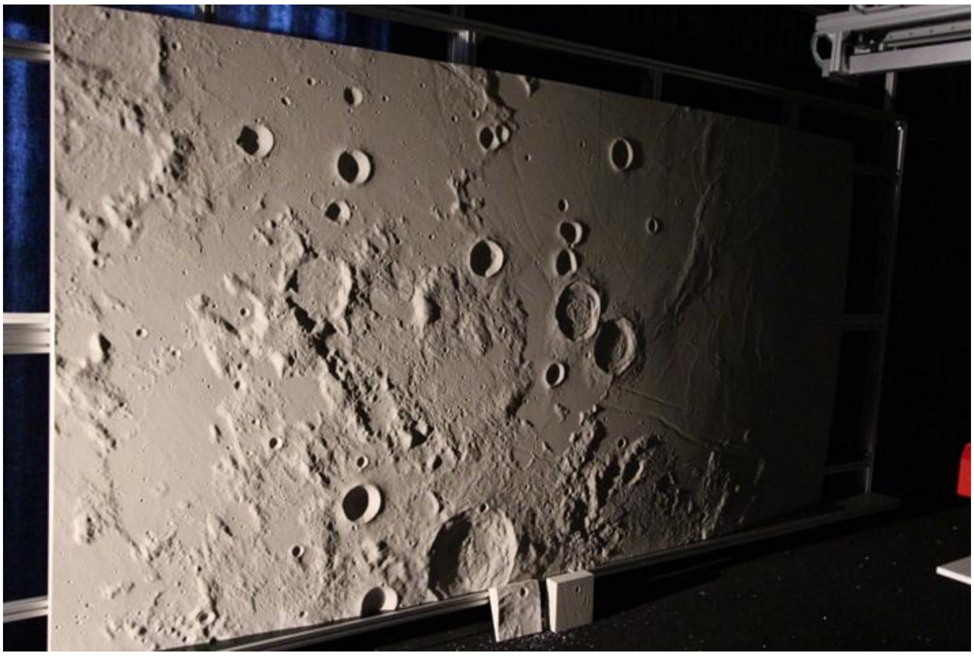


Fig. 3: *Photo of terrain model 2 (1:125000 scale model of the Moon created from Kaguya 3D data)*

Terrain model 3 is installed at the front wall of TRON. Its size is about 4,20 m x 2,20 m, the terrain dynamics is about 26 cm. The model reference data was obtained entirely by DLR via a process beginning with hand-modeling and ending at 3D scanning and post-processing as described in [8]. The model was then manufactured in two steps. At first a coarse milling step obtained the rough terrain structure. Afterwards a finishing surface layer was applied manually. Due to the hand-made finishing no manufacture marks such as milling lines are visible, leaving the model with a practically infinite resolution. Again the self-similarity of the model and the Moon can be exploited by applying a different scale to this model. This landing site model is not only representative for the lunar surface but also for many asteroid surfaces. It is predestined for using it for the simulation of the last phase of the landing. In this way the terrain relative navigation with respect to the landing site and the evaluation for safe areas can be tested hardware-in-the-loop. Combining this model with low scale factors makes it a useful sensor target for 3D imaging sensors. For the ATON project the model is considered having a scale factor of 1:100.

The TCP can be moved from a distance of 11 m to a distance of 1 m to terrain model 3, and in the same time with a radius of $\approx$1 m perpendicular to the rail. In this way for ATON an approach from an altitude of 1100 m down to 100 m can be realized. During its approach the SC, i.e. the sensor system, can make 200 m of lateral movements. With different scales applied the simulated vertical and lateral movements could be adapted according to the project needs. A trade-off might have to be performed between the necessary lateral movement and the acceptable errors for the individual instrument.

Other sensor targets In addition to the wall model two more sensor targets are available in TRON. The first is a 3D model of the asteroid 433 Eros (see figure 5). The asteroid possesses an oval-like shape with the dimensions of about 1.0 m x 0.3 m x 0.3 m. The model is a 3D print in scale 1:34000. It is mounted on an axis which allows rotating the asteroid to specific angles and with specific angular velocities. This model was manufactured for the SINPLEX project.

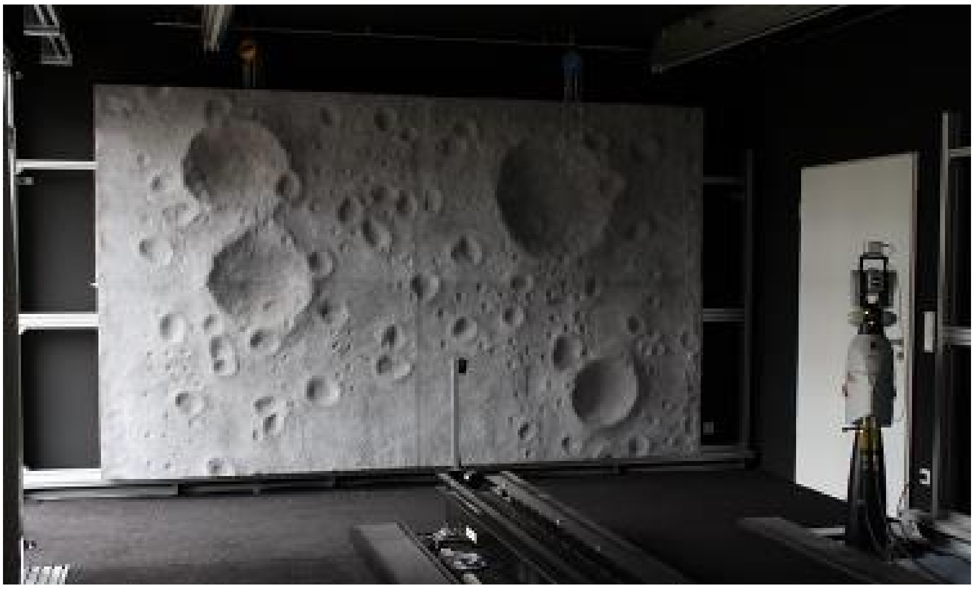


Fig. 4: *Photo of terrain model 3*

Fig. 5: *Image of asteroid model (433 EROS at scale 1:34000)*

The second available model is comprised by two flat panels sizing together at 2.0 m x 3.0 m. Several primitive bodies are installed optionally on the panels (see figure 6). This target was used for the characterization of the flash lidar in the FOSTERNAV project.

Optical environment The optical environment is simulated via the utilization of a black out system, an anti-reflection system and a lighting system. The black-out system comprises moving curtains, which can close all windows of the simulations section for excluding any light coming from outside the lab. The goal of the anti-reflection system is avoiding secondary or ambient lighting originating from internal light sources. Therefore all walls are painted black and covered with black curtains, the ceiling is painted black. The floor is covered with black carpet.

The lighting system comprises a 3-DOF gantry with the light source installed on it. The light source is the zoom profile spotlight ADB WARP, using the Hydrargyrum medium-arc iodide (HMI) technique to achieve an efficient light production out of its 575 W electrical power. The lamp is optimized for uniform lighting, the color temperature is 6000 K. The lamp can be rotated about 2 axis, also various other paraneters such as zoom, the

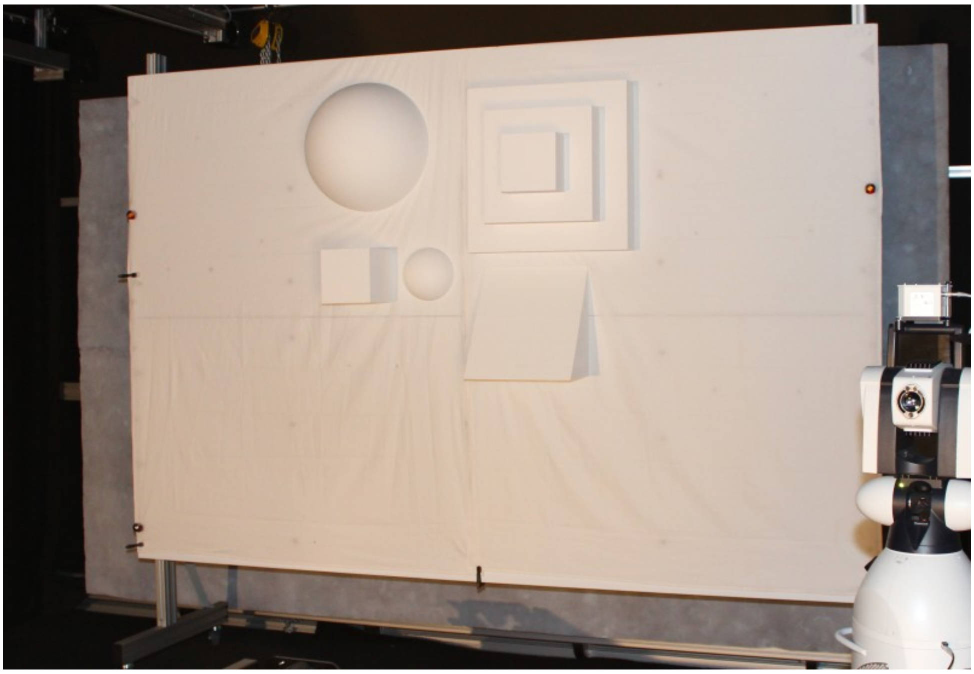


Fig. 6: *Photo of the flat plane with installed primitives (hemisphere 50 cm diameter, pyramid 60 cm quadratic lower base*

focus, gobos or the mechanical dimmer can be dynamically changed. In combination with the gantry the 5-DOF system provides variable solar irradiation angles within the whole simulation section.

TRON possesses a flexible design, which allows adjusting the terrain models or installing various lighting options. This way different environments for a variety of missions such as Moon, Mars and asteroids can be provided. For testing the sensor is installed on the robot for acquiring defined positions in the provided environment. The sensor may also be installed on the gantry system or in any other kind of position inside the simulations section to allow operations like camera calibration.

4. TENSOR - TEST ENVIRONMENT FOR NAVIGATION SYSTEM ON AIRFIELD RUNWAY

As discussed in section 2 for 3D sensors and integrated navigation systems unscaled trajectories are needed. Thus a test in a confined lab is not possible anymore. Large distances can be achieved outside buildings either with ground vehicles or flying vehicles. Test Environment for Navigation System On airfield Runway (TENSOR) provides this complementary long range outdoor testing environment. In contrast to TRON described in section 3, this facility offers not only longer range but also higher speed.

A. CONCEPT AND LAYOUT

As the name of TENSOR says it is a test environment which can be deployed on a an airfield runway. The dimensions are mainly limited by the available area and the size of the airfield. Figure 7 shows the concept of TENSOR. The device under test is mounted on a car which moves towards a target. Using this approach larger distances and higher velocities can be achieved.

The TENSOR test setup has two main parts: a moving part carrying the device under test and stationary elements including the target. In detail there are the following elements:

- Moving part:
  - Test vehicle (car)
  - Roof rack
  - Power supply

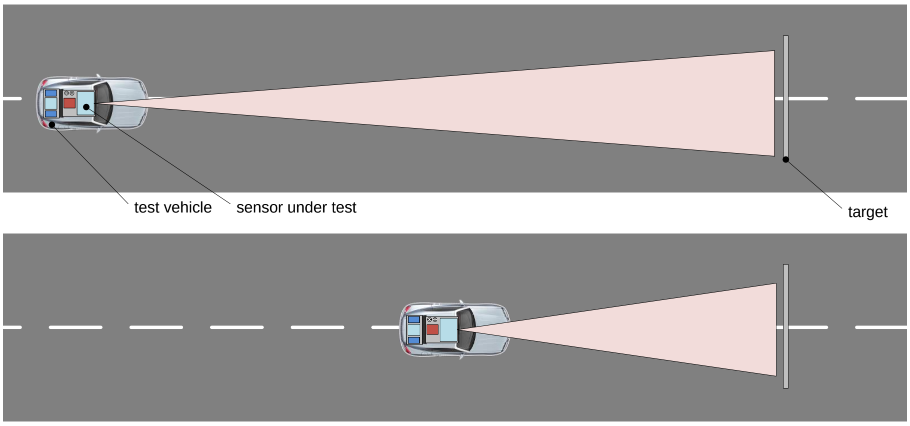


Fig. 7: Concept of TENSOR - Test Environment for Navigation System On airfield Runway

    - Computer (laptop) for operator
    - Moving part of reference navigation system including prism for tachymeter
- Stationary part:
    - Target wall
    - Power generator
    - Wifi access point including high gain antenna for large distances
    - Stationary part of reference navigation system
    - Tachymeter
    - Spotlights for illumination of target during night

Apart from the fundamental elements a test campaign with TENSOR needs quite more logistics and more material like a large tent to house the test car, tools etc..

B. DESCRIPTION OF ELEMENTS

The moving part is based on a standard car with standard roof rack adapters. The experimental rack is adaptable and can be attached to different roof rack adapters. The experimental rack carries the device under test, a prism for long range optical distance measurements and the reference navigation system. The reference navigation system is a hybrid GPS/IMU navigation system. It uses differential GPS measurements from a stationary GPS receiver. For getting accurate start position and attitude, tachymeter measurements are used to fix the initial static position before the test. Furthermore the vehicle carries inside a power supply for the device under test and auxiliary parts of the device under test. The operator of the device under test uses a laptop and has a emergency switch at hand for ensuring safety for critical sensors e.g. LIDARS with powerful laser beams.

The main element of the stationary part is the target for the sensor under test. It is a mobile wall which can be equipped with 3D primitives or textures. For illumination of the target spotlights are available which are powered by a mobile power generator. The stationary part of the reference navigation system houses a GPS receiver and sends its reference data via Wifi to the mobile part. In order to allow for large distance communication a high gain antenna is used which points along the way which the car will move. For getting accurate relative attitude and position measurements between car/sensor and target a tachymeter is used. When the car is not moving the 3D coordinates of specific points on the experimental carrier and the target can be measured with respect to the tachymeter. Since the location of three stationary GPS antennas is also know in relation to the tachymeter the coordinates measured by the tachymeter can be transformed into the WGS84 frame. The navigation filter of the reference navigation system can process these measurements as updates. This is usually done before a test run. It could also be repeated afterwards. This is more useful for post-processing (e.g. using a Kalman or Rauch-Tung-Striebel smoother) where all saved raw data can be re-processed.

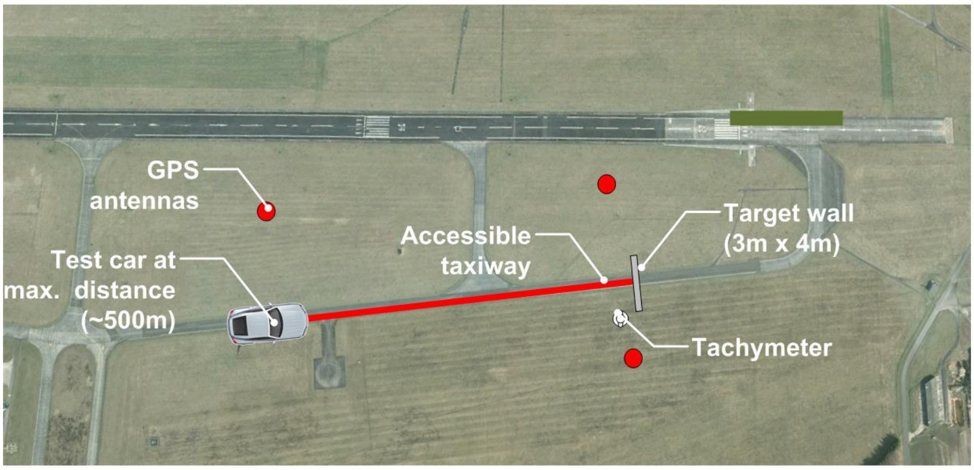


Fig. 8: *Setup of TENSOR on Fassberg Air Base*

The TENSOR setup was used for testing the flash LIDAR type sensor of the EU FP7 project FOSTERNAV (see [1]) and for testing the Small Integrated Navigator for PLanetary EXploration (SINPLEX, EU FP7 project, see [13]). For these tests the TENSOR facility was deployed at Fassberg Airbase (52°55'10"N 010°11'20"E). Figure 8 shows the setup of TENSOR on a taxiway of the air base. Figure 9 gives an impression of the tests for SINPLEX during a clear night. The night tests were needed to allow operation of the star tracker which is part the integrated navigation SINPLEX.

Fig. 9: *Test of the SINPLEX integrated optical navigation system using TENSOR*

5. ENSURING ACCURACY

The top level requirements which have been formulated for all tests performed in TRON so far can be summarized as:

- position a sensor with respect to an illuminated target according to reference data provided from customer

- provide ground truth for the actually assumed position and attitude of the sensor with respect to the target

For fulfilling these requirements the components used for a simulation in TRON must be aligned to each other. Naturally after its installation each component's individual reference system is initially unconnected to any other reference system. The robot is installed on the rail, the sensor is installed at the TCP, several terrain models are installed at the walls, the lighting system is installed on the gantry which is moving on rails fixed to the ceiling. For the alignment task the laser metrology equipment of TRON was used:

- laser tracker AT901-MR
- T-MAC, can be measured by laser tracker with accuracy better than 100μ and $0.01°$
- Reflectors, can be measured by laser tracker with accuracy better than 100μ
- T-Scan, can measure surfaces with respect to laser tracker with accuracy better than 0.2 mm

The basis for the alignment is a reference system which is physically fixed to the lab. All other reference system have been aligned to this one. The basis, called the TRON reference system is implemented by installing three holders for laser reflectors in the lab. Laser reflectors can be positioned with high repeatability in these holders and allow measuring these three points with very high accuracy with respect to the laser tracker.

The terrain model alignment exploits the quasi-planar surface formed by a stiff frame, where the models are installed on. On this frame a set of three reflector holders is fixed. Step 1 of the alignment is scanning the terrain model with the T-Scan and measuring the three reflectors. In this way the surface structure is aligned to the reference system defined by the reflectors. In step 2 the terrain model can be aligned by measuring the three reflector positions and any other system such as the TRON reference system.

The robot alignment was performed by placing a reflector at the TCP. With a series of movements along the robot's reference system axes, its unitary vectors and origin could be determined within the laser tracker space and therefore also within the TRON system. In the same way the gantry and the lamp were aligned to the lab basis.

For positioning the sensor it must be aligned to the TCP. For cameras this can be performed in the lab via hand-eye calibration, e.g. in the projects: ESA lunar lander, SINPLEX and ATON. For other types of sensor such as the flash lidar, an intermediate reference system can be defined, with the requirement of being measurable by the laser tracker. The calibration between the sensor and the intermediate system is performed by the customer.

The result of this first alignment iteration is an accuracy for positioning a sensor reference system with respect to a target reference system in the order of several millimeters. This value would also be valid for the ground truth. Since many applications desire a higher accuracy two methods have been developed for increasing the ground truth accuracy (see section A) and the positioning accuracy (see section B).

A. ENHANCING GROUND TRUTH ACCURACY

After the first alignment of the lab components the focus was put on increasing the ground truth accuracy for 2D camera sensor, which in this section is considered as the transformation between the camera reference system and the target reference system. For positioning the sensor with respect to the terrain model the following transformation chain was determined:

$$TM \Leftrightarrow LT \Leftrightarrow TRON \Leftrightarrow ROBOT \Leftrightarrow TCP \Leftrightarrow CAM, \tag{1}$$

where TM stands for terrain model, LT for laser tracker, TCP for tool center point and CAM for camera. Each entity in equation 1 described with capital letters stands for a reference system. Since for now the positioning accuracy is considered being sufficient enough it was possible defining a second transformation chain without the robot:

$$TM \Leftrightarrow LT \Leftrightarrow TMAC \Leftrightarrow CAM. \tag{2}$$

As it can be seen in equation 2 the number of transformations to be determined can be reduced, replacing potential error sources with a device which can be measured by the laser tracker directly with a high accuracy. For that purpose the T-MAC and the camera are installed together on the robot's TCP. The transformation between the T-MAC and the camera is determined by hand-eye calibration. For the DLR project ATON this approach was tested on terrain model 2. The terrain model surface and the reflectors attached to its mounting frame were measured in laser tracker space. Then a 2D camera with attached T-MAC was positioned with respect to this model. With the help of the T-MAC pose the transformation from the camera reference system to the terrain model reference system could be determined.

For testing the ground truth accuracy, the acquired camera image was undistorted and compared with a rendering based on the ground truth. The rendering was obtained by setting up a scene in the 3D rendering tool 3dsmax, containing the scan data of terrain model 2 and a light source. Additionally a camera was defined possessing the parameters of the real camera and assuming the ground truth pose. In figures 10 and 11 two images from the real camera and the ground truth camera are compared. After a visual inspection of the images a ground truth accuracy of about 1 mm could be determined.

It shall be noted that equation 1 is still needed for robot positioning. However, knowledge of the actual position has increased substantially.

B. ENHANCING POSITIONING ACCURACY

In order to ensure a high-accuracy ground truth, an iterative process for the calibration of the test trajectories has been set. Indeed, the high-precision, relative motion of KUKA robot has been coupled with the absolute high-accuracy 6DOF measurements capabilities of Leica Laser Tracker. The measurements have been performed via tracking of the T-MAC, a device statically connected to KUKA's arm able to measure both position and attitude, expressed in Laser Tracker (LT) Reference Frame. This information have been processed to adjust the commands for KUKA's position and attitude, so that the motion was as close as possible to the reference trajectory. The process of calibration of the trajectories in TRON can be divided in the following steps.

1. Run the current trajectory in TRON and measure it with the Laser Tracker in LT Reference Frame
2. Convert the information coming from the T-MAC in KUKA reference frame
3. Compare the measured trajectory with the reference trajectory in KUKA reference frame
4. If the error is above the prescribed threshold, generate a new calibrated trajectory based on the measured error
5. go to step 1

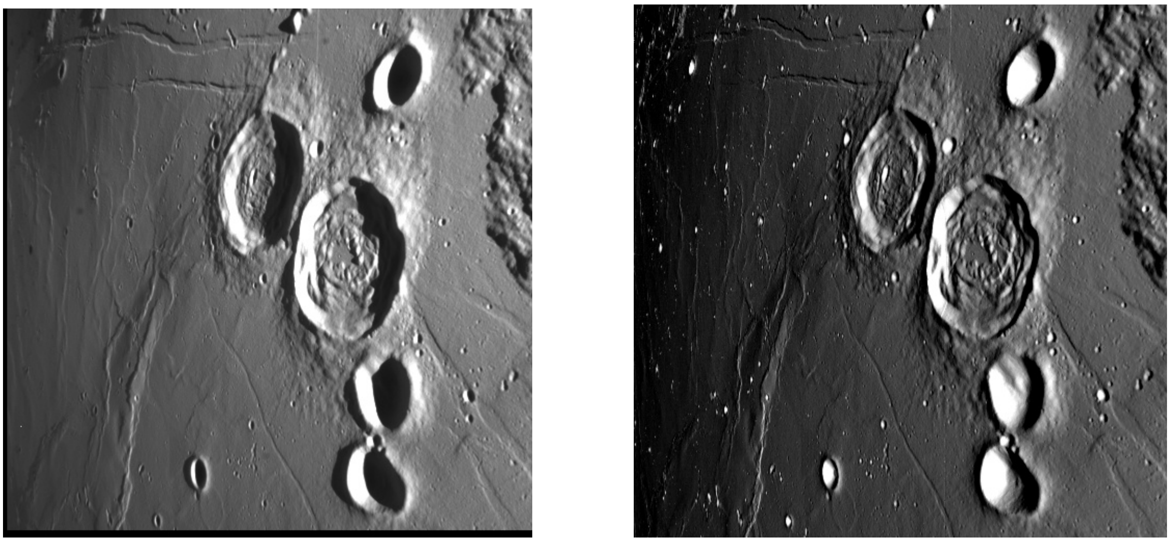
A scheme representing the workflow is shown in figure 12.

The process is initialized by running the reference trajectory. The threshold has been selected according to the repeatability standards of KUKA, reported in the Table below.

Calibration Thresholds	
Position (mm)	0.5
Attitude (deg)	0.3

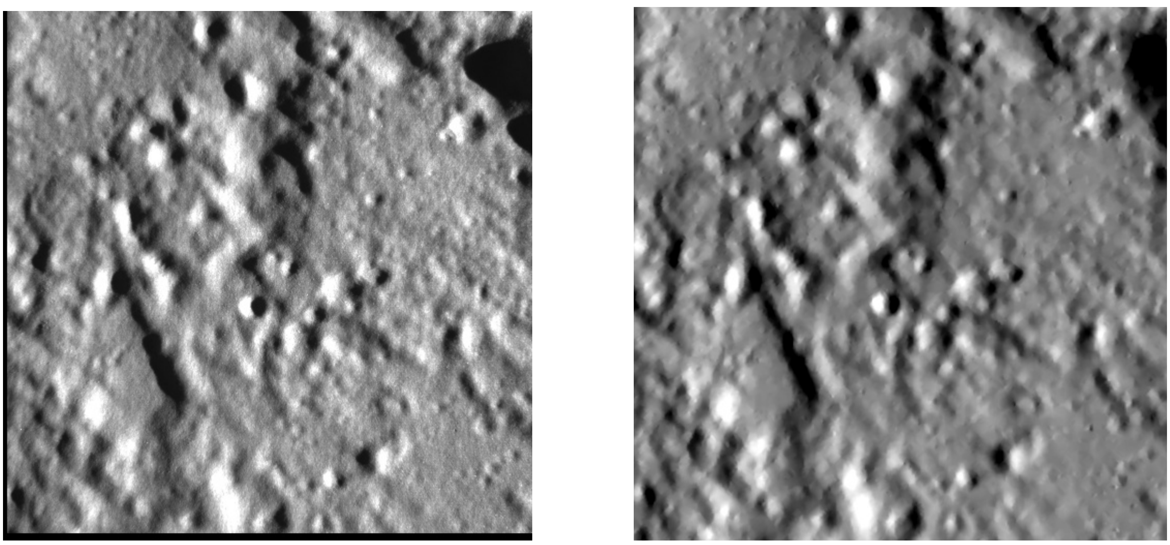
Table 1: *Trajectory Calibration Process Thresholds*

For the selected trajectory, two iterations were necessary to reach the prescribed threshold. Figures 13 - 15 show the obtained results.



(a) camera image high altitude (b) rendered image high altitude

Fig. 10: *Comparison of undistorted camera image and rendering of camera at ground truth position*



(a) camera image low altitude (b) rendered image low altitude

Fig. 11: *Comparison of undistorted camera image and rendering of camera at ground truth position*

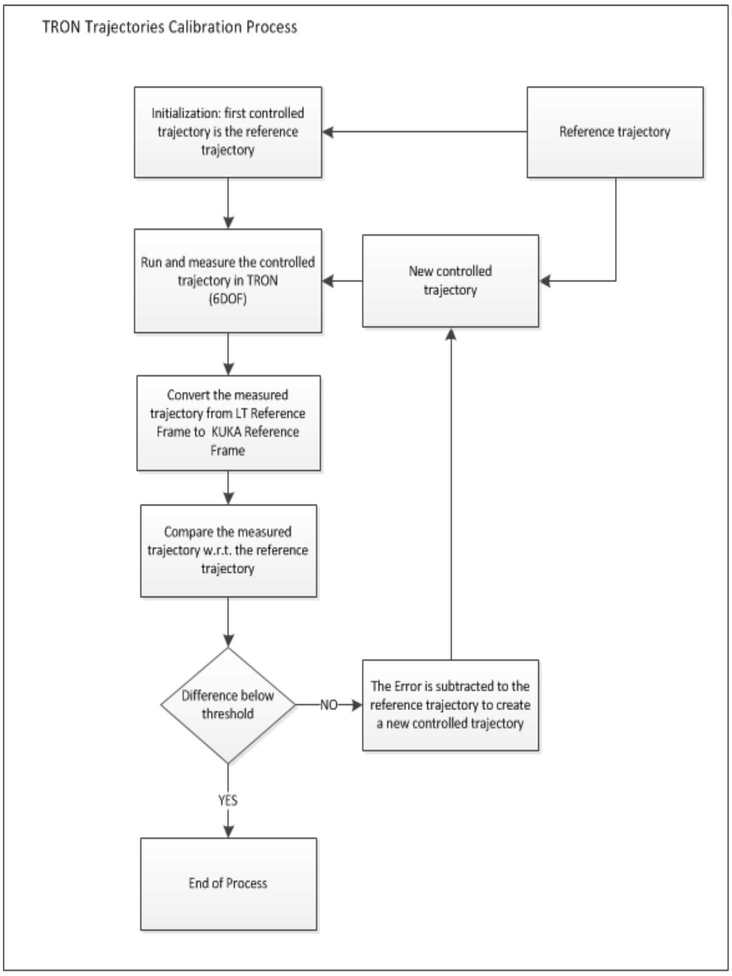


Fig. 12: *Calibration Process workflow*

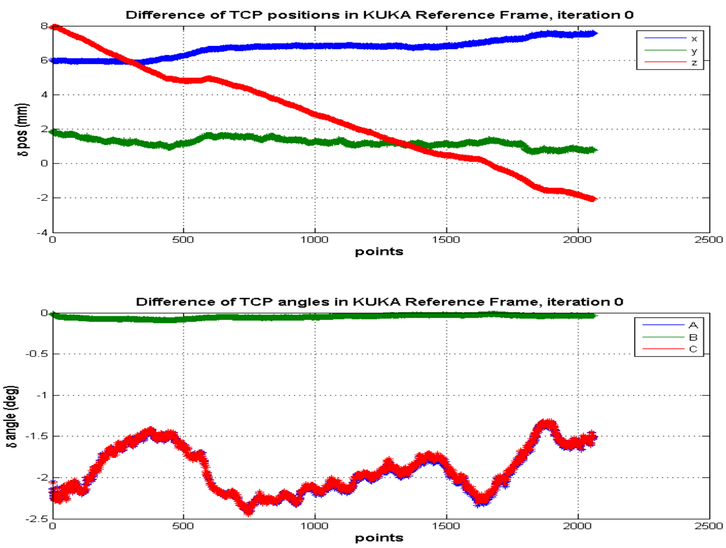


Fig. 13: *First run: difference between the reference trajectory and the measured trajectory in KUKA reference frame*

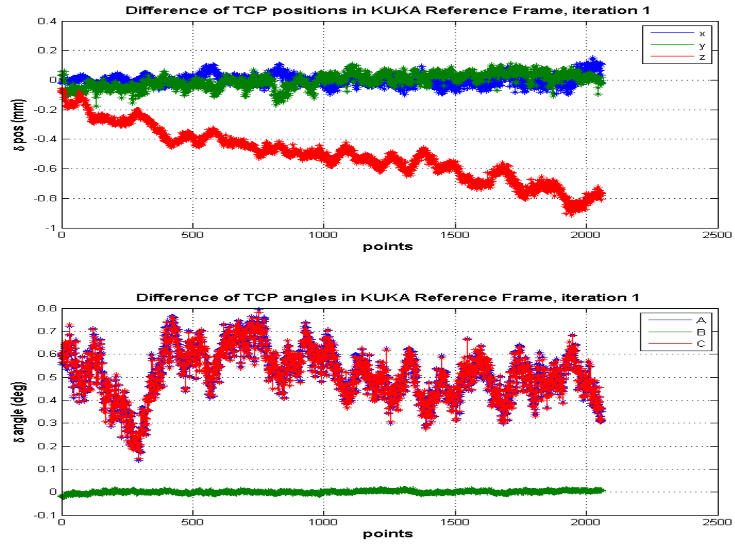


Fig. 14: *Second run: difference between the reference trajectory and the first compensated trajectory in KUKA reference frame*

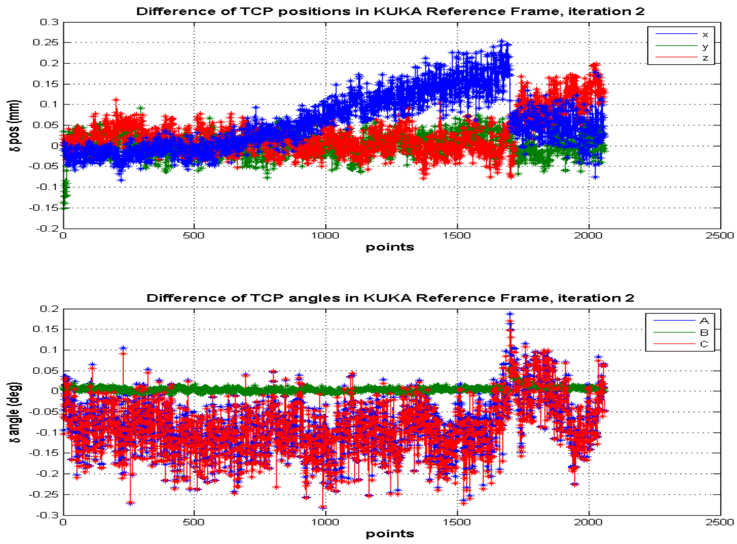


Fig. 15: *Third run: difference between the reference trajectory and the second compensated trajectory in KUKA reference frame*

From the analysis of the results it is possible to see that, after two iterations, the maximum discrepancy between the reference and measured trajectories decreased respectively from 8 millimeters and 2.5 degrees to less than 0.3 millimeters and 0.3 degrees. During the testing phase, further iterations have been performed, but no significant improvements in the magnitude of the error were observed.

6. CONCLUSION

This paper shows methods for on ground testing of optical navigation technologies for exploration missions. Many testing scenarios require a scale factor, this has been discussed for three groups of optical navigation technologies.

For 2D cameras high scale factors can be applied, allowing the simulation of mission scenarios. Of course a tradeoff between the scale factor and effort for terrain model manufacture and ground truth accuracy has to be made. Scaling for 3D sensors is limited due to non-scaleable measurement noise or limitations due to stereo baseline geometry. Despite this testing is possible in low-scale or true-scale. The testing of integrated sensor systems has been found to be possible by combining component-wise testing and software simulation or by adapting the navigation system to Earth's environment.

For enabling on-ground testing of all three sensor groups DLR developed two test sites. TRON offers a scaled lunar environment consisting of high precision manufactured terrain models, sun-like illumination and high accuracy sensor positioning and ground truth. This facility has been successfully used for testing 2D optical navigation sensors, e.g. in the frame of the ESA lunar lander or the camera component of the SINPLEX navigation system. TRON was also utilized for characterizing the FOSTERNAV flash lidar sensor in a true scale environment. TRON can be adapted to other scenarios by adding new targets such as the Eros asteroid or a flat target.

TENSOR is a test site complementary to TRON offering dynamic testing with higher speed and longer range. In this way mission elements such as the final approach phase can be simulated in true-scale. TENSOR has been successfully applied for flash lidar testing at speeds of up to 70 km/h and ranges of up to 200 m.

With the heritage of four successfully performed test campaigns, we feel confident of being on the right track for providing comprehensive testing environments for many kinds of optical navigation technologies.

ACKNOWLEDGMENT

A part of the activities reported in the paper have been carried out within the projects FOSTERNAV and SINPLEX of the 7th Framework Programme and the European Union and during the ESA lunar lander project.

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