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TARGET RELATIVE NAVIGATION RESULTS FROM HARDWARE-IN-THE-LOOP TESTS USING THE SINPLEX NAVIGATION SYSTEM

Stephen Steffes,[1] Michael Dumke,[2] David Heise,[2] Marco Sagliano,[2] Malak Samaan,[2] Stephan Theil[3]
DLR German Aerospace Center, Institute of Space Systems, Robert-Hooke-Str. 7, 28359 Bremen, Germany

Erik Boslooper,[4] Han Oosterling[5]
TNO, PO box 155, 2600AD Delft, Netherlands

Jan Schulte,[6] Daniel Skaborn,[7] Stefan Söderholm[8]
ÅAC Microtec AB, Uppsala Science Park, Dag Hammarskjölds väg 48, 75183 Uppsala, Sweden

Simon Conticello,[9] Marco Esposito,[10] Yuriy Yanson[11]
cosine Research B.V. , J.H. Oortweg 19, NL-2333 CH Leiden, The Netherlands

Bert Monna,[12] Frank Stelwagen,[12] Richard Visee[13]
SystematIC design B.V., Motorenweg 5G, 2623 CR Delft, Netherlands

The goal of the SINPLEX project is to develop an innovative solution to significantly reduce the mass of the navigation subsystem for exploration missions which include landing and/or rendezvous and capture phases. The system mass is reduced while still maintaining good navigation performance as compared to a conventional modular system. This is done by functionally integrating the navigation sensors, using micro- and nanotechnology to miniaturize electronics and fusing the sensor data within a navigation filter to improve navigation performance. A breadboard system was build including a navigation computer, IMU, laser altimeter/range finder, star tracker and navigation camera and has space for the redundant counterparts. Testing using the TRON hardware-in-the-loop testbench is ongoing. This

[1]SINPLEX Technical Manager, Guidance and Control Group Leader, stephen.steffes@dlr.de
[2]Research Engineer, GNC Department
[3]Head of GNC Department, SINPLEX Project Manager
[4]TNO Project Manager, Space Systems Engineering Department
[5]MAIT manager, Space Systems Engineering Department
[6]Electronics Engineer, ÅAC Project Manager, Space and Defense Department
[7]Systems Engineer, Space and Defense Department
[8]Electronics Engineer, Space and Defense Department
[9]System Engineer
[10]cosine Program Manger, Remote Sensing Instruments
[11]Scientist, Team Optics and Detectors
[12]Electrical Engineer
[13]SystematIC Project Manager

paper covers some key design properties of the built system and presents some initial performance results of the hardware-in-the-loop tests.

INTRODUCTION

For space missions which land on other celestial bodies modernizing and miniaturizing the navigation subsystem is an important objective. In particular, Dennehy[1] suggests that the most useful technologies would be miniaturized star trackers, laser altimeters and functionally integrating multiple GNC components, all of which is addressed by the SINPLEX (Small Integrated Navigation system for PLanetary EXploration) relative navigation system. The main goal of the SINPLEX project is to develop an innovative navigation system for exploration missions which include a landing and/or a rendezvous and capture/docking phase with a mass which is significantly lower than conventional systems. Reducing mass while maintaining good navigation performance is achieved by functionally integrating different sensors, utilizing micro- and nanotechnologies to miniaturize electronics and combining sensor measurements using sensor hybridization approaches to improve the performance of the complete navigation subsystem.

Within the project a breadboard system was produced, which includes a MEMS inertial measurement unit (IMU), star tracker (STR), navigation camera, laser altimeter/range finder (LA), navigation computer (NC) and power distribution unit (PDU). The system was designed to meet the combined requirements needed for a general Moon landing, asteroid landing and sample container rendezvous/capture mission scenario[2]. It is currently undergoing hardware-in-the-loop (HIL) testing at DLR's TRON (Testbed for Robotic Optical Navigation) facility[3] to measure its navigation performance and demonstrate its applicability for object relative autonomous navigation in space applications. More information about the SINPLEX project can be found at our website: `http://www.sinplex.eu` and in a previous paper[2] which describes the conceptual design.

This work describes the final design of the manufactured breadboard system and some initial performance results from the HIL tests. The paper starts by describing the breadboard design and the onboard navigation algorithms. The HIL test bench is presented, including the test trajectory used. Testing of the breadboard is limited to close range terrain relative tests, so only those algorithms in the system needed for these tests are described. Finally, performance results are shown.

BREADBOARD HARDWARE DESIGN

The SINPLEX flight model design (shown in Figure 1 and Figure 2) is a highly integrated, fully redundant, miniaturized, autonomous navigation system. The system features a suit of redundant components, each chosen to fulfill the performance requirements with minimal mass. A breadboard version was produced with non-redundant subsystems to demonstrate the technology. The mass and power breakdowns in Table 1 and Table 2 represent measured values from the built breadboard system and do not include redundant components. The overall volume is roughly $17 \times 21 \times 20cm$. The flight model is described in detail in [2] and is summarized here, highlighting the changes for the produced breadboard.

The IMU provides high-rate specific force and angular rate information. It uses four MEMS accelerometers (Colibrys MS9002, $10mg$ maximum bias) and gyros (Analog Devices ADXRS646BBGZ, $360deg/hr$ maximum bias) oriented in a tetrahedral and is placed in the top-center of the housing (Figure 3(a)). The main IMU electronics board is based on ÅAC Microtec's μRTU and is responsible for sampling the sensors, compensating for known errors from laboratory calibration and compensating for errors estimated on-line sent from the navigation filter run on the NC. Additionally, to

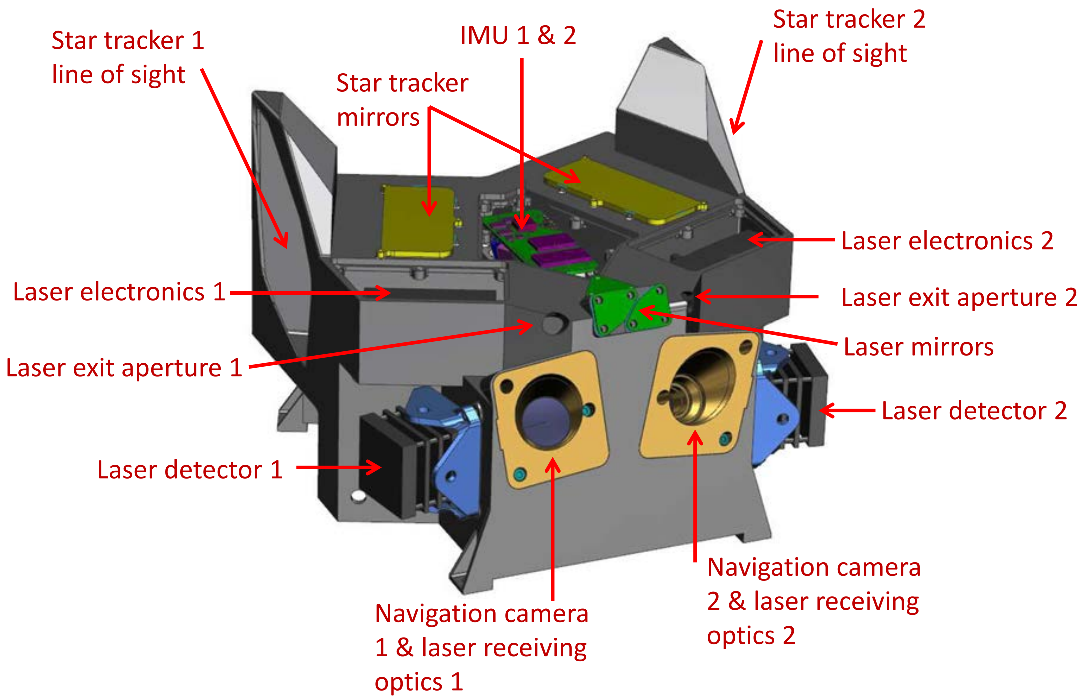


Figure 1. Front-top view of SINPLEX flight model.

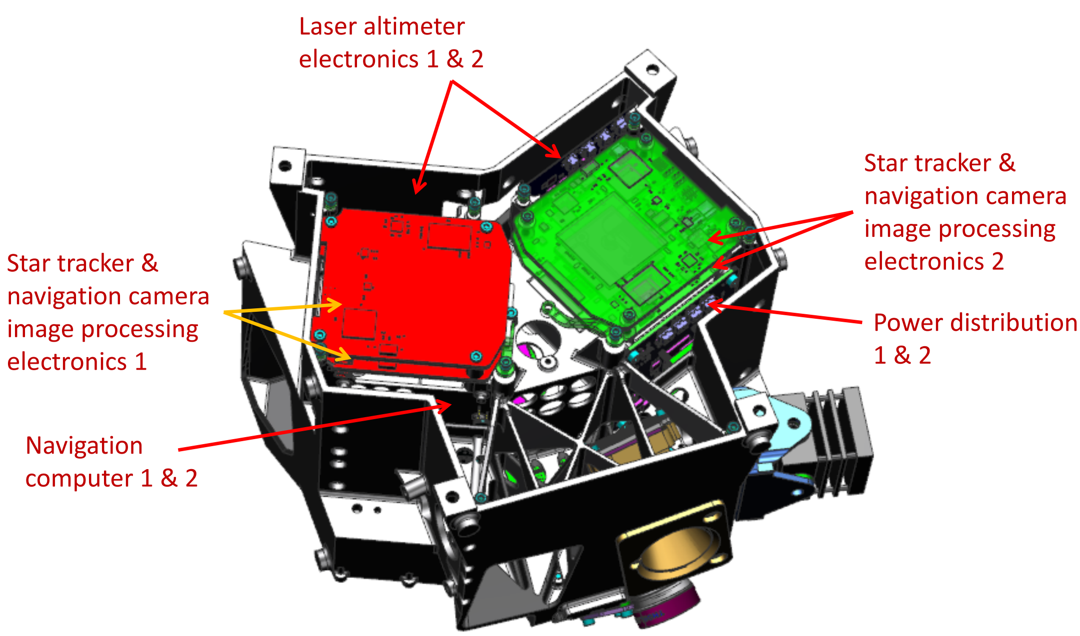


Figure 2. Bottom view of SINPLEX flight model.

conserve processing power on the NC, the IMU data is integrated at a high rate within the IMU processor instead of the more common approach of doing this on the NC.

The LA provides target range information synchronized with navigation camera images. The $532nm$ laser (Teem Photonics MNG-03E) emits short, powerful light pulses to the target surface and measures the time of flight of the reflected photons. A photodiode positioned close to the laser provides a START signal and a single photon avalanche diode (SPAD) (Sensl PCDMini-00020) provides the STOP signal for each pulse. These signals are fed into the LA analysis board, which performs the time-of-flight measurement and statistical analysis of the signal. The expected measurement accuracy of the LA is $12cm$ with a range up to $10km$, depending on the target surface properties. A commercial laser driver board is used to drive the laser and is in a separate box outside of the housing. The flight model combines both the analysis and driver boards into a single board, the design of which is finished but not produced for the breadboard.

The navigation camera provides images of the target surface, which are then processed to measure target relative position and attitude information. A lens barrel (Figure 3(b) and Figure 3(c)) forms the receiving optics for both the navigation camera and LA receiver. The green light for the LA is split out by a notch reflection filter and exits the lens barrel through a hole on the side. The remainder of the light goes through the filter to the navigation camera detector. The camera has a $40 \times 40deg$ field of view and the LA measures a spot in the center of the image. Images are processed on a custom FPGA board and the resulting measurements (feature, crater or container positions) are sent to the NC (see the following sections for algorithm details). Power consumption of the camera electronics can be greatly improved in the next generation of hardware.

The STR provides inertial attitude information. The optical design is based on the Multiple Aperture Baffled Star Tracker (MABS) developed by a team led by TNO[4] and has a $16 \times 20deg$ field of view. The images are processed by a custom FPGA board (same design as the navigation camera FPGA board) and a quaternion is output to the NC.

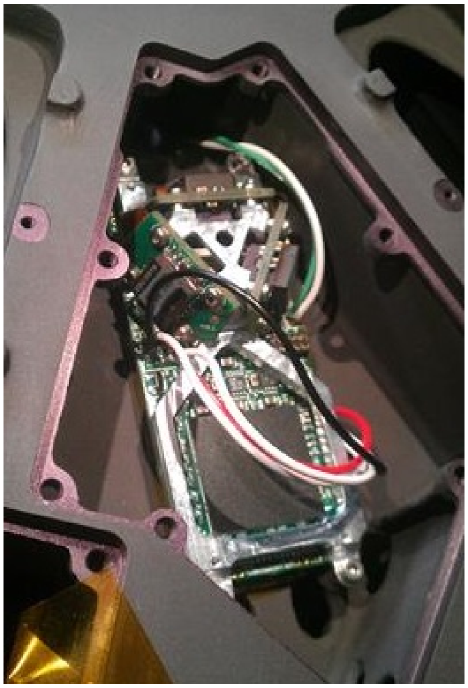
The NC hosts the navigation algorithms and is composed of an OBC Lite^{TM}EM with Ethernet add-on board. Additionally, the NC is the master computer in the system and controls all sensor scheduling and data passing between components. Data is passed between components using the SPA-1 (Space Plug and Play Avionics) protocol on an I2C bus.

Table 1. Mass breakdown of breadboard.

Component	Mass [kg]
Housing	1.5
Power Distribution Unit	0.04
NC	0.03
IMU Subsystem	0.06
LA Subsystem	0.9
Camera Electronics	0.18
Misc.	0.39
Total	3.1

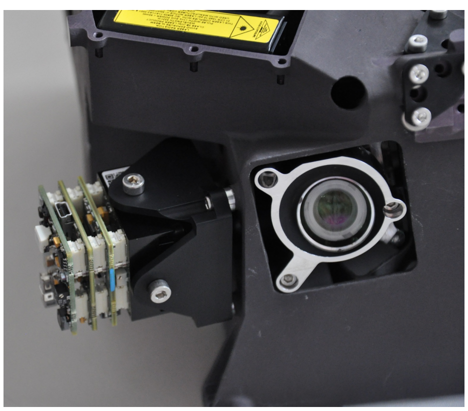
Table 2. Power breakdown for breadboard.

Component	Power [W]
Power Distribution Unit	0.3
NC	2.5
IMU Subsystem	1.0
LA Subsystem	5.5
2x Camera Subsystem	7
Total	16.3



(a)

(b)



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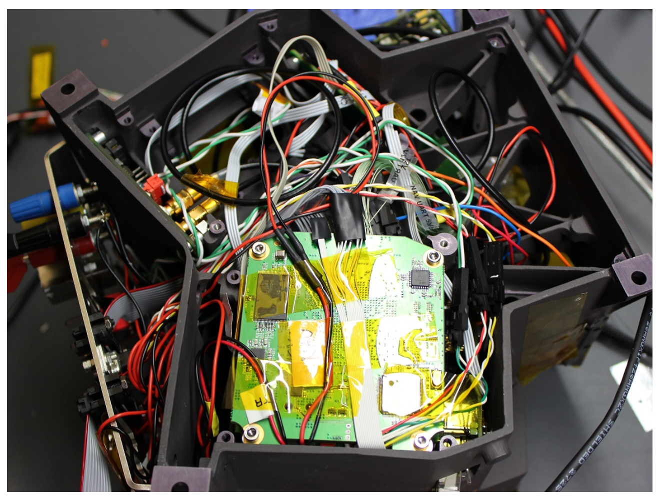


(d)

Figure 3. Breadboard components. (a) Integrated IMU. (b) Lens barrel showing LA receiving optics exit aperture. (c) Integrated SPAD and lens barrel. (d) Integrated electronics including debug cables.

IMAGE PROCESSING

A number of image processing techniques are used to obtain useful measurements for each mission phase. The algorithms implemented on the breadboard are limited to star tracking and feature tracking. Crater navigation and close and long range container finding are available offline and were not implemented due to budget and project timing constraints.

STR measurements are used in every mission phase using the STR camera. The STR FPGA board receives a trigger from the NC, which starts the integration period of the detector. The image is preprocessed using dark image subtraction and star centroiding to obtain accurate star locations. A lost-in-space algorithm identifies each star using the pyramid algorithm[5] and a quaternion is calculated using the q-Method[6] and then sent to the NC. A tracking mode is foreseen in the flight model and was not implemented in the breadboard. The attitude accuracy was measured to be $0.0015deg$ 1σ tangent to the line of sight and can be improved in software with more effort.

Feature tracking is used during the powered descent and landing phases of the moon and asteroid landing scenarios. An intensity-normalized navigation camera image is first searched with the ''Good Features to Track'' algorithm[7] to find suitable persistent features with properties that would be easy to find in subsequent images. Features are re-found in subsequent images using a brute force search around a window estimated using aiding data from the NC. Initial testing measured the feature refinding accuracy to be $0.4pixels$ 1σ for a selected trajectory, which can be improved in software with more effort.

NAVIGATION ALGORITHMS

The mission scenarios require an autonomous real-time navigation solution (vehicle position, velocity and attitude) at every mission phase. The SINPLEX system provides this by fusing sensor measurements on the NC in real-time with a delayed error state extended Kalman filter (EKF) similar to [8]. Sensor fusion aims to overcome the weaknesses of each sensor by combining all sensor measurements into a single accurate navigation solution. Processing of sensor measurements is distributed over all the components to offload much of the computational burden from the NC, allowing for lighter loads on the NC processor and communications bus.

The navigation algorithm on the breadboard computes both inertial and terrain relative navigation states. An inertial navigation solution is needed in the descent phase of the mission and is continued to be calculated throughout the landing phase since it is needed to calculate gravity and surface relative velocity. The terrain relative position is found by tracking up to four features over time using a variant of EKF-SLAM[9]. Using the filter, this provides updates to the inertial velocity and attitude states since any change in velocity or attitude affects the movement of the features in the image.

The navigation software is distributed over several subsystems, as shown in Figure 4. Additionally, the navigation algorithm is distributed over several software tasks running at three separate rates, as shown in Figure 5. Image processing algorithms are run on the camera FPGAs and only the final measurement results are sent to the NC. Raw and compensated IMU measurements are processed within the IMU subsystem, which uses the $100Hz$ high-rate (HR) navigation algorithm to provide $10Hz$ integrated delta-velocity and delta-angle increments to the NC, which are compensated for any rotations over the interval. Raw LA measurements are processed within the LA subsystem and range measurements are sent to the NC. There are two additional algorithms that are run directly on the NC: the navigation medium-rate (MR) and low-rate (LR) tasks. The MR task runs at $10Hz$ and is responsible for integrating the equations of motion, calibrating clocks and calculating the

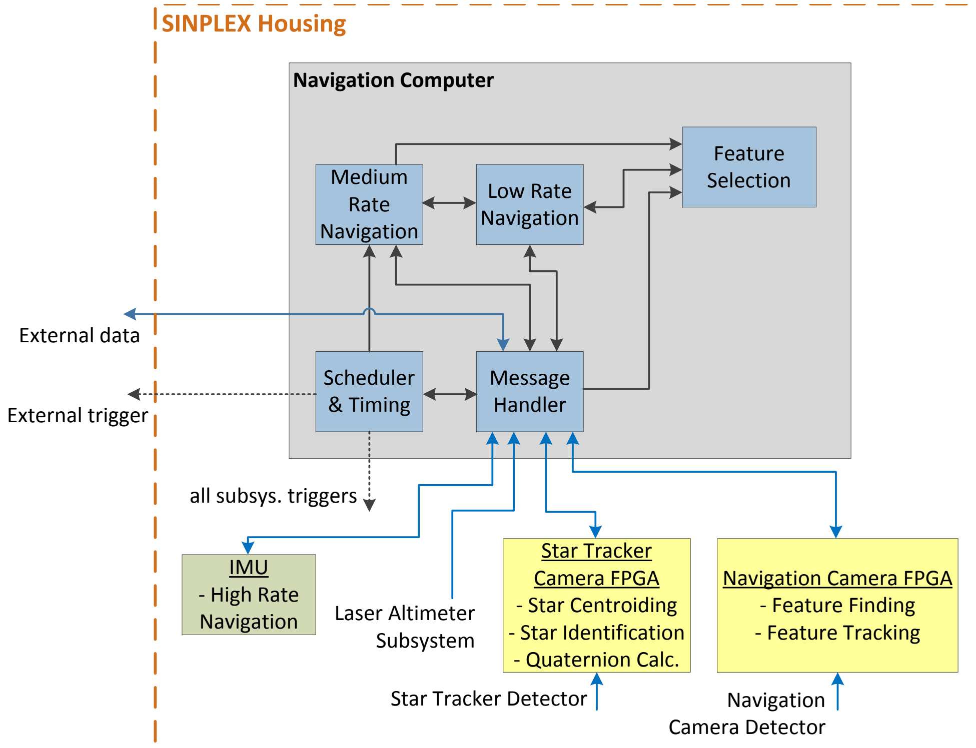


Figure 4. Block diagram showing the distribution of navigation and image processing software.

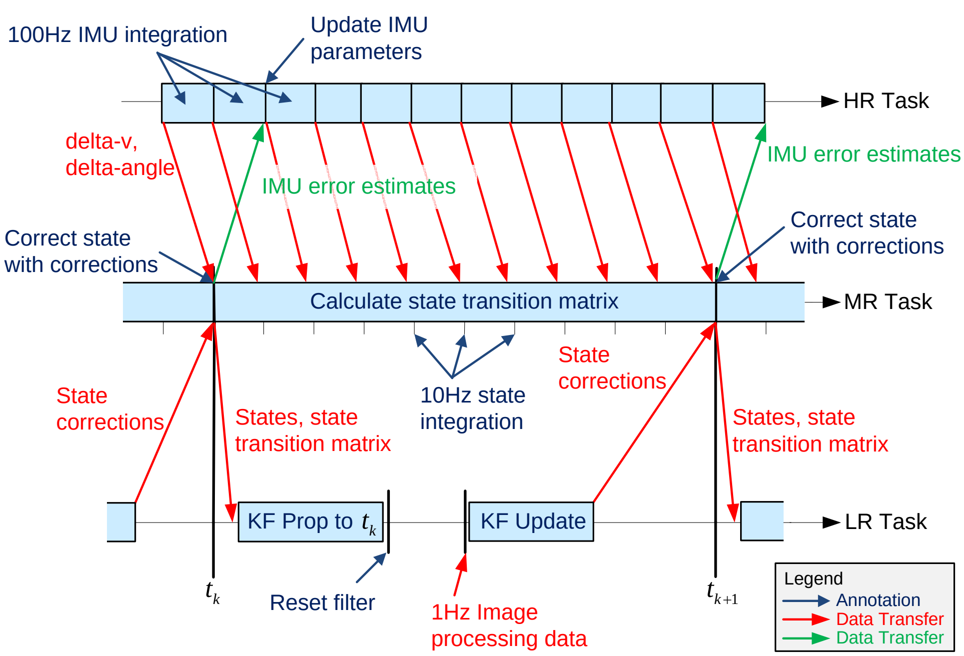


Figure 5. Distribution of navigation algorithm over three separate rates.

state transition matrix for the EKF. The LR task runs at $1Hz$ and is responsible for propagating the EKF with the state transition matrix and updating the EKF with the LA and image processing measurements. State corrections from the LR task are sent to the MR task to correct the navigation state. IMU error estimates (sensor biases and scale factors) are sent from the MR task to the HR task to compensate the integrated IMU measurements. A similar 2-rate approach was successfully used for the Hybrid Navigation System experiment[8], which allows for an optimal filter, reduced real-time constraints and the processing load to be spread out over time.

HARDWARE-IN-THE-LOOP SETUP

Terrain relative navigation tests are done in the TRON laboratory[3]. The SINPLEX breadboard is mounted to the end of a 7-DOF (degrees of freedom) robotic arm (Figure 6) which can move along a $10.5m$ track. The robot can then be precisely positioned in real-time using a dSPACE real-time simulator (a modular COTS real-time simulation platform) and can automatically run through any programmed trajectory, within the limits of the robot. Several 3D terrain models are present in the lab on 3 of the walls, which represent scaled Moon and asteroid landscapes. A sample return container model and a complete 3D scaled asteroid model are also available. A 5-DOF lamp and gantry system provide uniform lighting in a programmed direction and path. Figure 7 shows the breadboard attached to the robot and all the additional hardware components needed for HIL testing.

TRON can also provide an accurate measurement of the run trajectory by tracking the breadboard with a laser tracker (AT901-MR from Lecia). A T-Mac device is rigidly attached to the breadboard, which can be tracked by the laser tracker in 6-DOF. The position and attitude alignment between the T-Mac and navigation camera is measured by tracking the T-Mac with the laser tracker while the navigation camera views an optical calibration target in various poses. With this, the reference trajectory from the laser tracker can be transformed into the reference trajectory of the navigation camera. This provides an accurate reference trajectory to compare with the navigation data from the breadboard.

A Jenoptik Optical Sky field Simulator (OSI) stimulates optical camera systems for observing objects with an optically finite distance. It mainly consists of an optical head, which projects the image, and a control computer including remote interface software. The optical head includes a micro display with $800 \times 600 pixel$ resolution and is inserted into the STR baffle with a special adapter. The OSI host PC receives attitude commands remotely from the dSPACE system. The PC calculates and projects a simulated image of the sky (including stars, planets, the Moon, single event upsets, etc.) through the optical head as a collimated beam. The beam enters the camera, the NC triggers the camera, and the STR processes the captured image. Optical distortions in the STR image caused by the OSI orientation are calibrated and compensated in the STR and NC software.

For these tests a RaspberryPi is additionally attached to the breadboard to provide an interface for the subsystems to output debugging information remotely to the user. This is data which would otherwise not be accessible to the user. The RaspberryPi is only used for this purpose and is otherwise not needed for HIL testing.

An initial spiral test trajectory was created to test some aspects of the breadboard navigation system. The trajectory starts at one end of the lab with the navigation camera looking at the landscape, which is on the other end of the lab. The robot moves the breadboard in a spiral towards the landscape. The spiral extends $\pm 0.5m$ left and right, $\pm 0.3m$ up and down and makes one complete revolution as the robot travels from one end of the lab to the other. The attitude is fixed with respect to the lab,

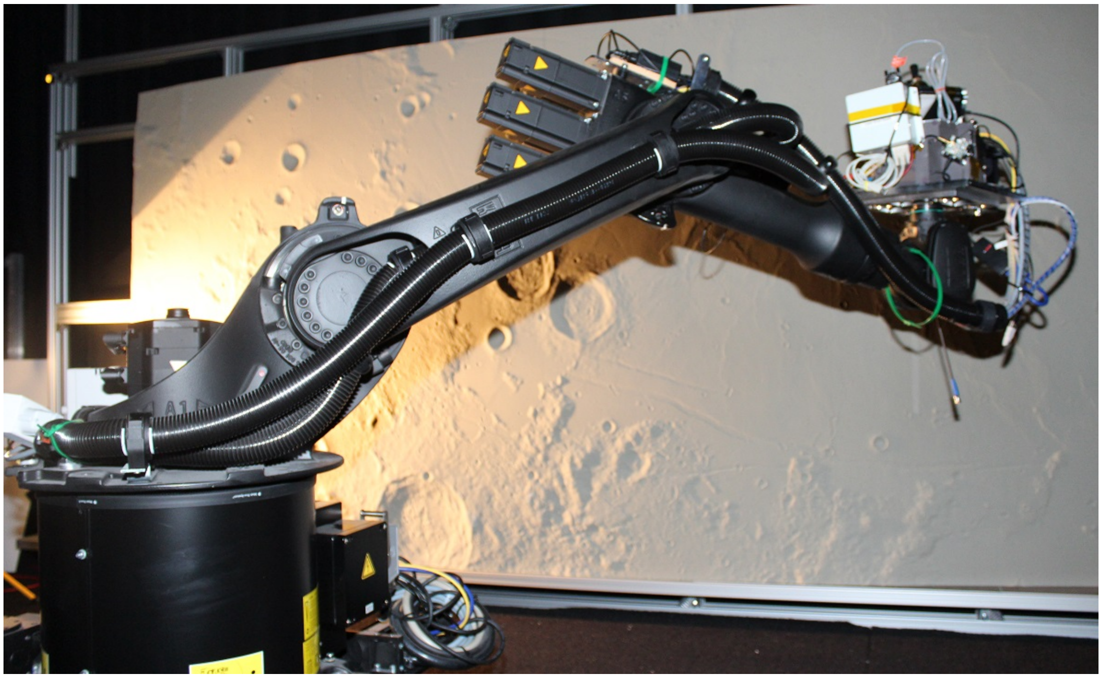


Figure 6. SINPLEX breadboard attached to TRON robotic arm.

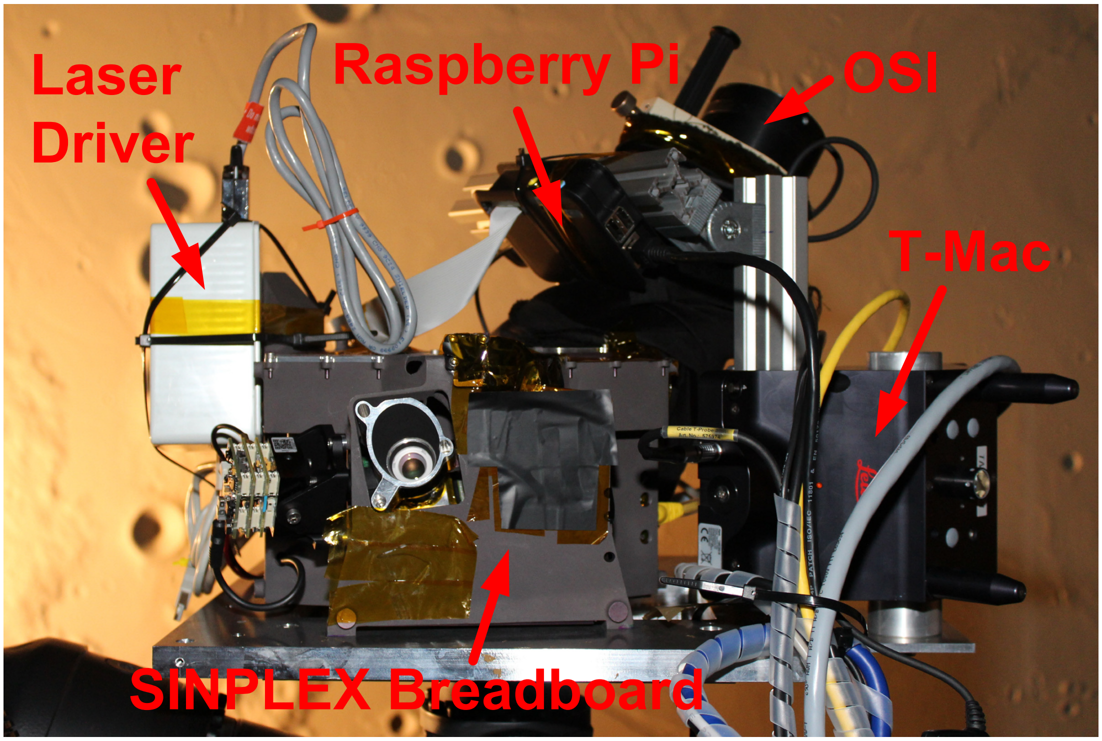


Figure 7. Additional hardware components attached to breadboard for HIL testing.

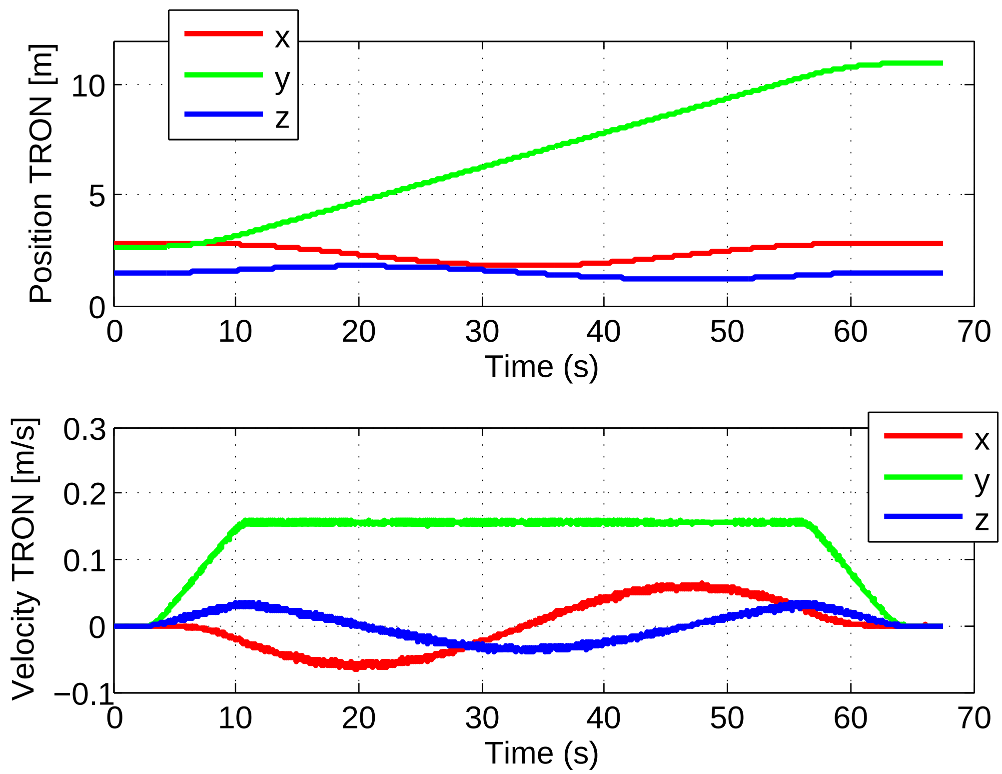


Figure 8. Position and velocity profile of the spiral test trajectory in TRON frame.

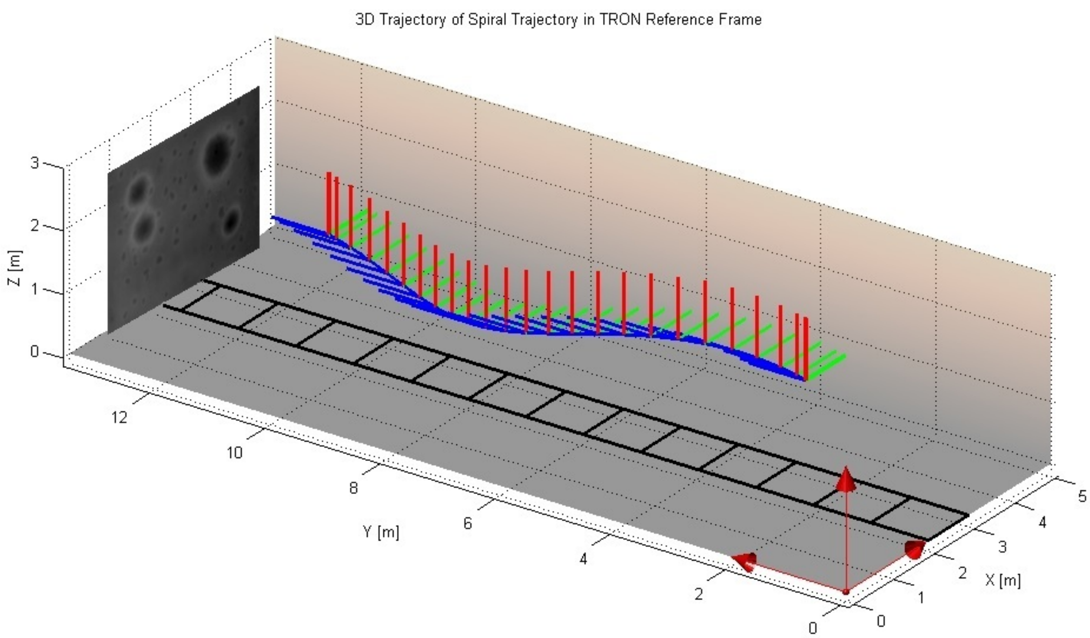


Figure 9. 3D view of the spiral test trajectory. Red, green and blue lines are the camera x, y and z axes.

meaning the camera always sees the landscape and the laser is perpendicular to the landscape plane. The trajectory data is shown in Figure 8 and a 3D plot of the camera axes is shown in Figure 9. A 3D asteroid landscape is on the wall at $y = 13m$. The 3D plot also shows how the TRON reference system is defined: the y-axis is along the long wall of the lab and is the direction of travel for the robot down the rail, the z-axis is up and x- completes an orthogonal reference system. This trajectory represents something close to the last $10m$ of a Moon or asteroid landing trajectory with some extra translational dynamics. Rotational dynamics are not included in this initial testing, but will later be included.

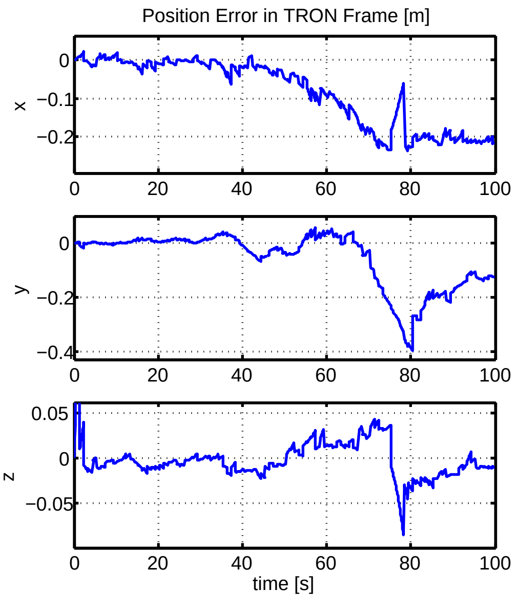
RESULTS

The breadboard system is currently undergoing extensive testing, but some initial results using the spiral test trajectory are presented here. The system is initialized assuming perfect knowledge of position, velocity and attitude. This is followed by a $30sec$ period of no motion when the navigation algorithm directly measures its accelerometer and gyro biases. The spiral trajectory then starts at $time = 30s$ and ends $70sec$ later.

The navigation algorithm cannot improve the initial absolute position estimate since no sensor measurements provide this information, but it can prevent the position from drifting over time by using the feature estimates. Absolute and target relative velocity are the same thing since the navigation state is estimated in a surface fixed reference frame, which can be directly observed by tracking features. Inertial attitude estimation is maintained using the STR results. Without the STR the navigation algorithm cannot improve the inertial attitude estimate, but it could prevent the attitude from drifting over time using the feature estimates. The navigation algorithm tracks 4 features throughout the trajectory, which may change if the feature tracker fails to re-find the feature. These 4 features can be fit to a plane, which then represents a rough model of the target surface. The error in the distance and angle of this feature plane is one measure of the accuracy of the feature estimates.

Figure 10 shows the absolute position, absolute/target relative velocity and inertial attitude errors, as calculated by comparing the navigation solution to the reference trajectory from the laser tracker. The position error is the worst in the y-direction (towards the target landscape) since movement along this direction is measured by the change in feature distance, which cannot be accurately measured since the LA does not measure this directly and since the landscape topography is unknown to the navigation system. The x-position error is comparable to the y-error, which is likely due to the choice of features in the image. Not surprisingly, the velocity error in the x- and y-directions are worse than the z-direction, for the same reasons given for the position errors. Attitude error is almost entirely driven by the gyro bias estimation accuracy, which is relatively poor due to a communication problem.

Features are found on-line and do not correspond to any precalculated landmarks on the target. It is only known that the true feature location lies somewhere on the target surface (which is approximately a plane with 0.1m surface roughness). Some measure of the feature position accuracy can be obtained by fitting the estimated feature positions to a plane and then comparing the distance and orientation of this plane to the true target surface. Figure 11 shows the errors in the estimated feature plane, calculated by comparing the estimated feature positions to the true target surface plane. Before the trajectory starts the feature plane errors are small and stable. After the trajectory starts these errors increase and vary wildly. Feature plane attitude estimation is greatly dependent on the spread of the features over the image. The current navigation algorithm chooses features close to the center of the



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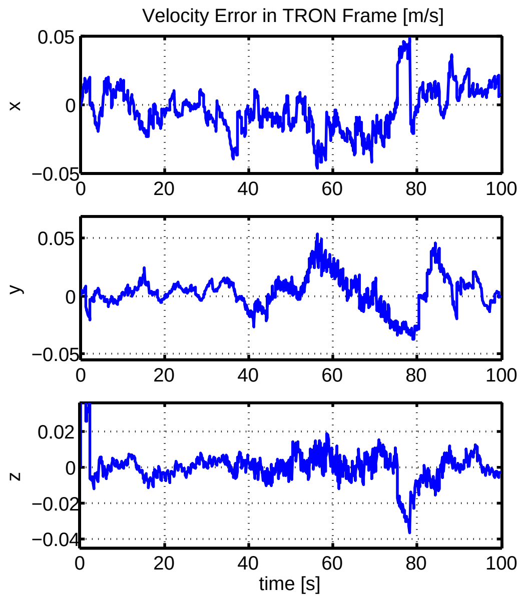

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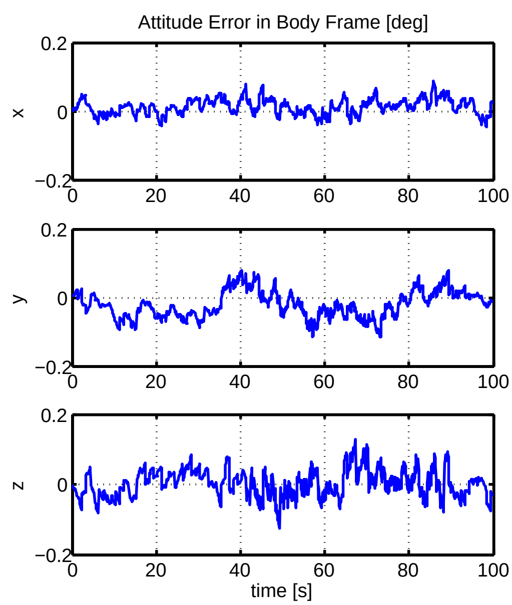
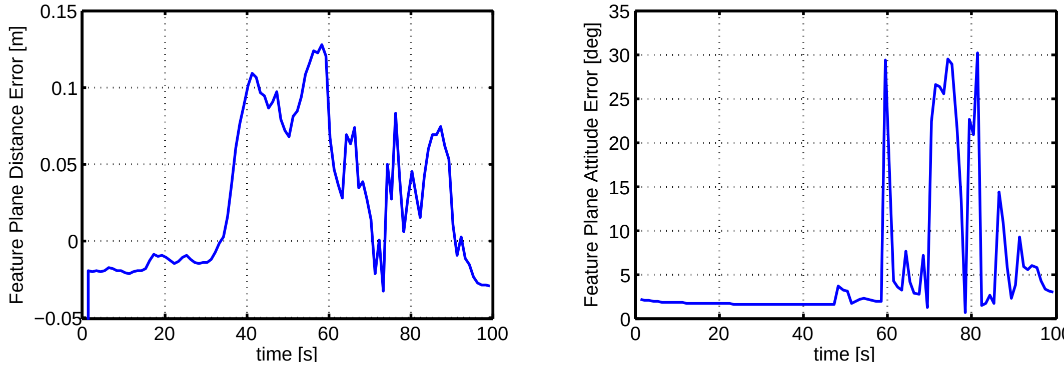


(c)

Figure 10. Results from spiral trajectory test. (a) Absolute position error. (b) Terrain relative velocity error. (c) Inertial attitude error.



(a) (b)

Figure 11. Results from spiral trajectory test. (a) Feature plane distance error. (b) Feature plane attitude error.

image so the LA measurement has a higher weighting when estimating the feature distance, which causes poor feature plane attitude estimation since the features are grouped close together. The large variation of the feature plane distance error is likely a result of poor feature tracking performance due to the contrast changes in the image throughout the trajectory. Some image normalization is done online for the navigation camera images, but the camera integration time (shutter time) is constant throughout the trajectory. Feature tracking performance can be greatly improved by using an auto-exposure algorithm.

SUMMARY

SINPLEX has the potential to be a powerful navigation system technology with significant mass savings compared to a suit of COTS components with similar performance. The produced breadboard model has been through extensive functional testing and is starting to go through performance testing. The initial data from a spiral landing trajectory shows promising results for the future performance of the system. Further testing in TRON is scheduled to run with realistic landing and translational trajectories and tracking of a sample container and full 3D asteroid models. Additional testing is scheduled for the TENSOR facility using much longer ranges, higher speeds and the night sky. A number of improvements to the breadboard model are in progress and the system performance will greatly improve in time.

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