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SINPLEX: A SMALL INTEGRATED NAVIGATION SYSTEM FOR PLANETARY EXPLORATION

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Abstract

SINPLEX is a sensor suite for spacecraft navigation purposes. This paper addresses the current status of the SINPLEX prototype and the systems engineering process that has led to this status. The SINPLEX prototype is currently being integrated with the aim to demonstrate Technology Readiness Level 4, i.e. a component and/or breadboard validation in laboratory environment. The ultimate goal is to reach series production of an integrated instrument sensor suite capable of navigating a spacecraft in the solar system for exploration and science missions, and for satellite servicing and related markets. The SINPLEX project is supported by the European Community Framework Programme FP7 Space, grant agreement no.: 284443.

Introduction

Navigating spacecraft through the solar system is one of the most technically demanding challenges imaginable. The EU FP7 project SINPLEX aims to bring together key sensor functionalities used in solar system navigation and integrate them as much as possible. This is enabled through miniaturization of sensor hardware, data fusion from different sensors and hardware integration of sensors. Figure 1 shows this in a graphical way.

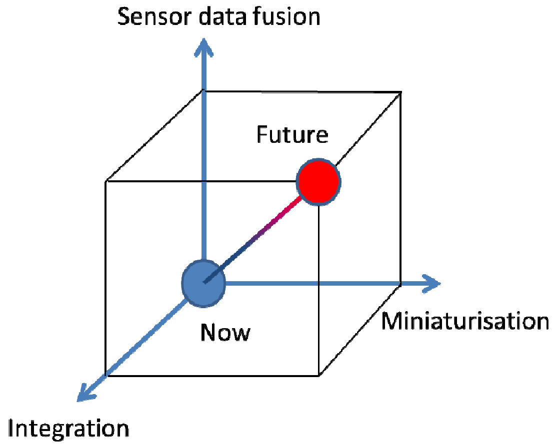

Figure 1: the three R&D dimensions for SINPLEX.

Navigation equipment for exploration missions in the solar system is often built from a stand-alone distributed perspective. Typical systems that are part of the navigation equipment are: star trackers, sun-sensors, laser rangers, laser altimeters, navigation cameras, inertial measurement units, GPS sensors (only for LEO operations) and a central computer running the necessary algorithms to create the state vector at a certain frequency to the spacecraft. A benchmark mass for a navigation system for exploration based on conventional components is about 10 kg. SINPLEX's aim is to integrate all the single components in order to reduce the mass of the complete navigation system below 5 kg (including redundancy).

The specification of the SINPLEX system was established taking into account four different mission scenarios:

1) Lunar descent and landing
2) Asteroid descent and landing
3) Container rendezvous and capture
4) Mars entry, descent and landing

Mission Scenarios

Lunar descent and landing

The Lunar descent and landing mission scenario used for SINPLEX is derived from the trajectories used by several Moon landing missions (including Surveyor, Apollo 11 and Altair). Figure 2 shows the general mission profile. The spacecraft starts in a 100 km circular polar parking orbit around the Moon. The landing area is manually selected before the mission and is near the equator. The scenario starts when the spacecraft performs a breaking manoeuvre, which brings the vehicle into a descent orbit (DO) with 10km periapsis. During the DO the optimal spacecraft orientation is chosen based on constraints from the navigation system. The powered descent (PD) phase then starts near the periapsis of the DO and the spacecraft descends on a controlled trajectory towards the landing area. The landing phase starts 2 km above the surface when the landing area is in view. During this phase the target landing location is autonomously refined based on landing safety considerations; however, this is not done by the navigation system. The landing phase ends at the chosen refined landing site, 1 m above the surface with a surface relative velocity of 1m/s. The spacecraft orientation during PD and landing is constrained by the thrust direction profile.

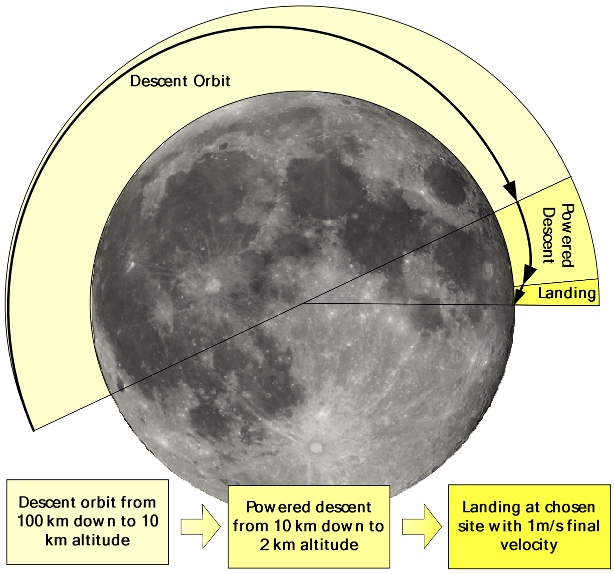

Figure 2: Moon descent and landing mission profile.

Asteroid descent and landing

The Asteroid descent and landing mission scenario used for SINPLEX is derived from the Marco Polo [1] and Hayabusa [2] missions. Figure 3 shows the general mission profile. The scenario begins with the spacecraft entering into a slow collision course with a small near Earth asteroid 1.3AU from the Sun (1km diameter, 5.10^{11} kg, spherical, C type, 7hr rotation period). The guided descent (GD) phase starts 400 m above the surface, aiming towards a predefined target landing location 10 m away from a navigation landmark. The navigation landmark is kept in the FOV of the camera during descent. The landing phase occurs at 50m altitude when vertical thrusters are turned off (free fall) to avoid sample contamination and ends at touchdown with the following terrain relative conditions: vertical velocity < 30cm/s, horizontal velocity < 5cm/s, attitude relative to local horizontal < 10 degrees. During landing, lateral control is turned off at 15m altitude. Descent and landing lasts 40 minutes. The navigation landmark may leave the FOV as the spacecraft gets closer to the landing location because the sensors must point downwards towards the landing location.

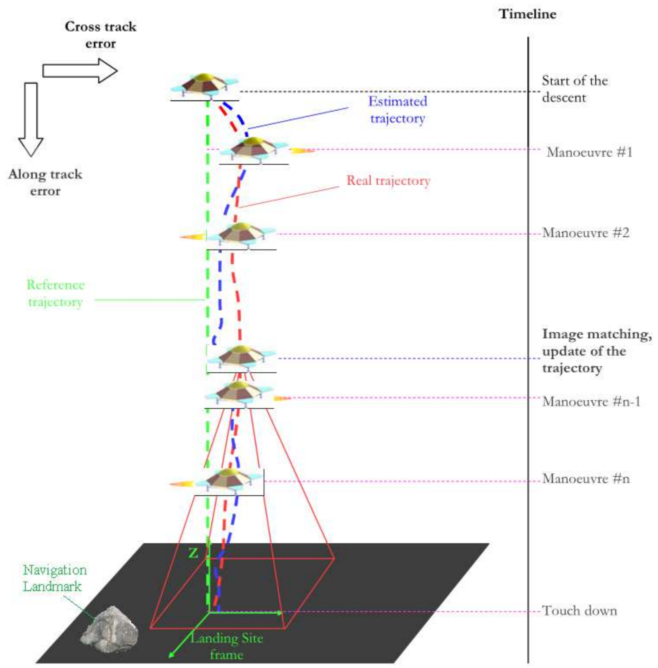

Figure 3: Asteroid descent and landing mission profile.

Container rendezvous and capture

The Container rendezvous and capture mission scenario used for SINPLEX is a Mars sample return (MSR) scenario derived from the HARVD [4,5] and FOSTERNAV [3] studies. In this scenario a spherical target sample container (20 cm diameter) is in a 500km circular orbit (2 hour period) around Mars and a chaser spacecraft with a capture mechanism executes manoeuvres to capture the target (Figure 4). Before the scenario starts, the spacecraft has successfully completed a search and approach phase, where the container is found and its orbit is estimated using a camera.

The scenario begins in the middle of the closing phase when the spacecraft is in the same orbit as the target and is 1 km behind. This is the distance at which competing navigation systems can detect the container. The spacecraft moves towards the target with a series of “hop” manoeuvres, the last of which brings the S/C to 100 m behind the target. During the terminal phase (the last 100 m) a forced translation manoeuvre is executed, where the spacecraft is continuously controlled to maintain a nominal velocity of 0.1m/s towards the target until the last 10 m. The capture phase starts when a final thrust is used to move the spacecraft towards the target at 0.1 m/s and is uncontrolled until target contact 100 s later. Figure 4 shows an example container relative trajectory.

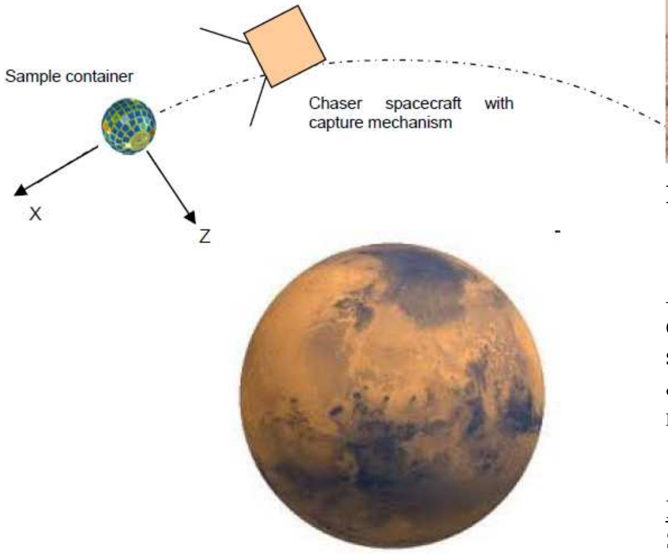

Figure 4: MSR target capture overview [3].

Mars entry, descent and landing

The Mars entry, descent and landing mission scenario used for SINPLEX is a typical Mars lander mission, as shown in figure 5. The scenario begins just before entry, when the drag forces on the spacecraft are very low. During the entry phase the spacecraft breaks via atmospheric drag to lose 5000 m/s, deploys a drogue parachute, jettisons the heat shield and slows down enough to release the lander and deploy the main parachute. The main parachute slows down the S/C further by losing another 400 m/s during the parachute phase. The propulsive phase starts at 1700 m altitude when the spacecraft fires thrusters to slow down and land at the target landing location identified during the descent. The camera is used during the propulsive phase to measure the surface slope and roughness and identify a landing location.

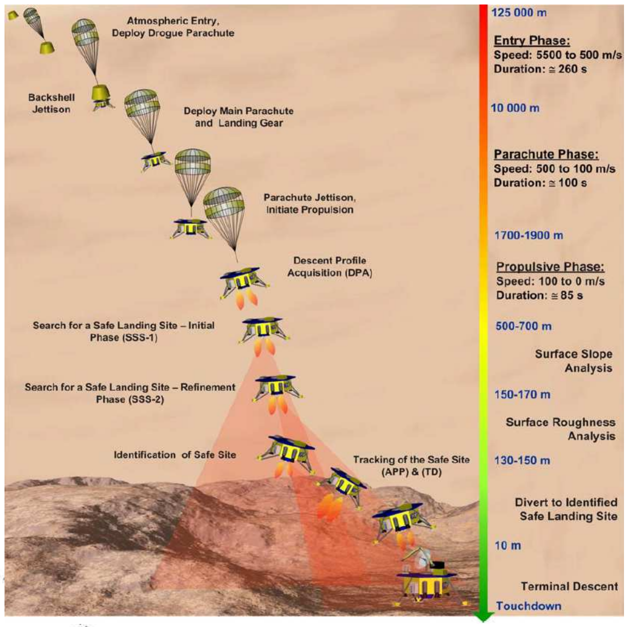

Figure 5: Mars entry, descent and landing mission profile [3].

All described mission scenarios in this chapter pose different requirements to the SINPLEX system, that should be the main actor in measuring the attitude and (relative) position of the spacecraft during the mission.

System Design & Hardware

From Requirements to Design

System Requirements were extracted from the mission requirements which were driven by the previously described mission scenarios.

These four mission scenarios each pose different challenges with respect to required functionality but we were able to create an instrument architecture (in combination with an assumptive spacecraft geometry) capable of sustaining all four scenarios.

Through a series of trade-offs we established the required functionality and redundancy levels. The flight baseline configuration of the SINPLEX is composed of the following functionalities or subsystems:

- 2 Star Trackers (STR) looking at opposite directions, providing the system with an attitude determination by identifying and comparing detected star patterns with a stored star catalogue. In case one of the Star Trackers is not functional because of solar interference, there is always one remaining star tracker available for operation on the other hemisphere.
- 2 Navigation Cameras (NavCam) that provide the system with images that shall be used for navigation and surface pattern recognition. The Navigation Cameras also act as Receiving Optics for the Laser altimeter/ranger functionality. The two Navigation Cameras have a partly overlapping field of view to enable stereoscopic observations.
- 2 Laser Altimeters/rangers (LA) that measure the distance to a target or a planetary surface.
- 2 Inertial Measurement Unit (IMU) that provide the system with both angular rate and specific force measurement data measured by gyro and accelerometer sensors. The IMU has an inherent redundancy as it comprises of a tetrahedron set-up of four gyros/accelerometers. As such, losing functionality for one out of four, this can be accommodated by the remaining three.
- 1 Navigation Computer (NC) collecting data from subsystems and using this data for the navigation algorithms, and outputting a state vector at a certain time frequency. The Navigation Computer (NC) also handles the communication with the S/C and is built on a master/slave redundancy design philosophy.

Figure 6 shows a system and subsystem overview of the SINPLEX system.

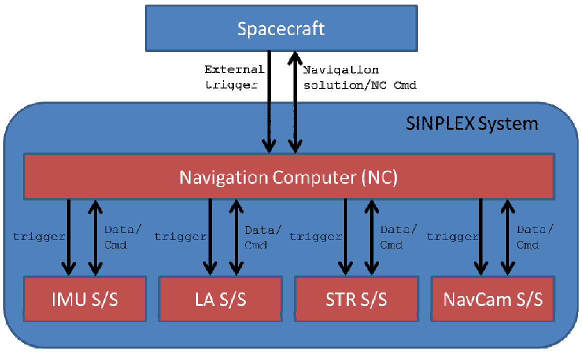

Figure 6: the SINPLEX system and subsystems

The aim is to build all this functionality into a single housing and as such reach a first level of integration. A second level of (real) integration is achieved in combining the Navigation Camera optics with the receiving optics for the laser altimeter/ranger functionality.

Sensor data fusion is enabled by the fact that different sensors could provide attitude data, although under different circumstances and with different accuracies. An example is the IMU which is independent of any external lighting condition. On the other hand, IMU's tend to be less accurate over large time periods so they need to be calibrated once in a while. Another example is the laser altimeter. Because the two navigation cameras have a partial overlap in their fields of view, this will also yield distance information to objects involved.

<u>SINPLEX flight design specification</u>

The flight design of the SINPLEX instrument has a mass of 4.8 kg and is packed with redundant sets of star trackers, navigation cameras, Inertial Measurement Units (IMU), laser altimeters and the navigation computer. The combination of these sensors should provide reliable, robust and high frequency information on the (relative) position and attitude such to enable the host spacecraft to perform timely and well-informed attitude and orbit actuation.

Figure 7 shows the flight design of the SINPLEX system.

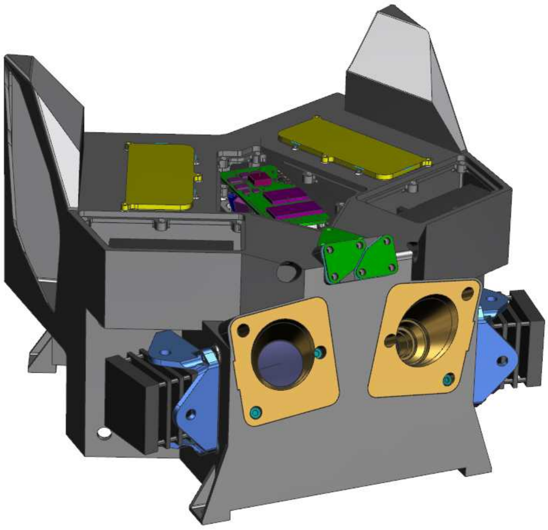

Figure 7: flight design of the SINPLEX system

The IMU is visible on the top, in the center. The electronics and detectors are all inside the monolithic structure.
The two 'eyes' on the front side are the apertures of the two Navigation cameras. Just above the two Navigation Cameras are two holes which are the beam exits for the laser altimeter/ranger. Next to the Navigation Cameras are the Single Photon Avalanche Detectors (SPADs) for the laser altimeter/ranger.
The light for the laser ranger detection system is split out by a notch reflection filter that reflects 532 nm and transmits the remainder of the light for detection by the HAS2 Navigation Camera 2d array detector. For the Navigation Camera this implies that the largest part of the visible spectrum will be observed, however a band around the laser wavelength of 532 nm will be missing. Since the objects under observation are broadband illumination this property of the filter does not significantly affect the imaging performance or properties.

Figure 8 and figure 9 show the optical raytracing inside the Navigation Camera. Figure 8 shows this for the Navigation Camera functionality with the lightbeams ending on the HAS2 detector plane. Figure 9 shows that the incoming light for the center direction with a wavelength of 532 nm is reflected off to the side where the SPAD is mounted.

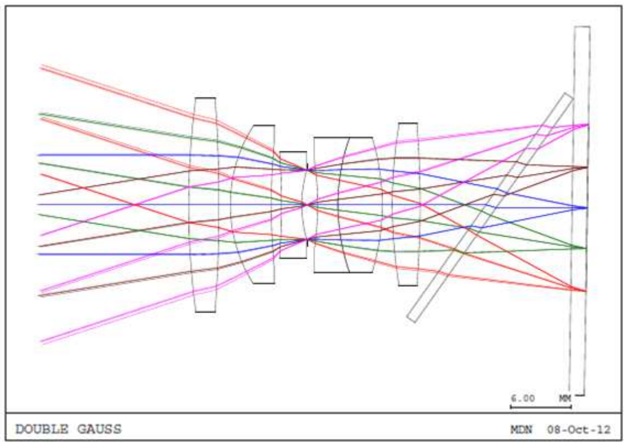

Figure 8: Optical raytracing for the Navigation Camera

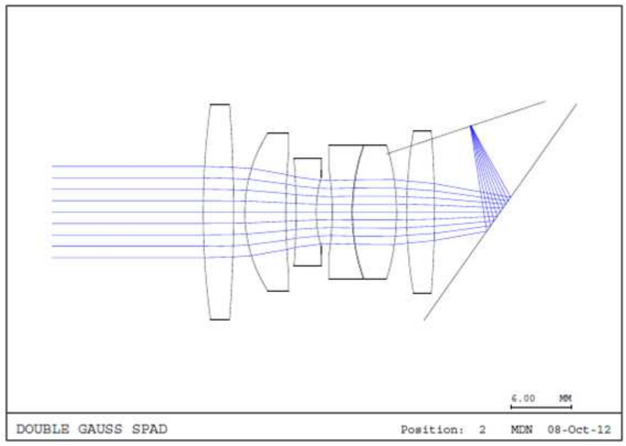

Figure 9: Optical raytracing for the receiving optics of the Laser altimeter

The two 'ears' on the top in figure 7 are the stray light baffles for the two Star Trackers. Figure 10 shows the two mirror optical design for the Star Tracker which is built inside the SINPLEX housing.

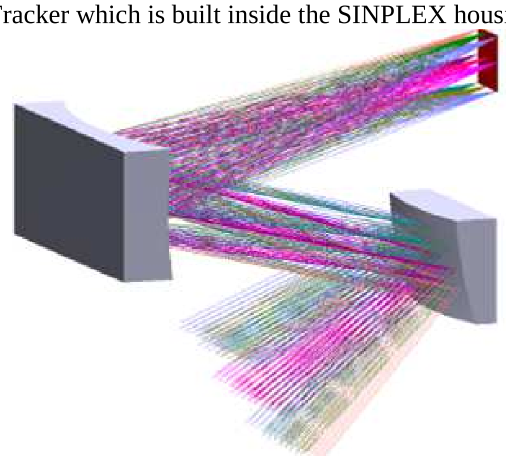

Figure 10: Two mirror optical design for the Star Tracker

This two mirror optical design was previously developed for the Multi Aperture Baffled Startracker (MABS) [7] and features a very compact design compared to its competitors.
Table 1 provides an overview of the specification of the SINPLEX system.

Parameter	**Value**	**Unit**
Maximum power use	51	W
Nominal power use	33	W
System mass	4.8	kg
System volume	7000	cm^3
Navigation Camera FOV	40x40	degrees
Navigation Camera aperture	10	mm
Navigation Camera overlap FOV	20x40	degrees
Star Tracker FOV	20x16	degrees
Maximum star magnitude level	5.6	N/A
Signal to noise of detector pixel at Maximum star magnitude level	11	N/A
Star Tracker pointing accuracy	12-25	arcsec
Navigation Camera and Star Tracker detector	ONSEMI HAS2	N/A
Laser characteristics: - Wavelength - Peak power - Pulse width - Rep. rate - Energy/pulse	 532 6 550 7 3.5	 nm kW ps kHz µJ
Working distance for Laser altimeter/ranger	15 – 8500	m
Navigation solution output frequency	1	Hz
Navigation Camera and Star Tracker FPGA	ProASIC3E	N/A
IMU Gyro performance: - Bias level - Random walk - Bias stability	 360 2.7 12	 deg/h 3σ deg/√hr 3σ deg/hr 3σ
IMU Accelerometer performance: - Bias level - Random walk - Bias stability	 10 0.0318 1.5	 mg 3σ m/s/√hr 3σ mg 3σ

Table 1: specification of system and performance parameters of the SINPLEX flight system

More detailed information on the SINPLEX system and subsystem design can be found in [6].

SINPLEX Prototype hardware

A hardware breadboard of the SINPLEX instrument is currently under construction with which we aim to reach Technology Readiness Level (TRL) 4, i.e. a component and/or breadboard validation in laboratory environment with a specific aim that the design is based on space qualified components. Where this is not possible financially or schedulewise, we aim for as much as possible space representative components or space qualifiable components.
This 3.4 kg prototype instrument represents a non-redundant version of the flight model design. The redundancy is not necessary for the validation of the TRL-4 level and also minimizes project cost.
For the housing of the SINPLEX prototype system though, we decided to build a flight representative model.
Figure 11-18 show prototype hardware that is being used in the assembly and integration of the SINPLEX prototype.

Figure 11 shows the aluminum casted housing for the SINPLEX prototype after anodizing surface treatment and accurate machining of mounting surfaces for optical components and printed circuit boards.

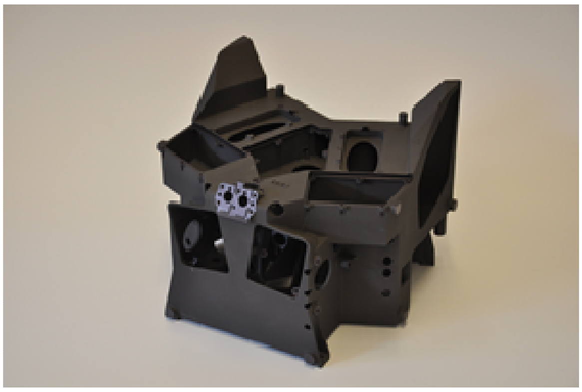

Figure 11: SINPLEX prototype housing after casting and mounting surfaces machining and anodizing treatment

The instrument housing is produced with the investment casting technology by the German company Zollern that enables integration of functionalities to the maximum extent. This technology is not yet space qualified. Currently no obstructions to space qualification are foreseen. The aluminium casting technology offers a great number of advantages. One of them is that the mechanical designer has full freedom to create structures that are otherwise not possible, i.e. with conventional production technologies such as diamond turning. This can lead to significant mass savings.

Figure 12 shows the Navigation Camera Lens barrel which holds the lenses for imaging light onto the HAS2 2d array detector mounted at the top. This unit is assembled and integrated separately from the SINPLEX housing structure. The Navigation Camera Lens barrell is inserted as a whole into the SINPLEX prototype housing structure (visible in figure 15).

Figure 12: Navigation Camera Lens barrel

Figure 13 and 14 shows the tailor made Inertial Measurement Unit (IMU) with the tetrahedron shaped geometry of the four accelerometer/gyro boards (on the right side of the unit).

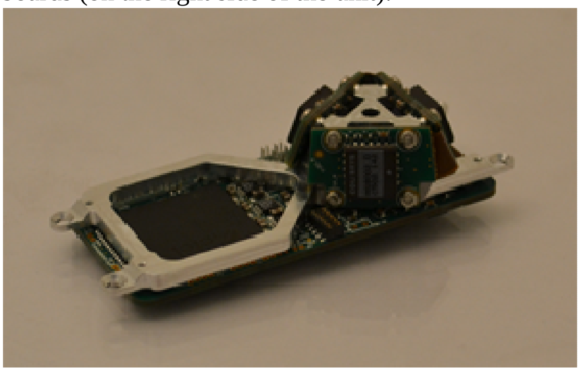

Figure 13: Inertial Measurement Unit (IMU) PCB with the tetrahedron shaped construction with the gyros/accelerometers

Figure 14 shows the IMU integrated into the SINPLEX prototype housing.

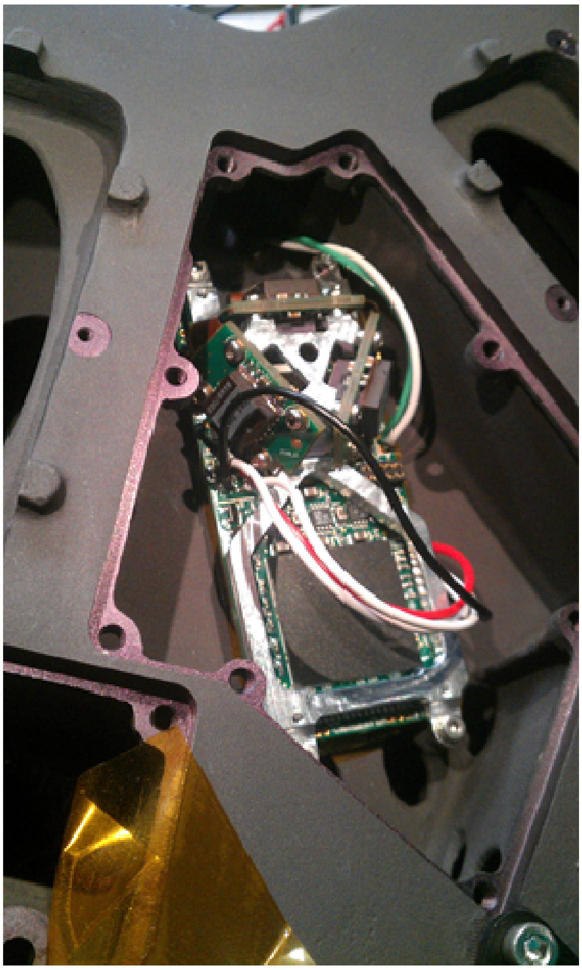

Figure 14: The Inertial Measurement Unit (IMU) integrated into the SINPLEX prototype housing

Figure 15 shows the integration of the Navigation Camera Lens barrel and the SPAD detector for the laser altimeter/ranger, with the SINPLEX prototype housing structure. Also visible in figure 15 is the laser unit, with a yellow top, which, through a beam expander with 3 mirrors inside the SINPLEX housing structure, points a beam to the center of the field of view of the Navigation Camera.

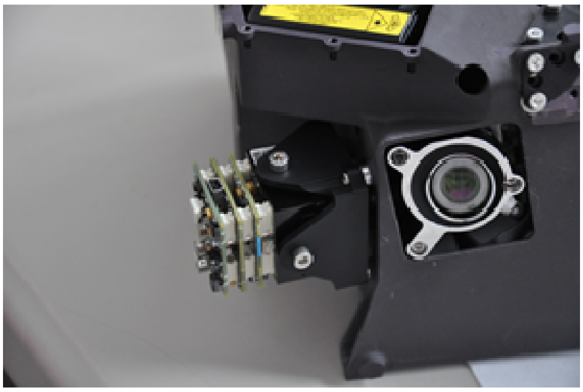

Figure 15: Laser module, SPAD detector and NavCam lens barrel

Figure 16 shows the two mirrors of the Star Tracker before integration into the SINPLEX prototype housing structure. The design of the two SINPLEX star trackers is an exact copy of the patented Multi Aperture Baffled Star tracker design by TNO [7].

Figure 16: SINPLEX prototype Star Tracker mirrors. The chosen solution for the star trackers is a patented reflective design called the Multi Aperture Baffled Star tracker [7]

Similar to the Navigation Camera, the Star Tracker uses the same HAS2 2d array detector, which leads to efficient development and use of electronics.

The Navigation computer for the SINPLEX prototype is composed of two printed circuit boards (PCBs). One of them is the DPCU (Distributed Power Control Unit), shown in figure 17.

Figure 17: DPCU-1 PCB

The DPCU-1 provides the power and data interface from the OBC-lite (On-Board Computer) to all the SINPLEX subsystems.

Figure 18 shows the OBC-lite (On-Board Computer) printed circuit board. The OBC-lite is also the data interface to the S/C.

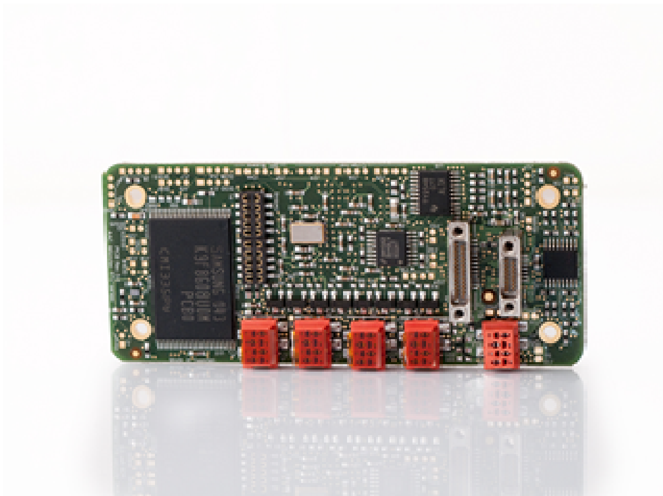

Figure 18: OBC-lite printed circuit board

All SINPLEX prototype hardware is currently being integrated into the SINPLEX housing and prepared for testing in the last months of 2013. Next to general functional tests of the SINPLEX prototype, the SINPLEX prototype will also be tested in two advanced test facilities at DLR premises in Bremen. Firstly, the SINPLEX prototype will be used in the *Testbed for Robotic Optical Navigation* (TRON) facility. TRON simulates all environment data relevant for an optical navigation system. This includes the dynamic, geometric and optical conditions which can occur during a planetary landing or container capture scenario. The facility consists of a robotic arm which shall host the SINPLEX prototype, a terrain model used as an optical target and a lighting system to simulate the terrain lighting conditions. Figure 19 shows the TRON facility with the wall, where the terrain model can be mounted, on the left. The center shows the rails on which the robotic arm is located and can be translated. On the right, the illumination source is shown.

Figure 19: the Testbed for Robotic Optical Navigation (TRON) facility at DLR in Bremen, Germany

The second advanced test that is planned for SINPLEX is in the *Test Environment for optical Navigation Systems On airfield Runway* (TENSOR) facility. This facility consists of a car which will host the SINPLEX prototype, a long straight road to drive on and an optical target at the end of the road. This facility is used to test the combination of all sensors in the SINPLEX prototype. The only difference to in-space operation is that the velocity range is much smaller than could be experienced in space.
Figure 20 shows the two main ingredients of the TENSOR facility: the runway and the car.

Figure 20: the TENSOR (Test Environment for optical Navigation Systems On airfield Runway) facility at the airfield of Lemwerder, Germany

Conclusions & Outlook

The market for SINPLEX systems is likely to evolve the coming decade, from strictly exploration and solar system science missions, to markets such as active debris removal and satellite servicing. Once the SINPLEX system is proven on an exploration or solar system science mission, and a robust configuration is established, this should lead to a production line of such systems for these new markets.

The SINPLEX project is supported by the European Community Framework Programme FP7 Space, grant agreement no.: 284443.

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