DEVELOPMENT AND TEST RESULTS OF SINPLEX, A COMPACT NAVIGATOR FOR PLANETARY EXPLORATION

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ABSTRACT

SINPLEX is an innovative, very compact, multipurpose and self-standing highly integrated suite of instruments designed for Guidance, Navigation and Control (GNC) applications. The GNC applications for which SINPLEX has been designed for is the support throughout various navigation phases, from space travel to rendez-vous and landing, to spacecrafts and their robotic landers. The system can be tailored to also fit applications such as Active Debris Removal (ADR). SINPLEX in its full redundant configuration exhibits a mass of 4.8 kg, a volume of 170 x 210 x 200 mm^3, and a power consumption of 32 W. The instrument is packed with redundant sets of Star Trackers (STR), Navigation Cameras (NAVCam), Inertial Measurement Units (IMU) and Laser Altimeters (LA). The two Navigation Cameras have a partly overlapping field of view to enable stereoscopic observations. The combination of these sensors provides reliable, robust and high frequency information on the relative position and attitude to enable spacecraft timely and well-informed attitude and orbit actuation.

SINPLEX is a research and development project funded by the European Commission (7th Framework Programme, project no. 284433) and has been developed by a consortium of European entities, comprising of DLR from Germany, TNO, cosine and SystematIC from The Netherlands and ÅAC Microtec AB from Sweden.

1 INTRODUCTION

The Small Integrated Navigator for PLanetary Exploration (SINPLEX) is a highly integrated payload composed of four separate instrument types: Laser Altimeter (LA), Star Tracker (STR), Navigation Camera (NAVCam) and an Inertial Measurement Unit (IMU). All the instrument data is conveyed in the Navigation Computer (NC), which computes the navigation solution. SINPLEX can be used to aid a spacecraft/lander in various phases of spaceflight, such as interplanetary navigation, descend and landing activities, and in orbit rendezvous and docking. The resulting payload is a low mass, low volume and low power consumption multi-purpose instrument suite, designed for easy integration on a number of different spacecrafts and for a variety of missions. Moreover, the single instruments can also be used individually throughout the different mission phases where needed.

The SINPLEX design is centred on component miniaturisation, hardware integration, resource sharing between the instruments and data fusion. In order to ensure the fault tolerance the flight model foresees all instruments in a full redundant configuration. A prototype of SINPLEX has been realized and it is being tested up to TRL 4.

2 SINPLEX DESIGN

The instruments of SINPLEX are accommodated in an aluminium casted monolithic housing, which enables integration of the optical systems to the maximum extent. The aluminium investment casting technology is not yet space qualified, however no show stoppers for the qualifications are foreseen. This manufacturing process presents many advantages, such as the possibility of creating a shape with inner cavities, that would be otherwise very difficult to machine, and good dimensional accuracy. Although resulting in complexity, the monolithic structure ensures very good thermal conduction and equal temperature distribution throughout the system. The walls of the compartments are 1.5 to 2 mm thick making it a lightweight structure, ideal to be implemented with internal baffles.

The single housing allows the integration of the pre-aligned navigation system on a spacecraft with simple defined interfaces.

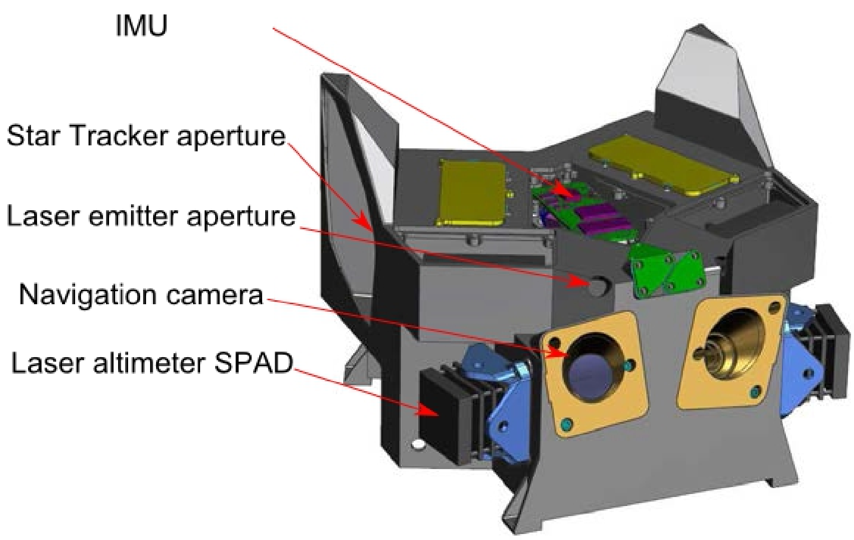

Figure 1: SINPLEX design with complete redundant instruments

Specifications of the SINPLEX instrumentation are detailed in Table 1.

Table 1: SINPLEX instruments specifications

Total Mass	4.8 Kg
Size (LxWxH)	30 x 30 x 30 cm
Power	Nominal 33 W Peak : 51 W
Laser Altimeter	
Wavelength	532 nm
Operational range	8500 to 15 m
Navigation Camera	
Spectral range	400 – 800 nm

FOV	40 x 40 degrees
Aperture	10 mm
Resolution	1024 x 1024 pixels
Star Trackers	
Spectral range	400 – 800 nm
FOV	20 x 16 degrees
Maximum star magnitude level	5.6
Resolution	1024 x 1024 pixels
IMU	
Accelerometer - Random walk - Bias stability	360 deg/h 3σ 2.7 deg/ √ hr 3σ 12 deg/hr σ
Gyroscopes - Bias Level - Bias Stability - Random walk	10 mg 3σ 0.0318 m/s/ √ hr 3σ 1.5 mg 3σ

2.1 Subsystem Integration

Subsystem integration is the key of the SINPLEX payload. The subsystems share the same housing and, when possible even the same optical components, reducing the number of interfaces and providing an increased stability. Given the radiometric requirement differences among the optical systems, the star tracker optics are self standing, while the Laser altimeter receiver and the NAVCam share the receiving optics. The optical paths of the laser altimeter and of the star tracker are folded inside the structure, in order to keep the dimensions of the instrument compact. The laser emitter consists of a beam expander with reflective elements. The laser beam is folder multiple times before exiting the SINPLEX housing (Figure 2 left) crossing the entire structure. The optical system of the Star Tracker is shown in Figure 2 (right) and consists of two mirrors which focus on the detector the light entering the aperture via a short baffle.

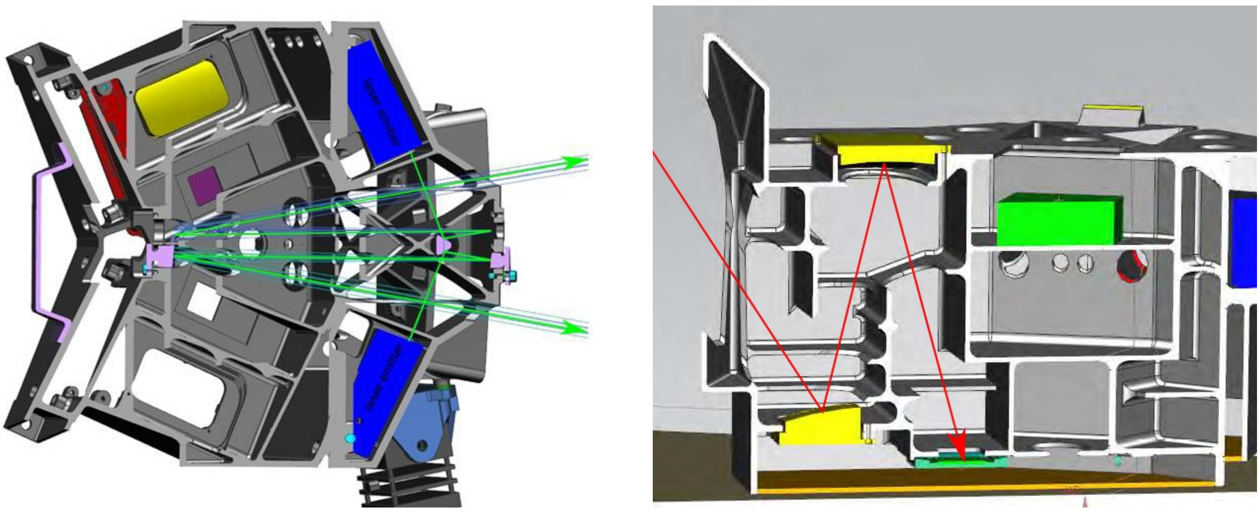

Figure 2: (left) folded laser path in the SINPLEX housing; (right) folded optical path for the star tracker

During certain navigation phases, such as descend and landing, the laser altimeter and the navigation camera need to operate simultaneously. Both instruments need therefore to be co-aligned, and the optical path sharing saves the corresponding structural mass needed for creating duplicated baffled optical paths. The 532 nm wavelength emitted laser light has to be separated from the visible light that is used for the NAVCam. This separation is achieved by a tilted beam splitter that reflects the laser light under an angle close to 45 degrees and transmits all other wavelengths to the NAVCam detector, as shown in Figure 3.

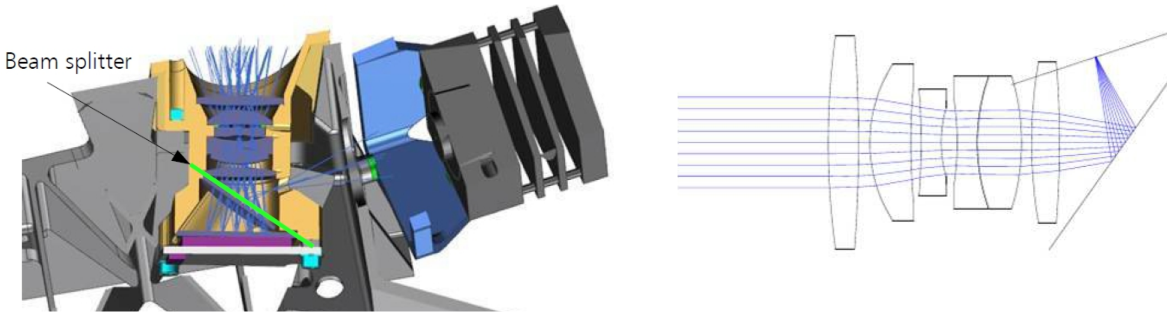

Figure 3: NAV Cam and laser altimeter receiver optics

Another level of integration is at processor level: all sensors share the same processor and data interfaces, eliminating the need for multiple sensor interfaces.

3 SUBSYSTEM DESCRIPTION

3.1 Navigation Computer

The Navigation Computer in directly interfaced to the spacecraft, and provides the navigation solutions generated from the fusion of the data from all the various SINPLEX subsystems. All measurement data generated by the single sensors is processed in order to achieve an accurate navigation solution. Hybridization of the different sensor measurements is achieved with image processing and navigation fusion software on the navigation processor. Timing and synchronization of measurements is also important, which are orchestrated by the navigation processor.

The Navigation algorithm is able to provide:

- Attitude information of the spacecraft without a priori information (lost-in-space mode);
- Terrain and crater navigation;
- Container finding from far and close range;
- Descend and landing.

3.2 Star Tracker

The Star Tracker is based on a reflective optics telescope and a 1 Mpixel CMOS detector. The two star trackers are facing opposite directions. A star catalogue is embedded in the navigation computer.

3.3 Navigation Camera

The NAVCam consists of a diffractive objective and a 1 Mpixel CMOS detector, and operates in the visible range (400 nm – 800 nm wavelength). The baseline design is based on a double Gauss design approach. The layout of the navigation camera is shown in Figure 4. The two navigation cameras are facing in the same direction and overlap in the central region.

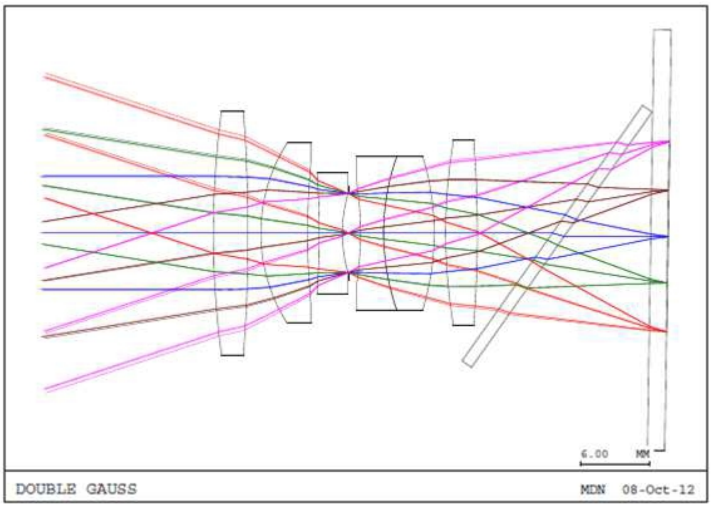

Figure 4: NAV Cam optical ray-tracing

The NAVCam uses the same detector as the Star Trackers. As the NAVCam signal processing is much more elaborate than the STR centroiding in the FPGA, more processing power is required. For some mission scenarios, i.e. crater navigation, each frame requires initial signal processing in order to locate the navigation landmarks in each picture. This requires part of the algorithm to be implemented in an FPGA, while another part of the algorithm has to be implemented in a microcontroller. The data is then forwarded to the Navigation Computer so that the identification process can determine the position from the observed scene.

3.4 Laser Altimeter

For the ranging measurements photon-counting laser altimeters are employed, which are pointed at the centre of the combined FOV of the two NAVCams. The Laser Altimeter works by emitting short, powerful light pulses to a surface and measuring the time of flight of the reflected photons. By using a single photon detector, the power of the emitted light pulse can be lowered dramatically with respect to traditional laser altimeters. This enables the use of passive Q-switched microchip lasers that emit short light pulses, typically on the order of a nanosecond, at repetition rates of a few to several tens of kilohertz and pulse energies of a few micro Joule. These high repetition rates allow statistical analysis of the time of flights, which reduces the effect of background or noise photons on the distance measurement while still maintaining high measurement rates. The measurement accuracy is determined by the pulse length, the timing resolution of the detectors and electronics and the number of samples are taken into account in the statistical analysis.

The Laser Altimeter is equipped with an analysis board. The board includes an FPGA with an embedded algorithm, which accurately records the time of flight of each of the returning pulses and performs statistical analysis on the time of flight of the received photons, through which the noise generated by background photons can be discarded. The resulting distance measurement and status information on the Laser altimeter is then fed into the SINPLEX Navigation Computer (NC).

3.5 IMU

The SINPLEX IMU pre-processes the measured data and delivers data in a three axes coordinate system. Each IMU is built up as a tetrahedron shaped structure and comprises four accelerometers and four gyro sensors, where the sensing axis vectors have the constellation orthogonal to the sides of a regular tetrahedron. The IMU, as the other systems, are full redundant on all axes in the flight configuration. The specialty of this structure is that a random combination of measurements from three of the four sensors sets results in an IMU measurement with constant accuracy thanks to the fact that the sensors on each plane measure a component of the acceleration and rotation of all three axes. In case all four sensor sets are used for a measurement, the accuracy of the measurement improves.

4 BREADBOARDING ACTIVITIES

A prototype of SINPLEX has been realized. For the purpose of validating the concept, the redundant instruments have not been included in the prototype. In order to keep the prototype as representative as possible of the flight Model, either components with a space qualified equivalent, or that alternatively are judged qualifiable, are used. The prototype therefore includes the following:

- 1x Laser Altimeter
- 1x NAV Cam
- 1x Start Tracker
- 1x IMU unit
- 1x Navigation computer
- 1x Power distribution unit

The prototype housing (Figure 5) was manufactured with the investment casting technique and the mechanical interfaces of optical components were milled out with very small tolerances. The housing was then black anodized in order to increase protection against oxidation, to eliminate electrical conductivity, and to reduce the amount of stray light in the system.

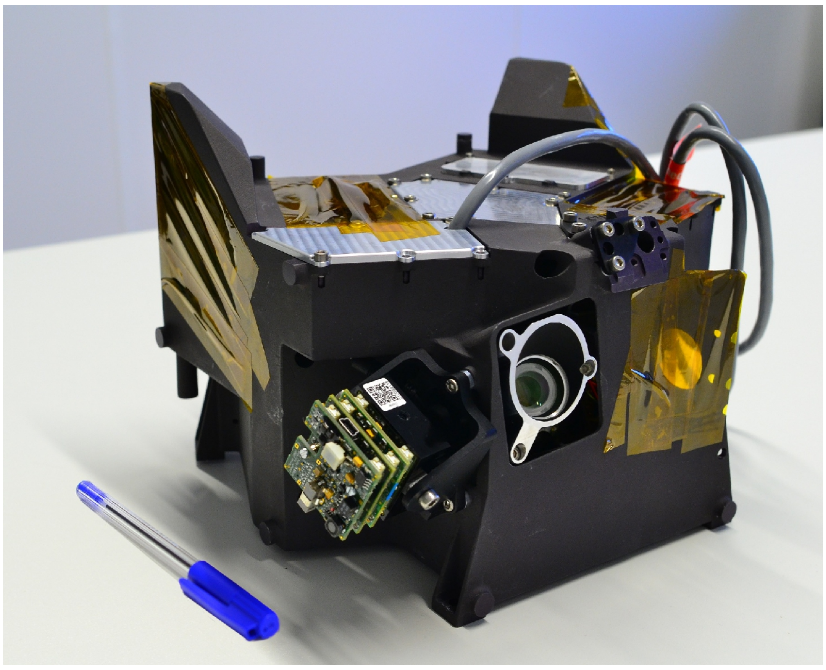

Figure 5: SINPLEX prototype housing

5 TESTING ACTIVITIES

5.1 Testing Strategy

Testing of the SINPLEX prototype is broken down into a number of small steps, with the final goal of testing the full integrated system in DLR’s Testbed for Robotic Optical Navigation (TRON) and the Test Environment for optical Navigation Systems On airfield Runway (TENSOR) using unscaled realistic trajectories of four different mission operational scenarios, which were used to drive the system requirements. The aim of the testing phase is to reach TRL 4 (validation in laboratory environment).

The operational scenarios are:

- Lunar descend and landing
- Asteroid descend and landing
- Sample container rendezvous and capture
- Mars descend and landing

Testing began in DLR’s Hardware in the Loop (HIL) laboratory where the functional performance of the system was evaluated. Each subsystem was tested individually to check that the sensor functionally behaves as designed, checking also the communication between the Navigation Computer and the various subsystems.

Testing continued in the TRON facility (Figure 6), where the system was mounted on a robotic arm and the navigation camera and the laser altimeter are pointed towards a 3D terrain model. Further sensor measurement performance tests were done, including static and dynamic tests. Integrated system tests were then done, where the navigation algorithm used multiple sensor measurements to navigate an unscaled controlled linear test trajectory. Finally, the system was tested using unscaled trajectories from the simulated mission scenarios.

In DLR’s TENSOR facility the SINPLEX navigation system will be mounted on top of a car with the navigation camera and laser altimeter pointing forward. The system will be driven towards a large stationary target at speeds similar to the moon landing scenario. This test will evaluate the performance of the full system with long ranges and high speeds. Testing in TENSOR facility is ongoing and results are not yet ready to be published.

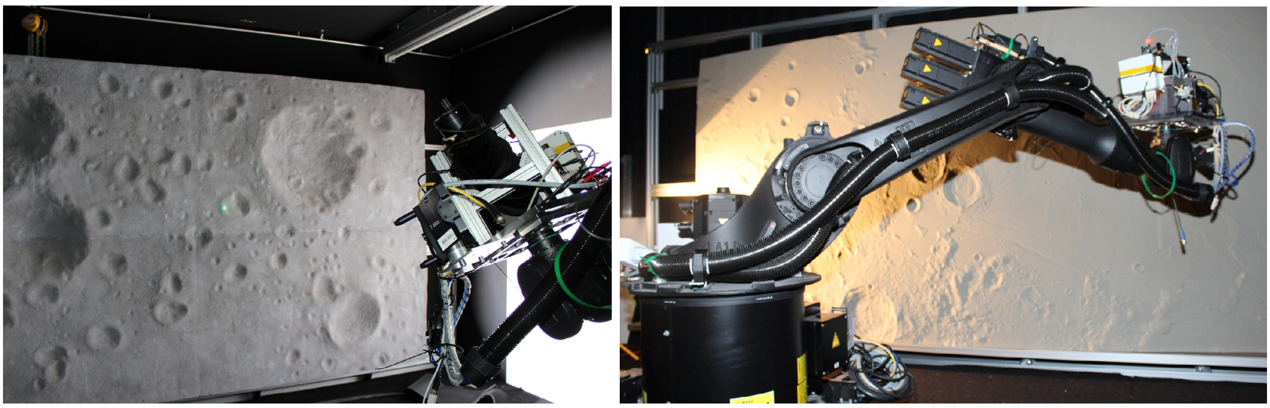

Figure 6: SINPLEX installed in the TRON facility with EGSE [1].

5.2 Test Results

The SINPLEX prototype was tested with several different sections of the Moon and asteroid landing trajectories. One set of trajectories pass laterally over the terrain at a (approximately) fixed distance and velocity and simulate parts of a descent orbit. A separate trajectory starts 10 m away from the terrain and moves mostly perpendicularly towards the terrain, which is based on the last 10 m of a simulated asteroid landing trajectory.

For the lateral trajectory 16 different runs were done on 2 different terrain models at various speeds. Speeds ranged from 0.07 to 0.73 m/s and the terrain relative (TR) distance was maintained at around 3.6 m. The performance of the system is summarized in Table 2. The system generally has better performance at lower speeds, but the biggest influence on performance is the quality of features in the navigation camera images. The wide range of performance values is indicative of the wide range of feature qualities seen during testing.

Table 2: Summary of SINPLEX performance in translational trajectory tests.

Parameter	**3σ error**
TR velocity [m/s]	0.05 to 0.1
TR position [m]	0.02 to 0.2
Attitude [deg]	0.1 to 0.3

Figure 7 shows the asteroid landing trajectory in the TRON reference frame. The navigation camera axes are colored red, green and blue for the x, y and z axes respectively. The prototype is driven along the y-axis towards the target and simultaneously moved in the –x-direction. The attitude of the prototype is constant throughout the trajectory and the navigation camera always points towards the target. Ten runs were done with the asteroid terrain model and a fixed trajectory. Speed and lighting remained the same from run to run. The system performance for these runs is summarized in Table 3. The system has similar performance in the lateral trajectory tests. Performance is worse for TR position and attitude since the distance to the terrain model is constantly changing, causing the system to continually re-evaluate its estimated terrain model [2].

Figure 8 shows the detailed results for TR velocity error, which is the most important performance metric. In the plot, the results from all 10 runs are plotted together in thin solid coloured lines. The thick dashed blue line is the 3σ error, combining all 10 runs. The thick dashed red line is the mission requirement value. There are two outlining runs which exceed the requirement in the z-direction, which is due to falsely identified features found during the run. Otherwise, the system performance meets or is very close to meeting the mission requirement throughout the run. There is still room for improvement in the SINPLEX design and these results will improve in the next generation [2].

Table 3: Summary of SINPLEX performance in asteroid trajectory tests.

Parameter	**3σ error**
TR velocity [m/s]	0.05 to 0.2
TR position [m]	0.05 to 0.2
Attitude [deg]	0.1 to 0.3

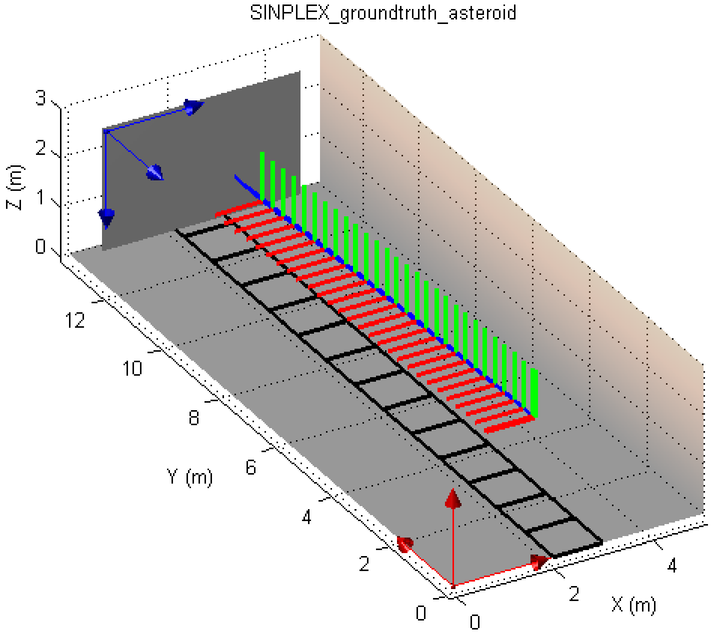

Figure 7: Asteroid trajectory in TRON reference frame.

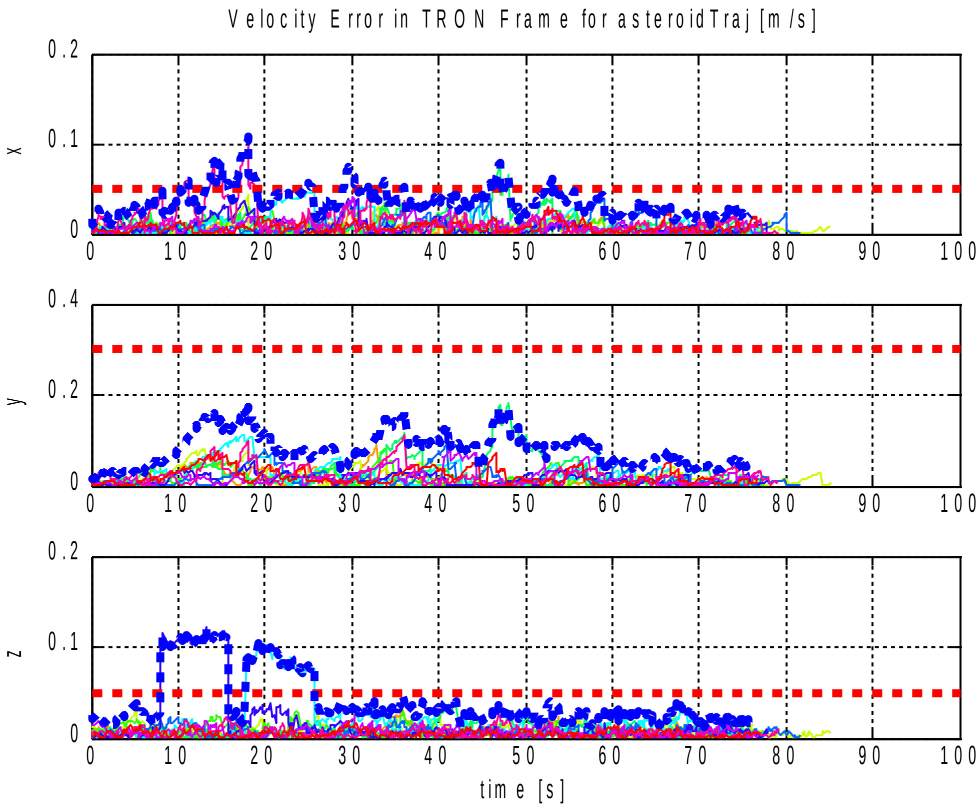

Figure 8: Terrain relative velocity error for asteroid trajectory tests.

6 CONCLUSIONS AND OUTLOOK

The proposed miniaturized integrated navigation system is an innovative solution for GNC subsystems providing autonomous, real-time, object-relative and precise navigation information using redundant components with a total subsystem mass below 6 kilograms, representing a valid alternative to the classical component/subsystem principle, where every detector has its own enclosure and (for optical sensors) its own aperture. The system has simple and well defined mechanical, data and power interfaces which allow to integrate the system on a number of different spacecraft missions reducing the integration and alignment efforts.

The breadboarding and testing activities performed in the last few years have demonstrated the feasibility of the SINPLEX concept. All subsystems have been tested after integration in the housing, and the tests showed the expected performance. A full system test has been set up in the lab and various tests with different conditions have been done to assess the performance of the system.

The near future development effort will focus on the advancement of the current technologies, both hardware and software, to increase the system TRL up to level 6, and to adapt the design to the specific application of Near Earth Objects (NEO) orbiting and hovering, including adaptation to high velocity NEO impactor spacecraft.

7 REFERENCES

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