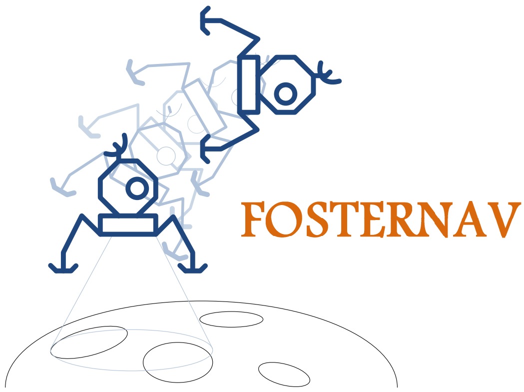
Flash Optical Sensor for Terrain Relative Navigation

FOSTERNAV



Final Report

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Executive summary

The smooth landing of Curiosity on Mars ground in August 2012 with a precision never achieved is a remarkable example of what can be accomplished by autonomous exploration spacecrafts.

In a close future several planned European or international exploration missions (Phootprint, Mars Precision lander) also include a phase of controlled descent and soft-landing with an even higher precision required. Their success stands largely in the ability to perform Terrain Relative Navigation (TRN) and surface Hazard Detection (HD) as these missions will land in areas crowded by craters, crevasses, boulders, etc.

The project “Flash Optical Sensor for Terrain Relative Navigation” FOSTERNAV is a contribution to maintain the autonomy of Europe for space exploration. It targeted the development and the test in realistic conditions of a vision sensor based on light detection and ranging techniques (LiDAR).

The targeted space applications for this type of sensor are not only the controlled descent and landing applications but as well applications such as in-orbit rendezvous, rover navigation, and the autonomous removal of space debris orbiting the Earth. This last application represents a critical environmental challenge for the international community in the future.

In Europe, FOSTERNAV was a pioneer activity allowing European actors (CSEM, VTT, DLR, Modulight and Airbus D+S) to collaborate in the development and assessment of the flash imaging LiDAR technology. This technology has a high potential for space but as well for terrestrial applications. This vision sensor architecture generating three-dimensional snapshot images of the scene of interest will have a strong impact on the autonomy of various types of vehicle. The use of such sensors is foreseen for example for the surveillance - due to its unique capability of seeing through foliage or camouflage - of national border where the sensor may be embarked on unmanned aerial vehicles. Its capabilities are also investigated for the autonomous driving in urban environments of cars and trucks.

The eleven milestones of FOSTERNAV have all been achieved with success. The main project outcomes are:

1. A fully functional Flash LiDAR prototype of TRL4 available for further testing,
2. A patent about the prototype transmitter design and manufacturing,
3. The increase of European expertise in design, fabrication and testing of sensors for space,
4. Settled and verified processes amongst several partners to build and test in representative operational conditions flash imaging LiDAR for space applications.
5. Competences in optical systems with high-power diode laser modulation and fibre-optic,
6. Establishment of test facilities and test procedures constituting a standard environment to test navigation sensors.

Contents

Summary of project context and main objectives

The origin of the project FOSTERNAV finds its roots in the stated need for new Guidance, Navigation and Control (GN&C) technologies that will allow fulfilling future robotic and human space exploration missions' terms of requirements. FOSTERNAV is aiming at providing to spacecraft GN&C systems, a new generation of vision-based sensors that will enable a variety of future space missions such as:

- In-orbit rendezvous and docking with cooperative targets or capture of uncooperative objects like space debris,
- Autonomous, precise, safe and soft descent and landing on celestial objects such as Mars, Near Earth Objects (asteroids) or the Moon,
- Autonomous planetary rover navigation

Step improvements in vision-based sensors performances and functionalities are needed to ensure the success of future robotic, cargo and manned exploration missions.

Project context

The context of the project is defined by the objectives of future missions imagined by space agencies worldwide. The missions' objectives are for example to land softly, precisely and autonomously on Mars or on Asteroids precious scientific instruments or to remove space debris with automated spacecrafts.

Currently, the benchmark of missions targeting a landing is defined by the Mars Science Laboratory (MSL) that landed in 2012 the Rover Curiosity smoothly and precisely on the surface of Mars. MSL used a navigation sensor based on RADAR technology for the Entry, Descent and Landing (EDL) of the descent stage. The precision of the guided landing was within a 20 km ellipse. To achieve such unprecedented precision the descent stage was equipped with a RADAR system called the "Terminal Descent Sensor" (TDS). It is made of 6 antennas: three emits canted 20° off nadir, two beams canted 50° off nadir, and one nadir beam (Figure 1). The TDS weights 25 kg and consumes 100 watts of electrical power. The sensor provides exact altitude and velocity data. MSL is a milestone mission which succeeded to land smoothly and precisely on Mars a payload of 1000kg.

In the future several planned exploration missions are also including a phase of controlled descent and, soft and pin-point landing with an even higher precision than MSL (e.g. OSIRIS-REx, Phootprint, Mars Precision Landing, etc.). The success of these missions stands partly in their ability to perform Terrain Relative Navigation (TRN) and Hazard Detection (HD) to land safely in areas crowded by obstacles of all sort. TDS is not able of TRN and HD.

To go beyond TDS, the orientation of the GNC community and mission planners is considering vision based sensors for achieving better performances and using less on-board resources. In this regard, **3D imaging Light Detection and Ranging (LiDAR) technologies** are considered as **key enabling technologies** for future exploration and ADR missions.

Main project objectives

Common need of the future missions is the necessity to have highly detailed and accurate digital elevation maps of the target available in real-time during the whole mission’s duration.

The core component of the sensor architecture developed in FOSTERNAV is a time-of-flight (TOF) detector array. Such detector generates three-dimensional (3D) images of the scene of interest. Such arrays have been designed to be used in first place for gesture recognition in “touch-free” interface for videogames.

The sensor architecture is derived from Light Detection and Ranging (LiDAR) instrument. Such device is capable of determining a range to a target by measuring the time-of-flight (TOF) of photons. The photons are generated by the sensor and reflected back to the sensor by the target. The sensor computes the time difference between the time of a given photon emission and the time of the detection of this photon.

The instrument obtained by inserting a TOF detector array in a LiDAR architecture is an imaging LiDAR. The term “flash” means that images of the target are captured in one snapshot. This is to qualify such LiDAR in opposition to another LiDAR family; the scanning LiDAR. Scanning LiDAR is equipped with a scanning mechanism while flash LiDAR is not. This leads to a key advantage for flash LiDAR in view of their miniaturization. The term “imaging” underlines the fact that such device provides images of the target in three dimensions as LiDAR are capable of providing not only light intensity and x,y information but also distance to a given object.

This kind of instrument is considered by the GN&C community to be a key enabling technology for mission phases involving autonomous planetary rover navigation, in-orbit docking of orbiting spacecraft with canisters transporting samples collected on celestial objects or with non-collaborative object such as space debris, and autonomous, precise and safe descent and soft-landing.

FOSTERNAV pursued the development of a flash optical sensor prototype to a technology readiness level of four (TRL4). At this maturity level, the functionalities of the sensor architecture can be demonstrated. The next development step – in the frame of another project – will be to define an approach allowing the LiDAR to survive in space environmental conditions. The main objectives of FOSTERNAV were threefold:

- the development of a novel **optical sensor architecture merging imaging technologies and time-of-flight measurements,**
- the **applicability evaluation of the sensor for object relative robotic navigation according to space mission scenarios**,
- the **design and realization of standardized assessment protocols reproducing reliably and realistically** missions' conditions.

This project is a contribution to the strengthening of the European position for space exploration. It targeted the maturation of a technology for relative navigation sensors.

The project was split in three phases: the first phase of the project focused on: the derivation of the specifications of the flash imaging LiDAR from missions' terms of requirement, the preliminary design of the sensor prototype and the definition of the test facilities and assessment protocols. The second phase was dedicated to the detailed design of the flash imaging LiDAR prototype, the preparation of the test facilities and the meticulous descriptions of the foreseen prototype assessment protocols. The third phase consisted in the assembly of the prototype and its static and dynamic assessment in various facilities representative of space applications (rendezvous, landing).

The progress toward the three main objectives was measured with 11 milestones:

Milestone number	Milestone	Achievement date (month)
1	Project start	M1
2	Finalization of the project structure and rules	M3
3	Summary of Entry, Descent and Landing missions' scenario	M6
4	Flash optical sensor list of specifications derived from missions' requirements	M7
5	Test facilities and test protocols specifications	M11
6	Sensor building-blocks specifications	M14
7	Operational test facilities	M20
8	Prototype specifications matching the test facilities features and capabilities	M23
9	Tested prototype building-blocks	M26
10	Complete sensor prototype tested statically	M30
11	Dynamic applicability assessment of the prototype	M35

Table 1: project's milestones list

All milestones and the main objectives were achieved with success. The key contributions of the project to the strengthening of the European position for space exploration are:

1. **European engineering capability to design and build an flash imaging LiDA**R for space applications demonstrated,
2. European **evaluation expertise** for vision-based sensor for automated relative navigation,
3. Availability of a fully functional **European TRL3-4 flash imaging LiDAR prototype** compatible with several test facilities.

Main Scientific & Technological results / foregrounds

FOSTERNAV consortium and partners' main role in the project

The consortium of FOSTERNAV gathers 5 organisations from 4 countries:

Country	Organisation name	Main role in project
🇨🇭	CSEM, Swiss Centre for Electronics and Microtechnology	**Project proposal lead and project coordination**, Sensor system engineering, LiDAR receiver and user interface.
🇫🇮	VTT, Technical Research Centre Finland	LiDAR transmitter and project web site.
🇫🇮	Modulight	Laser expertise, laser heads provision.
🇩🇪	DLR Bremen, The Bremen Deutsches Zentrum	Tests lead.
🇫🇷	EADS Airbus Defense and Space	Missions requirements analysis and derivation of requirements for the sensor.

Table 2: partners of the FOSTERNAV project consortium

Space missions review

The main objective first year of the project was to review several mission types where flash imaging LiDAR can play a major role in upcoming years. These missions have either a landing phase on small object (asteroids) or landing on large object (Mars), or proximity navigation or rendezvous docking phase with either celestial or Man-made objects.

At the beginning of the project in 2011 typical flag missions were Marcopolo-R (now cancelled) and Mars Sample Return (MSR). At the end of project the flag missions are Phootprint or Mars Precision Lander.

Between the various the requirements related to vision-based proximity navigation sensor may vary slightly. Roughly for such type of missions, a range spacecraft-target must be provided at several kilometres from the target. Then – around 1 kilometre - rough information about the target such as the slopes present in a given selected area of the target for an asteroid landing for example shall be provided. Finally, as the spacecraft get closer to target more detailed maps of the target shall be captured. At a few hundreds of meter from the target, the spacecraft will be in position to position itself very precisely according to the main axis of rotation of space debris or get precise information surface hazards (boulders, crevasses, etc.) present in the area selected to land. Figures are provided in the table below to define theses phases of relative navigation.

Parameter	Landing		Rendezvous Docking
	Massive body (e.g. Mars)	Asteroid	
Maximum range (m)	700m (imaging) 2km shall be targeted	500m (imaging)	5000 (ranging) XXXX m (imaging)
Minimum range (m)	10m	15m	1
Ranging accuracy %	< 1@ 1000 m <0.5@300 m	0.1	< 0.02 @ 5000 m <0.01@ 1500 m <0.06@ 150 m <1@1m
Angular resolution	0.02° x 0.02°	0.02° x 0.02°	0.05° x 0.05°
Measurement rate (Hz)	>10Hz	>0.1Hz	>1
Horizontal resolution (m)	20cm at 300m altitude	35cm at 500m altitude	N/A
Area to be imaged (m x m)	200mx200m at 700m 100mx100m at 300m	150mx150m at 500m	
FoV	> 20° x 20°	> 20° x 20°	> 20° x 20° (TBD)
Velocity relative to scene (m/s)	**Vertical**: • 20m/s between 700m and 200m • 10m/s between 200m and 10m • 1m/s below 10m **Horizontal**: • 0.5m/s between 700m and 200m • 20m/s between 200m and 10m • - 0.5m/s below 10m	**Vertical**: <1m/s **Horizontal**: <0.5m/s	<1m/s
Angular rate relative to scene (°/s)	< 2.5°/s (up to 10°/s during retargeting)	<2°/s	< 0.5°/s
Maximal view angle	70° @ 5000 m	10°	<10°
Mass (kg)	7	6	6
Power consumption (W)	40	30	30
Size of the safe landing site m x m	6 x 6	6 x 6	N/A
Local slope at the landing site °	< 20	<10°	
Target's radiometric characteristics	Mars surface	Asteroid surface	Man-made target
Operating temperature range (°C)	- 20 to 50		
Non-operating temperature range (°C)	- 30 to 60		

Sun aspect angle	> 15°		any angle
Lifetime in operating mode	> 1 day	> 2 years	> 3 days
Lifetime in non-operating mode	> 4 years	> 8 years	> 4 years

Table 3 : missions' requirements

The figures listed in the table shall not be considered as fixed for ever. They are considered to derive the specifications of the vision-based sensor that can provide all the performances to fulfil missions' requirements. However, the process is iterative by nature. Starting from missions' requirements, sensor's specifications shall be derived. Then, according to the possible performances and limitations of the technology, missions' requirements should be updated. So for so once, in iterative process until missions' requirements can be plainly satisfied and the technological constraints respected.

The prototype built in the frame of FOSTERNAV is the first generation of an European flash imaging LiDAR. Missions' requirements of Table 3 were not all targeted as for a first development they would be hard to achieve. Instead, from missions' requirements more achievable requirements were defined to define a frame for the prototype development. The table below summarizes the prototype's requirements. Three sets of requirements were defined for the phases of relative navigation: ranging (long range), slope (mid-range) and hazard imaging modes.

Mode of operation	Ranging (RAN)	Slope imaging (SLI)	Hazard imaging (HZI)
Prototype to target distance m	100	20	< 20
Ranging accuracy m	0.1	0.025	0.025
Horizontal resolution	TBD	0.025	0.025
Receiver FoV ° x °	TBD	TBD	20 x 20
Surface to be imaged m x m	15 x 15	TBD x TBD	TBD
Target or Prototype velocity m/s	TBD	TBD	TBD
Sun local elevation	<75° wrt optical axi (the angle relates to the solar background reflected by the target)		
Surface albedo	0.1-0.4		
Frame rate Hz	10		
Image time stamping precision s	0.001		
Mass kg	TBD		
Power consumption W	TBD		
Volume m x m x m	TBD		
Lifetime in operating mode days	N/A		
Lifetime in non-operating mode years	N/A		

Table 4: FOSTERNAV prototype specifications

Navigation data fusion

Unlike passive optical sensors, LiDAR sensors need to illuminate their target to measure the reflected light intensity and time of flight. The power needed for such illumination is the main contributor to the overall LiDAR consumption.

In the frame of autonomous space exploration missions, the relatively high LIDAR power consumption (compared to passive GNC sensors) is a stringent constraint. Using a flash imaging LiDAR in imaging mode makes no sense when a spacecraft is far from its objective. The energy requested to achieve a given precision is too large. Moreover, the provision of precise detailed 3D images of the objective in not a mission's requirement in these phases. At long distance mission's requirements are typically to get a range and line-of-sight (LOS) spacecraft-target.

Such considerations about the change of missions' requirements according to the range spacecraft-target leads to either define mode of operations for a given GNC sensor as the ranging, slope and imaging modes defined for the imaging LiDAR or to consider several sensors to achieve the requirements correspond to a relative navigation phase. For example, at long distance the combination of a passive standard camera and laser distance-metre or radar may be sufficient to provide the needed spacecraft-target range and LOS.

On the basis of these considerations GNC sensor combinations for planetary landing and rendezvous were proposed in FOSTERNAV.

Recommended solution for LiDAR-based planetary landing

The following solution is the best sensors combination among the different LIDAR-based landing GNC systems:

FosterNav LiDAR + Navigation camera (wide FOV) + IMU

For navigation, the LIDAR is used as an altimeter in ranging mode. It provides the depth information to the data navigation filter while maintaining the power consumption low thanks to the ranging operation mode (narrow beam divergence). This navigation system is used from parachute phase until 700m.

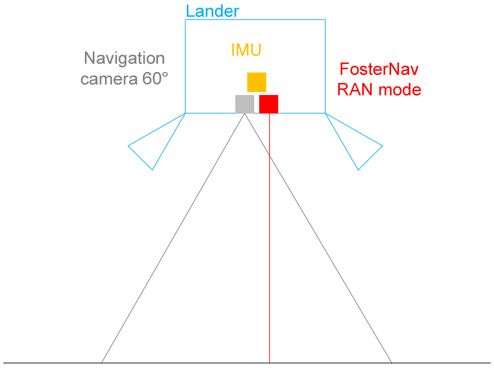


Figure 1: Baseline configuration for navigation

Below 700m altitude, the lander enters in new relative navigation phase and search for safe landing site with very low, constant vertical velocity. During this phase, the LiDAR switches from ranging to either slope or hazard imaging mode, and then optionally can be configured back to ranging mode to limit the power consumption.

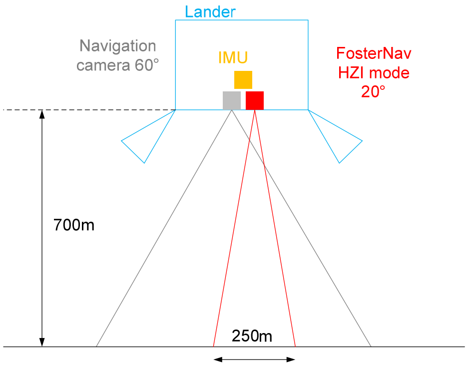


Figure 2: Baseline configuration for HDA

Recommended solution for LiDAR-based rendezvous

For rendezvous different GNC strategies were envisaged for in-orbit capture applications. Each strategy has its own strengths and weaknesses according to the optimization of a certain number of criterions like: vision-based GNC sensors field-of-view, spacecraft attitude control, target observability, hopes geometry, Fault Detection-Identification and Recovery, fuel consumption, time of operation.

In the project several relative navigation trajectory were considered that leaded to the following table. A number below 70% indicated an insufficient result and 90% an excellent achievement for a given criterion.

	Baseline	Small hops	Tensed hops	Blind hops	Straight line	Target tracking
LIDAR power consumption	70	85	85	75	90	**90**
Fuel consumption	80	80	30	80	70	**80**
Time of operation	80	50	100	80	80	**90**
Navigation performances	80	85	85	75	90	**90**
Blind spot influence	90	70	70	70	50	**50**
Safety / Robustness	85	90	70	50	85	**80**
Complexity / Implementation	80	80	75	70	90	**75**

Table 5: relative approach strategies assessment

Considering the results of the table above for each strategy the recommendations resulting from the FOSTERNAV invetigations give:

- **Strategy for ground-assisted rendezvous with intermittent ground station observability**: small hops strategy,
- **strategy for ground-assisted rendezvous with frequent ground station observability**: straight line strategy or target tracking strategy,
- **strategy for autonomous rendezvous**: target tracking strategy**.**

Prototype concept

Three modes of operation of the flash imaging LiDAR have been derived from the missions' requirements: the ranging, the slope and hazards imaging modes.

The **ranging mode** is considered for target illumination at relatively **long distance spacecraft-target**. Depending on the signal-to-noise ratio (SNR) measured in the image captured by the sensor, two illumination geometries can be considered: either the SNR is low, and hence all the optical power available is **used to get a distance in the centre of the image** (illumination geometry a), or the SNR is large enough to split the optical power available in 5 beams (illumination geometry b). The illumination geometry c is not considered for this mode. In this case the available optical power is spread in a beam with large divergence angle leading to lower optical power density on the target and hence on the detector after reflection. At long distances, the optical power density would be too low.

The **slope imaging mode** is considered for target illumination at **medium distance spacecraft-target**. Depending on the SNR measured in the image captured by the sensor, two illumination geometries can be considered: either the SNR is low, and hence all the optical power available **is used to get five distances in the centre of the image and in the four corners** (illumination geometry b), or the SNR is large enough to use the optical power available in one large beam (illumination geometry c). In the worst case, five independent distances can be measured which is sufficient to assess the relative attitude spacecraft-target. In the best case, a 3D image can be captured. The illumination geometry a is not considered for this mode. In this case it is considered that the spacecraft is close enough and the available optical power large enough to generate distance information either in illumination mode b or c.

The **hazard imaging mode** is considered for target illumination at **short distance spacecraft-target**. For this case only the illumination geometry c; **3D images are always captured**. Obviously, if the SNR measured would appear to be not sufficient the illumination geometry a or b can also used as back-up solution.

The illumination geometries associated with the operation modes are illustrated in the table below.

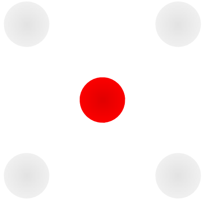
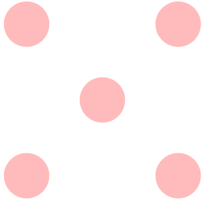
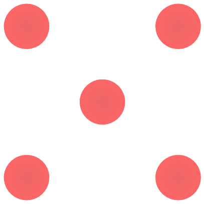
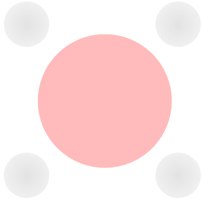
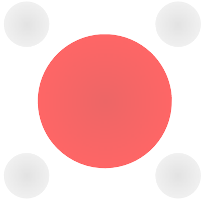
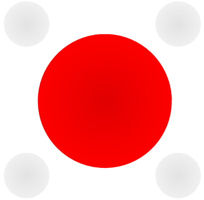
Ranging mode (RAN)	**Low SNR on imager (illumination geometry a)**	
	High SNR on imager (illumination geometry b)	
Slope Imaging mode (SLI)	**Low SNR on imager (illumination geometry b)**	
	High SNR on imager (illumination geometry c)	
Hazard Imaging mode (HZI)	**Low SNR on imager (illumination geometry c)**	
	High SNR on imager (illumination geometry c)	

Table 6: Illumination geometries and operation modes

Following the definition of the three modes of operation and of the illumination geometries, an architectural concept for the imaging LiDAR that can generate these modes have been imagined. The concept is illustrated in the figure below.

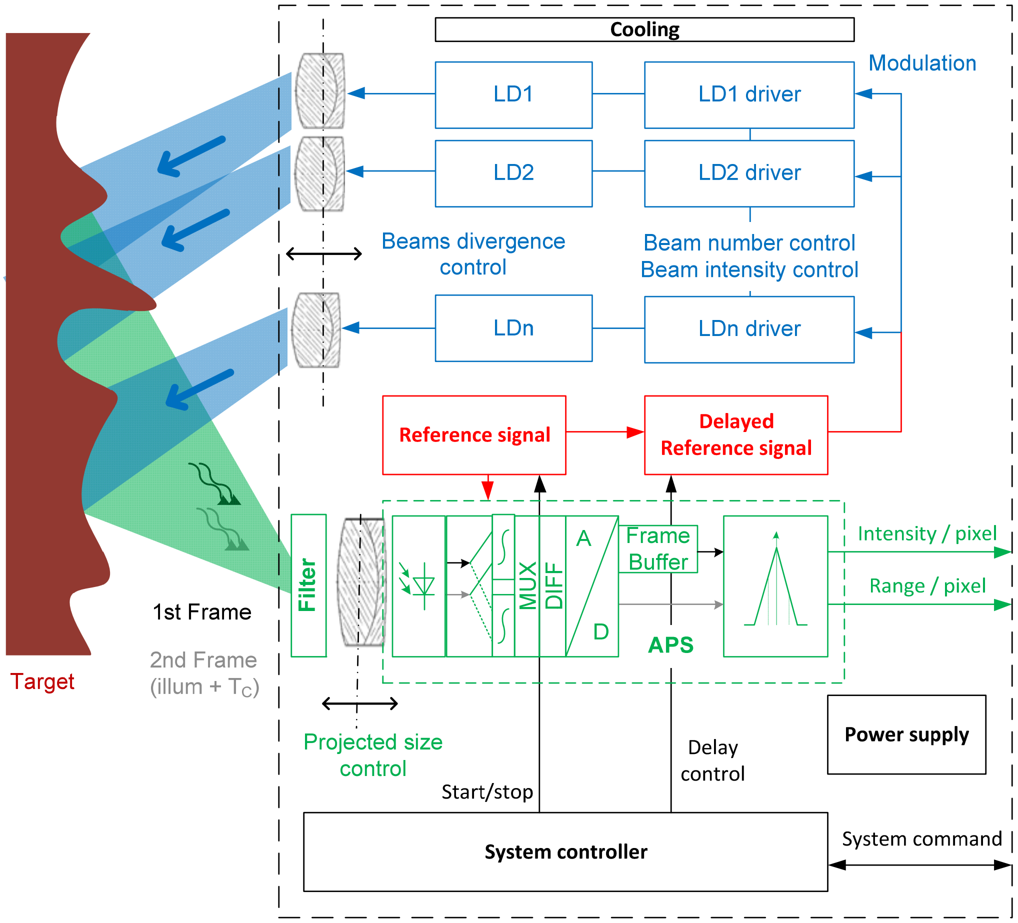


Figure 3 : architectural concept of the FOSTERNAV flash imaging LiDAR.

The flash imaging LiDAR has two main subsystems: the transmitter (parts in blue above) and the receiver (parts in green in the figure above). The LiDAR has other subsystems as the power supply and the computer which allows the user to control the LiDAR.

Model

To provide support for the system design, a model of the LiDAR has been created. The model has two parts like the architectural concept: one is related to the light emission and the other is describing the detection of photons in the receiver. The model was built essentially to allow engineering trade-off to optimize the different system performance criterions (e.g. total optical power, power consumption, receiver field-of-view, target detectability, etc.) and the selection/design of the sub-systems of the LiDAR.

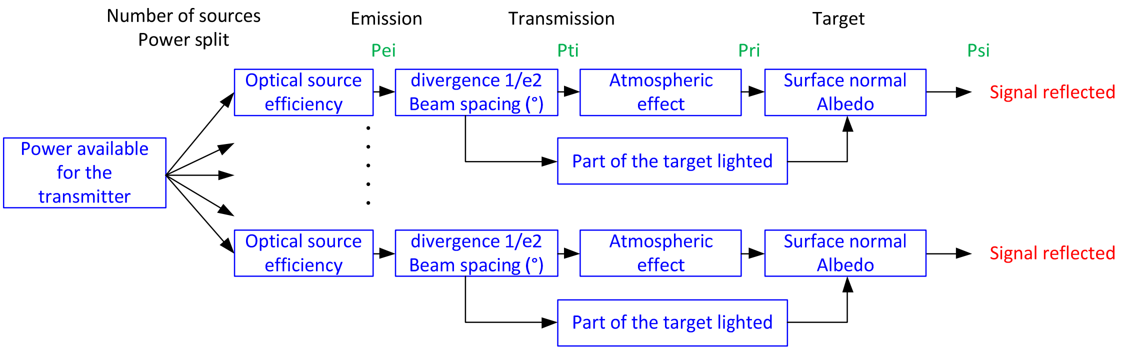


Figure 4: Light emission model.

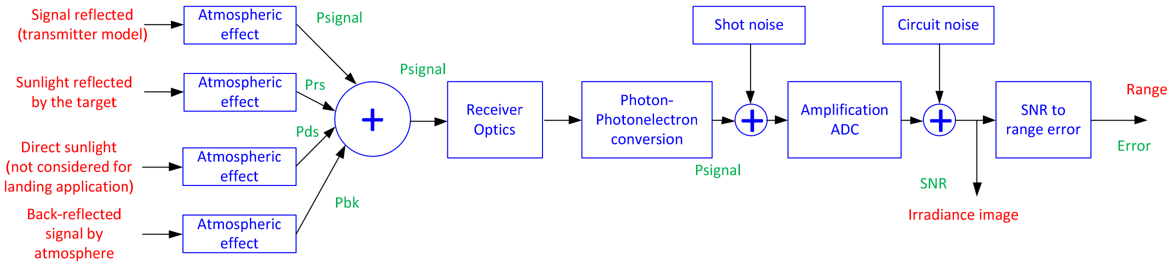


Figure 5: Light detection and distance measurement model.

The model and the resulting LiDAR design have been updated according to an iterative process as the first results obtained with the model were leading to unfeasible practical system. For example, one of the first simulation with the model resulted in a request to use 25 lasers to achieve the specified range precision. Obviously the accommodation of 25 lasers in a transmitter leaded to a too complex transmitter in practice. The figure below illustrates a transmitter concept with 25 lasers.

After several iterations between the system modelling and the system implementation practical trade-offs, 8 lasers were finally considered for the LiDAR prototype.

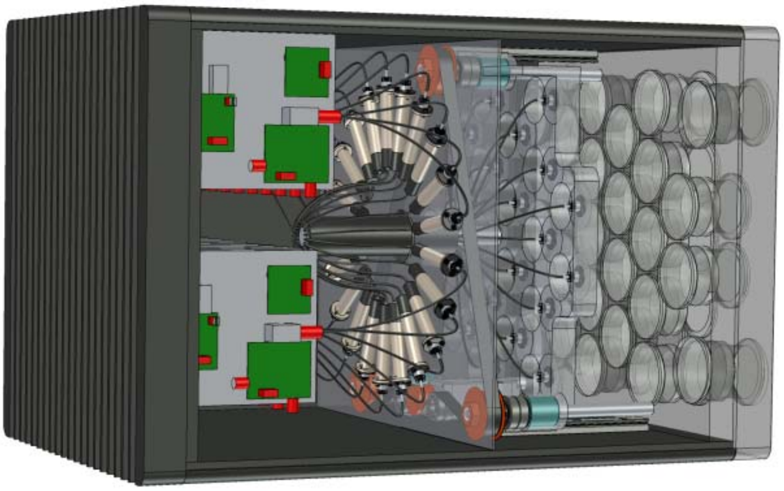
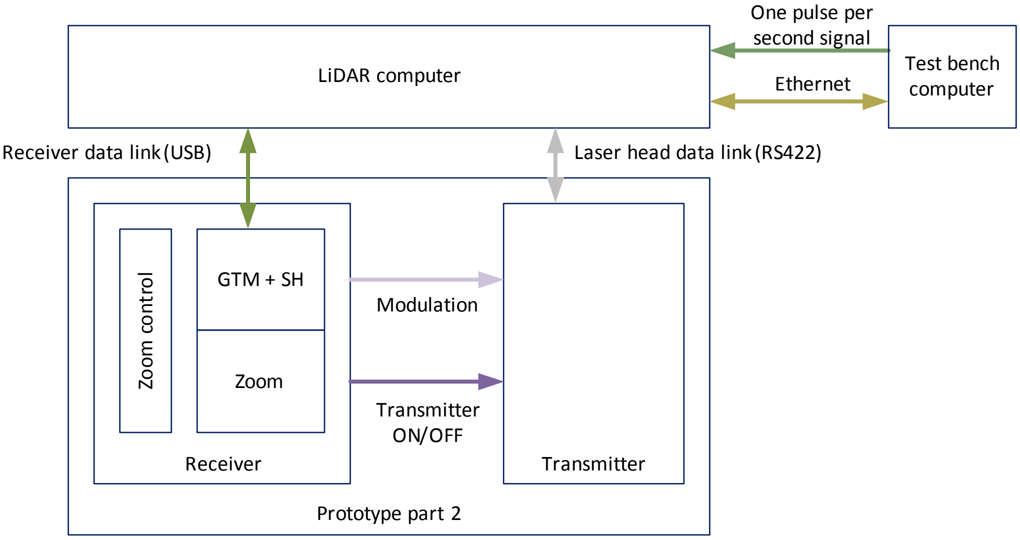


Figure 6 : concept of the LiDAR transmitter with 25 lasers.

System

For the needs of the project the system implemented includes more than a transmitter and receiver parts. The LiDAR prototype includes in addition a computer and a power supply parts. The computer allows the interaction of the user with the transmitter and receiver and, in addition with the computer of the test facility where the prototype is tested. The computer stores the images captured. The application running on the LiDAR computer is synchronized with the test facility computer. It is then possible compare the images captured with the prototype and the reference measurements provided by the test facility.



Transmitter

In order to generate the different illumination geometries several laser diodes are used in the transmitter. In total 8 laser diodes are used and 8 optics placed in front of the laser diodes. Four diodes generated the peripheral beams with low divergence (blue in the figure below) and four diodes generated the central beam whose divergence can be changed (red in the figure below).

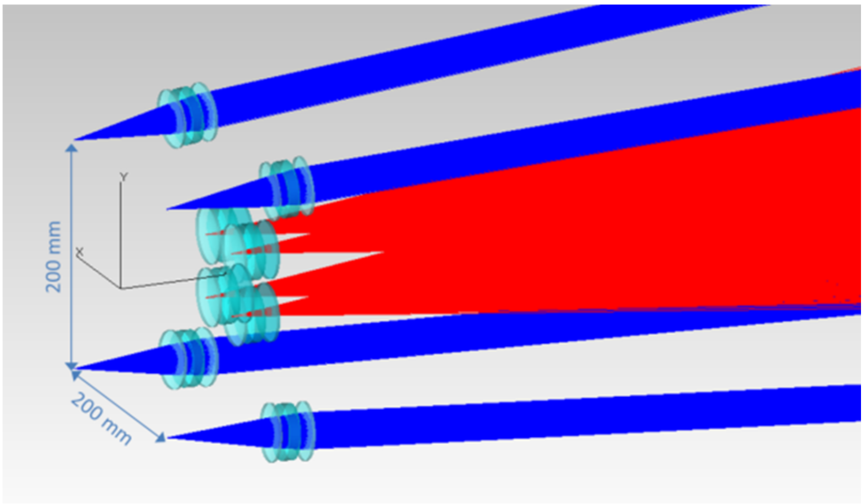


Figure 7: Illumination beams.

Each laser diode is control in temperature and the diode current is modulated. The transmitter has eight channels. Each of them is dedicated to one laser diode.

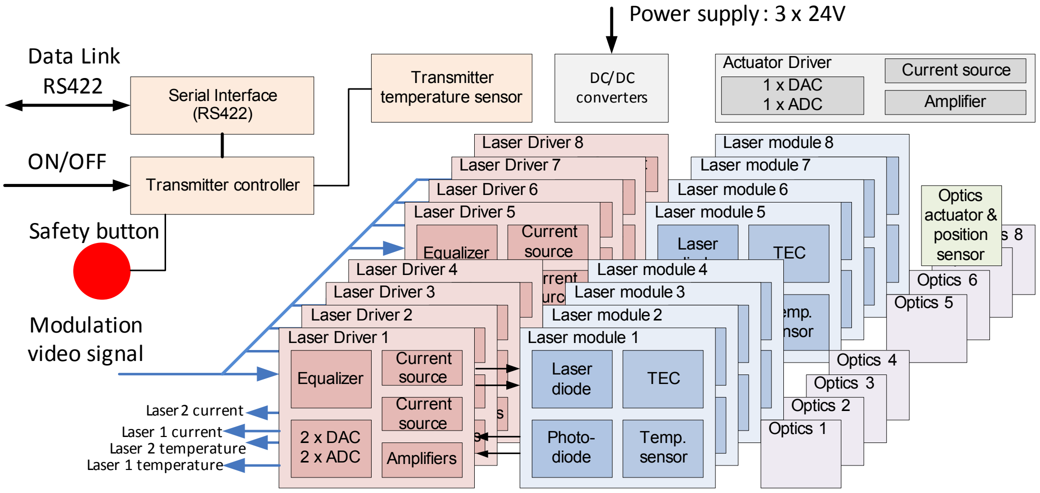


Figure 8 : transmitter block-diagram

After several iterations, the mechanical geometry of the diodes was defined.

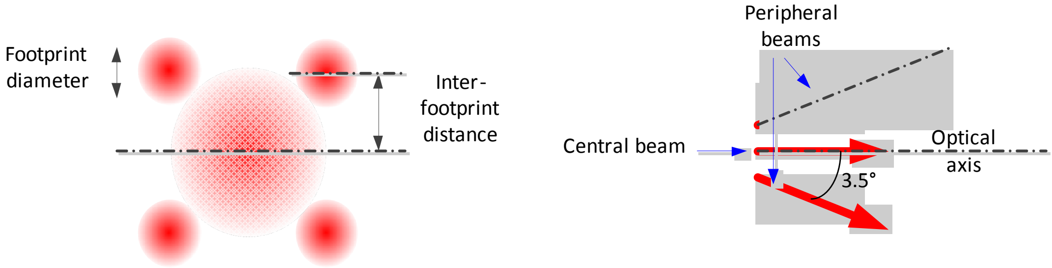


Figure 9: peripheral beams orientation.

The configuration chosen lead to illumination geometry illustrated below where in the first figure (Figure 10) the illumination geometry b and c are mixed and the second figure the slope imaging mode is simulated.

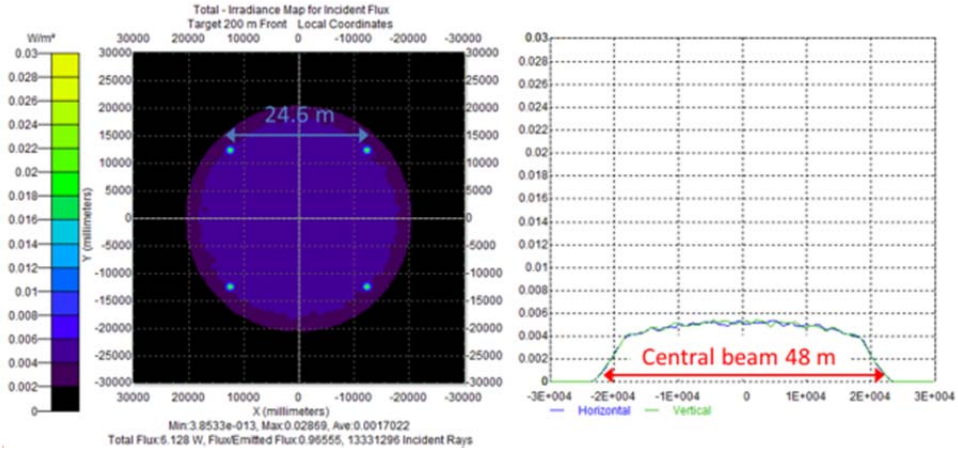


Figure 10: Irradiance distribution of four central and four peripheral lasers at 200-m distance. Flux of peripheral beams scaled down to 1 %.

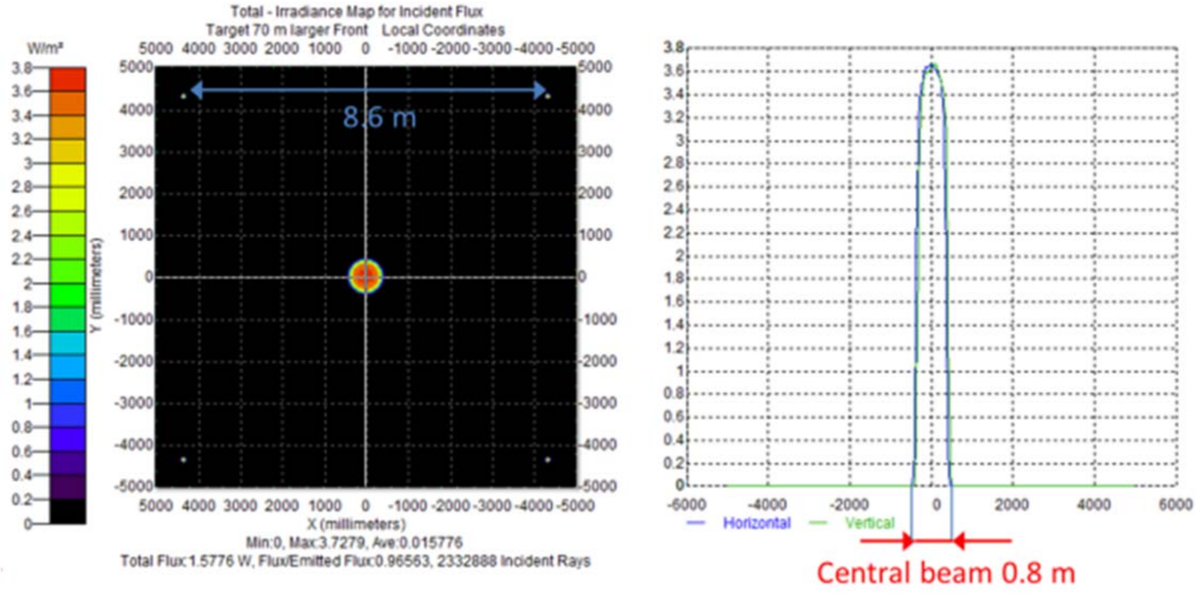


Figure 11: Irradiance distribution of SLI mode at 70-m distance: Scheme 1. Profile of central beam. Flux of peripheral beams scaled down to 10 %.

The trade-off between the simulation made with the model, the practical limitations of the transmitter implementation and the definition of the operation modes leaded to the realization of the transmitter illustrated in the figure below.

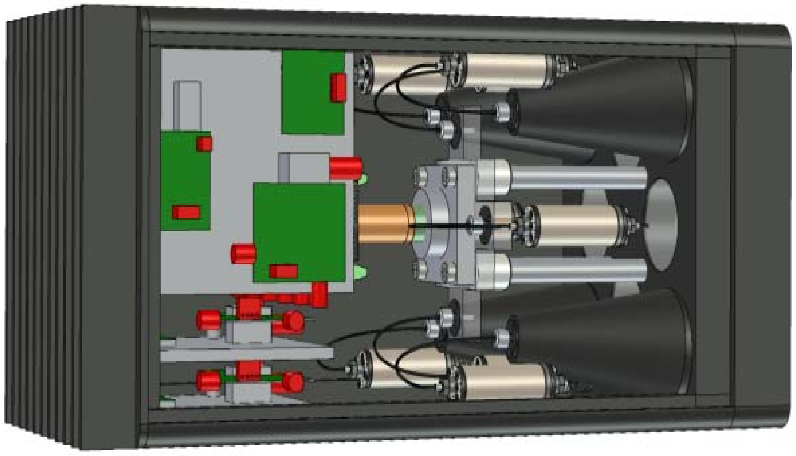


Figure 12 : Prototype's transmitter

Receiver

The detector array used for FOSTERNAV is a solid-state in-pixel photo-demodulation (IPPD) image detector developed in a standard CMOS process for Fluorescence Lifetime Imaging Microscopy (FLIM). The detector is not optimized for long range measurements.

The IPPD working principle is illustrated below: the photons captured by the photodiode can be transferred to two capacitors (C_{SN1} and C_{SN2}):

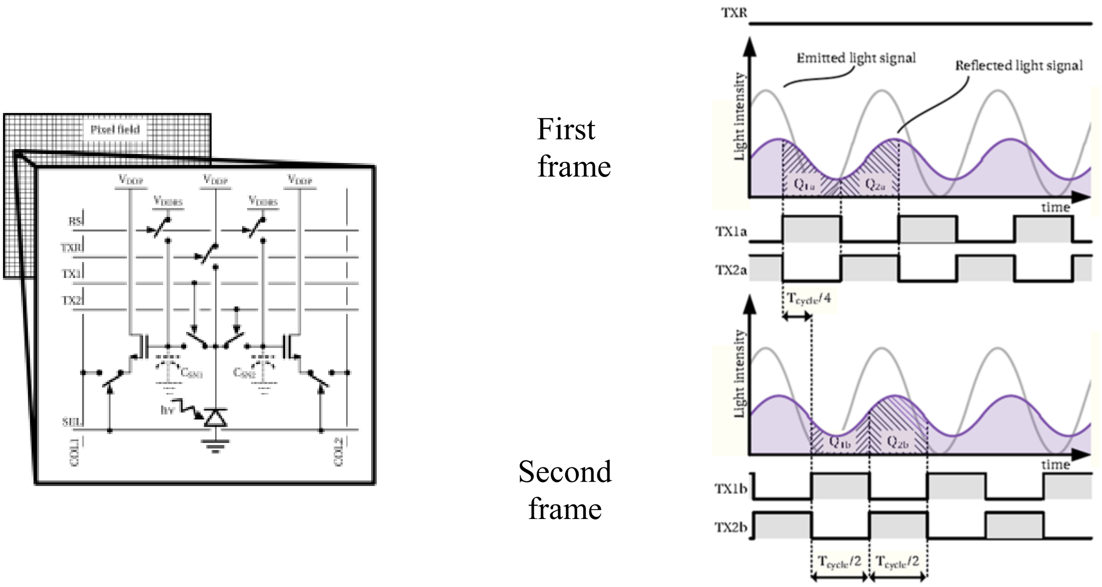


Figure 13: In-pixel photo-demodulation principle

As shown in the figure above, two frames (two taps detector) are used to calculate the distance of the object. The in-phase (I) and quadrature (Q) samples are collected in two subsequent frames. The reflected sine wave impinges on the sensor and is demodulated by TX1a and TX2a on frame A and TX1b, TX2 on frame B.

Following the Nyquist theorem, two samples is the strict minimum to reconstruct a sinusoidal signal. In TOF IPPD, it is more convenient in practise to realise an even number of samples. The figure below represents the model of a pixel using four samples and two integration nodes (two-tap) for the demodulation. In this approach, the optical signal is sampled twice (first and second frame) to have a complete demodulation.

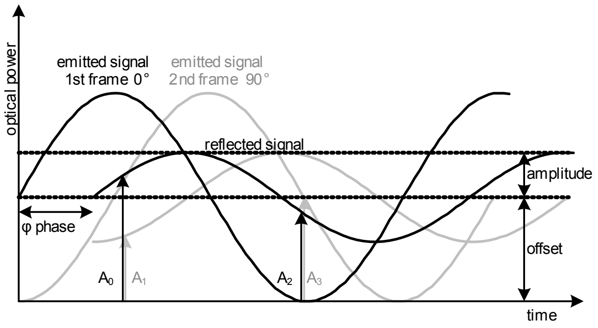


Figure 14: four samples and two integration nodes (two-tap) demodulation.

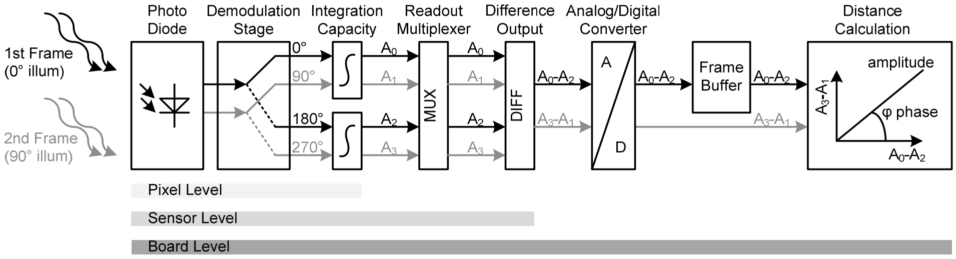


Figure 15: Optical signal detection in a 2 taps TOF system

Here below are the main features of the TOF detector used for the FOSTERNAV prototype:

Technology	CMOS 0.18 µm 4M2P
Frame rate fps	Typical 73, max 200
Drawn fill factor	14 %
Die size	5 mm x 5 mm
Pixel size	6.3 µm x 6.3 µm
Resolution (effective)	256 x 256 pixels (240x232)
Sense node full well	9560 e-
Input-referred RMS readout noise ($\sigma_{e,ro,inref}$)	36.7 e-
Pixel conversion factor	69.8 µV/e-
ADC conversion factor	122.07 µV/DN
System conversion factor	0.92 DN/e-
Sensitivity (660nm)	13 nW/cm2
Responsivity (660nm)	2400 DN/µW/cm2
Dark Signal Non-Uniformity (DSNU)	179.1 e^- (@405nm)
Photo Response Non Uniformity (PRNU)	2.8 % (@405nm)
SNR_{max}	35.6 dB
Dynamic range	47.1dB
Dark current	0.472 fA/pixel (@25°C)

Table 7: TOF detector features.

A receiver board centred on the TOF detector was built. The board has the functionalities to drive the detector and also to control the optics of the receiver. The board provides a reference signal that is used to modulate the light of the transmitter.

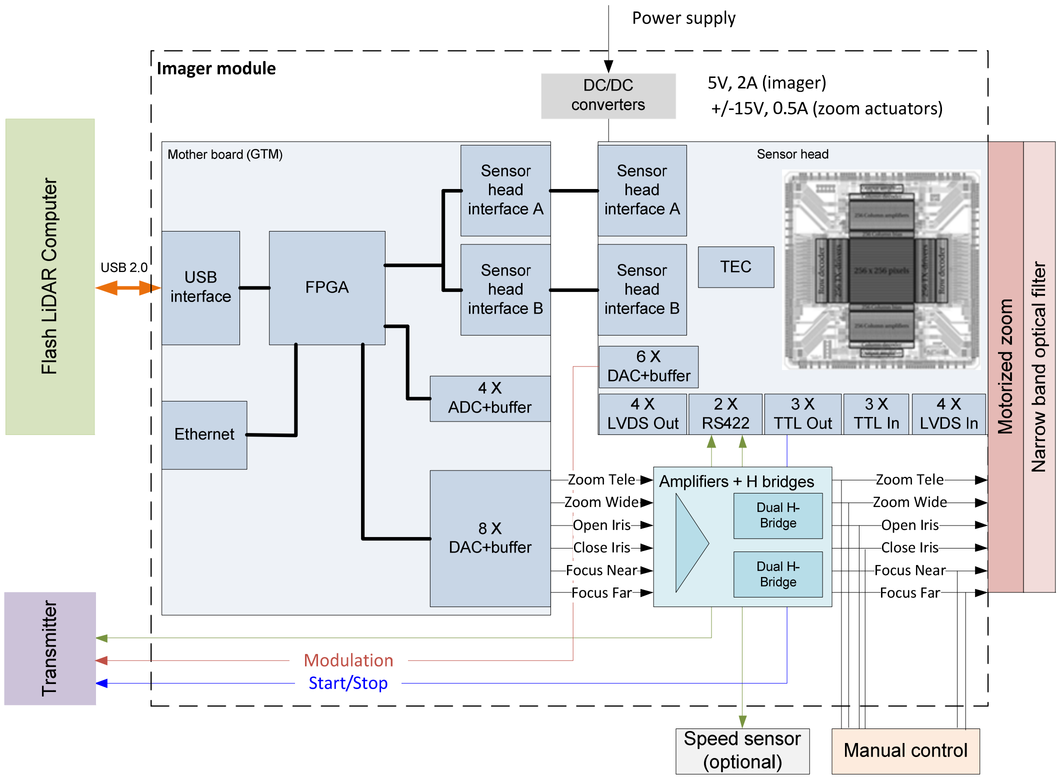


Figure 16: receiver board block-diagram.

Tests

The global test plan consists in making static and dynamic tests in several test facilities for GNC systems. The static tests are meant to assess the functionalities of the prototype and to calibrate it. The flash imaging LiDAR prototype had not only to match the specifications resulting from the operation modes definition, the results of the simulation and the implementation limitation of the transmitter and the receiver, it has as well to match the test facilities considered for the project.

Following all the engineering considerations quoted above, the prototype was finally split in three modules: the LiDAR computer, the power supply unit and the core part of the prototype which includes the transmitter and the receiver sub-systems of the LiDAR.

TRON test facility

The TRON facility is situated in DLR Bremen. Its purpose is to provide a hardware-in-the-loop testing environment for passive and active optical sensors. The main building blocks are:

- an industry robot installed on a rail providing 7 DOF,
- a lamp installed on a gantry system providing 5 DOF,
- a frame system for installation of targets,
- laser metrology equipment,
- real-time control system.

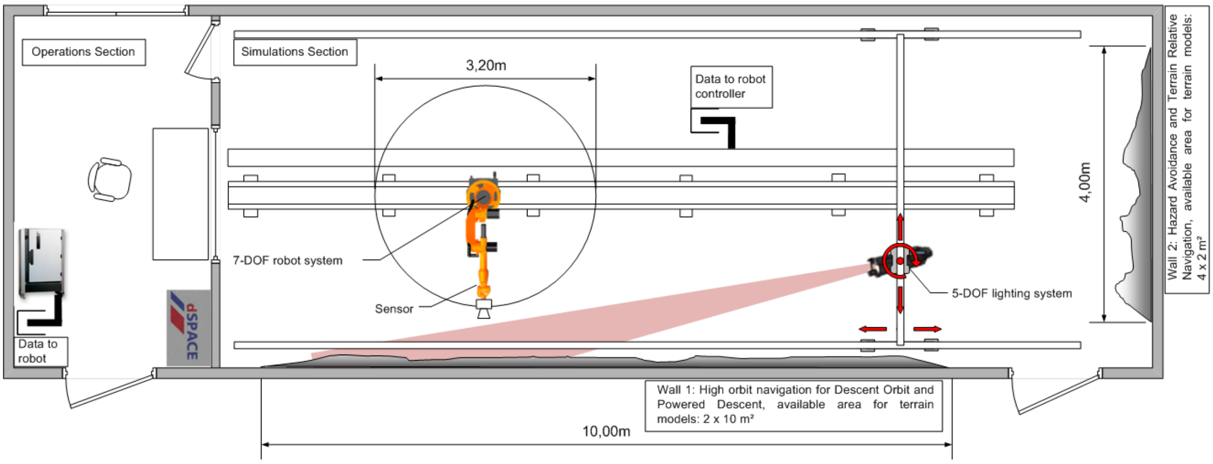


Figure 17 : TRON test facility, top view

EPOS test facility

The EPOS 2.0 facility is situated in DLR Oberpfaffenhofen. Its main purpose is providing test and verification capabilities for a complete RvD processes of on-orbit servicing missions. In addition to that the facility can be used for lander application simulation as well.

The facility comprises: two industrial robots (one fixed mounted, the second one installed on a 25m rail system, each has 6DoF), a Sun illumination system based on an high power floodlight which generates utmost realistic sun irradiation spectrum and power, and real-time facility control system

In addition the EPOS laboratory fulfills Laser safety requirements up to Laser class 4 and clean room requirements up to class 100000 (or ISO 8).

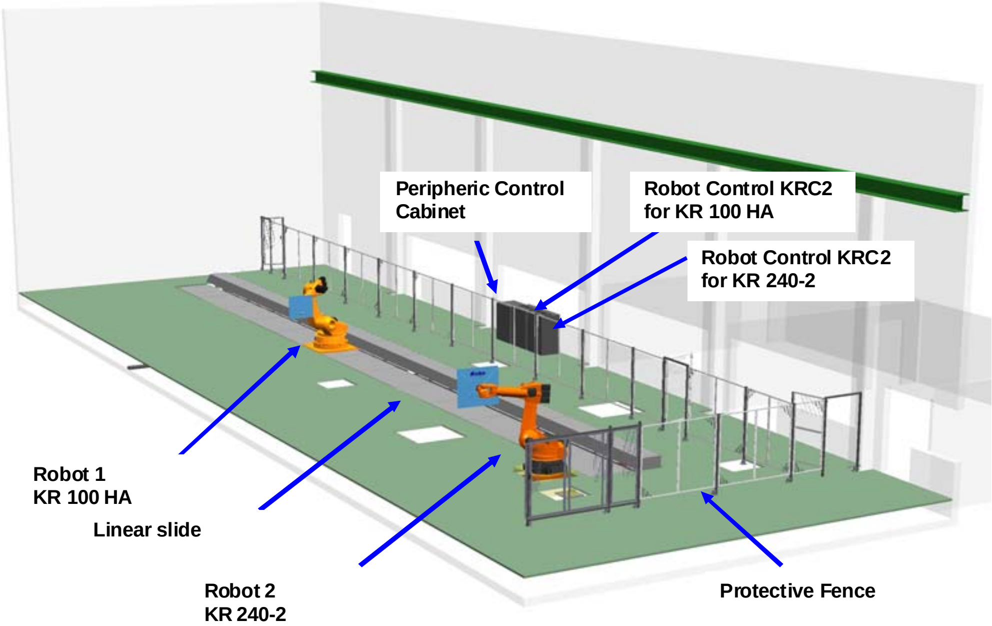


Figure 18: EPOS test facility

TENSOR test facility

TENSOR is a test facility allowing the evaluation of GNC sensors outdoors at relatively high velocity. Airfield is typically used for TENSOR. An airfield considered for FOSTERNAV is situated at about 30 km from Bremen. It provides an inoperative runway, which are suitable for long-range tests.

Both static and dynamic tests can be performed but radiometric measurements are not possible as this is an outdoor facility. It was possible to test at ~50 m/s the behavior of the flash LiDAR prototype. The prototype was placed on the roof of a car drinving over the take-off strip of about 2 km.

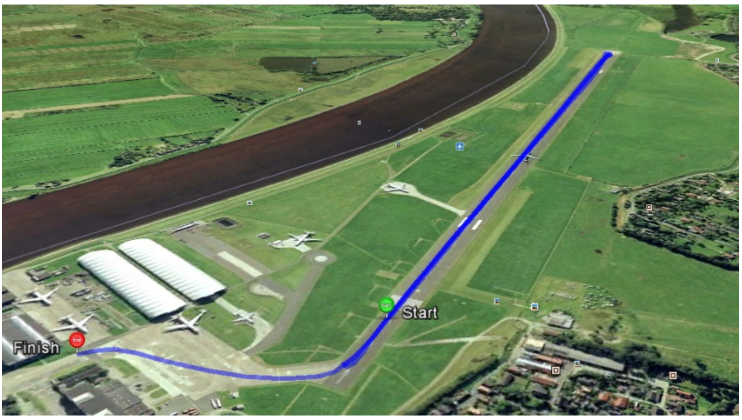


Figure 19 : TENSOR test facility. The blue trajectory is derived from GPS data acquired during the inspection visit of DLR in September 2011

Targets

Several targets were used for the prototype assessment. They are shown below. There is:

1. A flat panel covered with white blanket,
2. A flat panel covered with black blanket,
3. A panel on which 3D shapes (step pyramid SP, half spheres HS, cubes CU, ramp R) are fixed on,
4. A satellite rendezvous connection frame covered with highly reflective material.

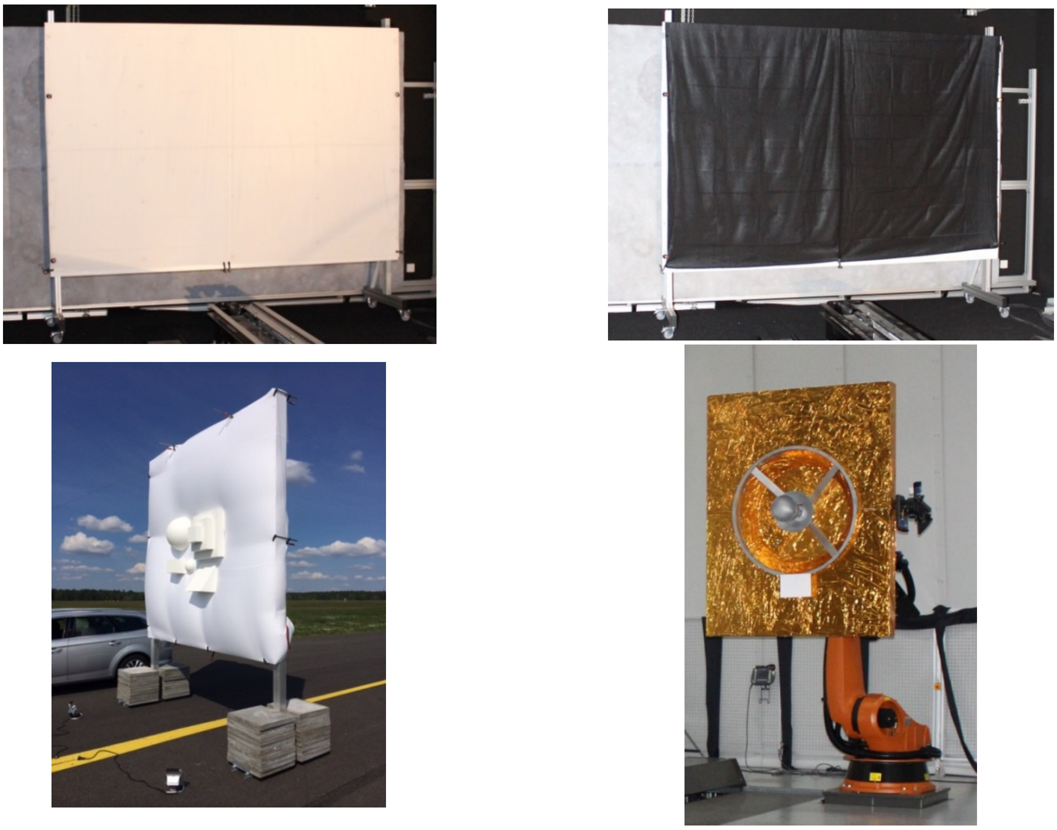


Figure 20: targets used in FOSTERNAV.

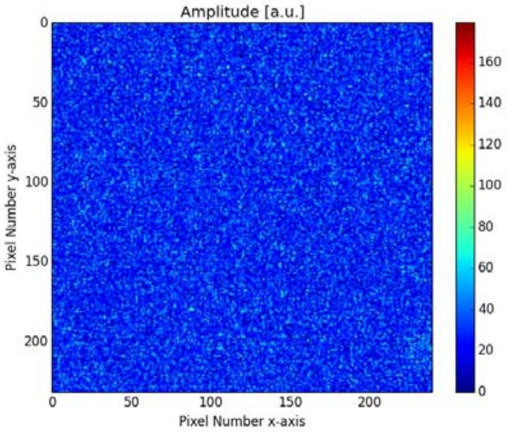
Typical results of a test outdoor

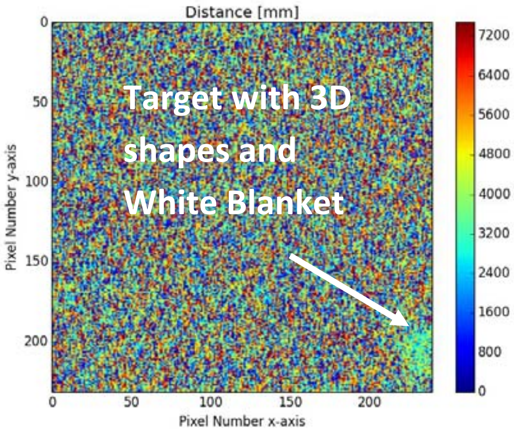
Here below are shown the images collected in one of the most demanding tests executed in the TENSOR facilitiy.

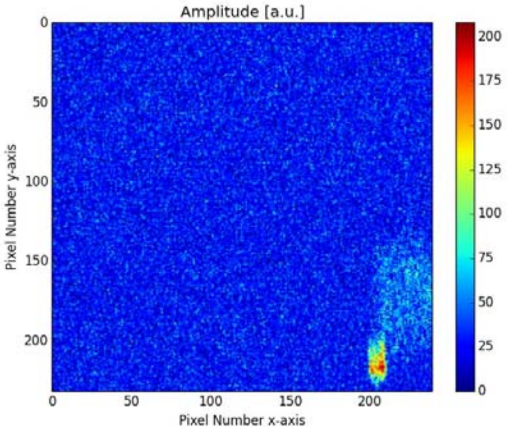
The test conditions were: two active lasers (number 5 and 8) at maximum optical power, frame rate 10 Hz, integration time between 4.5 and 75 ms, 50 km/h, white target with the 3D shapes on.

The first image is taken at around 200m from the target and the last one at 15m. The left images are an intensity image similar to images generated by standard camera. The right images are distance images.

Only 2 lasers over 8 available were used because of safety reason. Hikers may have been walking in the facility vicinity at ranges smaller than the safety distances.


Amplitude [a.u.]
Pixel Number y-axis
Pixel Number x-axis
0 50 100 150 200
0 20 40 60 80 100 120 140 160


Distance [mm]
Target with 3D shapes and White Blanket
Pixel Number y-axis
Pixel Number x-axis
0 50 100 150 200
0 800 1600 2400 3200 4000 4800 5600 6400 7200


Amplitude [a.u.]
Pixel Number y-axis
Pixel Number x-axis
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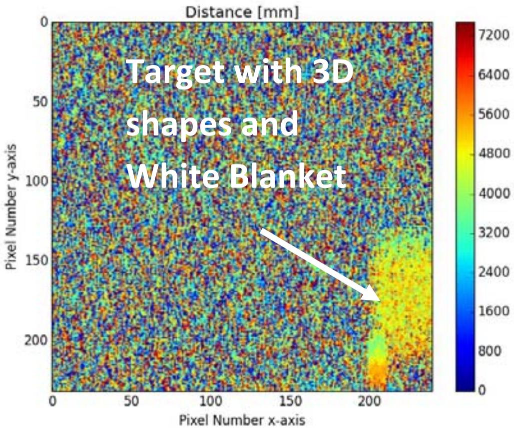
0 25 50 75 100 125 150 175 200


Distance [mm]
Target with 3D shapes and White Blanket
Pixel Number y-axis
Pixel Number x-axis
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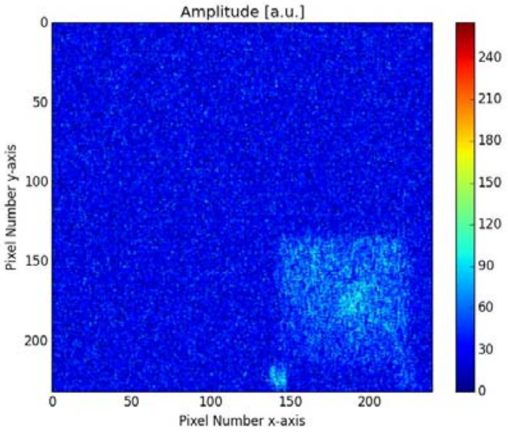
0 800 1600 2400 3200 4000 4800 5600 6400 7200


Amplitude [a.u.]
Pixel Number y-axis
Pixel Number x-axis
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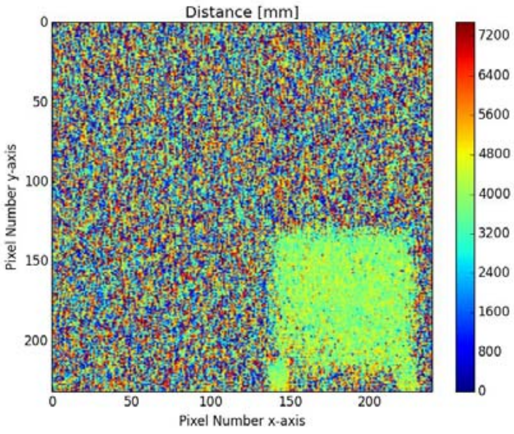
0 30 60 90 120 150 180 210 240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Pixel Number y-axis
Pixel Number x-axis
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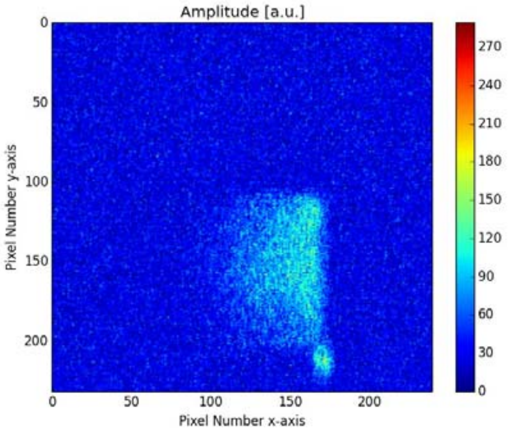
Amplitude [a.u.]
Pixel Number y-axis
Pixel Number x-axis
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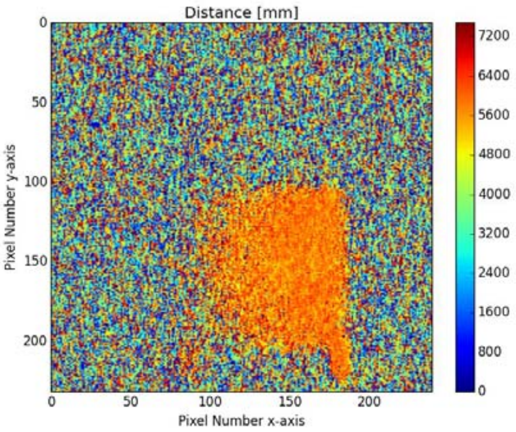
50
100
150
200
270
240
210
180
150
120
90
60
30


Distance [mm]
Pixel Number y-axis
Pixel Number x-axis
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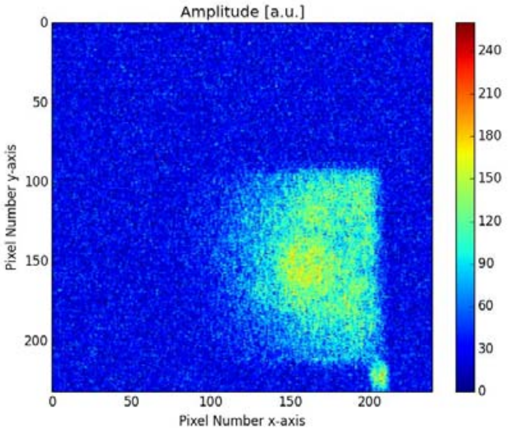
200
7200
6400
5600
4800
4000
3200
2400
1600
800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Pixel Number y-axis
Pixel Number x-axis
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210
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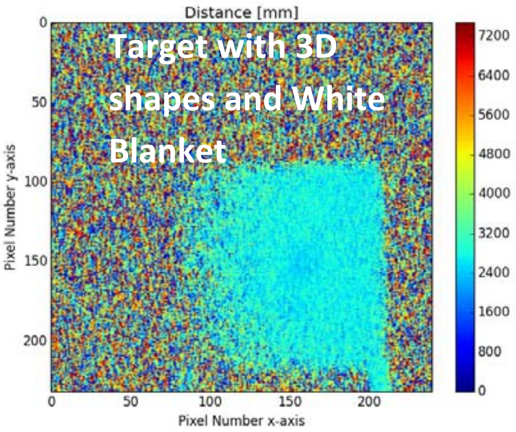
120
90
60
30


Distance [mm]
Target with 3D shapes and White Blanket
Pixel Number y-axis
Pixel Number x-axis
0
50
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5600
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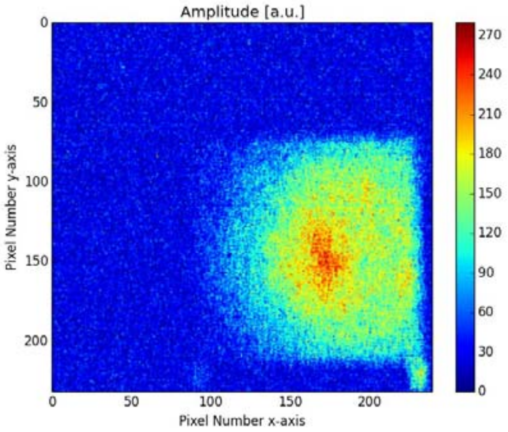
4000
3200
2400
1600
800


Amplitude [a.u.]
Pixel Number y-axis
Pixel Number x-axis
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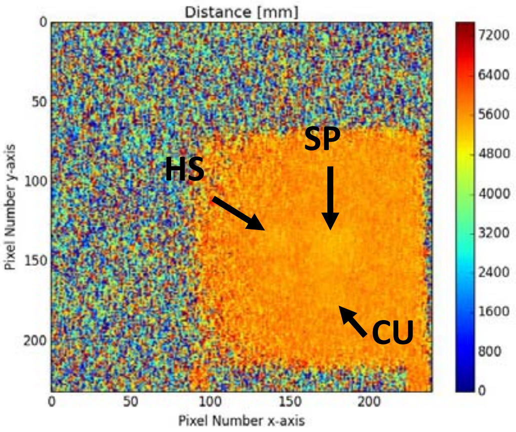
100
150
200
270
240
210
180
150
120
90
60
30


Distance [mm]
SP
HS
CU
Pixel Number y-axis
Pixel Number x-axis
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50
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7200
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4000
3200
2400
1600
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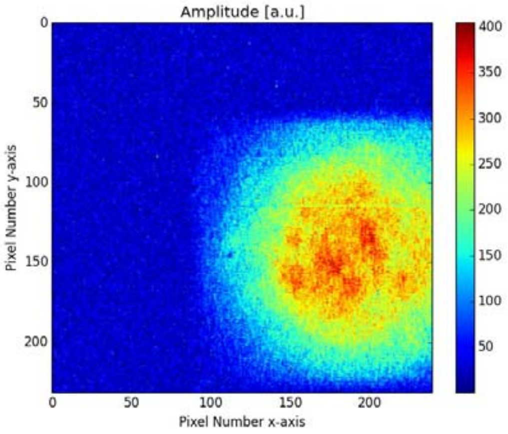
Amplitude [a.u.]
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Pixel Number x-axis
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150
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400
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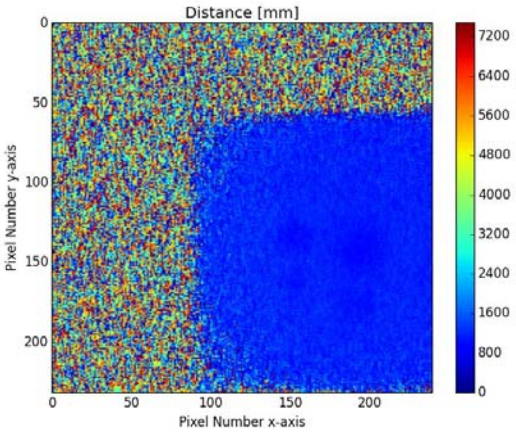
300
250
200
150
100
50


Distance [mm]
Pixel Number y-axis
Pixel Number x-axis
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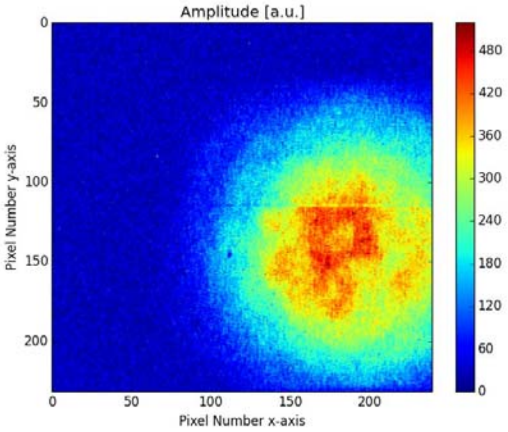
7200
6400
5600
4800
4000
3200
2400
1600
800
0


Amplitude [a.u.]
Pixel Number y-axis
Pixel Number x-axis
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480
420
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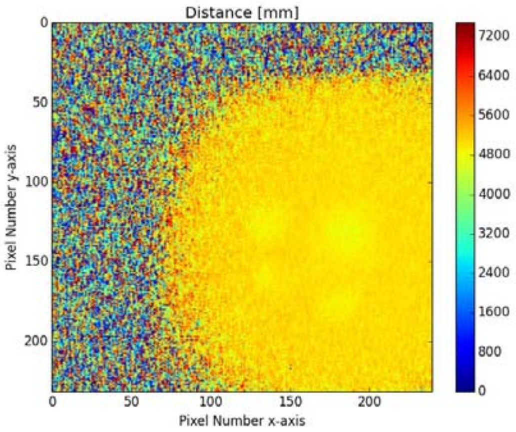
240
180
120
60
0


Distance [mm]
Pixel Number y-axis
Pixel Number x-axis
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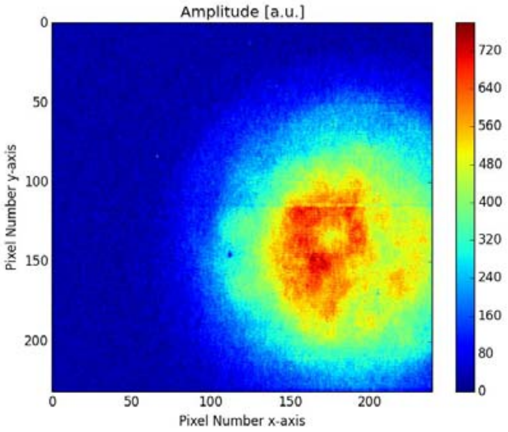
150
200
7200
6400
5600
4800
4000
3200
2400
1600
800
0


Amplitude [a.u.]
Pixel Number y-axis
Pixel Number x-axis
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200
720
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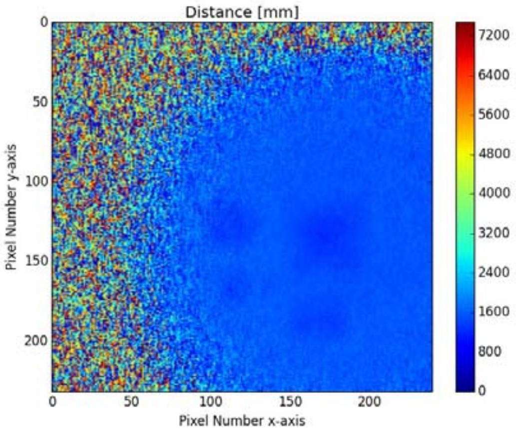
560
480
400
320
240
160
80
0


Distance [mm]
Pixel Number y-axis
Pixel Number x-axis
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50
100
150
200
7200
6400
5600
4800
4000
3200
2400
1600
800
0

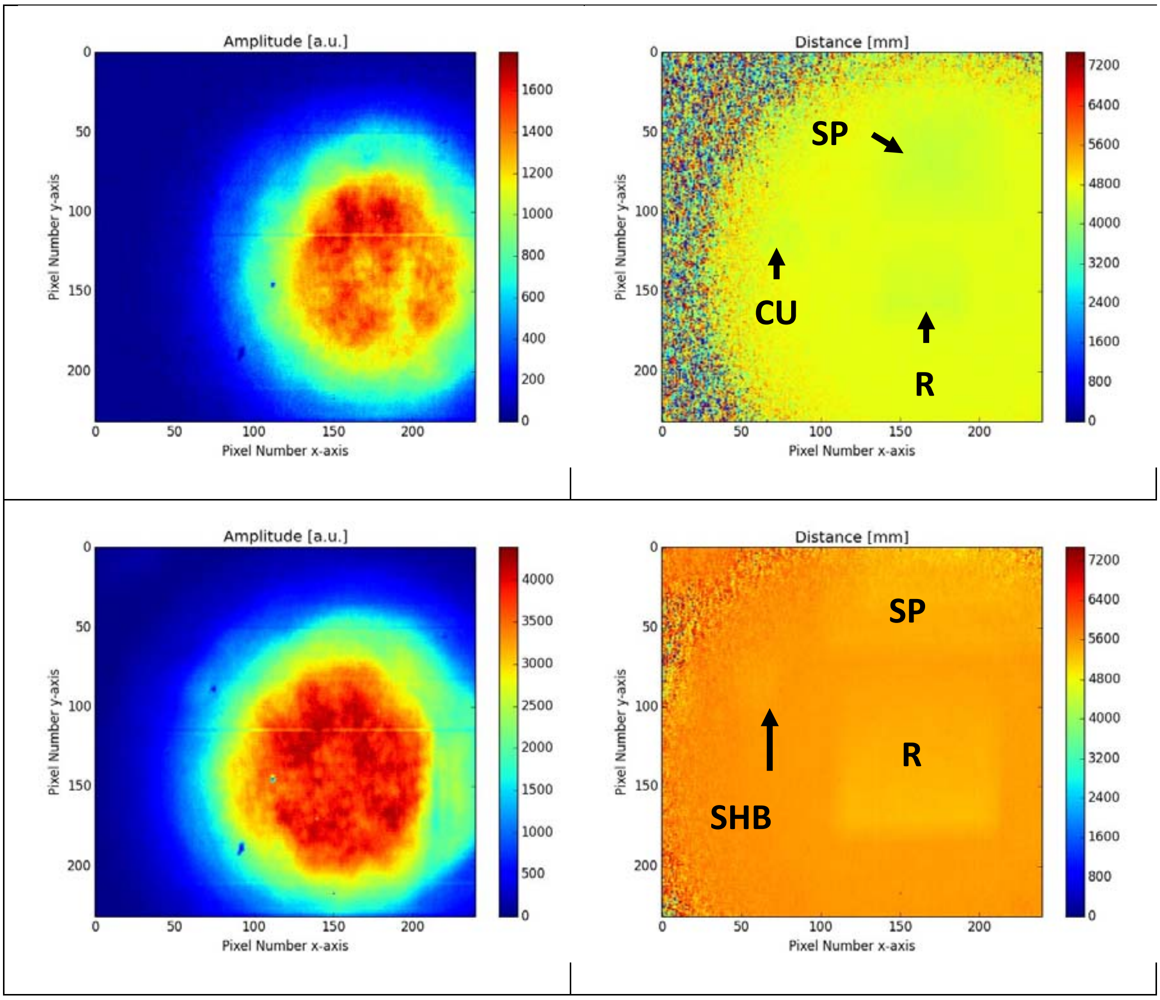

Figure 21: images captured during a test outdoors.

The figure below shows the GPS points acquired while images were captured. The GPS points are the references to which the distances measured by the LiDAR are compared.

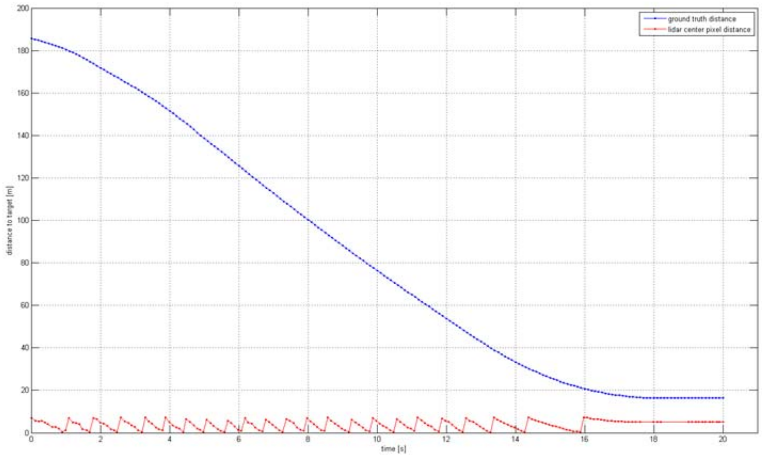

Figure 22 : distances measured with the reference sensor (blue) and with the prototype.

Conclusion

All the milestones defined in the project proposal have been achieved. See Table 1 for the list of the project's milestones.

The table below compares the specifications that were derived from the missions' requirements at the beginning of the project and the performances of the flash LiDAR prototype build in FOSTERNAV.

Mode of operation	**Ranging (RAN)**	**Slope imaging (SLI)**	**Hazard imaging (HZI)**
Prototype to target distance m	100 / >200	20 / >200	< 20 / >200[1]
Ranging accuracy m	0.1 / 0.05	0.025 / 0.05	0.025 / 0.05
Horizontal resolution	TBD / Single point measurement minimum beam divergence 1.2 mrad	0.025m / Not relevant. Measurement in five single points: One in the centre and 4 points at 4.9° from the centre	0.025/ tuneable between 0.004° to 0.04° (1.4 to 14mm at 20m)
Receiver FoV ° x °	TBD / tuneable from 1°x1° to 10°x10°	TBD / tuneable from 1°x1° to 10°x10°	20 x 20 / tuneable from 1°x1° to 10°x10°
Surface to be imaged m x m	N/A / Single point measurement minimum beam divergence 1.2 mrad	TBD x TBD / Not relevant. Measurement in five single points: One in the centre and 4 points at 4.9° from the centre (1.7 m from the centre at 20m)	TBD / tuneable from 1°x1° to 10°x10° (0.35mx0.35m to 3.5mx3.5m at 20m)
Target or Prototype velocity m/s	TBD / Max.19.5[2]	TBD / Max.19.5	TBD / Max.19.5
Sun local elevation	<75° wrt optical axis (the angle relates to the solar background reflected by the target) / < 45° tested		
Surface albedo	0.1-0.4 / 0.1-0.9		
Frame rate Hz	10 / 10 (demonstrated 200 Hz with EPOS and TRON tests see **Error! Reference source not found.** to **Error! Reference source**		

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[1] Images acquired at the maximum range of TENSOR shows this capability. Only 2 lasers were used to achieved this performance

[2] This is the maximum speed at which the FOSTERNAV prototype was assessed. The effective limitation depends on the ranging accuracy, the time to acquire one image (or inversely the time to acquire one image).

	not found.)
Image time stamping precision ms	1 / 1
Mass kg	TBD / 15 (computer and power supply not included)
Power consumption W	TBD / 120 (four lasers on)
Volume m x m x m	TBD / 0.37x0.62x0.52 (computer and power supply not included)
Lifetime in operating mode days	N/A / Not assessed
Lifetime in non-operating mode years	N/A / Not assessed

Table 8: specifications and performances achieved comparison.

All the specifications have been met. It shows the potential of the sensor architecture to satisfy the requirements for landing applications.

The project allowed assessing the current limitations of key components of a flash imaging LiDAR: the laser(s) of the illumination head and the time-of-flight detector array. An outcome of the project is to have identified the blocking points for the design of new version of these key components that would allow to match the missions' requirements.

Taking into account the potential improvements that can be gained either at component or system level, the table below shows the compliance table of a second generation prototype. This is the projection of the expected performances of a second version of the prototype that would comparable to an Elegant Breadboard (EBB) in ESA terminology.

Mode of operation	**Ranging (RAN)**	**Slope imaging (SLI)**	**Hazard imaging (HZI)**	**EBB FOSTERNAV concept**	**Match requirement**
Spacecraft altitude m	2000 > x > 700	700 > x > 200	< 200	>2000[3] in RAN mode >200 in HZI mode	YES
Ranging accuracy m	0.1	0.025	0.025	0.05	ALMOST
Horizontal resolution °	TBD	0.05	0.02	0.004° to 0.083°	YES
Receiver FoV ° x °	TBD	TBD	20 x 20	1°x1° to 20°x20°	YES
Surface to be imaged m x m	N/A	100 x 100	TBD	RAN = single range meas. SLI = 5 points meas. (5° x 5°) HZI = 1°x1° to 20°x20°	YES
Spacecraft velocity m/s	100	22	22	19.5	NO

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[3] This is an estimated range that may have been achieved with the FOSTERNAV prototype if the test facility would have allowed tests at this range.

Worst case for sun background	15° wrt optical axis	Expected to be compliant	YES
Surface albedo	0.1-0.4	0.1 – 0.9	YES
Frame rate Hz	10	Max. 200 Hz	YES
Image time stamping precision ms	1	1	YES
Mass kg	7	10	ALMOST
Power consumption W	40	80	NO
Volume m x m x m	0.5 x 0.5 x 0.5	0.37 x 0.62 x 0.52	YES
Lifetime in operating mode days	> 1	Expected to be compliant	YES
Lifetime in non-operating mode years	> 4	Expected to be compliant	YES

Table 9: expected performances of an EBB based on FOSTERNAV outcomes.

Taking on the matching of the performances expected from the EBB, there is a match with 11 specifications over 15 altogether (73%). In addition, there is an almost match for 2 specifications (ranging accuracy and weight) giving an overall match of 87%.

The two remaining specifications of an EBB that seem to be difficult to match with the mission's requirements are the spacecraft velocity and the power consumption. For both, the technical explanation to not match these specifications is the low sensitivity of the TOF detector array of the receiver available currently and the fact that the laser type used for FOSTERNAV has low modulation bandwidth.

Both issues can be addressed according to approaches explained in the project deliverables.

Foregrounds

The foregrounds generated by the project are:

1. A fully functional Flash LiDAR prototype of TRL4 available for further testing,
2. A patent about the prototype transmitter design and manufacturing,
3. Increase of European expertise in design, fabrication and testing of sensors for space,
4. Settled and verified processes amongst several partners to build and test in representative operational conditions flash imaging LiDAR for space applications.
5. Competences in optical systems with high-power diode laser modulation and fibre-optic,
6. Establishment of test facilities and test procedures constituting a standard environment to test navigation sensors.

Potential impact

Europe is several years behind in the development of flash imaging LiDAR in comparison with the United States of America (USA). The USA initiated the first development in this field 10 to 15 years ago. Today, as a result after several generations of prototypes, NASA is testing in real conditions (free flight) the latest flash LiDAR generation on its Morpheus platform[4].

Figure 23 : Morpheus lander with three different laser devices on the top (white) including one flash imaging LiDAR.

Morpheus is part of the long running large NASA's project Autonomous Landing and Hazard Avoidance Technology (ALHAT). The outcomes of ALHAT are numerous and several of them constitue the current benchmark for space applications. The flash LiDAR is one of these benchmarks.

The result is that NASA considers with more and more confidence the use of flash LiDAR for future missions targeting landing on massive celestial object like Mars or smaller ones like asteroids.

The flash LiDAR is an enabling technology for several applications in space including a landing phase but not only. It will play an important role as navigation sensor considered for future missions targeting the capture of space debris. The overabundance of debris in space might become an important societal challenge in a close future. Already nowadays parts of satellite are by time to time hitting the Earth ground in random places.

Figure 24: Saudi officials inspect a crashed PAM-D module in January 2001

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[4] http://morpheuslander.jsc.nasa.gov/

The number of space debris will keep on increasing rapidly in the near future and solutions will have to be found to address their potential threat to the Earth population.

Other space fearing nations are preparing or have already flown the own exploration missions (e.g. Japan, India, etc.). They are building their own vision-based sensors in relation with the requirements of these missions. The GNC sensors' combination of the Hayabusa missions to asteroids is one example. Hayabusa 2 shall be launched in 2014 or 2015 in the direction of the asteroid (162173) 1999 JU$_3$[5].

The concept of flash imaging LiDAR designed, built and assessed in FOSTERNAV is unique. For example, the three modes of operations are not completely exploited in other current solutions. With these three modes the prototype can be configured as distance-meter, inclinometer or pure imaging LiDAR. Such functionalities allow capturing the requirements of various missions scenario including relative navigation between a spacecraft and a target.

FOSTERNAV is one activity amongst quite rare activities in Europe where European flash LiDAR solutions are developed, built and tested. This is an important cornerstone that may allow Europe to keep pace with other space fearing nations with independent industrial development capacity for future missions.

The results of the project prepare the ground for future activities aiming at increasing the technological readiness of the sensor architecture and constitutive hardware or software building blocks needed to develop a standalone instrument that can be operated in closed loop in the future.

The demonstration of the applicability for landing and rendezvous of the selected flash imaging LiDAR architecture proves the European capability to build and assess an imaging LiDAR to compete with other fearing space nations at international level for future contracts related to space exploration missions, space debris removal and Earth observation.

Following the development of this sensor architecture for space applications additional markets such as the instrumentation for unmanned aerial vehicle and other autonomous vehicles can be targeted. It is also foreseen that the development at building blocks level (laser head, detector array, optics) will be beneficial for other markets.

Today, several ambitious missions are planned in a short time frame according to space mission standard. In all of them Europe plays a leading role. They all include a landing phase on a celestial body. These missions are for example: Lunar Resurs 1, Phootprint and MSR lander.

Lunar Resurs is a mission in collaboration between Russia and ESA. Currently the mission is in an early phase targeting the definition the technology cooperation between ESA and Russia. The mission should be submitted at the next ministerial council. The launch date currently considered is 2019[6]. Lunar Resurs targets to land on the Moon Luna-27, a large lander with an enhanced payload

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[5] http://www.jspec.jaxa.jp/e/activity/hayabusa2.html

[6] http://congrexprojects.com/2014-events/14c05a/introduction

capability. The mission will have near polar landing site in the southern hemisphere, targeting frozen volatiles in the sub surface.

Phootprint (Phobos Sample Return) is an ESA's mission. Currently the mission is in an early phase study. The launch date currently considered is 2022-2024[7]. It is preparing a post-Exomars mission of the Mars Robotic Exploration Programme (MREP), designed as technology precursors to Mars Sample Return. Missions selected under the programme are set for a decision "Go-No Go" at C-Min 2015. The mission's objectives are: to develop European capabilities to return a sample from a solar system body, to prepare critical building blocks for MSR, to obtain science information on the formation of Martian moons and better constrain the evolution of the solar system.

Mars Precision Lander (MPL) goal is to deliver a payload of 100 kg on Mars with landing precision below 7.5km. It is planned for 2022-2026. The terminal descent and landing sequence will include an Hazard Detection and Avoidance (HAD).

The success of these missions is dependent on the accession of new GNC sensors including flash imaging LiDAR. An European flash imaging LiDAR can play a key role for these missions if it can developed on time.

Dissemination activities

Activity type	Event	Date	Title
Publication /presentation	ESA GNC2014 congrex	June 2014	On-Ground Testing Optical Navigation Systems for Exploration Missions
Invited presentation	Workshop "Systèmes embarqués d'imagerie 3D par laser" OPTIM , Fondation "Sciences et Technologies pour l'Aéronautique et l'Espace"	April 2014	Systèmes d'imagerie 3D flash LiDAR pour applications spatiales
Publication	Coordinates Enzine	Feb. 2014	The future of exploration in Space – vision-based sensor for relative navigation
Invited presentation	SPAR Europe 3D measurement and imaging conference and European LiDAR mapping forum Amsterdam	Nov.2013	Navigation for Future Space Exploration Missions Based on Imaging LiDAR Technologies
Publication /presentation	SPIE Electro-Optical Remote Sensing Conference 2013	Oct. 2013	High-power multi-beam diode laser transmitter for a flash imaging lidar
Publication	Pan European Networks: Science & Technology 06	Q3 2013	Innovation for space exploration
Publication /presentation	35th Annual AAS Guidance & Control Conference Breckenridge Colorado	Feb.2012	Flash optical sensors for GNC systems
Publication / presentation	GNC2011 congrex Karlovy Vary, Czech Republic	June 2011	Flash optical sensors for GNC systems

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[7] http://forum.nasaspaceflight.com/index.php?topic=30258.0

Exploitation of results

Five main directions of the exploitation of the FOSTERNAV's results or outcomes are planned:

1. Exploitation of the fully functional flash imaging LiDAR TRL4 prototype,
2. Exploitation of the massive data (3D images geo-referenced),
3. Exploitation of the settled and verified processes amongst several partners to build and test in representative environments flash imaging LiDAR for space application,
4. Exploitation of new competences gained in optical systems with high-power diode laser modulation and fibre-optic,
5. Exploitation in combination of the test facilities TENSOR and TRON and, the related test procedures. They allow a standard test scheme for optical navigation systems. The test scheme has been implemented and evaluated successfully in FOSTERNAV. This establishes a standard test environment where competing navigation sensor concepts may be compared to each other on a fair basis.

The assessment of the FOSTERNAV prototype will continue after the project end. The prototype is a major mile stone to demonstrate the capabilities of flash imaging LiDAR in operational conditions representative of the applications that benefit from the functionalities of the flash imaging LiDAR.

A part relatively small of the data generated during the tests has been analysed during the project. The data will fuel several additional activities like internship, master or new projects. The data generated by flash LiDAR is quite particular. It is called often point cloud. A point cloud represents a large amount of information. New algorithms shall be invented to efficiently analyse such data.

FOSTERNAV allowed establishing efficient processes amongst the FOSTERNAV partners to develop, build and assess vision-based GNC sensor and its subsystems. The related expertise will be useful for upcoming new activities. The partners will bid together as often as possible when relevant for new activities on the basis of the lessons learned and the expertise developed in the frame of FOSTERNAV.

FOSTERNAV belongs to VTT's project family developing high-performance modules and instruments for harsh environments, such as space. The expertise gained in this project will be employed in activities developing hyperspectral imaging instruments from UV up to LWIR for applications ranging from colour inspection to remote sensing, and is applying laser modules for intra-satellite data communications.

One objective was to develop test sites and the belonging test procedures for testing optical navigation sensor, with the flash LiDAR prototype serving as enabling event and proof in the same time. With the heritage of the successfully completed test campaign we strongly believe that this objective has been achieved. With the combination of TENSOR and TRON test facilities, and the belonging test procedures, potentially a standard test scheme for optical navigation systems has been implemented. This is standard test environment where competing navigation sensor concepts may be compared to each other on fair basis. DLR plans promoting the new capabilities gained by developing the TENSOR test option to potentially interested parties, such as ESA, national agencies and industry.