DEVELOPMENT OF I3DS: AN INTEGRATED SENSORS SUITE FOR ORBITAL RENDEZVOUS AND PLANETARY EXPLORATION

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ABSTRACT

The Integrated 3D Sensors (I3DS) project aims at providing future space missions with a multi-purpose suite of sensors, with one single standardized interface with the core vehicle through an Instrument Control Unit (ICU) gathering sensors measurements and providing processing capabilities. This project focuses on two main space applications with an orbital suite of sensors developed for on-orbit servicing purposes, and a planetary suite devoted to rover ground exploration. This paper presents the current state of the sensors suite development, integration and validation in the I3DS project, that started at the end of 2016 and that will end at the beginning of 2019. In this project, versatile hardware and software solutions are proposed to fit the needs of future space missions by foreseeing the integration of new sensors and of new processing algorithms.

1. INTRODUCTION

Over the last 20 years, space robotic systems have known important steps forward toward on-orbit servicing with missions like ETS-VII [2-3] and Orbital Express [4-5], and toward planetary exploration with projects like the Mars or Lunar Samples Return [6-7]. In both cases, the systems complexity is constantly increasing to tackle more advanced tasks in the most autonomous way. Indeed, using robots allows to shift the performance of high-risk tasks from astronauts to mechanical systems and thus reduces human exposure and impact of life support systems at system level. To that end, the sensing capabilities of the robotic systems are critical to provide suitable and accurate measurements for both orbital and planetary missions.

Therefore, the Integrated 3D Sensors (I3DS) project consists in the system integration of a global suite of sensors into a common hardware and software framework, as well as in the demonstration and validation of their performance through two examples for orbital and planetary applications. The main goal is to provide one single standardized electrical and data interface between the core vehicle and the sensors, spread over the structure. To that end, I3DS intends to develop a preliminary list of sensors as modular as possible for integration in future systems or update with newer versions. It also provides a central processing element interfaced with the platform, called the Instrument Control Unit (ICU). This latter provides high-level measurements to the On-Board Computer (OBC) and then closes the loop for control and autonomy purposes. In order to make the suite as generic as possible, the sensors included in I3DS have been selected from a wide range of devices suitable for different scenarios. To illustrate this versatility, two main examples are defined to tackle the abovementioned orbital and planetary applications with the sensing solution for a close-range rendezvous of a space robot with a cooperative target, and for the planetary exploration by an autonomous rover performing localization and science.

This project brings together the following companies throughout Europe: Thales Alenia Space (EU), SINTEF (Norway), TERMA (Denmark), COSINE (Netherlands), PIAP Space (Poland), HERTZ Systems (Poland), and the University of Cranfield (UK).

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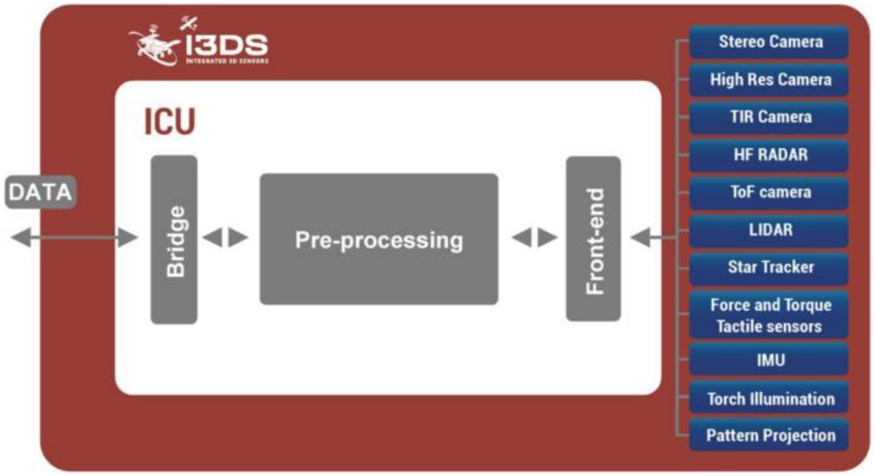

Figure 1 - Overview of the I3DS concept

In the scope of this paper, the I3DS sensors suite design and integration is described into details with a preliminary overview of the validation scenarios and facilities. The current section is introducing the context and the constraints of the I3DS project. The second section then defines the product as a whole, with the generic building blocks included (i.e., sensors and ICU), and the generic features of the proposed solution in terms of hardware and software. Through the third section, the two use-cases of application and their corresponding integrated suites of sensors are detailed to illustrate the I3DS modularity. Eventually, the validation of these integrated designs is overviewed through the current numerical results and with the coming experiments in the fourth section. A final general conclusion closes the paper on the on-going steps for I3DS project, and on the expected availability date of the resulting product with its foreseen performances.

2. I3DS PRODUCT DEFINITION

The I3DS sensors suite is made up of two main building blocks: the sensors and the Instrument Control Unit (ICU). A global illustration of the I3DS product is given in Figure 1.

2.1. ICU Description

The Instrument Control Unit is in charge of routing the information from each sensor and in charge of the pre-processing such that a unique common interface is obtained with the platform for all the sensors (N.B.: the . It is illustrated below from a functional point of view in Figure 2, with the front panel that will collect all the sensors data and trigger interfaces, and an electronic card that will collect, pre-process and route the sensors data to the On-Board Computer (OBC). It includes the networking plugs and equipments to connect the devices, a Multi-Processor System-On-Chip (MPSoC), and a FPGA to control, process and send the sensors streams to the platform. Within this ICU, the software components run on a real-time operating system and cover the pre-processing needs of imaging streams, the suite interface management for controlling and setting up all the sensors, and the system interface to receive/send data from/to the platform.

The ICU is physically located within an 8 slots PCI rack to include a Zynq processor and a Scalable Sensor Data Processor (SSDP). The Zynq ICU is based on a Xilinx UltraScale+ ARM-based MPSoC FPGA device which provides a suite of industry standard interfaces as well as being able to support bespoke interfaces in the FPGA logic (e.g., SpaceWire, Ethernet, USB, UART, CAN, DC/DC Power…). On the other hand, the SSDP contains a LEON3FT processor and two Xentium DSP cores implemented in FPGA logic as well.

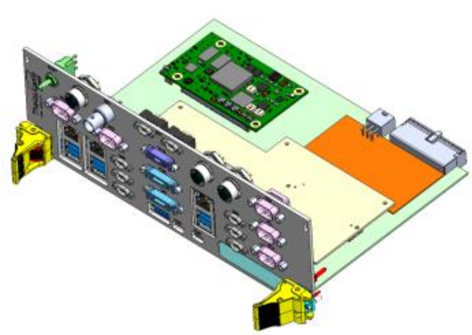

Figure 2 - ICU front panel and electronic cards

2.2. **Sensors Description**

The sensors provide the measurements required by the platform to ensure the control and autonomy requirements: for traditional mission, a given payload must be pointed toward a specific location in the inertial frame (e.g., Earth for communication or observation, stars for science…), while for rendezvous mission, either an inspection payload or a robotic arm must be controlled relatively to another target spacecraft. The sensors required to obtain these relative measurements are thus different from the inertial ones, and, most of all, are evolving at an incredible pace over the last years, in terms of performances, compactness, consumption and even price. Therefore, a modular and generic integration is clearly necessary to integrate them into a future spacecraft, with a unified way of receiving power or exchanging data with the platform through the previous ICU.

From the sensing point of view, the I3DS suite is currently made up of the following sensors and devices:

- <u>Inertial Sensors</u>
  - **T1 Star Tracker (STR) developed and integrated by TERMA,** to get the inertial orientation of the spacecraft using a visual sensor to compare the sky with a star catalogue (see Figure 3);
  - **DMU30 Inertial Measurement Unit (IMU) integrated by Thales Alenia Space UK** (provided by Silicon Sensing), to obtain the inertial rotational rate and the translational acceleration of the platform using MEMS gyro and accelerometer detectors (see Figure 3);
- <u>Relative Sensors</u>
  - **Radar unit developed and integrated by HERTZ,** to obtain the relative distance and the bearing angles of the target spacecraft at long range (see Figure 4);
  - **LIght Detection And Ranging (LIDAR) integrated by Thales Alenia Space France** (provided by Beamagine), to scan the scene and to generate a 3D point cloud at medium and close range at a low frequency (see Figure 5)
  - **Time-Of-Flight (TOF) camera integrated by Thales Alenia Space France** (provided by Basler), to get a depth map to generate a 3D point cloud at short range and at high frequency (see Figure 5);
  - **Stereo camera developed and integrated by COSINE,** to provide two synchronized image streams that are processed into a disparity map to obtain a 3D point cloud at short range and at a low frequency (see Figure 6);
  - **High-Resolution (HR) camera developed and integrated by COSINE,** to get a monochrome image stream at short range in the visible spectrum to compute either the pose estimation of the docking interface, or to inspect a target on the ground (see Figure 7);
  - **Thermal Infra-Red (TIR) camera developed and integrated by COSINE,** to provide a thermal image stream at short range mainly for sample characterization in the planetary scenario, but also useful in the case of a multispectral sensing solution for orbital rendezvous (see Figure 8);
  - **Contact unit made up a Force/Torque (F/T) sensor and of tactile sensors developed and integrated by PIAP Space,** to get the force and torque at the contact interface during the orbital docking with the target or for sample capture and handling (see Figure 9);
- <u>Illumination Devices</u>
  - **Wide-angle torch developed and integrated by SINTEF,** to provide a wide illumination over the scene at short range, and depending on the synchronization trigger from the stereo or HR cameras (see Figure 10);
  - **Pattern projector developed and integrated by SINTEF,** to provide a structured light source synchronized with the HR camera to extract 3D point clouds from the grey streams using mapping algorithms (see Figure 10).

These sensors and devices are integrated within the two I3DS suites for orbital and planetary applications, and their system parameters (i.e., mass, power, dimensions, dissipation) are crucial to develop the ICU and the mechanical housing accordingly. As an example, the following table lists the parameters of the current I3DS sensors, keeping in mind that they could be adapted by further developing the I3DS sensors themselves or by including another sensors in the suite. These parameters aims at providing preliminary values for high-level system analyses for future on-orbit rendezvous or ground exploration missions.

Table 1 - System parameters of each sensors

DEVICE	MASS [kg]	POWER [W]	DIMENSIONS [mm]
STR	1	6	125x165x165
IMU	0.3	3	69x65x62
Radar	4	60	550x550x160
LIDAR	2	30	150x150x140
TOF	0.5	30	142x76x62
STEREO	1.6	26	270x88x140
HR	0.9	22	96x76x91
TIR	0.3	22	96x97x146
F/T	3.4	13	140x140x40
Tactile	0.8	8	80x80x122
Torch	1.3	30	300x230x65
Projector	2.6	160	224x190x120
ICU	8	2	275x275x310

Figure 3 - Inertial sensors (IMU & Star Tracker)

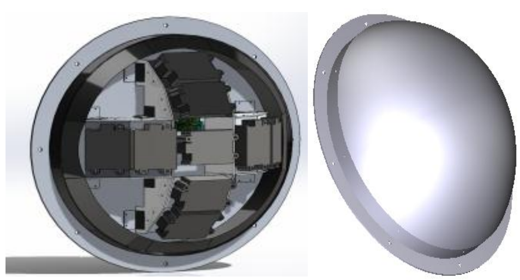

Figure 4 - Radar design with 9 different panels

Figure 5 - Relative lighting sensors (TOF & LIDAR)

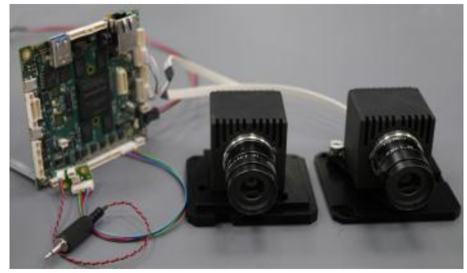

Figure 6 - Stereo camera with electronic board

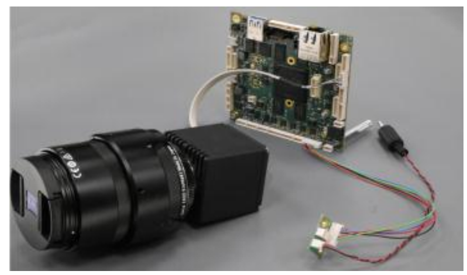

Figure 7 - HR camera with electronic board

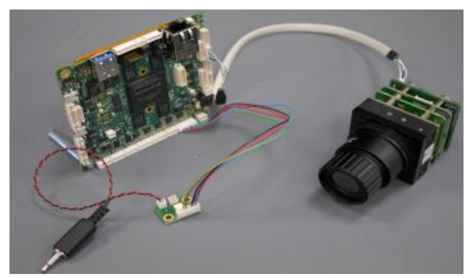

Figure 8 - TIR camera with electronic board

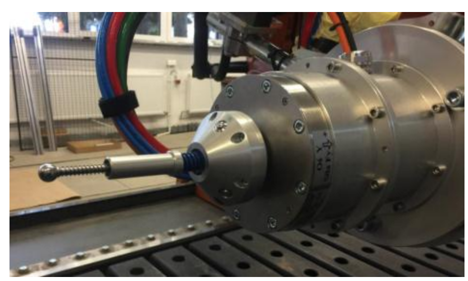

Figure 9 - Contact unit (F/T & Tactile sensors)

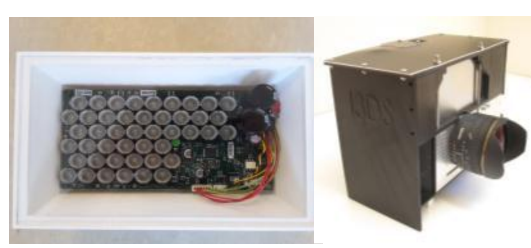

Figure 10 - Illumination devices (Wide & Projector)

3. I3DS INTEGRATED SUITES

This group of sensors has been selected to fit the needs of the two validation scenarios for orbital and planetary missions. In the sequel, a short recall of the validation scenarios is given before providing the list of sensors of the two I3DS suites being integrated for the validation experiments.

3.1. Use-case Definition

Two main scenarios of application drove the design of the I3DS sensors suite: one orbital mission for rendezvous and capture, and one planetary mission for autonomous sample characterization.

Orbital: Based on past missions results and feedbacks, the orbital scenario is focused on the rendezvous and capture of a cooperative target spacecraft [1], like it was done for the Japanese "ETS-7" mission [2-3] and for the American "Orbital Express" one [4-5]. The I3DS suite defined for this application also aims at covering additional scenarios like the on-orbit servicing with module replacement & refuelling, the assembly of complex structures. Besides, it will allow to explore the performance limitations of the sensors suite for challenging missions like the space debris removal.

Regarding the validation scenario by itself, it focuses on the rendezvous of a spacecraft orbiting the Earth with another cooperative and collaborative spacecraft, as illustrated in Figure 11. By cooperative, it is meant that the target is controlled and behaves in synchronization with the chaser, while its collaborative nature refers to the spacecraft design including visual markers and specific docking interface to ease the capture and servicing phases. This target is assumed to be pointed toward the Earth while the chaser performs a relative navigation to approach it, to inspect it, and then to capture it by mean of a robotic arm.

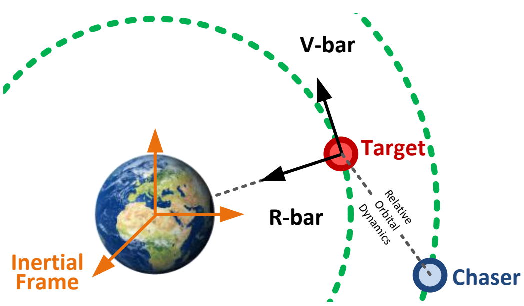

Figure 11 - Orbital scenario overview

Planetary: Regarding the planetary use-case, two main missions are foreseen with the Mars Sample Return (MSR) and the Lunar Volatiles Prospector (LVP) missions. In the first case, the Sample Fetching Rover (SFR) [6] of MSR mission is a small rover (i.e., mass below 60kg) where key design drivers are speed and reliability, with surface operations during 180sols to acquire and transfer a sample canister, over a cumulated track distance of at least 15km. On the other hand, the LVP rover mission aims instead at the mapping of volatiles at Moon south pole region with a medium class rover (i.e., mass below 250kg) with a mobility range in the order of 50km. Rover perception will be challenged by complete darkness, stray lights due to sun inclination and long shadows [7].

The validation scenario focuses on the performance of Autonomous Science while Traversing. During this exploration phase, the rover performs mapping and relative localization tasks, identifies and approaches a science interest site and can characterize a sample, in particular to ensure that the sample temperature does not exceed a given threshold. This scenario can be split in three different tasks with (a) the Mapping and Localization where the rover traverses a terrain generating point clouds and generating a Depth Elevation Map (DEM) to identify obstacles and find a viable path towards its destination (see); (b) the Site Characterization when the rover gathers and processes detailed data about the samples of interests in the science area; (c) the Sampling Execution Monitoring where the rover collects the samples using the embedded sensors to evaluate if the sampling is successful and the if size and type of the sample are adequate.

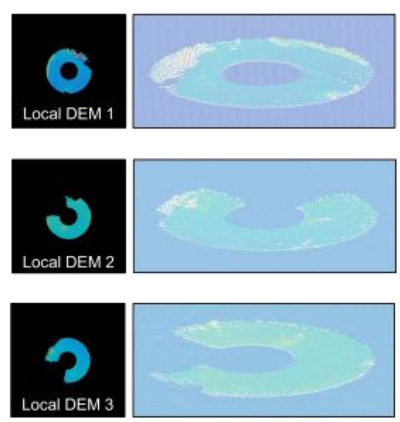

Figure 12 – Examples of consecutive DEM around the rover to build a global 3D map

3.2. Orbital & Planetary Suites

The two use cases led to the selection of the following sensors for each I3DS suite:

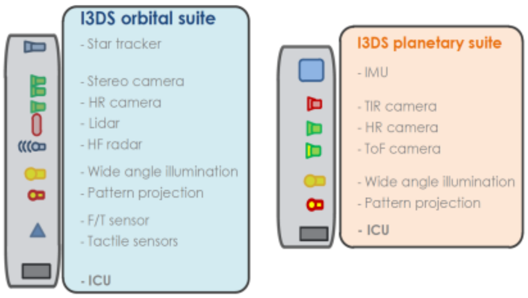

Figure 13 - Sensor selection for both I3DS suites

Their choice is based on a system-level analysis to ensure that most of the previous requirements coming the mission are fulfilled by the suite. To that end, the sensor data and their performances have been used to trade off the orbital and planetary suite. In addition, a budget limitation also applied to select the sensors, preventing the selection of space-grade sensors for example.

For both suites of sensors, a hardware housing has been designed and built by PIAP Space. They must comply with a list of requirements mainly driven by the experimental validation in the scope of the I3DS project, and not of the mission implementation. Hence, the resulting housings are obviously not representative of the sensors accommodation on the real spacecraft or rover, but they aims at supporting the functional testing and validation of the two suites.

They are illustrated in Figure 14 for the orbital suite, and in Figure 15 for the planetary one.

To illustrate the mass and power impact at system level, the orbital housing weights more than 25kg while the planetary one is limited to approximately 15kg. A strong impact is coming from the Radar, the pattern projector and the contact unit since the current design are preliminary and their dimensions could be optimized. In terms of power consumption, both the orbital and planetary housings require a maximum power of 250W. The major impact is coming from the pattern projector that is based on a laser source. Again, an optimized sensor design could lead to substantial reductions of mass and power consumption at system level.

Eventually, the output frequency measurement of the suites are expected to reach at least 1Hz for 4Mpix cameras, while it could be upgraded to 10Hz with smaller imaging sensors.

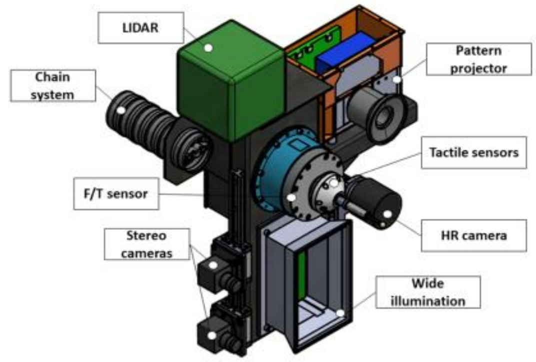

Figure 14 – Housing of the orbital I3DS suite

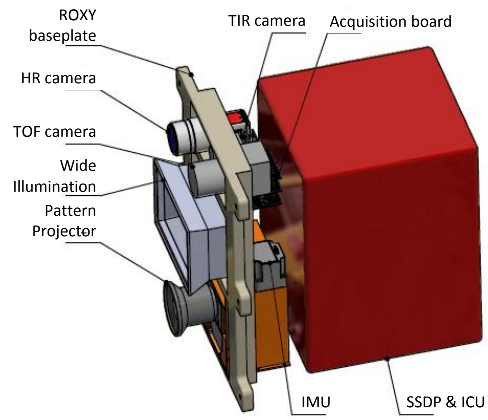

Figure 15 – Housing of the planetary I3DS suite

4. I3DS VALIDATION PLAN

The validation of the functional behaviour and of the performances of the I3DS product will be assessed twofold: by numerical simulations on the orbital use-case only, and by experimental tests for both of them. In the scope of the European Strategic Research Cluster on Space Robotics, I3DS product is developed by the Operational Grant 4 (OG4) and will be validated within OG4 first, and then within OG6 with dedicated facilities at GMV and Airbus DS-UK.

The validation plans are based on sub-phases of the use-case presented earlier:

- **Orbital**: two main rendezvous phases are considered for the validation with (a) an inspection of the target spacecraft by the space robot along a relative ellipse, (b) a final straight line approach to capture and dock with the target;
- **Planetary**: the three previous phases will be reproduced on a Mars-like terrain, and an additional test will focus more specifically on the IMU.

4.1. Sensors Testing

The sensors will be used as follows for the orbital use-case:

- Ellipse of inspection with the LIDAR, and the stereo camera coupled with the wide illumination;
- Straight line approach with the HR camera coupled with the pattern projector.

It is worth mentioning that the performances of the star tracker and of the radar will only be assessed at sensor level and not in the integrated suite, because of safety rules and facilities at hand.

The planetary sensors are used as follows:

- Mapping and localization with the stereo camera coupled with the wide illumination, and the TOF camera;
- Site characterization with the HR camera coupled with either the wide illumination of the pattern projector;
- Sampling execution monitoring with the TIR camera;
- Rover attitude testing with the IMU.

In both cases, the ICU manages the sensors powering and measurements depending on these high-level setting corresponding to the operational modes of the suite.

4.2. Numerical Validation

As mentioned earlier, only the orbital use-case is reproduced in simulations in the scope of the I3DS project. The ellipse of inspection and the straight line approach are simulated separately with the corresponding sensors. The details of the two trajectories are given in the sequel using the Local Orbital Frame (LOF) reference to describe the location of the chaser spacecraft with respect to the target one. Using the convention introduced in [1], this frame is located at the target centre of mass, with the Z axis oriented towards the Earth (i.e., along R-bar), and the X axis oriented along track (i.e., along V-bar).

The parameters and illustration of the ellipse of inspection are provided in Table 2 and Figure 16.

The parameters and illustration of the straight line approach are provided in Table 3 and Figure 17.

The introduced manoeuvers are derived from the analysis of the orbital mechanics and depends on the mission parameters, such as the ellipse dimensions or the approaching speed [1].

Table 2 - Parameters of the ellipse of inspection

DATA	VALUE
Orbit altitude [km]	500
Orbit period [s]	5677
Ellipse semi-minor axis [m]	20
Ellipse semi-major axis [m]	40
Amplitude of initial manoeuver [m/s]	0.022
Initial relative position in LOF frame (at impulse time) [m]	$[-40\ \ 0\ \ 0]^T$

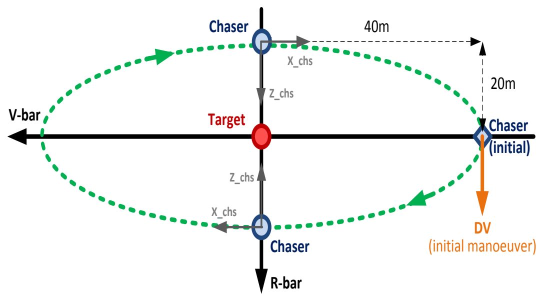

Figure 16 - Overview of the ellipse of inspection

Table 3 - Parameters of the straight line approach

DATA	VALUE
Chaser mass [kg]	1000
Orbit altitude [km]	500
Orbit rate [rad/s]	0.0011
Straight line length [m]	20
Straight line approach speed [m/s]	0.01
Straight line duration [s]	2000
Initial/Final manoeuver amplitude [m/s]	0.01
Constant forced acceleration along R-bar [m/s^2]	2.2 x 10^{-5}
Constant force along R-bar [N]	0.022
Initial relative position in LOF frame (at impulse time) [m]	$[-20\ \ 0\ \ 0]^T$

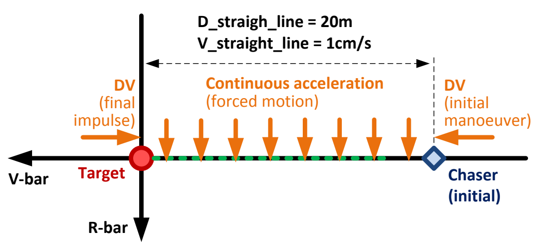

Figure 17 - Overview of the straight line approach

4.3. **Experimental Validation**

The internal validation of the I3DS suites will take place during the summer and autumn of 2018. The facilities used for these tests are illustrated below.

The orbital use-case will be validated in Thales Alenia Space in France using the ROBotic facilitY (ROBY) for rendezvous in Figure 18. It consists in a test bench with two industrial robotic arms to reproduce the relative dynamics of the I3DS sensors on-board the chaser spacecraft, and of a mock-up of the target spacecraft.

The planetary use-case will be validated in Thales Alenia Space in Italy using the ROvers eXploration facilitY (ROXY) in Figure 19. It consists in a rover base on which the I3DS sensors will be mounted. This rover will then move around the Mars-like terrain to perform the different mission phases.

Figure 18 - ROBY test bench in Thales Alenia Space in France

Figure 19 - ROXY test bench in Thales Alenia Space in Italy

5. CONCLUSION

This paper presented the I3DS project led by Thales Alenia Space for the design and integration of a generic sensing solution for future space robotic missions, ranging from orbital to planetary applications. An overview of the I3DS product was given with the ICU processing element and the sensors involved. Two examples of integration were proposed for an orbital rendezvous for servicing and for a ground exploration for samples execution. Eventually, the validation plan of both suites was partially presented since the experimental parts will be performed in 2018 with a final I3DS product available in 2019.

Acknowledgement

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