VALIDATION AND VERIFICATION OF MODULAR GNC BY MEANS OF TAS-I ROBOT MANAGEMENT FRAMEWORK IN OUTDOOR ROVERS EXPLORATION FACILITY

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ABSTRACT

The objective of STEPS2 "Rover Surface Navigation" work package was the design, development, validation and verification of innovative solutions suitable for the future (manned and unmanned) space robotics mission. A particular focus has been put in the autonomous capabilities to be implemented for the baseline mission scenario: sample canister acquisition and return, simulated in TAS-I ROvers eXploration facilitY.
This paper gives an overview of the adopted System Development Life Cycle, that is based on V-model and agile methodologies. Then the infrastructure, including the ROXY facility and research robots are detailed.
The paper focuses on the Test activities and relevant results for the Modular GNC developed on the TAS-I Robot Management Framework architecture.
Finally, the future envisaged activities are presented, including upgrades to Methodology, ROXY facility and GNC modules and their usage in the frame of TAS-I research activities and ESA funded contracts.

1. INTRODUCTION

The objective of STEPS2 "Rover Surface Navigation" work package was the design, development, validation and verification of innovative solutions suitable for the future (manned and unmanned) space robotics mission. A particular focus has been put in the autonomous capabilities to be implemented for the baseline mission scenario: sample canister acquisition and return. According to [1], the baseline mission scenario is divided in three phases:

- **Sample Canister Identification**, by looking at the rover Tracking Camera pictures, the sample container is identified and manually selected by a human operator;
- **Rover Traverse**, a tracking algorithm estimates the selected sample container position and provide it as goal to the rover GNC. Then the rover automatically approaches the target;
- **Sample Canister Acquisition**, once in the neighbourhoods of the sample canister, the robotic manipulator is commanded to acquire the sample canister, using the visual feedback to approach the sample canister interface.

Due to the similarities between the forward and backward traverse phases, and the lack of an ascent vehicle mock-up, the return phase of the mission has not been included in the baseline. Indeed, the developed technologies are suitable for the execution of the entire mission scenario.
The scenario is the subject of the project final demonstration, while the software modules implement the capabilities and so they have been validated and verified according to the process described in chapter 2.
Chapter 3 presents TAS-I ROvers eXploration facilitY (ROXY) located in TAS-I Turin site, while Chapter 4 provides an overlook on the research robots used for the outdoor validation and verification activities of the Modular Robot Control Software summarized in Chapter 5.
In Chapter 6 the test activities outcome are presented and discussed, and activities conclusions are summarized in Chapter 7.
Finally, Chapter 8 outlines the future work relevant to the robotics R&D activities starting from May 2015.

2. ROBOT DEVELOPMENT LIFE CYCLE

Alongside with the pure technical challenges of the project, the team has decided to implement and test a formal methodology for the Robot Development Lifecycle (including HW ans SW).
This methodology, which will be addressed as V-scrum, is a mixed approach between the classical V-model development lifecycle and the scrum agile framework.
Although an exhaustive description of the adopted methodology is out of the scope of this paper, the authors find beneficial to provide an overlook on the

formal process which has been applied to manage the development, validation and verification activities.

The V-model provides a structured and formal process to manage the systems development, aiming to minimize project risk and costs while increasing product quality and communication between the stakeholders.
Scrum is an iterative and incremental agile software development methodology aiming to provide high flexibility upon requirements changes and unpredicted challenges which may arise during project life cycle.
To couple the formal and structured development process provided by the V-model and the flexibility provided by the scrum agile framework, the V shape of the life cycle has been kept and the scrum methodology has been applied to iterate on the life cycle phases (Fig.1).

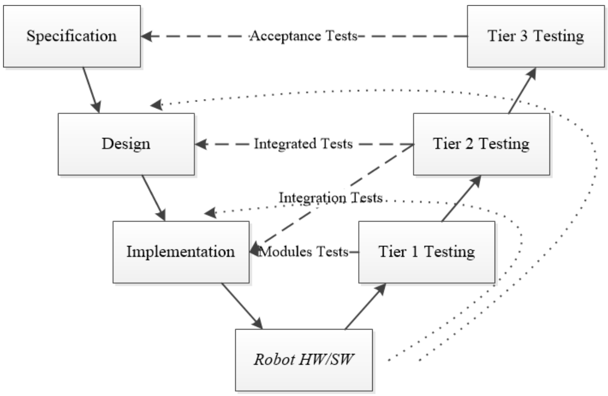

Figure 1. V-scrum model

Once the mission scenario and high level requirements have been specified, the iterative approach started. A set of lower-level and more detailed requirements has been derived from the high-level ones. Then, the V-model flow is applied, from the design to the coding and back on the testing phase, which closes the iteration loop. At each iteration, the lower level requirements are analysed and updated according to the needed changes ensuring requirements traceability, and the process is repeated.
Once the integration activities started, the iterative process embraced the higher levels to include recurrent integrated tests.
This way, the high level requirements and design are stable and fulfilled by the faster changing lower level requirements and design adaptations, that follow the agile schema.

3. ROVERS EXPLORATION FACILITY

TAS-I ROvers eXploration facilitY is a technological area dedicated to robotic systems design, development, validation and verification. It is located in TAS-I Turin site, covers an area of about 600m^2, including a Mars playground, control room and workshop.
The **outdoor playground** covers an area of ~400m^2, reproducing Mars-like planetary morphology in terms of colour, landscape, boulders, smaller rocks and slopes. The perimeter is surrounded by a uniform background which isolates the terrain from external interferences like peoples and vehicles (Fig.2).
The **control room** hosts the software development validation and verification infrastructure, as well as the presentation system.
The **workshop** provides a secure area where to store the robots and to perform integration, test and maintenance activities. Moreover, the workshop office box can be transported on truck to be relocated on the field to provide on-site logistics during field test campaigns.

Figure 2. ROXY Playground

3.1. Ground Truth and Reference Frames

To ensure adequate reliability of the tests results, the following set of ground truth measures have been acquired during STEPS2 project test phase:
- **Trajectory and Time:** Differential-GPS, consisting in a base station and one rover station for each rover, providing ground truth of rover trajectory (1cm+1ppm accuracy +/- 0.75mm precision) and time (20ns accuracy). The system provides also a synchronization source for on-board computers clocks via pulse-per-second signal;
- **Relative Distance:** Laser range finder (0.05 – 250m range +/- 1.0mm accuracy);
- **Climate Conditions:** acquired from Italian government Regional Agency for Environmental Protection (ARPA), in particular: temperature, wind direction, wind velocity, humidity;
- **Sun Elevation:** acquired online from Sun Earth Tools;
- **Luminous Flux:** using a Luxometer (0-200000lux range with 0.2% + 1digit accuracy).

The following reference frames have been defined:
- **<roxy>:** the main reference frame. Located at the Mars playground south-west corner. With x-axis pointing to the playground entrance, y-axis pointing left and z-axis pointing upwards, thus resulting in a right-handed frame;
- **<rover>:** rover moving frame. Located at the rover center of rotation, at the wheels axes height. With x-axis pointing the rover forward motion direction, y-

axis pointing left and z-axis pointing upwards, thus resulting in a right-handed frame;

- **<camera>:** reference frame for monocular, stereo and ToF cameras. With z-axis perpendicular to the imaging sensor plane, pointing in the sight direction; y-axis on the imaging sensor plane pointing downwards and x-axis on the imaging sensor plane pointing right, thus resulting in a right-handed frame.

4. RESEARCH ROBOTS

Three all-terrain research robots have been designed and integrated in the frame of STEPS2 activities. A fourth robot, suitable for wheelchair-accessible terrains (both indoor and outdoor), was already available from previous projects [2, 3] and it has been upgraded and used for preliminary integration and testing during the ROXY facility construction.

All the robots consist in a rover locomotion platform with a modular support structure integrated on-top, which provides interfaces easing the integration of GNC sensors, actuators and ground-truth equipment. This makes all the research robots very flexible as their hardware configuration can be easily changed and rovers re-used for different purposes. More specifically, three robot configurations have been implemented:

- **Scout Rover**, to explore and build a consistent map of the environment, without a-priori knowledge of the area and relying only on on-board sensors;
- **Surveyor Rover**, to acquire imagery and provide video feedback of the surrounding environment, increasing operators situational awareness;
- **Master Rover**, to implement all the capabilities for sample canister identification, acquisition and return scenario execution.

Scout Rover and Surveyor Rover configurations are summarized in Tab.1, while Master Rover Configuration is reported in Tab.2.

Table 1. Scout and Surveyor Rover Configuration

	Scout Rover	**Surveyor Rover**
Dimensions	49x52x115 cm	
Rover Base	Adept MobileRobots Pioneer3-AT (4WD, skid steering)	
Core PC	Versalogic Mamba (Intel Core2-Duo @2.26GHz, 4GB DDR3, 240GB SSD)	
PC#2	Lenovo X220T (Intel i5 @2.50GHz, 4GB DDR3, 256GB SSD)	
LocCam	BB2-08S2C-25, 1024x768, 100°HFOV	
HeadPTU	Flir PTU D46-70	
HeadCam	2x MESA SR4000 69x55°FOV, 5m	BBX3-13S2C-38, 1280x960, 66°HFOV

Table 2. Master Rover Configuration

Dimensions	135x85x200 cm
Rover Base	Adept MobileRobots Seekur Jr (4WD, skid steering, IP67)
Core PC	Versalogic Mamba (Intel Core2-Duo @2.26GHz, 4GB DDR3 240GB SSD)
PC#2	Versalogic Mamba (Intel Core2-Duo @2.26GHz, 4GB DDR3 240GB SSD)
PC#3	Panasonic ToughPad CF-D1 (Intel i5 @2.70GHz 4GB DDR3 128GB SSD)
LocCam	BB2-08S2C-25, 1024x768, 100°HFOV
NavPTU	Flir PTU D46-70
NavCam	2x MESA SR4500 69x55°FOV, 10m
TrackPTU	Flir PTU D46-70
TrackCam	BBX3-13S2C-38, 1280x960, 66°HFOV

The robots have been controlled by means of served as TAS-I Robot Management Framework and modular Robot Control Software [1].

5. MODULAR ROBOT CONTROL SOFTWARE

The software Development, Validation and Verification (DVV) infrastructure is based on distributed team collaboration systems, enabling the synchronization between development environment (e.g. bench computers) and target environment (rovers computers). To comply with TAS-I Robot Management Framework modular DVV approach, the application specific development happens in a modular fashion trying to maximize code reuse and to avoid, code redundancy. So the Robot Management Framework and the modular Robot Control Software are collections of reusable software packages and modules which can be deployed on the target platforms according to the application-specific architecture.

Thus, only the specific configuration parameters (e.g. reference frames, rover dimensions, trafficability parameters) has to be changed to ensure that the modules have the right inputs at start-up.

6. TEST ACTIVITIES AND RESULTS

The following paragraphs present the test activities and results regarding the modules developed in the frame of STEPS2 project, including the integrated tests with the complete RCS.

The modules not included in this section have been developed in the frame of [2, 3] and related projects, and so they will not be matter of discussion.

6.1. Vision-Based Guidance

Multiple experiments were performed in order to test and validate the performance of the Visual Target Tracking and the Marker Tracking modules described in [1].

The *first experiment* was performed to assess precision and accuracy of the Marker Tracking module, our success criteria was to achieve a ranging relative error below 5% and a standard deviation below 0.5%. The Master Rover's head camera was placed in front of a marker table made of four elements with marker's edge size of 0.135 m, parallel to the image plane. Accuracies and precisions were measured on a basis of 50 measurements for each trial each at different distances. The results are reported in Tab.3. With no claim of exhaustively characterize the algorithm these 4 tests were performed to evaluate its performance in worsening conditions. Initially, the distance is increased (Tests 1-2), in Test 3 distance is brought to the visibility limit with a worsened lighting condition and finally, Test 4 replicates Test 3 except for the fact that it was performed at night with camera mounted artificial illumination. For each test the luminous flux was measured at the centre of the marker table.

Table 3. Marker Tracking characterization results

	Test 1	Test 2	Test 3	Test 4
Sun elevation [deg]	28	26.67	11.9	0.73
Luminous flux [lux]	7000	7000	1900	8
Distance (Ground truth) [m]	1.498	2.106	3.933	3.933
Marker's edge size to focal distance ratio	0.0899	0.0640	0.0343	0.0343
Distance measurement error	0.13%	3.21%	4.28%	4.24%
Standard deviation	0.0054%	0.0158%	0.0142%	0.0355%

The *second experiment* performed was intended to assess precision and accuracy of the Visual Target Tracking module, our success requirement was to obtain a ranging relative error below 5% and a standard deviation below 5%. The camera was mounted on the master rover and pointed towards a sample canister mock-up placed on the ground at different distances. The same instrumentation and measurements of luminous flux and distance were used and collected as in the previous experiment. Due to the high variability introduced in the experiments by the inevitable human factor (human operator has to select the target area) and other factors such as k-means clustering and usual environmental conditions we chose to perform four tests, in which we collected 20 measurements for each test, and calculate statistical parameters on the full dataset. Measurements were collected at distances ranging from the closest (i.e. the distance at which the rover is able to pick up the sample canister) to the furthest (i.e. maximum visibility distance of the object by human eye) in order to reproduce the sample canister approaching scenario. The results are reported in Tab.4.

Table 4. Visual Target Tracking characterization results

Average Sigma	3.41%
Average Error	2.96%
Maximum Sigma	5.60%
Maximum Error	4.25%

The last and *third experiment* was performed to compare the two algorithms running in the same conditions using the same test setup as in the first experiment and instructing both algorithms to track the same marker table. The results of this comparison test are reported in Tab.5.

Table 5. Visual Target Tracking and Marker Tracking modules comparison test results

	Visual	Marker
Sun elevation [deg]	39	39
Luminous flux [lux]	16000	16000
Distance (Ground truth) [m]	3.609	3.609
Marker's edge size to focal distance ratio	0.0374	0.0374
Distance measurement error	0.059%	4.39%
Standard deviation	0.0246%	0.0164%
Fps	2	15

6.2. Digital Elevation Map Generation and Fusion

DEM generation and fusion has been tested using the double ToF camera assembly integrated on Scout Rover and Master Rover. The DEM generation process can be summarized as follows:

- **DEM Generation and Filtering**, the 3D point cloud is acquired, transformed and filtered to reduce noise. Multiple sensor readings are possible to increase reliability.
- **Fill Blind Area**, the blind circular area at the centre of the map is filled to ensure surface continuity and smoothness.
- **DEM Fusion**, based on rover odometry data input, the local DEM is merged with the global DEM.

The Perception and Localization Data Fusion modules have been configured to generated 1024x1024 pixels DEMs, with 0.05m/pixel granularity. The following test runs have been performed:

- **Static DEM Generation**, the rover was commanded to generate a DEM and then was manually moved to the next location. No GNC nor data fusion were performed.
- **Stop-and-Go DEM Generation and Fusion**, the rover was commanded to execute a given trajectory in stop-and-go mode and, at each stop, a DEM was acquired and merged with global DEM.
- **Continuous DEM Generation and Fusion**, the rover was commanded to execute a given trajectory in continuous mode, DEMs have been generated during rover motion and merged with global DEM.

The success criteria was to compare the estimated and ground truth object dimensions and relative distances in pixels as the absolute measures measure may fall or not in the correct pixel location on the DEM with 0.05m granularity. Different DEM granularities lead to different errors but it was out of the scope of the project to perform such characterization. Tab.6 summarizes the average and maximum DEM generation errors.

Table 6. DEM Generation results

Average Error [pixel]	0.5
Maximum Error [pixel]	1

The Fill Blind Area algorithm has been numerically verified first. Then its performances have been only evaluated qualitatively by looking at the DEM plot. As expected, in the Static DEM Generation tests no noticeable errors nor artefacts have been identified,.

Although the 6DoF DEM fusion algorithm has been numerically verified first as well, small discontinuities can be noticed in the tests results. These errors shall be imputed to the rover mechanical odometry (estimating only x-y-heading) which was used during the DEM fusion tests.

Fig.3 depicts the quality of merged DEM obtained as outcome of a three-step test, where the discontinuities artefacts are visible. Those errors do not jeopardize the rover capability to traverse the terrain.

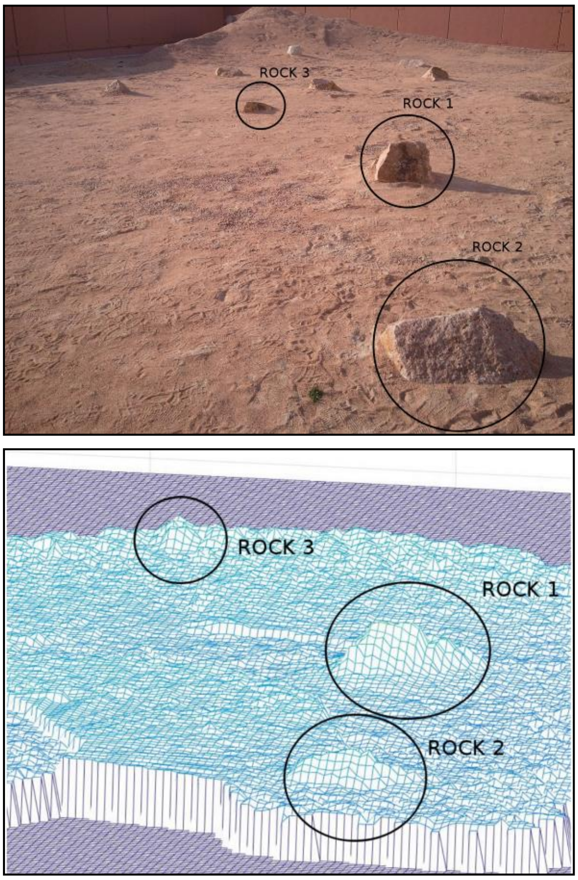

Figure 3. ROXY terrain (top), Global DEM (bottom)

6.3. Visual Odometry

In order to validate and to measure the performances in terms of estimate precision and timing execution of the visual odometry system, some tests have been done. The tests conducted are based on synthetic and real images, to measure the behaviour of the visual odometry system in the ideal case, that is in a controlled environment with no noise, with an ideal camera and with perfect surrounding conditions as well as in real cases.

For the ideal case, the synthetic images used are part of a dataset provided by ESA and are the result of a virtual simulation, which morphologically reproduce the Mars terrain conditions. This offline test consisted in a virtual rover following a quite general trajectory, with a series of rotations and translations and covering a total distance of about 181 m.

In Tab.7 are summarized the final errors of the visual odometry system for this test.

Table 7. Absolute errors for the synthetic images test

Final 3D error [m]	3.360
Normalized final 3D error	1.85 %
Final Roll error [deg]	0.80
Final Pitch error [deg]	1.20
Final Yaw error [deg]	3.50

The tests on real images used the frames acquired by the stereo vision system on-board of a STEPS2 rover and computed estimates online while the rover was moving in the ROXY's outdoor playground environment. The tests have been conducted using both Scout Rover and Master Rover configurations.

These set of online tests practically consisted in moving the rover in a series of simple trajectories i.e. straight, circular, rectangular shape trajectories as well as in more general one. In the results of following tests the translation on the z axis and the rotation around the roll and pitch aren't taken in consideration because the ground truth available didn't give information about them.

Tab.8 shows the results for these tests.

Table 8. Test results for common shape trajectories

		Trajectory shape		
		Straight line	**Circular**	**Rectangular**
Sun elevation [deg]		48.05	39.00	48.05
Luminous flux [lux]		51400	32100	51400
Total distance [m]		7.36	22.56	27.87
Position error [m]	**Avg**	0.017	0.153	0.200
	Max	0.0.48	0.439	0.578
	Final	0.007	0.143	0.319
Orientation error [deg]	**Avg**	2.49	7.21	6.32
	Max	4.65	17.54	32.43
	Final	3.89	7.20	2.44

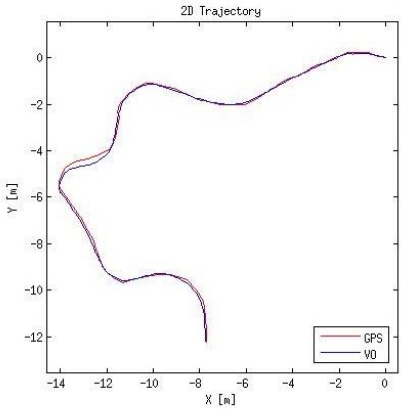

Figure 4. Ground truth (red) and visual odometry trajectory (blue) on the x-y plane

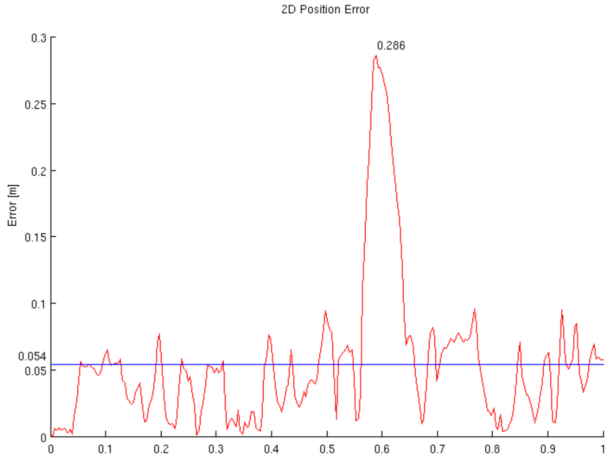

Figure 5. 2D position error on the x-y plane

Fig.4 shows the DGPS ground truth and the visual odometry estimated trajectory for a general shape path covering a distance of about 28m. As it is possible to see the estimated trajectory is quite similar to the ground truth in fact the average distance between the two trajectories is just 0.054m while the maximum error is 0.286m. (Fig.5) In Tab.9 are listed the errors for this test.

Table 9. Test results for the general trajectory

Sun elevation [deg]		29.22
Luminous flux [lux]		3270
Total distance [m]		28.349
Position error [m]	**Avg**	0.054
	Max	0.286
	Final	0.081
Orientation error [deg]	**Avg**	4.48
	Max	14.66
	Final	0.78

To have a better characterization, the information about date, time, weather conditions and luminosity intensity were measured during the tests.
Moreover, in the online tests since the robot framework and the visual odometry software were executed on different computers, the robot framework needed a way to correctly use the estimated poses. Since the network and the visual odometry estimation pipeline introduces delays, the robot framework, in order to merge correctly the data from the visual odometry, needed to know exactly what was the time in which the pose estimated state was valid. To have a common timing reference, both the computers were connected to an on-board DGPS equipment allowing them to synchronize. In practice every time the stereo camera captured a pair of images, it was tagged with a timestamp.

6.4. Manipulation System with Visual Servoing

As described in [1] our modular GNC, thanks to the Manipulator and the Marker Tracking modules, implements the ability to approach, acquire and store a sample canister. To perform these operations a marker table made of 4 markers with 8cm edges was chosen. Different tests were executed to test the system functionality with a success criteria which required the system to successfully pick up the sample canister and place it in the on-board tray. Each test was performed with the master rover and a sample canister mock-up at distances between 0.8m and 1.5m (inside the arm workspace) between their respective centres. For six times the arm was activated and instructed by the operator to move from its predefined stow position to three different deploy positions, respectively in front, front-left and front-right positions. These positions allow the operator to move the end effector mounted camera at approximately 0.8m from the ground pointing downwards ready to track any marker in the field of view. The sample canister mock-up was placed in different positions to test the effectiveness of the system which completed each test successfully.

7. CONCLUSIONS

Marker Tracking results show that the algorithm performance meets the 5% accuracy and +/-0.5% precision in all conditions ranging from short to maximum distances, including night time testing with artificial light. Visual Target Tracking results meet the 5% accuracy requirement and exceed of 0.6% the +/-5% precision requirement in the worst test condition.
Tab.5 shows interesting differences between the two algorithms. In the same very good light conditions the Visual Target Tracking module provides much better results in terms of accuracy while in terms of precision the Marker Tracking module is two times better than the Visual Target Tracking module.
The DEM Generation and Fusion algorithms performances fulfil the 1pixel accuracy +/-1 precision requirement
The visual odometry system in exam has shown appreciable accuracy performances both in terms of position and orientation precisions, which fulfil the 5% accuracy +/-1% requirement. Moreover, with these hardware configuration the visual odometry system was

able to be executed at about 7 fps, which is a speed suitable for robot navigation purposes.

8. FUTURE WORKS

The ROXY and Research Rovers exploitation has two main objectives: the former to support the R&D activities towards a TRL raising of the Robot Management Framework and modular Robot Control Software, the latter to provide a state-of-the-art infrastructure and platforms for studying and prototyping new algorithms, modules and solutions leveraging on the cross-fertilization between the space and non-space robotics applications.

To achieve the first objective a flight-representative on-board computer is going to be designed, procured and integrated. A refinement of the V-scrum development life cycle is envisaged to comply with the ECSS standards. To achieve the second objective, the research rovers and the development environment will be upgraded with new on-board computers providing more computational resources.

To increase research robots operating lifetime in view of an extensive field test, an upgrade of the power system is envisaged. This upgrade will include a solution to provide adequate power supply to the robotic manipulator removing the umbilical cable.

Finally, TAS-I Surveyor Rover has been selected by ESA as robotic partner of Eurobot Ground Prototype in METERON SUPVIS-E experiment. The rover will be controlled from the ISS using a flight MMI developed by TAS-I. It will provide additional situational awareness to the astronaut and will be used to simulate opportunistic science operations. Due to the very dynamic nature of the project, the V-scrum approach is being applied to manage the development life cycle.

In order to better characterize the vision algorithms an in depth series of tests is foreseen in an indoor facility where a Vicon tracking system is available, this will allow to collect a bigger dataset allowing to test estimations in all its translation and attitude components and with more controllable light conditions as well as collect data to perform tests at with marker tables with different sizes. Moreover, we foresee to increase the frame rate of the Visual Target Tracking module through code optimization and to implement an object database which will allow the robot to interact with a complex environment where all the points of interaction or interest are tagged with a marker table.

9. ACKNOWLEDGMENTS

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