A FACILITY FOR THE VERIFICATION & VALIDATION OF ROBOTICS & AUTONOMY FOR PLANETARY EXPLORATION.

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ABSTRACT

The development of complex autonomous surface robotic systems will be critical to future planetary exploration missions. These missions will encounter dynamically changing environments with high levels of uncertainty and will require the use of specialist test facilities to fully test these systems. This paper presents the results of a study conducted on behalf of the European Space Agency (ESA) by a consortium composed of RAL Space, Astrium and SCISYS. It investigated the feasibility of a European facility for the validation and verification (V&V) of landed robotic and autonomous systems aimed primarily at the exploration of extra-terrestrial planetary surfaces. This facility would focus its activities on three key aspects: the support of rigorous Field Trials to gather "ground truth" datasets, the simulation and modelling of robotic and autonomous systems including the critical correlation with the field test data, and the fostering of a European network of facilities and expertise to support these activities. By branching out beyond the space sector, it is anticipated that it will also be able to support a range of similar terrestrial applications.

1 INTRODUCTION

The development of landed robotic systems displaying increasingly complex autonomous behaviour is an enabling technology for future exploration missions. Whether targeting the Moon, Mars or beyond, they will provide a critical capability to maximise the quantity and the quality of the scientific return.
Robotic and autonomous missions, (including rovers, landers, sampler missions, and penetrators), face a dynamic environment with high levels of uncertainty. While the development of such systems will share some of the methods and processes used for the development of in-orbit systems, they also require the development and testing of systems and functions significantly beyond those of typical spacecraft.
A range of testing facilities and expertise is therefore required to support the design, testing and validation of these systems. In addition, these facilities could also find applications to non-space organisations who operate in a variety of markets including agriculture, automotive, first response, mining, oil and gas exploration.

This paper therefore presents the results of the Harwell Robotics and Autonomy Facility (HRAF) study conducted on behalf of the European Space Agency (ESA) by a consortium composed of RAL Space, Astrium and SCISYS. The study investigated the feasibility of a European facility for the validation and verification (V&V) of robotics and autonomy for the exploration of extra-terrestrial planetary surfaces and by extension for terrestrial applications.

1.1 Study purpose and methodology

The study focussed on a review and a proposal for a European test facility for robotics and autonomy indicatively to be established at the ESA Harwell centre in the UK.

To identify the most suitable scope for this facility, the study implemented the following methodology, as illustrated in Figure 1:

- Analysis of the robotic and autonomy needs of future exploration missions and opportunities
- Review of the V&V process for integrated landed robotic platforms
- Survey of relevant V&V facilities available across Europe to identify and highlight missing capabilities

- Interaction with potential user communities to capture existing capabilities and determine current and future needs
- Definition of a facility complementary to existing facilities while exploiting valuable synergies in the space sector and beyond.

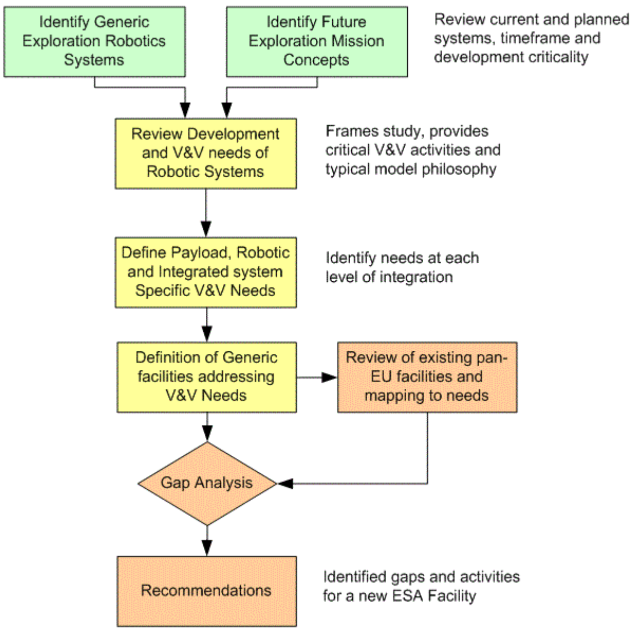

Figure 1 : System Level V&V Analysis

2 THE VERIFICATION AND VALIDATION PROCESS

The definition of the terms Verification and Validation have been standardised in ECSS-P-001B. Based on these ECSS definitions, they can simply be defined as follows:

- **Verification:** Proving that the system meets its requirements and that the deliverable product corresponds to the qualified design, i.e. is free from workmanship defects and is acceptable for use.
- **Validation:** Proving that the system requirements are correct, and the correct processes and methodologies are applied.

This approach can be summarised by illustrating the critical relationship of the Verification and Validation activities across the project and its integration levels as shown below in Figure 2.

The V&V of robotic and autonomous systems is a complex and multi-domain problem that is only successful when all the hardware, software, environment - and their respective interactions - are shown to meet the specifications, as well as being functionally fit for purpose.

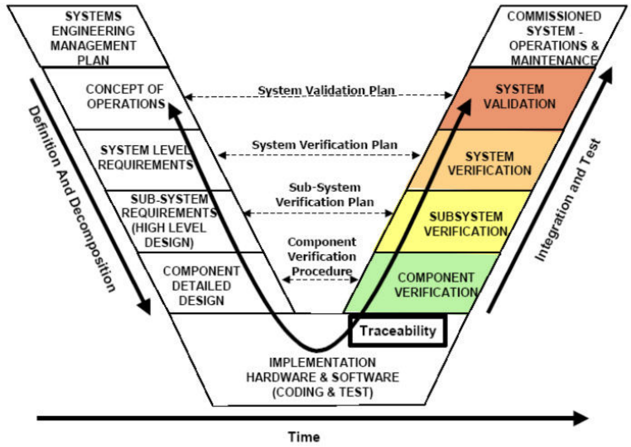

Figure 2 : The Systems Engineering "V" Diagram

The development of robotic systems for planetary exploration largely shares the methods and processes used for the development of in-orbit systems. However, they do possess specific development steps and verification needs inherent to robotic systems. In addition, with the drive to introduce increasingly complex on-board autonomous behaviours, the development and verification process must be able to adapt and evolve to maximise the safety of the system and the success of the mission.

The development of a robotic system for a planetary surface exploration mission introduces an additional level of complexity compared to purely space-borne missions, whether it is operating at a lower gravity, traversing on an unknown terrain or implementing increased levels of autonomy. The dynamics, kinematics and environment models used in the robotic system simulators are relatively new developments which have to reflect a relatively unstructured environment and do not have the extensive heritage of comparable models used in satellite simulators. To acknowledge the inherent risks of such new developments, a number of tests aim at building confidence. This is necessary so that, for example, a vehicle semi-autonomous mobility will behave as expected on Martian terrain. Or to demonstrate that a robotic manipulator will achieve its performance targets.
Some of these tests may not be part of the typical formal hardware qualification process, and are therefore not mandatory for this purpose. However, they can also be performed to verify operational procedures of the whole integrated system and are beneficial to further the understanding of such activities beyond the outputs provided by software simulations. These system tests also provide data to calibrate models and simulations.

3 REVIEW OF THE SYSTEM LEVEL V&V NEEDS

3.1 Target Robotic and Autonomous Systems

From the analysis of future mission concepts [1] the study has found that any new facility will need specific capabilities to support the V&V of a range of robotic systems including mobile/static platforms and manipulators. This also includes payload deployment, sample collection and object manipulation, as shown in Figure 3.

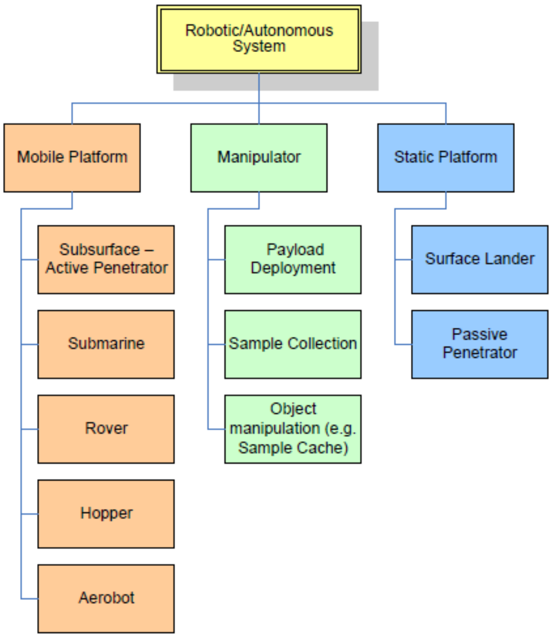

Figure 3 : Typical Exploration Robotic Systems

This V&V support is found to be required at all levels of integration, from equipment unit to subsystems, but also critically at system/mission level with the operation of the integrated system (payload + platform). This applies across all mission phases from development to post-launch operations.

In addition, as shown in Figure 4, autonomy is, in itself, also applicable to a wide range of applications in future missions.

3.2 Robotic and Autonomous Systems V&V Needs

Three main aspects need to be verified at various, if not all, levels of integration:

- Electrical design, function and interfaces
- Mechanical, thermal design, function and interfaces
- Operation – platform and payload, validation of autonomy

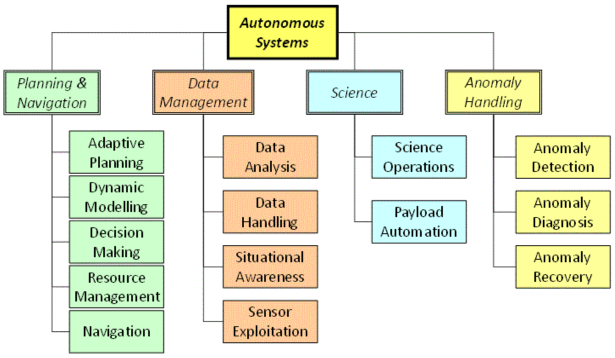

Figure 4 : Application of Autonomous Systems

While the electrical and mechanical aspects can be readily addressed by conventional methods, the operational aspects of a landed robotic and/or autonomous system may need additional V&V activities to:

- Increase the robustness of the complete system (platform + payload) and its operation,
- Ensure the operations can be completed successfully and safely within the resources available and,
- Generate the human factor of 'trust' that leads to technology acceptance and uptake.

In the absence of operational missions on which to exercise these complex systems, the use of high fidelity physical or software based simulations is therefore required to model the system and the environment in which it will be operating. To pick out the facility requirements, the study surveyed a broad range of existing European test facilities and compared them against a complex set of V&V needs to cover the full gamut of activities involved in the testing of robotic and autonomous systems.

While the verification strategy will be highly dependent on the actual mission and system, in the context of exploration robotics, three main aspects of V&V can therefore be identified:

- At Payload level - verifying and validating the payload or instrumentation against scientific requirements
- At Robotic system level - to ensure performance criteria are met
- At Integrated System level - where integration and operation of the integrated system are demonstrated to meet the necessary requirements and its fitness to fulfil the mission.

4 REVIEW OF EUROPEAN CAPABILITIES AND FACILITIES

4.1 Facility Survey

A number of facilities and tools already exist across Europe serving the space and planetary robotic community, it is therefore of high importance to propose an enabling infrastructure building upon existing centres and capabilities, while filling the gaps identified, and federating existing and future actors around this new facility concept.

To this end, a representative end-user community was identified early in the study and contacted to capture existing capabilities and determine current and future needs. Through a number of questionnaires and a dedicated workshop held in February 2012, the feedback from 37 space and non-space facilities was recorded to produce a detailed capability/facility database. While it was not meant to be an exhaustive record of all the European facilities with a capability to support these V&V activities, this survey provided a representative cross-section of the existing competences across Europe.
As shown in Figure 5, universities, research institutes and private companies provided a detailed snapshot of their facilities covering some 45 expertise/capability criteria split across a number of categories including component level (not a strong focus), sub-system, platform, and integrated system. These were applicable to both the hardware and the software/autonomy aspects.

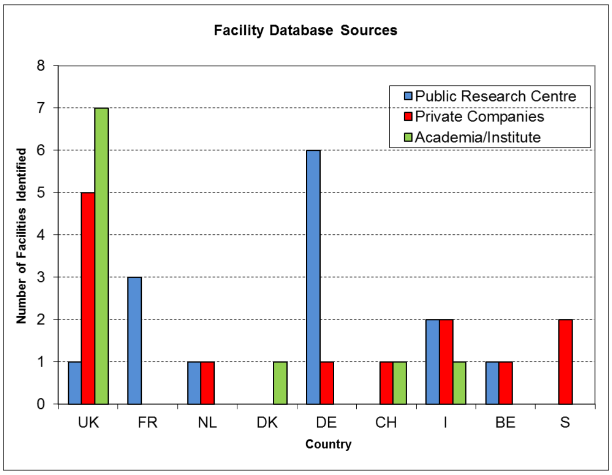

Figure 5 : Facility Database Extract – Number of responses per country

4.2 Survey Data analysis and gap identification

A detailed analysis of the capability database identified a number of key points:

A mature European environmental testing capability

Well-established European heritage has been identified for component level testing and especially environmental testing facilities. These test facilities are not only applicable to robotics systems but also to a wide range of space applications, and are applicable to high TRL items.

Planetary Environment Simulation
A wide range of Planetary Environment Simulation facilities exist. However, they tend to concentrate on specific aspects/level of testing e.g. single-wheel test bed to characterise wheel performance, or Mars Yard for full locomotion testing. Representative lighting systems are not mainstream and only a few facilities are able to accommodate dust tests (i.e. representative fine Moon or Martian dust beyond the normal sand dust in Mars yards).
The higher the TRL the more complex it will be to simulate the environment and the operation of the actual physical system. However, the number of future robotic missions cannot justify the building of large-scale facilities to replicate parameters such as gravity offloading or a variety of soil, terrain and environmental conditions (Mars/Moon/…). The development of appropriate models and their calibration is therefore critical to achieve the necessary validation of the final integrated system that cannot be tested physically (i.e. Phase C/D hardware will not be tested in a non-clean environment).

Infrastructure Supporting System Level V&V
The database showed that hazardous testing is rarely supported (laser, RF, etc), and aseptic facilities compatible with planetary protection integration processes are not currently available. However they are not anticipated to be addressed at this stage due to the specialist and narrow scope of application to the wider community.

As a development evolves from a low to a high TRL, it will require a range of software and hardware facilities from initial modelling to prototyping, testing, manufacturing and validation.
A simulation and modelling environment has been recognised by industry and agencies as a major catalyst to reduce design and development costs across the development stages. As the TRL is raised, so will the accuracy of the simulation - calibrated and correlated parametrically with data generated by field trials using physical prototypes – to ultimately contribute to the validation of an integrated system at flight readiness.

Subsystems models do exist and are used by the majority of the community (both industry and academic), but a clear need was identified to build an infrastructure that will allow the virtual integration of robotic platforms and payloads into a representative and accurate simulated environment.

Field Testing Support and Remote Operation

The survey showed that across Europe a number of entities have tested semi-representative robotic and autonomous platforms. These tests have been mainly performed in a laboratory environment, with a few in an outdoor controlled environment and even fewer in an outdoor natural setting.

Physical testing represents a critical step in understanding the behaviour of the combined hardware and software and builds the necessary datasets to calibrate the simulation models that will be used to perform the final validation of the system. In addition, it provides an opportunity to build first-hand operational experience of the joint platform/payload operation, (control, navigation, autonomy) and optimise the future operations of the system.

The control and operation of these platforms is generally done locally in the field. In only two cases has outdoor (Mars yard) testing been remotely operated (see ESTEC-CNES remote operation test [2,3]). To date the control of these platforms is mainly ad-hoc and no facility exists that enables the remote testing of these systems or provides logistical support to deploy them in the field. Similarly, a formally defined test infrastructure does not currently exist, including environment characterisation and mapping, or site and test data repository.

4.3 Towards a new facility concept

Many of the capabilities examined by the survey are not readily available for use by external organisations.
There appears to be a need not only to fill the gaps in the range of capabilities identified but to:

- Help make capabilities that already exist more readily available/accessible.
- Identify synergies and opportunities/infrastructure for integration between existing capabilities.
- Provide facilities that can raise the TRL of emerging technology bridging the gap between research and operational deployment.
- Enable simulation models developed for subsystems, instruments and environment to be brought together in a plug-and-play environment.
- Enable hardware to be seamlessly integrated into the simulations models.
- Enable the operations and planning tools to be validated and calibrated.
- Build confidence in the system design.
- Allow a distributed network of scientists and engineers to remotely participate in field trials simulations in real time
- Provide critical experience in operating the robotic system (e.g. rover), improving the operation planning and providing a training arena for both scientists and engineers.
- Reduce lifecycle costs by producing a robust system earlier and through more efficient validation, testing and operations.

5 PROPOSED ESA FACILITY

5.1 Overview

Based on the analysis of the European robotics community needs, this study has not only identified gaps in the European capabilities, but also its strengths and potential synergies. The following concept takes the opportunity to build upon these to make the proposed concept a relevant facility for all European activities in planetary and terrestrial – non-space – robotics in unstructured environments. The role of the new facility is to provide advanced capabilities for supporting the testing of robotics and autonomy, as well as providing capabilities of value to industrial and academic researchers in other fields.

As illustrated in the following Figure 6, the concept is articulated around the three needs expressed by the European community during the early study workshop, and the synthesis of the gap analysis:

- Field testing
- Simulation and Modelling
- European networking and data archiving.

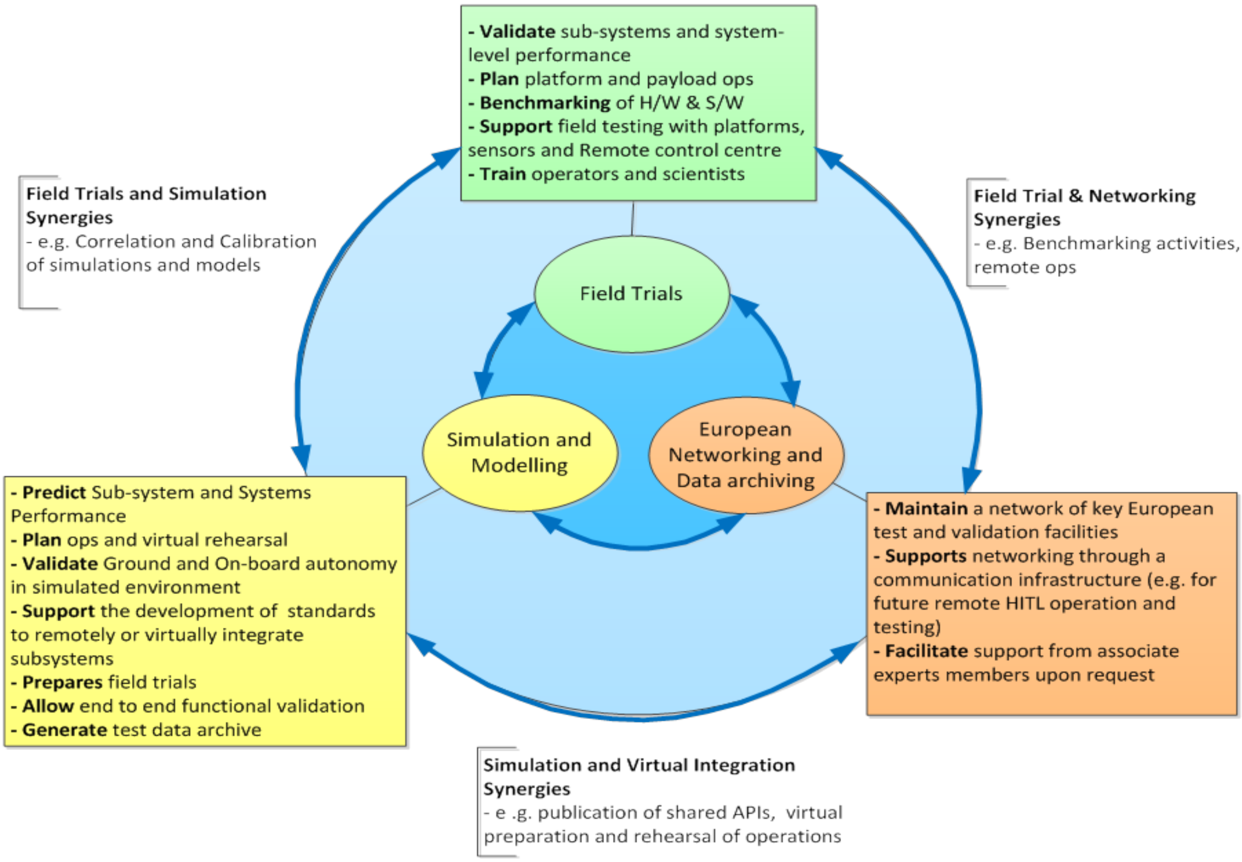

Figure 6 : New Facility Concept Addressing the V&V needs of Exploration Robotic and Autonomous Systems

In addition, it capitalises on the highly valuable synergies between these domains: field trials will provide high-quality data to calibrate and validate the simulation environment which will provide a realistic platform for virtual integration and hardware-in-the-Loop testing in the later stages of the project, and possibly performed remotely at another facility. The networking activities will allow development of a coordinated and coherent repository of reference field trial and simulation data as well as a framework to facilitate inter-facilities testing activities.

5.2 Field Trial Support Unit and Remote Test Operation

A Field trials support unit with focus on integrated hardware testing (platform + payload), autonomy validation, and surface operations rehearsal and validation. It answers the European robotic community need to have access to reference platforms with published application programming interfaces in order to benchmark and test autonomy functions on a number of platforms, rapidly and easily. In addition, the support unit will help organise field trials (technically and logistically), provides reference and metrology instrumentation which are necessary for characterising and mapping field sites, and by providing accurate test site characteristics for both remote areas and European local trials. This support will be a key enabler in the acquisition of physical real world data for correlation with the corresponding virtual model.

A Remote Robotics Operations Test Centre based at the facility will then be used to enable the remote testing of systems in the field. It will allow the setup of a realistic mission operation scenario to help validate the operational concepts during trials at local sites or full scale remote testing.

5.3 Virtual Engineering Lab Supporting Modelling and Simulation

The Virtual Engineering facility addresses the needs expressed during the study and in particular during the workshop:

- Simulations and models have an important role to play, especially when linked to a data archive; models of subsystems are already used to test functions, such as GNC, but are not integrated systematically into a dynamic environment model
- There is a significant gap between instrument

testing and robotic testing, a better understanding of instrument operation with respect to its robotic platform is crucial. Many groups are working towards virtual integration but a systematic approach supported by an enabling ESA centre is desired

- Field trials are recognised to be valuable but costly: reducing them through extended simulation will reduce costs and project risks. At the same time, integrating subsystems models into a virtual environment prior to field testing will allow the optimisation of field campaigns duration and complexity, and will allow functional testing of operations prior to campaigns.
- Finally, the community expressed the need to better correlate simulation models with field trials data to improve the accuracy of the simulated models and their environment.

A Virtual Engineering lab will facilitate the development and validation of autonomous systems concepts throughout the lifecycle. Through a mix of virtual integration and simulation, it will support development activities and rigorous risk assessment, allowing a wider range of concepts to be validated and refined before a project is committed to the expense and time of building a real system. The facility would therefore provide the generic resources and expertise in, virtual engineering, virtual integration and autonomous systems domain knowledge.

As more complex simulation models are produced, the need to validate efficiently these models becomes increasingly important. As the project evolves from design to implementation, the virtual engineering and modelling aspects also evolve from supporting the design of a system, to supporting its validation, to finally support its operation and troubleshooting on the planetary surface. The fidelity of these models is therefore critical to fully capture the behaviour of the system in an operational context. A number of ESA activities such as SWIFT and EXPERTISE are currently investigating the correlation and calibration of wheel-soil interaction models with actual test data. This facility would therefore build on the lessons learned from these developments, and many more, to facilitate the validation of simulated models and their use across a range of increasingly integrated applications.

5.4 Field Data Repository and European Networking

The data archive enables field trials, simulation datasets and models to be archived and distributed to the user community. The repository should initially store and catalogue data from ESA and other pre-cursors (e.g. ESA Startiger SEEKER and SAFER studies), to allow users to test autonomous systems in a variety of conditions and locations before committing to a field exercise. The data stored is therefore key to the Virtual Engineering activities. In addition, it can contain open dynamic models, simulation models, and a data base of field sites and their characteristics

The study underlined the need in Europe for a federation of the space robotics and autonomy community; the facility infrastructure would be brought to bear to enable exchanges and remote connections between sites to take part in activities such as virtual engineering work and testing. In addition, the facility will foster the engagement of the European community through the identification of e.g. “associate members” across academia, industry, and non-space bodies. Such associate members should be experts in a range of relevant fields supporting robotics and autonomy systems, e.g. validation using Formal Methods, Model Checking, promotion of data archive access, organisation of networking and exchange events, etc.
The European networking team will facilitate access to the associate members that will be available upon request to contribute to project work hosted by the facility. Their participation and commitment will ensure efficient expertise during all projects undertaken by the facility, and will contribute to further networking. Over the course of the study, a number of experts already expressed their interest in supporting the activity, highlighting the desire of the community to contribute to the proposed concept.

6 IMPLEMENTATION

It is anticipated that the facility concept will be established through a phased implementation that will see the setup and demonstration of its various constituting elements.
A number of pilot projects are being drafted to be conducted as part of this initial development involving the European planetary surface robotics community. They will aim at demonstrating, using existing facilities, hardware and software, how the engineering processes embodied in a fully operational facility could be of benefit to ESA in the validation and verification of robotic autonomous systems.

The scope and content of these projects are still to be defined. One scenario would include a representative Planetary Exploration Mission derived from the current ESA Missions Roadmap to demonstrate parallel virtual/physical engineering capabilities as proposed for the facility concept. In particular, it would make use of the combination of exploration hardware and autonomous software to exploit the ability to correlate data generated by virtual and physical engineering environments – key elements of the facility concept. The overall objectives of the demonstration would therefore be to develop a technological capability complementary to the current Mars Robotic Exploration Programme (MREP) and MREP-2 programmes while showcasing the setup of a team working with the proposed principles methods and (partial) facilities to demonstrate the potential of a fully operational centre.

7 SUPPORTING ROBOTICS AND AUTONOMY BEYOND THE SPACE SECTOR

The facility has been defined to primarily benefit the European space community for planetary exploration; yet its capabilities are of high relevance to a number of applications far beyond space autonomy and robotics design and testing.

The proposed facility could therefore support and encourage the use of its capabilities for non-space applications and generate a valuable synergy that will ultimately benefit space applications through the gathering and sharing of best practice processes, tools and methods.

Specific opportunities have already been identified in all of the markets identified below, from large system integrators to SMEs and academic institutions. These applications are generally aimed at reducing the need for humans to operate in hazardous environments or minimise the amount of staff required to do dull and repetitive tasks:

- Agriculture – precision farming
- Assisted Living/Health – 24/7 availability of assistance
- Automotive – safety and provision of facilities for disabled motorists
- Construction – reduce cost and risk to humans
- Defence – minimise casualties
- Emergency Services – access to dangerous and inaccessible locations
- Energy Exploration – access to inhospitable and dangerous locations
- Mining – cost reduction and safety
- Nuclear Power Decommissioning – access to hazardous areas
- Transport – flexible and continuous access
- Water industry – access to pipes, tunnels etc

8 CONCLUSION

The HRAF study investigated the feasibility of a European facility for the validation and verification (V&V) of robotics and autonomy for the exploration of extra-terrestrial planetary surfaces. A thorough review of existing European capabilities and the valuable feedback of the user community were critical to the study. These helped not only to identify the gaps in the capabilities and facilities that are required to perform V&V activities at system level, but also to capture of this community's requirement for such V&V.

From this assessment, a facility concept was derived that concentrates on the three key aspects of field trial, simulation and networking. These three core activities possess valuable synergies involving local experts and the community at large to further the methods and processes involved in developing robotic autonomous systems and making them more robust.

These capabilities have found direct applications to a range of applications beyond the space sector. The facility will therefore aim at supporting similar non-space activities involving similar systems. It is expected that this will foster cross-sectorial exchanges benefiting both the future space and non-space projects and developments.

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