PERASPERA

HORIZON 2020

Report

D3.4 Master Plan of SRC activities

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1 INTRODUCTION

1.1 Background

This document has been produced in the frame of the project "Per aspera (ad astra)" (Latin meaning "Through hardships to the stars") in short PERASPERA, funded by the European Commission (EC).

The EC grant financing PERASPERA was awarded following the "Competitiveness of the European Space Sector: Technology and Science – 2014" call, topic "COMPET-4-2014: Space Robotics Technologies".

The PERASPERA project belongs to the Strategic Research Cluster (SRC) in Space Robotics Technologies.

A Strategic Research Cluster is a hierarchical set of projects that aim at developing a joint overall objective.

The projects are divided in two categories:

"**Programme Support Activity**" (PSA): The main role of this PSA is to elaborate a roadmap and implementation plan for the whole SRC (referred to hereafter as the SRC roadmap) and provide advice on the calls for operational grants. There is a single PSA activity per SRC, which is awarded at the beginning of the SRC and continues for the whole duration of the SRC.

"**Operational grants**" (OG): The operational grants address different development steps identified in the roadmap. There are possibly many OGs in a SRC. As OGs aim at developing a joint overall objective, they abide by a coordination mechanism that allows late OGs to use the results of earlier OGs.

The PERASPERA project is the PSA for the SRC in Space Robotics Technologies.

The overall objective of the SRC in Space Robotics Technologies is to deliver, within the 2023/2024 framework, key enabling technologies and demonstrate autonomous robotic systems at a significant scale as key elements for on-orbit satellite servicing and planetary exploration.

1.2 Purpose of this document

This document is the main output of the PSA, it constitutes the roadmap i.e. the description of the final joint overall goals of the SRC and the intermediate development stages on the way to the goals.

The roadmap itself will go through 3 stages of maturation:

- Initial Stage: the roadmap defines a set of final goals for the on-orbit servicing and planetary scenarios and identifies in detail *technology maturation* activities for common building blocks
- Intermediate Stage: the roadmap reduces the set of final goals for the on-orbit servicing and planetary scenarios and identifies in detail *technology maturation* activities and *concept studies* for the on-orbit servicing and planetary scenarios
- Final Stage: the roadmap defines two final demonstration goals (one for the on-orbit servicing and one for the planetary scenarios) and defines the *system definition activities* for the demonstrations.

The initial stage is presented in this first issue of the document. The following stages will be presented in 2 future issues of this same document, which will be published ahead of the 2 other Calls of the SRC.

The *technology maturation activities* aim at designing and manufacturing, validation in relevant environment, of building blocks, with the goal of producing reliable, dependable and high-performance subsystems, components, and software that can be used at later stages for the composition of robotic concepts.

The *Concept studies* will produce designs and breadboards of space robotics applications, making use of the building blocks to showcase the increased performance and lower cost of missions making use of space robotics. To overcome some of the obstacles for a broader application of robotics in space missions these concept studies have to cover not the robotics aspects only, but also the impacts on the servicing objects, like the satellite design or the design of the robotic carrier.

Finally the roadmap shall concentrate on *system definition activities* that intend to specify (at Phase-B[1] level) the *demonstration, at a significant scale*, in the most relevant environment (i.e. space itself for orbital robotics and Earth analogs for planetary exploration) allowed by the selected space application.

Technology maturation activities. concept studies and *system definition activities* will be implemented during the duration of the SRC by means of Operational Grants.

It is important to note that this document cannot be specific about which Operational Grants will be implemented in the Calls. Final decision on the Call topics, challenges and expected impacts are a prerogative of the H2020 Space Programme Committee, which will examine the recommendations of the PERASPERA consortium, as presented in this document, and decide about the effective implementation.

1.3 How the roadmap was constructed

The PERASPERA roadmap has been developed with a process schematised in Figure 3. The process was designed to:

1. Account for current and past work sponsored by the many European stakeholders (EC, ESA, National Agencies)
2. Consider the possibility offered by spin-in/spin-over allowed by similarity of needs in terrestrial robotics sectors (e.g. servicing robotics and in particular offshore robotics)
3. Assume the needs of European stakeholders

The first step of the process implemented the acquisition and organisation of the information documenting the three bullets above.

The SRC goal is to increase the maturity of space robotics technologies and demonstrate them in the 2023-2024 time framework with sizeable demonstration missions.

Therefore, for the second step of roadmapping, two system studies were carried out, for the orbital case and for the planetary case, in order to identify two sets of demonstration missions that could be possible end goals of the SRC.

Finally the last step has been to define the individual activities of technological maturation and validation/verification, select the priorities of implementation and integrate all in a synthetic plan (this) that would also consider the EC constraints for Calls in the SRC.

[1] According to the standard ECSS–M–30A Space project management - Project Phasing and Planning

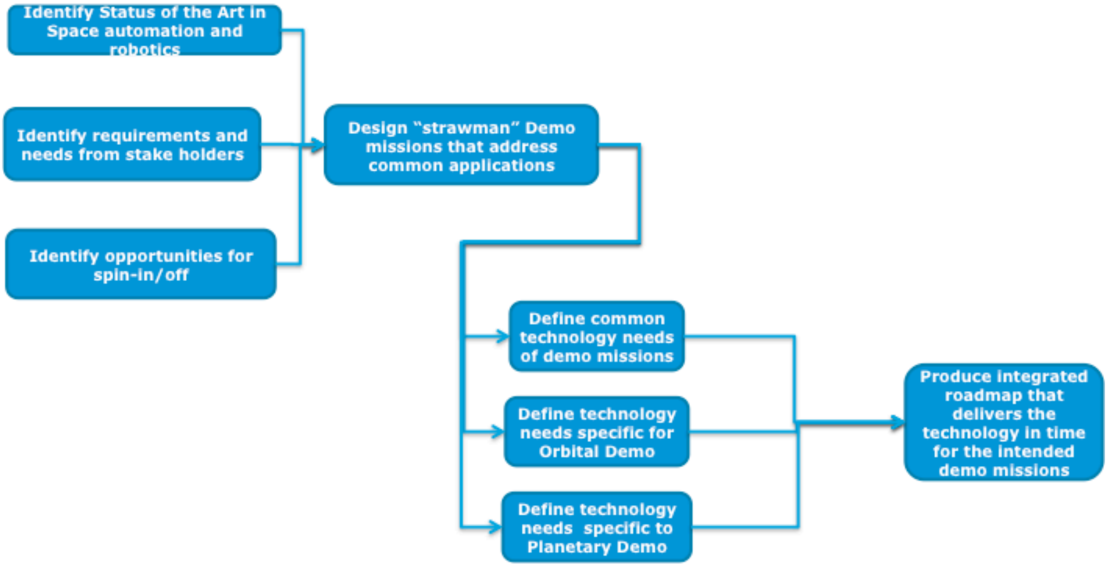

Figure 1: How the roadmap was produced.

It is important to understand that the roadmap so produced is an initial one. The process of roadmapping, so far described, will be performed two more times in the course of the SRC duration.

Since the inception of PERASPERA it was clear that the roadmap had to be structured along three "tracks" of development:

- An orbital robotics track: aiming at the maturation of technologies for the specific subject and ending with the detailed definition of a demonstration mission (for the 2023-2024 framework)
- A planetary robotics track: aiming at the maturation of technologies for the specific subject and ending with the execution of large scale field tests
- A common building blocks track: that aims at the maturation of technologies usable for both planetary and orbital track.

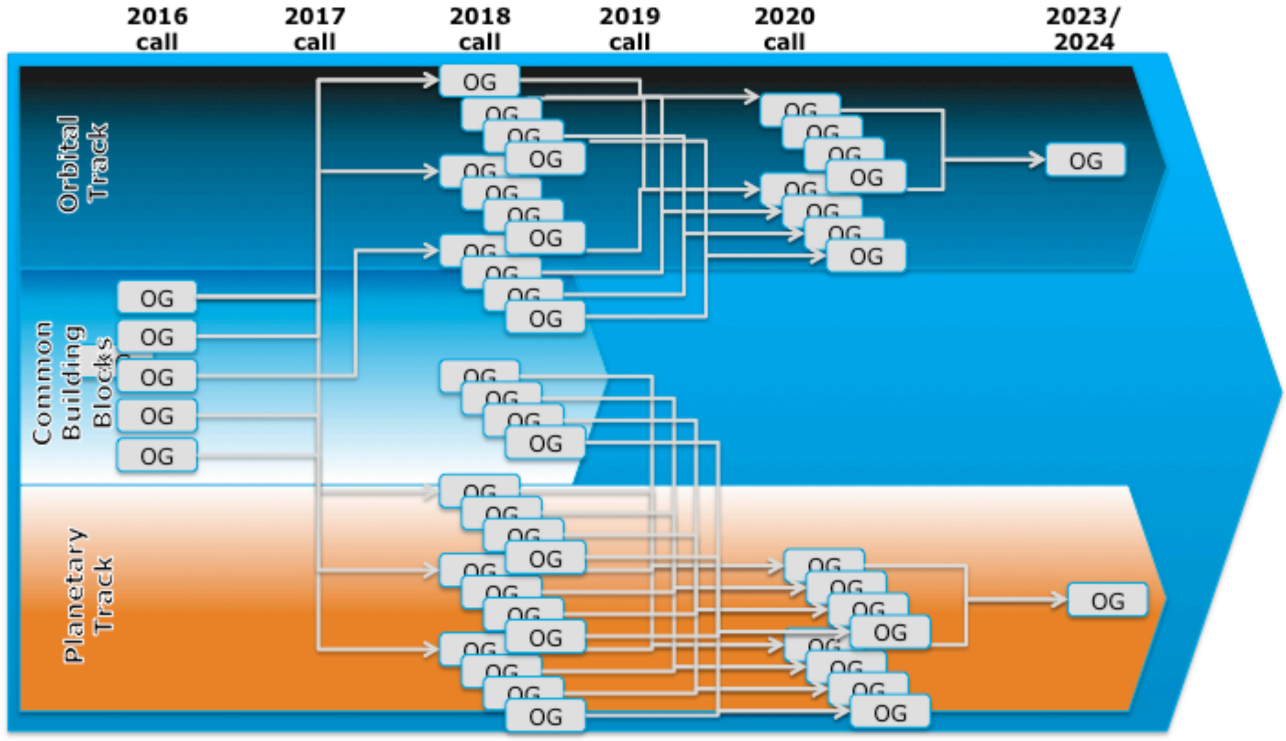

Figure 2: representation of the roadmap showing the 3 different tracks and how they may relate to each other. The representation is just exemplar and number and connectivity of the Operational Grants are not factual

1.4 Structure of the document

The SRC roadmap is not developed in isolation with respect to Europe-wide Space Robotics activities, plans and events outside the SRC. On the contrary the SRC roadmap is heavily coordinated and complementary to these. In the intention of the PERASPERA project team, the roadmap aims at demonstrating technology, concepts and applications that will possibly become full-scale applications in the 2025-2035 decade.

Therefore, before presenting the goals of the SRC, and the intermediate steps necessary to attain those, the document will present what are the expected applications of space robotics in the decade 2025-2035.

The document will hence proceed in presenting a first set of end goals for the SRC (these as explained previously are to be considered conjectural in the first issue of the roadmap).

Finally the document will conclude with an analysis leading to the definition of a set of common building blocks that will need to be developed as foundation of the SRC.

2 SPACE ROBOTICS APPLICATIONS IN THE DECADE 2025-2035

This chapter provides a concise thematic description of the applications of Space Robotics as seen by European stakeholders. This information is extracted from the document “D2.3-Stakeholders needs for Space Automation and Robotics Technologies” and the following “D2.9-Orbital Study report “ that have been produced by the PERASPERA consortium.

2.1 Orbital Robotics

A generic model to describe on-orbit servicing missions has been devised in the course of the “Satellite Servicing Building Blocks” activity. The model allows the introduction of the different servicing operations that may require space robotics.

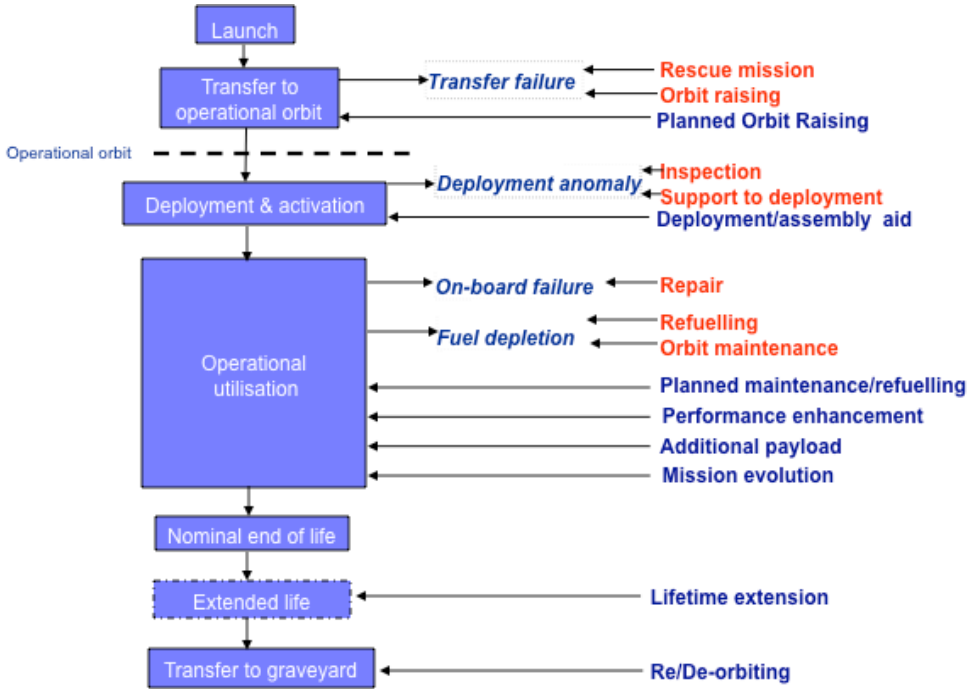

Figure 3: Lifetime of a spacecraft and possible orbital servicing operations. Planned operations are in blue text, unplanned operations in red.

The operations are discussed in the following, with the intention to present the related space robotics capabilities and the likelihood these will be needed in the reference period.

Rescue mission/orbit raising: this requires a dedicated or general-purpose space tug to **robotically capture** (in case of uncooperative target) or **robotically berth**/dock (otherwise) with the stranded satellite. This operation has been proposed several times in the past and even executed by a Shuttle mission. Unfortunately the economics of the operation is totally unviable and so this operation is not likely to happen in the reference period unless cost of launch becomes sensibly lower.

Planned Orbit Raising: this concept requires a general-purpose space tug to dock or **robotically berth** to the client satellite(s) to pull it (them) to higher orbit. It is an attractive concept for very big space infrastructure in which the payload to be delivered in orbit is bigger than the launcher capacity. So staging of the payload is necessary. The payload is divided in multiple launches, gathered on a low orbit and then by means of the tug, pushed on the operational orbit.

Commercial infrastructure envisaged for the reference period will not require such service. However the next institutional infrastructure (post ISS) aimed at Earth Lunar L2 may benefit of such service.

Inspection/Support to Deployment operations following deployment anomaly have been studied on a number of occasions. Unfortunately this operation has proven to be economically unviable and is not likely to happen in the reference period unless the cost of launch becomes sensibly lower.

Deployment/Assembly Aid: Every spacecraft undergoes the transition between the tightly packed state at launch, which allows the spacecraft to stay within the launcher fairings, to the expanded deployed state in orbit, in which all appendages are extended to their operational state. The possibility of using spacecraft-mounted robot manipulators to deploy/assemble the appendages has been studied and also tested successfully in orbit. There is also the possibility that great part of the spacecraft may be assembled in orbit by means of dedicated robot. This would allow improving the mechanical environment of critical components at launch making spacecraft lighter and more performing.

These operations have definitely non-zero probability to happen within the reference period as the obstacles to the realisation of them are not fundamental economic limitations but just maturity of the technology involved.

Repair, Refuelling and orbit maintenance operations following failure or early depletion have been proven to be economically viable (though marginally) where the failed spacecraft belongs to a constellation and a general purpose servicer can be stationed in advance in proximity of the constellation. However these applications have not received the interest of their only potential customers: space insurers. In fact commercial spacecraft are insured by operators against failures and early depletion, so costs are borne by the insurers, which to recover the losses increase premiums to the particular operator (as well as to new insurance contracts).

Planned maintenance/refuelling, performance enhancement, additional payload and mission evolution: these operations require a client spacecraft to be re-engineered to support them. Also to be economically viable, they need to target a constellation of spacecraft all requiring operations at the same time. Of all these operations, the one that appears more likely to happen in the reference period is refuelling as it is the one that requires the least level of modification of client spacecraft.

Lifetime Extension refers to the operation that allows a telecom satellite to continue its operation despite the fact it has depleted its fuel and therefore cannot remain autonomously stationary. It can be realised by different robotic means. One form studied in the past is the so-called captive carrying. An auxiliary servicing satellite is permanently attached to the client and performs station keeping. Another more speculative way foresees a servicing satellite that periodically attaches to the client satellite and recovers the orbital drift that has occurred since its last visit. This last form can only be advantageous if there is a constellation of closely placed satellites that can be visited with negligible delta-V. Lifetime extension may be financially viable only if the whole cost of the servicing satellite is well below the revenue that the additional lifetime of client satellite(s) generate.

Even in the most benign analysis Lifetime Extension offered limited benefits and many risks, so it has failed to attract support of its possible customers (satellite operators). It is not likely that in the reference period this situation will change.

Re/De-orbiting; in recent times there has been an increased awareness of the risk posed by debris (dead satellites, upper stages and their fragments) to the operation of functional satellites. Self-disposal of satellites at the end of their operational life has become a formal practice (and in some countries obligation) for new satellites.

For satellites in GEO, re-orbiting to the Graveyard Orbit (GYO) is the required practice. In the past the use of a dedicated servicer to re-orbit constellations of telecom satellites (a sort of satellite undertaker) has been studied and found to be marginally financially viable. However the concept has failed to attract support from the potential users as GYO re-orbiting was (and is) not yet mandatory, so the percentage of operators that actually re-orbit their spent satellite is still low.

For satellites in LEO the fact that there are infinite LEO orbits makes the concept of a common servicer impossible. So new LEO spacecraft must implement independent passive or active de-orbiting means.

For all defunct satellites already in orbit, which constitute some form of threat to the usability of their orbit, the only available solution is to perform robotically Active Debris Removal (ADR).

If the threat to highly critical orbits (such as the Sun Synchronous Orbit –SSO) is confirmed, by analysis and observation of the evolution of debris population, there will be a development of ADR in the reference period.

2.2 Planetary Robotics

The following scheme represents a typical rover planetary missions aimed to reach the area of interest, perform in-situ scientific analysis, collect samples and store them into a bio-container, and transfer them between planetary assets, ready to be returned back to Earth.

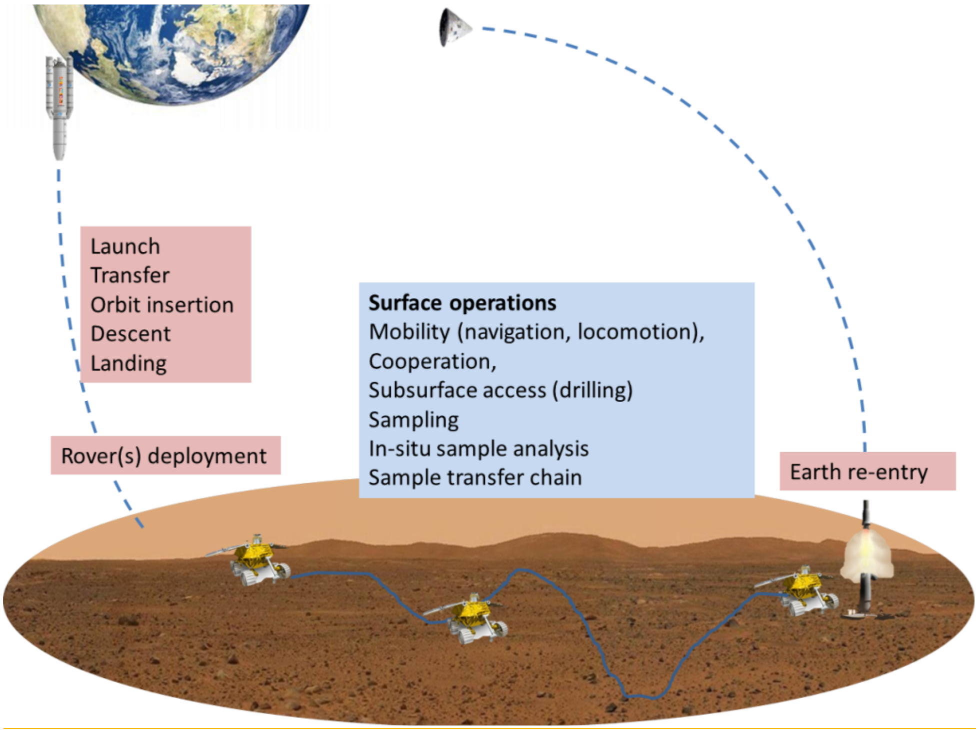

Figure 4: general schematics planetary sample return mission

In the following, the space robotics capabilities required are described in more details (referred to cyan box in the above scheme).

Vision based Autonomous Navigation (Map building & merging and self-localization)
In the context of planetary exploration this capability is of key importance due to rare communication links (MarsREX and Exomars scenarios) and is even more essential for missions like MSR where a crucial aspect is the accuracy of the localisation. In the case of a vision-based navigation, the surface vehicle relies on data fusion from its on board sensor set, which include its cameras/stereo-benches: the extraction of some visual features from the acquired images can be exploited to increase the accuracy in the vehicle relative position / orientation determination (with respect to its landing position or its operational goals) and/or its absolute position on the planet. The 3D environment reconstruction is an added output the on board visual sensor bench can provide, for benefit of the opportunistic science and on board autonomy devoted to smartly and efficiently schedule the on-the surface vehicle activities

Autonomy & Locomotion in harsh environment
Future missions foresee very complex and articulated on ground activities, potentially executed in demanding scenarios like shadowed craters, highly sloped and irregular terrain low gravity bodies for advanced exploration. Moreover, selection of the most convenient area to perform science,/detailed exploration/modules and plant settlement/ sample collection can only be accomplished after reconnaissance on a vast area. Exploring quickly and efficiently large surface areas may also require for vehicles better tuned for visiting large areas than 2D

surface robots. Different surface vehicle types could be combined according to the exploration area scale and to the requirements on exploration velocity and area revisiting.
Those scenarios ask for capabilities which can be categorized into:

- Advanced on board autonomy: a decision making skill on board the vehicle is fundamental to be reactive and cope with the environmental uncertainties for the sake of the vehicle and the mission, and to smartly schedule on-site its activities consistently with the best on board limited resource exploitation. Declarative and reactive reasoning mechanisms are foreseen on board, which also allow dealing with a more effective FDIR management timely. On board autonomy is also fundamental whenever a multi-vehicle scenario is supporting the mission for the on ground scientific and servicing operations, to robustly and timely manage the different vehicles coordination in performing their distributed tasks harmoniously.
- Advanced Locomotion: the capability to move safely on the surface no matter of its configuration is needed to ensure robust evolution of the on ground operations and to enhance the science feasibility; very harsh environment such as craters, caves, highly sloped regions, typically scientifically very important, can be reached. Adaptable and flexible wheels, legs, tethered systems, rolling elements and bladed wheels are intended to be advanced locomotion solutions.
- Long range mobility including 1) aerial vehicles, such as balloons, airplanes, helicopters, for supporting surface robots and exploring large surface domain, and 2) surface robots, capable to support and adapt to long range transfers.. Both aerial vehicles and advanced surface robots require long durability/high energetic efficiency, advanced materials for mechanisms and actuators, fusion of multiple sensors to accurately perceiving the environment for navigation, control, decision making. Advanced surface robots must implement alternative locomotion concepts based on legs and/or poly-articulated wheels (such as configurable robot or robot teams with complementary capabilities) to access difficult environment such as steep slopes and terrains cluttered with obstacles.
- Advanced sensing: Harsh and unknown planetary environments include shadowed/dark areas (i.e. craters and caves), and highly dusty regions (i.e. Mars, Moon surfaces). There is a need for sensor kits capable to support robotic exploration in these demanding environments.
- Energy Efficiency: The more challenging requirement to the robotics for surface exploration relates to energy availability, both in terms of amount and duration. New and more efficient energy generators are needed together with multi-functional mechanisms capable to store and recover energy losses. These technological enhancement are fundamental to relax the strong constraints imposed by the on-board power availability on exploration of very demanding areas (i.e. cold traps, dark regions). Smart materials which can change their structure thanks to adaptable parameters, may represent a valid solution to reduce the power demand from the on-board mechanism, and to differently solve some of the actuation tasks on board.

Relative Autonomous Navigation w.r.t. other assets (base/lander, rovers) → RF and vision based
In the reference scenarios (planetary sample return) a surface robot needs to determine its own relative position with respect to other planetary assets, like landers, bases or other vehicles. This capability is crucial in exploration scenarios, which include activities to be performed and coordinated among teams of cooperative vehicles. Examples of tasks that require such functionality are 1) transport of samples collected from a specific location to a landing station for in-situ analysis or for sample return to Earth. 2) transportation of a payload from a storage place to a delivery location 3) return of a scout rover, to its carrier companion.

Autonomous Science
The capability of a mobile vehicle to identify unpredictable opportunities for science, detected while travelling in the planetary surface is key to maximise scientific return of a mission. Autonomous science requires a vehicle to be able to detect interesting regions in its surroundings, to judge and score their relevance according to the scientific mission objectives and goals, and to revise its own a-priori activity plan to include visiting and sampling of the interesting area, while respecting resource constraints.

Autonomous sample / payload manipulation, transfer between planetary assets
In the case of sample return missions, a mobile vehicle must be able to grasp an object (sample container, payload), release it from its support, transport and deliver it to its destination with a high positional accuracy. This capability relies mainly on a manipulator arm equipped with vision and force sensing. Vision based positioning is also required since the various object locations cannot be precisely known in advance. This functionality is mandatory for Mars and low gravity bodies exploration and particularly useful on the Moon to reduce the workload of human operators (TransTerra scenario).

Multi robots cooperation
In the context of planetary exploration, multi-robot systems could be essential , since a single robot is not able to cover wide and/or topologically different areas and acquire all the required information. In this view the cooperation among multiple robots allows to increase the locomotion by combining different specialized vehicles and, therefore, explore various types of terrains (a wheeled rover for even terrains and a legged scout for terrains cluttered with obstacles). The multi-vehicles asset increases the system flexibility and robustness too, by distributing tasks and functions whenever complex activities must be carried out such as large infrastructure building, elements transportation, coordinated area exploration, astronauts activities support

Hardware/Software reconfiguration
Reconfiguration is particularly needed in the case of multi-robots cooperation. A distributed, reconfigurable decision making architecture is required to make the team of robots working harmoniously and to adapt to the chancing configuration of the tasks and the number of robot team members. Multi-agents architectures are required to cope with coordinate local global planning scheduling, reaction, perception and reconfiguration capabilities. SW reconfiguration capabilities may require HW reconfiguration capabilities , as well. Finally standardisation in both SW and HW interfaces is required as a side aspect for reconfiguration functionalities.

Telerobotics / telepresence for rover and manipulator tasks
In presence of low latency and high bandwidth communications, like it could be for a lunar mission (TransTerra / RIMRES), telerobotics/telepresence approach is suitable to operate a robotic system. In order to allow the operator to monitor / intervene at different levels in the task execution the implementation of a flexible control / communication / human interaction architecture is necessary.

Sample collection and preparation for scientific in-situ analysis
Sample collection capability is a fundamental capability of planetary sample return missions. Different devices (micro sampler, drilling/sampling for very hard soil , very deep drill) can perform sample collection, e.g. a driller fixed on the rover or tools located at the manipulator end effector . Martian and Lunar mission require sample collection up to 2 meters in depth, dealing with different types of soil. In addition, a sample preparation and distribution functionality is necessary to allow the sample be analysed by the scientific payload an board the rover.

Sample handling for bio-container storage
After being collected the sample has to be adequately stored to prevent the backward contamination, once back on Earth. The sample bio-container and the sample handling system shall be designed to preserve the sample properties as required by scientists during manipulation, interplanetary transfer and release on Earth.

3 THE SRC ROADMAP

3.1 End goals for the Orbital Robotics Track

Elaboration of the status of the art, the needs of the stakeholders, the study of the possible demonstration within the Orbital Robotics Track has produced the following end-goals:

(OT-1) Active Debris Removal, which targets the final demonstration of re-orbiting of a small ESA-owned Earth Observation satellite. The demonstration mission that will be the final goal of the scenario will allow to showcase a number of robotics technologies to rendezvous with a highly uncooperative real debris (by 2023 the chosen satellite will be just that), capture it and insert it into a <25 years re-entry orbit. The scenario will use common building blocks, mature the dedicated RV and grasping technologies and finally develop the demonstration mission in its last operational grant. This grant will need to have adequate funding for procuring the spacecraft hardware and the launch opportunity.

(OT-2) Future Low-cost EXchangeable/EXpandable/EXtendable SATellite (FLEXSAT), which targets the demonstration of robotics servicing technology aimed at achieving composable, re-configurable and refuel-able spacecraft. The demonstration mission, that is the final goal of the scenario, will feature a small satellite system that, through robotics technology, can deploy/reconfigure/extend itself, thus allowing the spacecraft mission to evolve. The scenario will use common building blocks, mature the dedicated manipulation and assembly technologies and finally develop the demonstration mission in its last operational grant. This grant will need to have adequate funding for procuring the spacecraft hardware and the launch opportunity.

(OT-3) EUROBOT, which aims at demonstrating humanoid crew assistant robots to be employed on the International Space Station. EUROBOT is a concept studied by the Human Spaceflight and Microgravity directorate of ESA in order to drastically improve the efficiency of Extra Vehicular Activity on the ISS (and in future orbital infrastructure). EUROBOT is a humanoid robot that can climb along the outer surfaces of the ISS to reach operating sites and perform highly dextrous manipulation while being teleoperated from inside the ISS or from ground. The EUROBOT concept, besides offering benefits on the operation of orbital infrastructure, presents very promising spin-off potential for the off-shore and disaster relief robotics applications. The scenario will use common building blocks, mature the dedicated telemanipulation technologies and finally develop the demonstration mission in its last operational grant. This grant will need to have adequate funding in order to cover for the extensive safety provisions that are required to fly on the ISS.

3.2 End goals for the Planetary Robotics Track

Elaboration of the status of the art, the needs of the stakeholders, the study of the possible demonstration within the Planetary Robotics Track has produced the following end-goals:

(PT-1) Martian Long-range Autonomous Scientist, which targets the demonstration of highly autonomous technologies that will allow future Martian rovers to roam across the vast extents of the Martian surface and return autonomously detected science, compatible with the limited energy and telecommunication budgets associated to Martian missions. The scenario will use common building blocks, mature the dedicated autonomous navigation and science detection technologies and finally develop a demonstration field trial in its last operational grant.

(PT-2) Martian Cliff Explorer, which targets the demonstration of a master/scout rover couple for the scientific exploration of Martian gullies. Martian gullies are the place where puzzling Martian surface processes have been detected. The concept developed by this scenario will feature a comparatively large conventional rover that can deploy a very agile tethered scout rover that can rappell into the gully. The scenario will use common building blocks, mature the dedicated agile locomotion and science detection technologies and finally develop a demonstration field trial in its last operational grant.

(PT-3) Martian Crossover Explorer, which targets the demonstration of a rover with high locomotion capabilities to enable the exploration of not easily accessible areas (and therefore increase the scientific return of the mission). These capabilities will have to be compatible with the limited energy and computing resources budgets associated to Martian missions. The scenario will use common building blocks, mature the dedicated locomotion and navigation technologies and finally develop a demonstration field trial in its last operational grant.

(PT-4) Lunar Crater Explorer, which targets the demonstration of a master/scout rover couple for the scientific exploration of cold traps on the Moon and the collection of samples from these. The Lunar south pole is known to have accumulated unknown volatiles in the surface areas rarely illuminated by the sun (cold traps). The concept developed by this scenario will feature a comparatively large conventional rover that can deploy a very agile tethered scout rover able to rappel into the cold trap and collect soil samples from there. The scenario will use common building blocks, mature the dedicated agile locomotion and sampling technologies and finally develop a demonstration field trial in its last operational grant.

(PT-5) Planetary Deep Driller, which targets the demonstration of autonomously accessing and sampling subsoil one order of magnitude deeper than present technology can. Drilling technology developed for ExoMars can reach and sample at 2 m of depth at most. This depth is the minimum requirement in order to reach possible signature of life not cancelled by radiation. In reality the deeper you sample the less is the cancellation by radiation. The concept developed by this scenario will feature a rover-mounted drill system that can drill and sample in the order of a few tens of metres. The scenario will use common building blocks, mature the dedicated deep drilling and sampling technologies (derived from the mining industry) and finally develop a demonstration field trial in its last operational grant.

4 THE SRC ACTIVITIES

The SRC activities treated in this chapter are those that could become the subject of Operational Grants.
The activities are described in different subchapters. Each activity is listed in a table containing the subject of the task, a task description, an analysis of the status, the need, the expected results and priority in the roadmap. References to the *State-of-the-Art* and *Stakeholder Needs* document are implemented to describe status and the needs due to the task. The impact on future missions comprises the analysis of the system studies and describes, how the results of the task effect and can be applied respectively in future missions.
The priority of an activity, a number from 0 to 4, has been elaborated by the PERASPERA consortium, considering the existing TRL of the technology, the level of dependency that demonstration missions have on it and finally how it may fit with the 3-Call system of the SRC. The higher the priority, the more likely that the technology will become subject of an Operational Grant.

4.1 Common Building Blocks Maturation

This section contains proposed technology maturation activities regarding both, planetary and orbital track reference scenarios. The common building blocks encompass basic functionalities such as mechanisms, software, and hardware relevant for the targeted robotic applications.

4.1.1 Ground Support Equipment

Title	**Analogue Field Trials**	
Task Description	Implementation of analog field trials will enable researchers and scientists to discover real-life problems presented by rover operation in planetary exploration scenarios.	
Analysis of the status	• The SEEKER and SAFER projects demonstrated the sorts of problems created by a high-fidelity analog of Mars (the Atacama desert in Chile). The project showed a rover navigating autonomously across 6km of analog Martian environment and return where it started. *See D2.1 - Ch2.4.5.*	
Need	• Use of large (~20km), unstructured testbeds will be required to validate advances in mobility, and the rover's ability to overcome specific problems such as deploying a miniature scout rover to rappel down a cliff or crater,	

	as posited in the Martian Cliff and Crater explorer projects. • There is also a need for provision of an analog testbed for autonomous science *See D2.2 Ch4.*
Impact on future missions	• Increased awareness of how to avoid and/or overcome specific problems encountered in analogs of Mars and/or the Moon, and improving understanding of the robustness of rover capabilities, particularly when traversing greater distances, and more treacherous terrain. • Greater understanding of capabilities and limitations • Greater confidence in the use of autonomy, and therefore greater ROI • More effective use of field trials as most appropriate analog site selection and greater efficiency in running the campaign
Expected Results	• Validation of technology advances in: autonomy (planning, FDIR, opportunistic science) mobility, perception and manipulation.
Priority	4, As V&V is an important phase of maturation, test vehicles and analog sites ought to be identified as a very high priority. The need for the SRC to produce tangible, verified results is of paramount importance, and something that cannot be done without the use – and, where necessary, development – of appropriate analog field trials.

Title	**Physical Robotic Testbeds**	
Task Description	Provision of testbeds for validation of robotic technology in both planetary and orbital scenarios.	
Analysis of the status	ESA has developed a ground testbed for assessing EUROBOT in a planetary exploration context. The UK, Germany, Italy, France, and Spain all have significant testbed capability able to validate and demonstrate differing aspects of autonomous navigation, science, sampling, locomotion and decision-making by the rover. Further afield, Canada and Hawaii both have substantial testbeds for the testing of science and sampling, autonomous teleoperation, human-assistance vehicle navigation technologies.	
Need	• Equipment and testbeds for demonstrating and validating SRC robotics developments (esp. new manipulator, end-effector, gripper exchange interfaces, manipulator payloads. • In mobility, demonstrator testbeds for autonomous rovers working as part of heterogeneous robot swarms, crawlers crossing extremely rough terrain. • Finally, planetary mock-ups and virtual testbeds for verification of methods used for extremely fast 3D map generation for planetary landing and operation.	
Impact on future missions	• Increased awareness of problems encountered when teleoperating or using robots in planetary scenarios, and how technologies developed in other scenarios (ie orbital) fare when applied in a planetary context.	
Expected Results	• Greater understanding on viability of (re)applicability of robotics technologies in different environments • Demonstrate orbital and planetary robots in non-conventional unstructured environments • Greater understanding on how to verify and validate complex autonomous systems	
Priority	4, As V&V is an important phase of maturation, testbeds ought to be identified as a very high priority. The need for the SRC to produce tangible, verified results is of	

	paramount importance, and something that cannot be done without the use – and, where necessary, development – of appropriate physical and virtual testbeds,.

4.1.2 Basic Software

A robot control system is the basic software that allows robot control software to run. One of the main priorities of the Cluster is to develop a standard open source RCOS (Space Robot Control Operating System).
The Operating System must be generic and flexible, to control any robot spacecraft system whether a planetary or orbital robotic application. But with the adequate Space grade Reliability, Availability, Maintainability and Safety (RAMS).

The other objectives of the roadmap in Basic Software are creating generic control building blocks that could be reused in new space robotics projects and applications, with special focus in modular systems. Also it is necessary to realize standardization in the software, interfaces and methodology of design and testing.

Title	**Robotic control operating system**	
Task Description	Specific open source Space Robot Control Operating System, with space-grade reliability, availability, maintainability and Safety.	
Analysis of the status	Terrestrial RCOS are divided between proprietary systems, developed by industrial robot companies, and "university lab" ones (OROCOS, ROCK, GENOM, ROS). The first ones are not usable for space robotics because of IPR incompatible with space development, the second do not have sufficient RAMS properties	
Need	RCOS are needed to control any robot/spacecraft systems whether for orbital or planetary applications, for all phases and modes of the mission, with space-grade (RAMS) properties. The RCOS (Robot Control Operating System) must provide the following features: • hardware abstraction • low-level device control • scheduling of hard/soft real-time tasks • communication and synchronisation between tasks • run-mode/run-level/runtime-configuration management and monitoring • Fault Detection, Isolation and Safing/Recovery • filesystem access and filesystem management • networking • consistent data types across communication, networking and file system operation • logging/telemetry generation and command processing • Application Programming Interface for all the above functions	
Impact on future missions	The output will be used in all SRC follow-on OGs.	
Expected Results	The output will be used in all SRC follow-on OGs. Furthermore the very high standards of RAMS sought by this topic will certainly make it usable in future full fledged space robotics missions.	

Priority	4, A robot control system is the basic software that allows robot control software to run. One of the main priorities of the Cluster is to develop a standard open source RCOS (Space Robot Control Operating System). The Operating System must be generic and flexible, to control any robot spacecraft system whether a planetary or orbital robotic application. But with the adequate Space grade Reliability, Availability, Maintainability and Safety (RAMS).

Title	Basic Software Design, Development, Verification and Validation Methodology	
Task Description	The activity shall develop a modelling language for robotics architectures inheriting the accumulated expertise from all traditional software methodologies (i.e. UML, SysMl, AADL). It shall define the major entities and attributes of robot components from a design point of view and provide analysis support for most typical trade-offs during avionics design phases (e.g.: data acquisition and commanding, on-board computer and memory resources, bus/network load analysis). The approach should consider the whole design, development, verification and validation process of a robotics system including an incremental approach (software-in-the-loop, hardware-in-the-loop) and testing in on-ground facilities The activity shall investigate the development of automated algorithms-to-code methodologies in order to ease the cycle development and apply it over satellite and planetary exploration applications The methodology shall support high-level code design, automated code-generation and verification either from algorithms-oriented frameworks (e.g. Matlab/Simulink) or model-driven environments (UML-based techniques) as well as correct-by-design coding. The methodology shall be compatible with the Space Robotics framework	
Analysis of the status	• Input from state of the art (reference to the chapter)	
Need	• Input from stakeholder needs (reference to the chapter)	
Impact on future missions	• All robotics missions	
Expected Results	• Developed methodology • Tested methodology from design to validation	
Priority	4, space mission are one-off endeavours. It is not possible to realise incrementally reliability, availability and safety once the mission is launched, everything has to work perfectly from the start. Any little problem not identified prior to launch may lead to total mission loss. This is why in space missions software verification is so thorough. If robots must become central elements of space missions, as advocated by the PERASPERA ambitious goals, they must reach the same level of RAMS as conventional spacecraft software. This technology is therefore capital	

Title	**Dynamic S/W architecture for modular spacecraft (space robot)**	
Task Description	This activity shall generate a dynamic S/W architecture for to control a full modular space platform. The S/W controller can seamlessly rearrange its resources (e.g. cores, memory, clock) over the whole space system to provide optimal performances and power use. Modules of the spacecraft can be removed/added	

	according to plug-and-play-principal.
Analysis of the status	• Nowadays robotic controllers are specially developed for robotic payload elements or subsystems • No generic system wide intelligent controllers exit
Need	• Input from stakeholder needs: Ch. 4.1 • Active payload modules or modular spacecraft require dynamic control software that supports plug-and-play principal for parts of the spacecraft
Impact on future missions	• Realization of full modular intelligent space systems space robots)
Expected Results	• Top level S/W framework as robotic controller (robot = complete modular spacecraft) • A demonstrator of reconfigurable and
Priority	4, a fundamental problem in space microelectronics is the gap in performance with respect to terrestrial microelectronics. The gap is created by the process of hardening chip technology against the space environment. Computing performance in space robots will regrettably be always less than what available on Earth. Therefore the little computing resources available on a space robot need to be used (and reused) as much as possible. This is the primary need for dynamic reconfiguration. This technology will also allow constructing spacecraft that have independent computing modules.

4.1.3 Perception and Navigation

Title	**Perception and navigation core**	
Task Description	The activity shall produce a set of perception, localization, map building and path planning modules that will be compatible with a wide spectrum of applications within the orbital and planetary tracks. Meanwhile, this activity shall improve the perception and navigation capabilities of the future missions.	
Analysis of the status	• Mars REX mission : The main challenge of this mission concept study is to fit into a small allocated volume/mass a rover system with scientific and/or exploration capabilities that would be valuable enough • TransTerra : This mission concept study is devoted to Lunar exploration with a team of multiple robots. It addresses both scientific and technology demonstration objectives • RIMRES : The main objective of this project is to address the technical issues associated to the design of a modular and reconfigurable Robotic Exploration system to reach a higher level of performance and robustness for a lunar type mission. • ExoMars : This programme will demonstrate a number of essential flight and in-situ enabling technologies that are necessary for future exploration missions, such as a Mars Sample Return (MSR) mission. • INVERITAS: The main objective of this project is to address the technical issues associated with the on-board autonomous relative navigation and capture of mobile systems. The task was to investigate and develop a prototype of a generic multi-mission-capable rendezvous and capture system including the associated core technologies.	

Need	• Sensor data fusion techniques (visual and laser data) in unstructured and structured environments,
	• self localisation w.r.t. another vehicle (i.e. structured object)
	• landmark tracking (either terrain object or planetary asset)
	• path planning:
	  ○ for manipulators in a static or dynamic environment (including the coordinated motion with the carrier vehicle).
	  ○ for exploration vehicles over large a priori unknown areas
	• large scale map building with a data representation compatible with on-board resources and long term path planning
	• generic target detection and localisation, rendezvous, inspection flight around, and close manoeuvring, as well as autonomous tracking based on continuously sensing the environment and relative navigation

Impact on future missions	• The output will be used in all SRC follow-on OGs.
Expected Results	• Integrated perception and navigation solution (algorithms) for orbital and planetary (can be separately) applications • Considering input from multiple sensors -> solution regarding sensor data fusion • Increased scientific return of exploration missions
Priority	4, this activity is an important generic building block enhancing capabilities in both orbital and planetary tracks, the PERASPERA consortium believes that this a subject to pursue with urgency

4.1.4 Mission Control

Title	**Mission Control for robotic applications**
Task Description	Improve mission control system for robotic application
Analysis of the status	• DLR's KARS project implements a database-driven hierarchical control and command structure for autonomous spacecraft. • ESA's PROBA-2 is controlled via autonomous MCS and a dedicated tracking terminal in Redu. Proba-2 also has autonomous navigation enabled; all navigation and manoeuvring computations done autonomously on board. • Proba3 will demonstrate dual spacecraft flying in formation, validating relevant control algorithms, while ESA's Rosetta demonstrated the overcoming of challenges such as long comms turnaround times (100 mins), low data bit rates (8bps), and low power availability; all challenges that would be encountered on a long-range robotics mission.
Need	• Further demonstration of autonomous handling of mission difficulties encountered in Rosetta in a planetary or orbital environment. • Development of algorithmic computation of navigation and environmental assessment in orbital and planetary scenarios • Adaptive Ground operations concepts for reconfigurable space systems
Impact on future missions	• Reduction of costs owing to greater robustness of mission control • Greater allowance of computational power to be directed towards high level mission goals rather than low-level algorithms

	• Support of full modular spacecraft, which can reconfigure themselves to adapt to new mission tasks
Expected Results	• Increased robustness of Mission Control Systems • Allowing greater human resource to be directed towards the achievement of mission goals rather than low-level computation and navigation
Priority	3, this technology is very important, however it appears not urgent within the SRC scheme at this time. The reason being that it is a technology very much tailored to the application. For example the Mission Control System (MCS) for a Mars mission that has to cope with a operating cycle of 1 sol and where the robot (a rover) is mostly autonomous has little in common with the MCS for a satellite servicing mission where the space robot is likely to be operated with interactive autonomous mode that has a cycle time of seconds.

4.1.5 Avionics

Robotics is one of the main driver of the advance in avionic system in space. Robotic applications require avionics with a degree of performance and flexibility not seen in many other space applications.

Robotic avionics has typically been customize for each robot, but a more standardized processor architecture will allow increase in the cost efficiency, reliability and effectiveness.

Also, the future of robotic missions of planetary exploration and orbital servicing will require more complex processing and greater energy efficiency than the actual systems and this need to be improved.

The next efforts in space robotic avionics must be the developing of high performance, reconfigurable platform with increase in the on-board computing power while lowering the power consumption and cost. These architectures will allow for example the possibility to implement more complex vision& navigational algorithms, or the possibility to increase the autonomy and intelligence of the systems.

However despite the needs is there, the PERASPERA consortium believes that developments in this sector are not affordable for the SRC.

Title	**Advanced processor architecture**	
Task Description	New architectures for high performance computing	
Analysis of the status	Advanced stereovision & navigation systems, require a high computational burden, which conventional space avionics cannot currently stand. Their on-board implementation requires therefore the development of a specific computer architecture based for instance on FPGAs (see SPARTAN ESA study)	
Need	development of a specific computer architecture	
Impact on future missions	Advanced computer architectures	
Expected Results	The maturation of high performance computing platforms for specific robotic use will allow the processing of more complex algorithms.	

Priority	2, it is noted and agreed that processing power will be a limiting issue however considering the budget/time required to implement a new generation of robotic-capable processors this development is not compatible with the SRC. Besides ESA, EC and National Agencies are already in the process of production of new avionics (multi-core LEON, MUSEs FPGA).

Title	**Dedicated motion-control systems**	
Task Description	The activity shall investigate the need for dedicated motion control system for different actuators and applications, including the use of model predictive controller techniques for optimizing control effort taking into account restrictions (e.g. power consumption, tasks duration). A dedicated interface layer would be able to communicate against data buses (CAN, MIL-1553, Spacewire, Ethercat...) either for wheels traction/steering motors or robotics arms actuators. It shall be supported specific motion primitives for planetary rovers (eg. Crabbing/Ackerman/Turn-in-spot) or direct/inverse kinematics for generic robotic arms. The modules shall be compatible with space-oriented operative systems (i.e. RTEMS) with constrained capabilities in terms of CPU/memory and data throughputs portable to space-oriented operative systems.	
Analysis of the status	• Input from state of the art (reference to the chapter)	
Need	• Input from stakeholder needs: Ch. 4.2, Ch. 4.3	
Impact on future missions	• Planetary rovers • Robotic arm control	
Expected Results	• Test with representative rover/robotic arm • Benchmark against state of the art	
Priority	2, although it is recognised that it is a technology of importance, it is believe that the technology maturation in this field is very much mission dependent and therefore does not appear to be a "general building block	

Title	**HW/SW co-design of robotics tasks for vision algorithms**	
Task Description	The activity shall apply the HW/SW co-design methodology to the design and development of robotics tasks. It shall establish the hardware/software methodology for the definition and design of robotics actions, identify most common and used capabilities and implement them using suitable languages (e.g. SystemC, VHDL). The HW/SW codesign shall be tested with visual odometry algorithms (or map generation algorithms) and be tested on space-representative FPGAs or multi-FPGAs platforms. The activity shall also produce a new generation of fast and robust visual algorithms allowing a rover to traverse larger distances than the current state-of-the-art (i.e. Exomars). Limited on-board computing resources should be overcomed by the use of dedicated hardware for vision capabilities.	

Analysis of the status	• Input from state of the art (reference to the chapter)
Need	• Input from stakeholder needs: Ch. 4.3
Impact on future missions	• All robotics missions
Expected Results	• Test with representative hw architecture • Benchmark against existing data sets
Priority	2, although it is recognised that it is a technology of importance, there are other activities that need to be pursued with higher urgency, particularly considering that this technology is very tailored for a particular application

4.1.6 Actuators

Actuators are commonly used in space for moving, controlling and operating mechanisms and sub-systems in scientific payloads, on both satellites' platforms and surface modules.
The harsh environmental conditions to which actuators are exposed in space can cause failures which might lead to severe effects on spacecraft operations, eventually to the loss of the mission. In fact, operating temperature ranges, deep vacuum, radiations and outgassing are critical to the survivability of the components which make up those systems. Nevertheless, their employment in space hardware is not evitable for nearly all applications; on the contrary, the performances and requirements for space actuators are constantly becoming more and more challenging in terms of precision, accuracy and stability, mass, energy and operation temperatures.

In orbital missions, appendages like solar arrays, antennas or payloads must be deployed and, in some cases, these appendages need to be continuously rotated or repointed during the mission: the majority of spacecraft have instruments on board requiring actuation either for pointing purposes (scanning mechanisms), or optical path adjustment (optical wheels, shutters, choppers) and refocusing of mirrors. In particular, the orbiting systems envisaged in the present framework make extensive use of mechanisms for servicing and orbital maintenance.

In planetary exploration missions, autonomous mobile robots need to perform long range travels to gain access to difficult terrain (steep slopes, boulders, cliffs, canyons) in order to reach particular areas of interest. Furthermore, surface modules as those of our interest shall embark mechanical devices devoted to soil drilling and to sample collection, thus making extensive use of actuation, e.g. for deploying the mechanism and manipulating the sample to be released in a proper container. Also, if the robot is equipped with an antenna for communication with other rovers, payloads or with the orbiter, it could be necessary pointing its antenna.

Historically, actuators are based on electric motors technology: the most used, with good performances and high reliability. However, as already highlighted, mechanisms are single point failures, which play a major role in assessing the global risk of premature degradation of a mission.

Though electric actuators are heavily used for orbital and planetary applications, qualification for specific mission is still a hurdle for any robotic mission. In the context of the SRC qualification of actuators is out of scope (as specifically stated in the EC call describing the scope of the SRC) . However some activities in the SRC will definitely have to investigate and characterise the dust problem/solution in analogue tests.

Other technologies are being explored to be employed in actuation: in particular, smart materials actuators are considered to be promising candidates to fulfil the requirements of future missions in a large range of applications, providing extremely high precision and long operational life, guaranteeing low mass and volume allocations.

Although promising, many smart materials suffer of electro-magnetic compatibility problems due to the high voltage often required for their actuation; also, they have compatibility limitations with space environmental conditions (e.g. vacuum, radiation and contamination).
Some smart materials are already used for space applications: **piezoelectric components** certainly represent the most mature and consolidated technology for space mechanisms and structures applications. It has been successfully used in many missions, mainly in instruments (ROSETTA, MISSE7, CURIOSITY), laser beam pointing and control (AEOLUS, PHARAO, ARTHCARE, SWARM), pointing mechanism (ARTEMIS, PHARAO, EARTHCARE, SOHO) as well as active micro-vibration and damping of sensitive scientific payloads isolation (PICARD, Solar Orbiter).

Shape Memory Alloys are the second most mature smart technology for space applications: it has been successfully used in several on-orbit experiments and missions for several deployments systems.

Under the H2020 framework, it could be desirable to identify tasks aiming at increasing the maturity of low TRL smart material actuators in order to meet the demanding space requirements.
However considering that even for terrestrial use, many of these technologies have not yet developed into viable components, for all the subject of smart material actuators the PERASPERA consortium recommends not to entertain in any development within the SRC.

Title	**Electro-active Polymers (EAP)**	
Task Description	investigate, prototype and test EAP in relevant environment to assess their applicability and performance in mobility/manipulation actuation, grasping, covers actuation, deployment and reconfiguration.	
Analysis of the status	• EAPs research is at prototyping level in many terrestrial application: it si currently active in the medicine field for artificial muscles prototyping and in robotics for miniaturized manipulators, artificial fingers grasping forces implementation, different sensors component actuation (filter changes, cover placement, etc), aeronautics for morphing wings.	
Need	• Future space assets foresee relevant robotics actuation with increased level of precision, flexibility, vibrations effects containment, resource demand reduction. • Input from stakeholder needs: 4.2.1	
Impact on future missions	• In orbit servicing end effectors capabilities enhancement; increased flexibility in end effectors for sample grasping/payloads manipulations in surface exploration; advanced actuation for mobility on surface (legs actuation) and in air (morphing wings), moveable and disturbing on board components reduction for vibration dumping; applicability to small mechanisms repeatable actuation such as those for complex payload components movements and sample collection and curation robotic chain (i.e. canister cover actuation)	
Expected Results	Increase TRL (currently 2-3) Supersede limitations: • outgassing, contamination and radiation compatibility, • extremely high voltage units and harness, with complex power electronics and expensive controller strategies, • low reliability and process repeatability, and occasional unpredicted behavior, • fast degradation and high dispersion of functional performance in	

	vacuum.
Priority	0, this technology may have great potential benefits, however the maturation of it is beyond the possibilities of the Space Robotics SRC as the maturation effort in time and budget appears much greater than the usable benefits

Title	**Magneto(electro)-strictive materials**	
Task Description	investigate, prototype and test Magneto(electro)-strictive materials in relevant environment to assess their applicability and performance in displacement actuators for structures deployment, energy vibration harvesting, actuation in cryogenic environments and tribology	
Analysis of the status	• Magneto-strictive materials research is at a very low technological readiness level. Current application scenarios are similar to those for piezoelectric materials as they can ensure a lighter solution with a longer survivability. Still the hysteretic behaviour is a critical aspect in modelling and control.	
Need	• Accurate pointing payloads ask for vibration reduction. The magneto-strictive materials couple the benefit of disturbance reduction and energy harvesting to be stored on board for further utilisation. Increase in reliability and robustness in mechanisms for components release and deployment. Re-configurable vehicles for enhanced surface exploration can benefit from displacement actuators such the magneto-restrictive materials are. Sloshing effects dumping by means of active membranes in tanks can be also a benefits in high precision relative manoeuvring such as those for servicing and refuelling, as well as in propellant feeding lines actuators and control to significantly reduce the s\s mass and increase the fuel rate tuning accuracy. • Input from stakeholder needs: 4.2.1	
Impact on future missions	• Reduction in mass for mechanism; efficient exploitation of wasted energy; elongation of mission duration thanks to longer mechanisms lifetime; increase in motion control accuracy for moveable components (i.e. end effectors relative manoeuvring); low temperature environments (caves, cold traps, low gravity bodies, shadow) robotic exploration and manipulation enhancement	
Expected Results	• Increase TRL (currently 2-3) • Step forward in the intrinsic hysteresis control • Assessment of performances in relevant applications for space by modelling, prototyping and testing. Supersede limitations: • Operational and non-operational temperature ranges	
Priority	0, this technology may have great potential benefits, however the maturation of it is beyond the possibilities of the Space Robotics SRC as the starting TRL is very low and the maturation effort in time and budget effort in time and budget appears much greater than the usable benefits	

Title	**Magneto-rheological fluid dampers**	

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Task Description	investigate, prototype and test Magneto-rheological fluid dampers in relevant environment to assess their applicability and performance in space application for vibration reduction joints, locomotion devices, landing legs, docking devices energy dumpers, re-configurable vehicles/components, actuation for deployment/folding of specific components actuation.
Analysis of the status	• Magneto rheological fluids basic and applied research focuses on reducing their intrinsic aging and performance degradation because of abrasion effects. The automotive is the largest field of application to improve reactiveness and accuracy in brakes and dumpers control.
Need	• Planetary landers to support complex surface activities need to finely control the kinematic and dynamics conditions at the surface contact, ensuring soft landing and nominal attitude acquisition after landing. Surface mobile robots on harsh terrain need reactive and adaptive dumpers to safely transverse complex terrain structures, Active dumpers embedded in legs will provide the performance. In orbit proximity manoeuvring for servicing ask for reactive and adaptive dumpers to preserve interacting spacecraft safety during operations. • Input from stakeholder needs: 4.2.1
Impact on future missions	• Enhancement in planetary landing design and control; evolution of advanced locomotion systems on challenging surfaces; availability of configuration change functionality for components such as rolling to stow and deploying to use of large elements; mass reduction.
Expected Results	• Increase TRL (currently 2-3 for space) • Step foreward in aging reduction and abrasion control • Assess the materials applicability in space environment through prototyping and testing • Develop on the low dependency on temperature changes (as opposed to viscous dampers) and on their small power consumption to: • Design and demonstrate a possible application in a space system (to be completed)
Priority	0, , This technology may have great potential benefits for some very specific applications, however the maturation of it appears unaffordable for the Space Robotics SRC, considering the very restricted field of application

Title	**Pan-cake mandrel(s)**
Task Description	Develop mandrel type actuator(s) allowing subsurface micro-sampling and logistics without drill string extraction. Characteristics such as wide' central passing hole (e.g. d>10/15 mm), torque and speed as required, minimum number of reducers, direct measure of output torque and force, minimum height impact, will be important during the development. TRL: N.A
Analysis of the status	• Two 'sub-surface type' drill systems have so far been studied: Rosetta SD2 (landed on Comet) and ExoMars (in qualification). These two examples will be analysed as starting points.
Need	• Allow subsurface micro-sampling and logistics without drill string extraction. • Input from stakeholder needs: 4.2.1

Impact on future missions	• Next generation drill systems will likely require the collection and analysis of sub-surface samples as intact as possible (composition, size, state of volatiles, minimum thermal contamination). The availability of samples directly collected down-string with minimal alteration will be important.
Expected Results	• Availability of technology for pan cake type mandrels finalization and construction
Priority	3, this technology is important, however it is very much application dependent an therefore it cannot be defined as generic building block. Therefore the it is not considered a technology for urgent development.

4.1.7 Sensors

Sensors are the foundation of autonomy for every technical system. The more modalities can be sensed, the more situations can be perceived, and appropriate reactions can be planned. The increase in density of sensors with increasing resolution and sensitivity, together with the need for multi-modal sensing systems poses several challenges for future systems. Local sensor processing, high sensor integration as well as the integration of multi-modal sensing systems are the key features of future space systems. Future space systems require modular components that can be easily re-combined and re-configured for reuse in various space system setups. Preferable is a standard interface for H/W and S/W connection of sensors to a platform.
Sensors for close range operations need to enable Servicers to estimate the pose of a Client. This needs sensors with precise 3d imaging capabilities at high update rates that are robust when scanning typical Client materials.

Title	**Close range 3D imaging system**		
Task Description	Development of a new close range 3D sensor that is more robust and precise than currently available systems when scanning highly reflective materials that are often used on Client satellites.		
Analysis of the status	Until now, systems like a 3D lidar did not deliver enough resolution and too low update rates and had problems with laser rays being reflected of the client surface with mainly specular reflection and low diffuse reflection, so that not enough rays come back to the lidar for good scan results. Higher laser power or different 3D imaging techniques could overcome such problems.		
Need	New close range 3D sensors that are more robust and precise and deliver higher update rates than currently available systems when scanning highly reflective materials that are often used on client		
Impact on future missions	• Autonomy increase due to accurate sensor data generation • Operations under varying light conditions without problems		
Expected Results	• Survey of possible alternatives for getting precise 3D Data of a Client with a high update rate. • Prototypic realisation of an applicable sensor system for close range operations. • Development of pose estimation algorithms for the new sensor. • Tests of the prototype system in a HIL simulator		
Priority	3, this technology is very important for close range operations. Close range 3D imaging system need to be robust and must deliver data in higher resolution and update rates than current systems. However, this technology is also very dependent on the application (e.g. laser sources and detectors need to use a light band tuned with the operating environment). Therefore the subject will need to be considered in the future, when application specific technologies will be developed.		

Title	Sensor data fusion		
Task Description	Development of solutions for sensor fusion in robotic systems, taking into account proper sensors for orbital and planetary robotic applications.		
Analysis of the status	Sensor fusion is a method that has already been studied and been applied in a number of terrestrial applications. However, the transfer of the full capabilities of this method to on-orbit systems is still open.		
Need	The methodology of sensor fusion has to be developed, taking into account different measurement principles, external sensors and embedded sensing capabilities and local sensor processing (smart sensors).		
Impact on future missions	• Reduce the number of sensors • Efficiency increase in data handling		
Expected Results	• Concepts and architectures for sensor data fusion • Solutions for sensor fusion of different sensor (algorithms)		
Priority	4, this activity is an important generic building block enhancing capabilities in both orbital and planetary tracks. A solution for sensor fusion in robotic systems is required in order to design an optimized integrated suite for sensors and reduce the number of necessary sensors to a minimum. The PERASPERA consortium believes that this is a subject to pursue.		

Title	Haptic Sensor Arrays		
Task Description	Development of sensor arrays needed for dexterous grippers to perform delicate manipulation tasks in orbital operations, i.e. haptic sensor arrays to deliver information about the force distribution on the gripping elements.		
Analysis of the status	For terrestrial applications haptic sensing has been widely studied and commercial solutions are already available. So far, little research is gone into how these solutions can be used in orbital or other space scenarios.		
Need	Precise manipulation tasks require force feedback information. Actuators like e.g. used in ROKVISS experiment already provide force torque information. However, no such information is provided for the touching part of the end effectors.		
Impact on future missions	• Opens possibility for sensible robotic servicing operations (cutting screwing, etc.) with specialized end-effectors.		
Expected Results	• Identification of haptic sensor concepts for the use in orbital robotics • Breadboard design tested under relevant environmental conditions like temperature and vacuum.		
Priority	0, this technology may have great potential benefits, however the maturation of it is beyond the possibilities of the Space Robotics SRC. There are terrestrial developments on the subject ongoing, which have not yet achieved use beyond the laboratory/demonstration realm. SRC efforts and budgets in the maturation of the technology appears would be too high with respect to the benefits produced. PERASPERA will await the terrestrial parts. Furthermore the technology maturation within PERASPERA aims at technology based on enhanced robotic servicing missions, e.g. means of cooperative robotic design of S/C (docking/servicing ports).		

Title	Sensor Suite		

Task Description	Development of a solution for a suitable sensor suite for space robotics application. The task should focus on the interface (H/W and S/W) between the different sensors and the platform, aiming a modular sensor suite easy adaptable according to mission objectives.
Analysis of the status	• According to state-of-the-art: Ch. 5.1
Need	• H/W framework/interface for different types of sensors for robotic applications • S/W framework to support different type of sensor and manage data traffic
Impact on future missions	• Reduce the integration effort • Plug-and-Play-principal for sensor integration
Expected Results	• Solution for sensor framework for different sensor types (H/W and S/W) • Solutions of sensor suite configuration for relevant robotic tasks
Priority	4, this activity is an important generic building block enhancing capabilities in both orbital and planetary tracks. An easy adaptable, standardized integration of suitable sensors into a spacecraft (both hardware and software) via a universal interface is the basis for a modular sensor suite. This is required for easy adaptation to varying mission objectives. The PERASPERA consortium believes that this a subject to pursue.

Title	**"Smart Sensors" for Space**		
Task Description	With increasing frequency and resolution, the amount of data sampled by each sensor system is constantly increasing. Embedded sensors with local preprocessing capabilties (smart sensors) are thus needed to cope with the increasing data volume directly at the acquisition point. This capabiltiy enables the possibility to realize more complex modular setups that generate high-level information at early steps in the processing chain.		
Analysis of the status	• Standard sensors today collect large volumes of date which they indiscriminantly transfer to (external) data processing units. This causes a strain on the communication as well as on the data storage and post-processing infrastructure (large volumes of redundant and irrelevant data). • "Smart Sensors" for terrestrial applications are already under development in a number of application domains. For on-orbit application, the concepts have to be adapted and refined to meet the specific constraints of space qualification.		
Need	• Highly integrated space-qualified "smart sensors" with advanced data pre-processing capabiltities able to pre-select relevant information on-site and thus reduce the amount of redundant and irrelevant data. • This includes the establishment of sensor hardware and a processing architecture for sensor data to enable a flexible network of "smart sensors" and to enable the implementation of sensor processing chains.		
Impact on future missions	• Allow to reduce sensor data amount • Lower energy consumption		
Expected Results	• Survey of existing approaches towards the "Smart Sensor" concept; • Concept for implementing "Smart Sensors" and steps to adapt existing Sensors into a "Smart Sensor" environment regarding relevant space applications; • Development of a working bread-board for a relevant proof-of-concept		

	application.
Priority	1, this technology may become very important for Space Robotics, however the development of it is likely to come from the terrestrial sector, where the resources devoted to the development of the technology can be much higher. In the terrestrial sector are different approaches under development. In space problems can't use them due to missing qualification. PERASPERA cannot entertain at this stage in qualification activities especially if silicon is involved.

4.2 Orbital Track

In this section, the proposed activities regarding the orbital end goals and demonstration scenario are described. The end goal and demonstration scenarios target orbital operations in close proximity and direct interaction with more or less cooperative structures. Many relevant aspects are already covered by 'Common Building Blocks' activities.
In this section special activities for Manipulators and Tools, Teleoperation and telepresence as well as human-machine interface are described.

4.2.1 Manipulators and Tools

Robotic in-orbit and surface exploration systems require appropriate systems to manipulate objects in order to perform service operations such as maintenance and construction work on technical infrastructures or to carry out scientific investigations and experiments.

Title	**Modular space-qualified robotic manipulators**		
Task Description	Design and implementation of a multi-purpose modular space-qualified manipulator and its components. This includes the mechanical design of joints, links and a complete robotic arm.		
Analysis of the status	Current robotic manipulators used in on-orbit systems (e.g. ISS) are developed as unique solutions and with a specific application in mind (example: Canadarm). Relevant work in the area of new manipulator concepts has been presented, for example, in the projects ROKVISS, RIMRES EMI, TransTerrA-shuttle (Payload deployment mechanism)		
Need	Future robotic on-orbit operations need manipulators that are based on modular architectures that can easily be re-configured and re-located.		
Impact on future missions	• Manipulator is adaptable to new mission tasks		
Expected Results	• Concept for modular robotic manipulator including definition of required number of DoF, torques, modularity in (sub)system design • Design of a generic manipulation interface. • Development of innovative joints (e.g. 3DOF joints) as part of a modular manipulator architecture • Demonstrator of a robotic manipulator capable of reconfiguration and		

	repositioning on modular structures
Expected Results	• A flexible IK solution subject to adaptions due to reconfiguration of the manipulator • Dynamic motion planning of a manipulator on a given modular structure • Topology reconstruction of modular structures, needed as input for motion planner
Priority	3, this technology is very important, especially for the capabilities of re-configuration, re-location and extension, a modular design of manipulators is mandatory. However, it appears not affordable within the SRC scheme at this time but for specialised development at later time within the schedule.

Title	**Control algorithms for dynamic on-orbit service manipulation**
Task Description	Development of algorithms to be used for the control of free-floating manipulators that perform on-orbit service operations. The algorithms account for contact- and robot dynamics for the control of forces appearing on the interactions.
Analysis of the status	• Single specific algorithms for controlling free-floating manipulators are available. • There is no system integrated all those capabilities and/or generic and modular solutions which can be applied to any system.
Need	• A generic software solution for real-time integration of dynamic control of free-floating manipulators in contact events
Impact on future missions	• Support modular adaptable and multiple manipulator to perform servicing tasks • Support high precision tasks (accuracy <10 mm)
Expected Results	• Real-time control methods of manipulators mounted on a floating or flexible base and in contact with other systems • Control techniques for flexible manipulators • Dynamic control of collaborative manipulation (multiple arms) • Efficient distributed computation of dynamics for high number of degrees of freedom • Model-based reconfiguration of runtime software manipulation components
Priority	4, this activity is an important generic building block enhancing capabilities in both orbital and planetary tracks. The consideration of real-time aspects of the dynamic control of manipulators is mandatory for dexterous operations. The PERASPERA consortium believes that this a subject to pursue.

Title	**Servicing Tools**
Task Description	Development of a novel tools for servicing tasks on current non-prepared spacecraft and future spacecraft which are prepared for servicing due to e.g. an existing servicing port.
Analysis of the status	• Input from state-of-the-arts document: Ch. 4.1
Need	• Input from stakeholder needs: Ch. 4.2 • A novel client-capturing system that has a very high precision and reliable control and thus low risk of damaging the captured client.

	• Servicing system that transfer energy and data to a maintainable client
Impact on future missions	• Unified servicing ports for spacecraft • Plug-and-play-principal for spacecraft extension
Expected Results	• Survey of servicing methods • Innovative and integrated concept for featured servicing methods • Prototypic realisation of a new servicing hardware with according control software
Priority	4, this activity is an important generic building block enhancing capabilities in both orbital and planetary tracks. The development of novel tools for servicing tasks on current non-prepared and future spacecraft which are prepared for servicing (e.g. an existing universal servicing port) is required for manipulating objects in space. The PERASPERA consortium believes that this a subject to pursue.

Title	**Interfaces Standardization for modular S/C elements**
Task Description	Realize a set of interfaces (mechanical, data, electrical, thermal) that allow coupling of payload to robot manipulators, payload to other payload or client to server.
Analysis of the status	The realization of a modular reconfigurable system depends, among other things, on interfaces. This includes mechanical interfaces connecting the blocks to one other, electrical interface for power transmission, thermal interfaces for heat regulation and interfaces to transmit data throughout the satellite
Need	Multi-functional "Intelligent" interface (mechanical, electrical, data, thermal, fluid) can be used to interconnect building blocks and also to connect to the satellite with a servicer
Impact on future missions	The standard interfaces will allow on one hand to develop the SRC end goals (such as FLEXSAT)
Expected Results	• Open standard architecture with flexible platform configuration, • Modular architecture consisting of ' block sets' • Cost efficient development logic and a consequent customer oriented design to cost approach
Priority	4, this activity is an important generic building block enhancing capabilities in both orbital and planetary tracks. A new type of an universal interface, which can be used for satellite building blocks (e.g. active payload modules/elements). PERASPERA takes tool concepts as universal interface solutions into account. The PERASPERA consortium believes that this a subject to pursue.

4.2.2 Teleoperation and Telepresence

Teleoperation and telepresence are the foundation of every tele-manipulation, and in particular for spacecraft maintainability and on-orbit servicing applications. But also, now that the budget for landing humans has been drastically reduce; the teleoperation is taking more and more importance for planetary exploration, where humans can explore remote environments in a safe way.

The cognition and physical integration between the human operator and the robotic alias is fundamental for telepresence. The increase of global awareness is basic for the future developments, but also the improvement of the latency problems and communications delays.

The teleoperation systems have to be verified with tests and simulations, as prove-of-concept, within an analogue or virtual scenario.

Title	Enhanced close-to-reality teleoperation
Task Description	For teleoperated robot agents allow more intuitive, user-friendly and immersive interfaces.
Analysis of the status	• ESA has continued the development of its line of Robot Control Stations with TRASYS (B) and Space Applications Services (B) with focus on both the haptics teleoperation and rover control • The ESA developed Exoskeleton is intended to be flown in the METERON project[66] • DLR-RM (D) is developing a bimanual haptic control station. Through the human system interface the operator is capable to immersively control a remote robot like the humanoid JUSTIN with all its degree of freedom (49) including neck, arms, hands and posture. The HMI provides a realistic impression of the remote (or virtual) scene by using a 3D Head-mounted display and giving 6D force-feedback to each of the human hands.
Need	• supports (automated) imitation learning of (complex) manipulation tasks based on human demonstrations on-site / during EVAs / EVA simulations • 3-D visual view of remote operation theatre • Display of additional information (augmented reality) • Haptic feedback (force feedback through active exoskeleton) in hands (= grippers) and to upper body/arms (= manipulators). • focus in enhanced close-to-reality simulation to allow thorough validation of the programmed/autonomous behaviour. • integrating the human and the robot perception • improved interaction-error evaluation on the basis of multimodal data analysis, • self-evaluating mobile and multimodal interfaces for control and interaction to enable adaption to different users / user states / interface states, • methods for the real-time detection of operator situation awareness through bio-monitoring (e.g. EEG-based monitoring of cognitive state)
Impact on future missions	Having an astronaut control a robot's actions from the safety and security of HQ is an advantage, whether the robot is carrying out operations in orbit, or on planetary surface. The ability of the robot to 'push-back' sensations.

Expected Results	• Multisensory evolution
	• Force-Torque Sensors
	• Algorithms but their capabilities are strongly driven by memory/CPU resources:
	    ○ Robotic real-time controller
	    ○ Path planning, Collision Avoidance Manoeuver
	    ○ Feature detection
	• Communication framework with low latency and high dependability
	• Operator input and data feedback devices

	• Algorithms to provide sensorial feedback with time delays and data loss compensation • Tele-robotic software architecture • Ground control stations, shared controllers and adequate MMI
Priority	3, this technology is very important, however it very much application oriented and therefore not having the highest priority at the time of the firs call.

Title	**Adjustable levels Autonomy based on building blocks**	
Task Description	The activity shall develop further the current state-of-the-art regarding the AI capabilities of robots from the point of view of planning and execution. In order to increase the consistency of plans the autonomy layer shall include formal verification methods to ensure the robustness of the software The autonomous system, based on these building blocks, shall be adjustable in terms of autonomy depending on complexity of robotic operation (tele-presence, tele-manipulation, semiautonomy, full autonomy), be capable of auto-adaption of MMI to operator (e.g. operator monitoring, learning of operator profile) and support operations by means of visual/navigation-aids when controlling remote robots	
Analysis of the status	• Input from state of the art (reference to the chapter)	
Need	• Input from stakeholder needs (reference to the chapter)	
Impact on future missions	• Planetary rovers • Interplanetary missions	
Expected Results	• Test with earth analogue scenario	
Priority	4, this activity is an important generic building block enhancing capabilities in both orbital and planetary tracks , the PERASPERA consortium believes that this a subject to pursue within the more general subject of autonomy	

Title	**Man-Machine Interfaces**	
Task Description	The activity shall investigate fully/semi-immersive control interfaces for the remote on-ground control of robotics arms placed in-orbit satellites, ISS or Moon. The system should compensate for network-induce time delays and packet loss allowing to teleoperate robots either in bilateral or multilateral control modes using the sensorial feedback system of the remote environment. This activity shall also generate new visual-servoing algorithms allowing to detect, track and manipulate complex objects for in-orbit satellite applications. Visual systems shall determine the pose estimation of the target satellite and pave the way to robotic arm manipulation tasks.	
Analysis of the status	• Input from state of the art (reference to the chapter)	
Need	• Input from stakeholder needs (reference to the chapter)	

Impact on future missions	• All missions • Robotic arm teleoperation
Expected Results	• Test with ground facilities
Priority	2, although it is recognised that it is a technology of importance, it appears that it is a technology very much application dependent, there are other activities of more general scope that need to be pursued with higher urgency

Title	**Teleoperation protocols for space robotics**	
Task Description	The activity shall design new methodologies for increasing the situational awareness of the operator when remotely controlling a complex robotics system (i.e. wheel/legs, robotic arm, pan&tilt, cameras) with high QoS. It shall create an end-to-end validation facility where from simulation to real implementation the robotics designer can implement a full space mission as a proof-of-concept. This activity shall allow enhancing existing on-ground testing facilities for verification and validation of manipulation systems under simulated weightless environments. It shall design and manufacture standard mechanical, electrical and software interfaces for contact, positioning and attitude sensors; sun and start simulated sensors; calibration procedures for millimetre localization accuracy and dynamic and kinematic simulated components (space free-floating conditions).	
Analysis of the status	• Input from state of the art (reference to the chapter)	
Need	• Input from stakeholder needs (reference to the chapter)	
Impact on future missions	• All missions • Robotic arm teleoperation	
Expected Results	• Test with ground facilities	
Priority	4, this activity is an important generic building block enhancing capabilities in both orbital and planetary tracks , the PERASPERA consortium believes that this a subject to pursue within the more general subject of robot control operating systems	

4.2.3 Human-machine cooperation

Title	**Human-machine cooperation**	
Task Description	Intuitive commanding/feedback human-machine interaction technologies that allow the implementation of "robot astronaut assistants". A robotic astronaut assistant is a robotic actor that contributes to the fulfilment of astronaut's effort.	
Analysis of the status	• These technologies have been investigated in the course of past ESA activities for very simple pre-programmed tasks in the frame of the EUROBOT programme.	
Need	• Next generation of missions that will see autonomous robots and humans cooperating in orbit and in planetary environment	

Impact on future missions	• The use of the technology is an enabler for "robot astronaut assistants", however the achievement of these assistants is much more dependent on the "autonomy" technology • The use of this technology appears to be beyond the target timeframe
Expected Results	• EVA astronauts capable to co-work with EUROBOT-like robots on orbital infrastructure • Exploration crews capable to co-work with centaur-like assistants on planetary environment
Priority	1, this technology may become very important for Space Robotics, however the development of it is likely to come from the terrestrial sector. Even in this sector, effective use of this technology has note yet happened, so the SRC will wait for this development to happen

4.3 Planetary Track

This section describes the proposed contest for the implementation of a planetary exploration mission by means of innovative planetary robotics systems. The challenging reference scenario here depicted is the planetary sample return mission, which asks for many capabilities to succeed such as on-ground mobility to support both science and sub-surface access, the soil-sampling, sample in-situ scientific analysis, sample storage into bio-container to prevent the backward contamination and sample container transfer between planetary assets (eg. from the rover to the return vehicle). The mission target can be one of the rocky bodies of the Solar System, including the small ones (e.g. asteroids) where the different environmental conditions and in particular the very low gravity imposes the development of specified capabilities; in fact, in these scenario the robotic probe should approach the target, reach it and be properly linked during the operations, in a similar way of the orbital servicing procedures.
The aforementioned functionalities intersect both with common building blocks as well as the maturation of technology specific for planetary exploration scenarios. The planetary track shall define the means to implement a demonstration/proof of achievement of higher performance and less risk in an environment of relevance. In particular, the proposed mission concepts can include:

- cooperating, coordinating multi=robot scenarios (e.g. scout=mother rover, aero=robot=rover, multi-rover);
- surface infrastructure assembly;
- robotic devices for planetary p\l and robotic platform deployment on surface;
- Deep drilling access to subsurface specimen and sampling;
- Sample handling and storage, In-situ science.

In particular, the means of demonstration shall target on field tests in selected terrestrial analogue environments, that will allow the proper verification of functionalities and performances in similar environmental and operative conditions, hence obtaining the expected increase of the technology TRL.
In the following subsections the planetary exploration specific technologies as target of the on-ground demonstration will be introduced and described, highlighting the current and final expected status, together with the possible application in forthcoming scientific missions.

4.3.1 Autonomy

Title	**Temporal/spatial planning, scheduling and deliberative / reactive reasoning**	

Task Description	Exploitation of decision-making capability to help a robot/rover (re)plan, navigate, investigate and operate within a planetary environment in a logically autonomous way.
Analysis of the status	• ExoMars, Seeker, Safer, GOAC, and Chameleon have all demonstrated robust rover capability to autonomously navigate across difficult terrain
Need	• Autonomous management of Navigation in order to reach locations defined by GC (i.e. environment mapping, path planning, locomotion, localization) for mobile robots in the planetary but also planetary realm (e.g. EUROBOT) • Adaptive execution of the GC prescribed activity sequences • Validation of the uploaded planning in terms of compatibility with the available on-board resources • Management of the coms link phases to maximize data transmission
Impact on future missions	• Reduce teleoperation of human control • Reduction of power consumption • Allows greater amount of computational power to be granted to autonomous science investigations and less on mobility and communications • Increase in science return and ROI (less downtime waiting for instructions from Earth) • Decreasing of operational margins, allowing greater mission scope
Expected Results	• Autonomous navigation across large / difficult / hazardous terrains • Ability to (re)plan in the event of mission difficulties or hazards • Ability to manage resources when such scenarios necessitate the need
Priority	4, The ability to plan, evaluate and make decisions accordingly is a fundamental technological building block applicable to both Orbital and Planetary Tracks. The theme of autonomous decision-making has also been deemed to have one of the widest areas of impact, with respect to future mission scope, ROI and spin-out opportunities. Also, to enable the SRC to get the optimum return from the autonomous capabilities it should be considered in the early mission developments, not once the mission parameters have been established. It is through such complementarity that the greatest impact and step changes will be achieved in autonomous capability, as well as greater efficiencies such as reduction in cost and/or manpower. The SRC should therefore pursue this subject with the highest priority.

Title	**Failure detection Isolation and Recovery**	
Task Description	The development of SRC activities to cover the maturation and validation of technology that will allow planetary robotics systems to operate in a logically autonomous way.	
Analysis of the status	FDIR for space robotics missions is currently being addressed as typical space-software FDIR. This presents the problem that the emergent behaviours (and related faults) offered by autonomy tend to create an explosion of the fault trees which leads often limitation of what the autonomy can do.	
Need	• Detection and management of non-nominal conditions (e.g. available resource lower than ones expected, longer activity durations due to unexpected conditions, etc.) • Detection and management of on-board failures. • Validation and demonstration testbeds offering adverse conditions or "unexpected" scenarios encountered by the rover, requiring an autonomous assessment and response	

Impact on future missions	• Improved FDIR will allow better management of resources (including time), and reduce risks of catastrophic failure • Reduction of space insurance premiums
Expected Results	• Ability to autonomously identify a problem and adapt accordingly • Provision of demonstration testbeds presenting such problems
Priority	3, FDIR has been identified as a crucial aspect of autonomy-based capability; however, the limits of budget, and the pressing need to develop the higher-level layer of autonomy, take precedence in this instance. Even so, it has been accepted that the state-estimation and monitoring attributes of FDIR are a critical part of that high-level autonomy layer, and therefore the development of state-estimation and monitoring technologies also should be considered to be the very highest priority level.

Title	**Opportunistic science**	
Task Description	Rovers developed and tested to autonomously identify interesting artefacts and features of the landscape will be equipped to carry out scientific investigations, adding significant value to a mission and uncovering areas or items of interest not previously identified by mission control.	
Analysis of the status	MASTER has Previous projects have been programmed to identify interesting features in a scene that have been predicted to be interesting by subject matter experts, then programming a system to find them. The MASTER project is looking to find things that are interesting because they were not predicted; this is in contrast to previous projects, where platforms are programmed to identify features in a landscape that have predicted to be interesting.	
Need	• Validation of autonomous identification of unpredicted objects in unstructured environments. • Opportunistic science must also be demonstrated to be efficient, and not detract from overriding mission parameters.	
Impact on future missions	• The added value offered by opportunistic science could be great, though could add significant extra burdens eg on power consumption, computational reources • Increased ROI	
Expected Results	• Demonstration and Validation of autonomous science capability eg in a testbed containing unpredicted • Greater understanding of the trade-offs of using autonomous science and therefore an understanding of where autonomous science should be used	
Priority	3, Opportunistic Science represents an excellent opportunity to increase the scope of future missions, and thus levels of ROI. However, the development and innovation in the fundamental aspects of autonomous (re)planning and decision-making capabilities remains a higher priority. It is anticipated that, once SRC mission goals and parameters are established later in the project, Opportunistic Science becomes a higher priority.	

4.3.2 Energy

Title	**Space Electrical Power**

Task Description	There are significant power challenges for space robotics, particularly in planetary exploration scenarios.
Analysis of the status	• Novel autonomous rover navigation concepts for exploration in low light using unique sensor capability,
Need	• As future missions utilise more advanced, and more autonomous, capability, and push the boundaries of what is possible scientifically, the power burden upon landers, rovers, and scouts will become ever more stringent. Rovers displaying autonomous capability to manage and alter its own power consumption, or rendezvous with landers for power re-charging • New technologies enabling energy harvesting and scavenging
Impact on future missions	• Improved longevity and more robust missions
Expected Results	• Very low power systems • Energy scavenging and harvesting • mission management to minimise power consumption
Priority	3, Space Electrical Power is an important common building block, enabling the advances in other areas to be realised. While the development of SEP technologies is most likely to be required by the SRC, the development of more mission-critical and mission-enabling technologies should take place first. This will then allow the consortium to determine the specificity of power requirements or performance demands for future calls.

Title	**Nuclear Power Sources & Systems**	
Task Description	Innovative advances in the usage of nuclear power sources to propel and provide energy to rovers, landers and scouts used for planetary exploration.	
Analysis of the status	Traditionally. Nuclear power systems have been used in the form of RTGs and RHUs. These have been used for over half a century primarily by the USA and Russia. However, the use of Pu-238 makes this an unattractive proposition for the future. Europe is at the forefront of development of nuclear power sources fuelled by Am-241.	
Need	• The attractiveness of Am-241 as a fuel for robot platforms is owing to its significantly lower toxicity (although its radiation count is higher), lower criticality, lower cost, whilst retaining conventional nuclear properties such as longevity and efficiency	
Impact on future missions	More capable spacecraft, extended lifetime, continuous operation, cost savings. Nuclear power also has a distinct advantage over solar power as nuclear-powered vehicles, platforms and probes are able to access colder, darker and inhospitable environments which solar-powered vehicles cannot.	
Expected Results	• Isotope production phase 3 • Development of RTG breadboard for planetary exploration using non-nuclear power sources producing equivalent levels of thermal energy	
Priority	3, The use of nuclear power sources would clearly have transformative effects and value, both economically and scientifically, increasing the range of destinations by expanding the number of onboard instruments and enabling them to operate for longer periods of time. Without this capability Europe will remain dependent upon collaboration with international competitors Russia and Nasa, often as a junior	

	partner. Nuclear power would therefore enable a European SRC to take a significant step towards global industrial leadership in this field. However, there are severe budgetary limitations, especially with respect to the price of nuclear fuels. Lastly, Peraspera is a space robotics project, and not strictly geared towards the wider roadmapping of exploration technologies, where nuclear power sources may be better accounted for. It therefore has been decided

4.3.3 Mobility

Past surface missions relied on comparable mobility designs. Varying gravitational, atmospheric, terrain, or soil properties have limiting effects on some mobility approaches. The main goal here are novel, robust, and efficient mobility approaches.
This task shall develop the specification and planning of SRC activities covering maturation of technology that allow robot systems to move in a planetary environment. These may include:

Title	Mobility system for long range traverses and difficult areas	
Task Description	Task should develop a suitable, energy saving mobility concept for exploration on long traverse and accessing difficult areas. A combination of different locomotion strategies should be investigated support different types of terrain.	
Analysis of the status	• Input from state of the art : Ch. 4.2	
Need	• Input from stakeholder needs: Ch. 4.3	
Impact on future missions	• Efficient exploration of planetary surface	
Expected Results	• Locomotion strategies for different surface characteristics • Prototypical implementation of locomotion H/W and S/W and test in HIL-scenario	
Priority	4, this activity is an important building block enhancing capabilities in planetary tracks but also as a means to exercise the capabilities of high autonomy. For efficient exploration, systems need to cope with long range traverses and difficult areas. The PERASPERA consortium believes that this is a subject to pursue.	

4.3.4 Machine-machine cooperation

It showed in terrestrial demonstration that a single robotic agent with a singular suite of sensors has narrow limits in various regards. Some if these are navigation accuracy, small number of scientific in-situ measurements, and single point of failure for its mission. Multiple cooperating agents are a way to tackle these shortcomings.
Features of the approach include:

- Each agent can act as navigation landmark for the other;
- Multiple suites of sensors and computational capacity may increase robustness and redundancy;
- Cooperative manipulation of heavy or large objects;
- Wider area of operation;
- Concurrent task execution.

To coordinate a group of robotic agents in a meaningful way, the following activities aim to establish software, hardware, and communications capabilities necessary for machine-machine cooperation.

Title	**Cooperating coordinating multi-robot frameworks**	
Task Description	Task should develop a robust multi-robot coordination framework for cooperation scenarios	
Analysis of the status	• Input from D2.1 State of art in space automation and robotics technologies (section 4.2)	
Need	• Input from D2.3 Stakeholders needs for space automation and robotics (section 4.2 and 4.3)	
Impact on future missions	• Robust multiple-robot mission for faster exploration • Effective work cooperative assistance between robots	
Expected Results	• Innovative concept for machine-machine-cooperation • Prototypical implementation of S/W framework on heterogeneous robot group in a demonstration scenario	
Priority	3, this technology is very important. The demonstration scenarios specifically include machine-machine cooperation. However, it appears a relevant approach also interesting and required for terrestrial applications (e.g. search and rescue). . It is therefore more appropriate to develop such technology in the later part of the SRC.	

4.3.5 Sampling tools

The sampling tools here targeted, range from micro-sampler up to deep drilling & sampling device, able to cope with a wide types of soil, from different solar system bodies.

Title	**Micro samplers**	
Task Description	Develop micro sampler(s) capable to collect amount of materials already dosed for the instrument without need of extra invasive and lengthy procedures.	
Analysis of the status	• The three types of sampling tools for planetary exploration available from Rosetta SD2 activity, DeeDri development, Exomars and Lunar Drill activities, together with tools studied/developed by specialized organizations (e.g. ultra-sonic drill of Magnaparva), will provide a starting point. In general these tools have been conceived for collecting of a fixed amount of material and are not normally used to fine dose it. Usually, sample preparation and distribution mechanisms are located upstream and are used to handle the sample to the scientific instruments. Such an architecture act in an invasive way on the pristine sample by perturbing it, e.g. from a thermal point of view. • input from D2.1 State of art in space automation and robotics technologies (sect. 3.1.3 and 4.2)	
Need	• Different scientific instruments require different amounts of material to analyse and amounts well in excess to the needs results to be problematic	

	as well as a non-sufficient amount. • Input from D2.3 Stakeholders needs for space automation and robotics (section 4.4.3)
Impact on future missions	• Effective operations of scientific instrumentation devoted to in-situ analyses.
Expected Results	• Feasibility verification and bread-boarding of the key aspects of a micro-sampler based drill.
Priority	3, this technology is very important only for the planetary track, so there appear to be no rationale to include it in the first priorities of the SRC, which are common building blocks

Title	**Drilling/sampling tools for very hard soil**	
Task Description	Develop sampling tools capable to drill and core very hard soils	
Analysis of the status	• The three types of sampling tools for planetary exploration available from Rosetta SD2 activity, DeeDri development, Exomars and Lunar Drill activities, together with tools studied/developed in the frame of ESA technology development project have been conceived for acting on soils with hardness up to approximately 100 MPa range in defined operating life. • Very tough soils (e.g. 200 MPA class) may impact the life of the tools. Hard bits together with interchangeability could help the achievement of sustained sampling operations in very hard soils. input from D2.1 State of art in space automation and robotics technologies (sect. 3.1.3 and 4.2)	
Need	• Collection of solid type samples (core like) in surface basaltic type rocks and in bedrocks, not affected by local weathering, may be important in the future exploratory missions. Hard conditions can be met not only in very hard roks, but also in presence of high water ice content in regolith type soils at very low temperature. • Input from D2.3 Stakeholders needs for space automation and robotics (section 4.4.3)	
Impact on future missions	• Allow scientific investigations of material not altered by local environment.	
Expected Results	• Feasibility verification and bread-boarding of drilling/sampling tools for very hard soils.	
Priority	3, this technology is very important only for the planetary track, so there appear to be no rationale to include it in the first priorities of the SRC, which are common building blocks	

Title	**Very deep drill**	
Task Description	Develop drilling and sampling tools for extended vertical mobility. Two elements need be developed: the driving stem (e.g. coil tube based) and the cutting/sampling front end (e.g. mole, roto-hammer, peristaltic device…).	

Analysis of the status	• Very deep drilling, tens of meters, requires cutting and sampling devices embedded in special front end likely acting as mole or peristaltic devices. Such sample collection front end should be capable to handle the sample to a transportation system in charge of sample delivery to surface without uplifting the whole drill string • input from D2.1 State of art in space automation and robotics technologies (sect. 3.1.3 and 4.2)
Need	• Support the deep exploration of planetary body surfaces • Input from D2.3 Stakeholders needs for space automation and robotics (section 4.4.3)
Impact on future missions	• Allow vertical mobility and sampling down to very high depth
Expected Results	• Feasibility verification and bread-boarding of the key aspects of sampling in deep drill conditions.
Priority	3, this technology is very important only for the planetary track, so there appear to be no rationale to include it in the first priorities of the SRC, which are common building blocks