AMOCT EXECUTIVE SUMMARY

INTRODUCTION AND STUDY WORK FLOW

Space science missions have continually become more ambitious, from early planetary flybys, to orbiters, to recent long duration surface rovers, to future missions towards alien moons. Future ESA goals include further exploration of the our Moon, Mars and elsewhere in the solar system. These future science missions will require of increasingly capable systems to achieve the goals they are designed for. In most cases new innovative technologies should be injected in order to exploit science opportunities, to enhance the capability to manage uncertainties during the mission (including the possibility related to react with the appropriate recovery plan to the presence of faults) and reduce overall operation costs. The first two points clearly state that the ultimate payoff for ESA should not be just the reduction of mission costs, although this imperative is fully acknowledged. Rather it is in the enabling of whole new mission classes, especially those leading to new kinds of in-depth scientific studies supported by sustained presence throughout the solar system.

The role for A.I. technology as enabling in many cases, is readily apparent. In particular, augmented operations automation and autonomy (intended as human independent decision making process) are among the hot topics considered and thoroughly studied. In fact, on-board and on-ground autonomy could potentially enable the space community to consider considerable improvements for several types of space missions

On this basis, the objective of the study is twofold. Firstly is to provide the strategies and the tactical roadmap for affectively and efficiently introducing new advanced technologies in ESA missions operations. On the other hand is to identify the set of ESA missions that could be used to validate the viability of the identified technologies for supporting the corresponding new operations concepts

Study Work Flow

Analysis and Requirements: The first phase of the present study has been devoted to the analysis of ESA past and future missions, identifying main requirements and objectives in terms of on board and on ground autonomy functionalities and tasks. Several advanced mission operations concepts were carried out by means of a requirements analysis and grouping.

Technology and Survey: In parallel with the previous activities, a set of new technologies potentially applicable for the proposed new operations concepts has been identified and assessed with special reference to the maturity level. The above approach considered not only the maturity and applicability of technologies, but also performed a sustainability analysis to evaluate the real impact of the application of the identified technologies in the framework of available space and ground systems.

Technology & Prototyping Road map: On the basis of the identified level of technologies readiness level, the appropriate roadmap for the implementation of the identified technologies in the framework of future ESA mission has been outlined. The objective was to draw a roadmap, which on one side is able give the opportunity to ESA to have clear understanding of the possible evolutions of mission scenarios and operations concepts, taking on the other side the overall risk, related to the injection of new technologies, under control.

TECHNOLOGY & SUSTAINABILITY ANALYSIS RESULTS: ROADMAP

Identification of the Operation Concepts

As per ESA request, the study focused on the ESA missions to be performed after the 2015. On this basis, a set of future mission candidates for innovation injection has been identified:

- Interplanetary Deep Space Missions
    - PROBA-IP
    - Don Quijote
    - Solar Orbiter
    - Marco Polo (Cosmic Vision 2015-2025 candidate)
    - LAPLACE/ EJSM (Cosmic Vision 2015-2025 candidate)
- Space Observatory Missions
    - Darwin
    - Hyper
    - LISA (Cosmic Vision 2015-2025 candidate)
    - XEUS (Cosmic Vision 2015-2025 candidate)
- Planetary Exploration Missions
    - NEXT Lunar Lander +rover
    - Exomars (2018 mission)
    - MSR
- No Earth Observation Missions have been selected because currently all planned to be launched before the 2015 and/or in an advanced development phase

The scope of autonomy comprises the major space system functions. Depending on the type of the mission, Planetary Orbiter (such as Earth Observation or Space Observatories) or Planetary Exploration, some functionalities may not be available. Here a list of the basic identified functional areas where autonomy can be applied: On board diagnosis and reconfiguration, Navigation (depending on the mission), Planning/Scheduling and Intelligent Execution, Command Sequence Generation, and Data handling, Spacecraft/Payload data processing. An additional Ground Segment functional area has also been considered to collect all advanced concepts implementable on the Earth operational level.

Three operation scenarios with a specific human involvement and space & ground functions autonomy level regardless the mission typology have been carried out: Telepresence, Supervision, and Semi/Full Autonomy. The identified operation scenarios allowed to easily link the several advanced operation concepts combinations to the operation functionalities both on-board and on-ground, and to perform a qualitative analysis of the impacts on operations, on-board capabilities, flight-to-ground interfaces, operators' roles

As result of the requirements analysis, the study outlined a list of Operations Concepts defined as a set of functional operations technologies necessary to fulfil one o more operational capability requirements. These operational concepts have been mapped against the mission categories (Deep space missions, Observatory Missions, Surface Planetary Exploration, Earth Observation, Constellation/Formation Flying) with the following scheme:

Functional Areas	Operations Concepts	Potential Technologies	Mission Categ. Applicability		
			Cat#1	…	Cat#N
Functional Area#1	FA#1_Ops Concept#1	Tech1, Tech2, etc	X		
	…..	Tech1, Tech2, etc		X	
	FA#1_Ops Concept#n	Tech1, Tech2, etc			X
Functional Area# …	FA#..._Ops Concept#1	Tech1, Tech2, etc	X		
	…..	Tech1, Tech2, etc		X	
	FA#..._Ops Concept#n	Tech1, Tech2, etc	X		
Functional Area#M	FA#M_Ops Concept#1	Tech1, Tech2, etc		X	
	…..	Tech1, Tech2, etc		X	X
	FA#M_Ops Concept#n	Tech1, Tech2, etc		X	

For each operation concept, a link to a set of potential technologies (not only A.I technologies) necessary to implement the concept has been added. The outline is the input used as starting point to identify the most appropriate and suitable technologies able to successfully implement the identified advanced operations concepts.

Identification and selection of the A.I. Technologies

In this study the analysis of advanced technologies has been restricted to the AI work that is more related to the issues of the autonomy. The AI technologies have been organized in the following areas:

- Knowledge Representation and Reasoning (KRR),
- Planning and Scheduling (P&S),
- Constraint Satisfaction Problems (CSP),
- Machine Learning (ML) and
- Multi-Agent Systems (MAS).

KRR techniques allows to represent knowledge about the world in symbolic form. Reasoning is then achieved by means of symbol manipulation techniques.
Due to their logical features, knowledge-based systems are extremely useful as high-level intelligent control systems, thus representing the backbone of an advanced autonomous system. The KRR technologies analysed are the Rule-Based systems and the Ontology-based knowledge engineering.
P&S techniques allow to express the set of possible actions, the desidered goals, and the constraints related to the problem. Integrated P&S is an approach that allows a natural integration between the definition of the plan and the creation of the schedule. This allows users to easily describe real world problems, considering concurrent actions, time constraints, and resource constraints. Recent space applications have shown that the timeline based approach is the most suitable P&S technology.
CSP technique allows to express complex problems as set of variables and a set of constraints. CSP techniques solve this kind of problems by providing a consistent assignment of values to the variables. This paradigm can be used to build constraint-based models of real-world problems: many problems can indeed naturally represented as a set of elements and a set of constraints between those elements (e.g., configuration problems).

Constraint logic programming technology can indeed be adapted to different class of problems, exploiting problem-specific knowledge.

ML techniques are used to extract knowledge from data by using inductive methods. Extracted information can be used even if not explicitly represented. This kind of techniques are very useful when dealing with vast amount of complex data. They can indeed be used to analyze data in order to extract only the relevant features. Moreover, ML techniques can be used when little information is available about the characteristics of the data, as in this situations it is not possible to design a traditional data analysis algorithm. The Inductive Logic Programming and Inductive Logic Programming are the selected technologies in this area.

MAS technologies allows to model problems where a set of agents must interact in order to achieve cooperation and communication. In this sense, MAS techniques aims at providing reliable communication protocols and globally correct cooperation procedures. MAS techniques can be viewed as an extension of other A.I. techniques, since KRR, PS, CSP and ML techniques must be adapted to multi-agent situations.

All the proposed advanced technologies have been analyzed with respect to their applicability and maturity level. Anyway a list of alternate potential technologies grouped in technology areas is also provided with a rationale explaining the inadequate for space applications. It is worth mentioning that machine learning, i.e., case-based reasoning techniques could be integrated when planning the experiments needs to learn from scientist decisions. Genetic Algorithms can be used to optimize routes in the Navigation functionality. And data mining techniques can be used to pick up the relevant information from the data received.

Trade off analysis

The applicability assessment selected the most promising technologies on the basis of a qualitative prioritization made by the experts. Also the inadequate of the alternate potential technologies for space applications has been assessed on the basis of AI technologies research groups experience and expertise participating in this study. It should be also noted that selected and not selected technologies are not often completely alternate and could be integrated to obtain a more efficient system but with an augmented complexity and costs.

From quantitative point of view, it is worth to underline that:

- quantitative measures (metrics) of the gain for the selected mission families demonstrated an high/medium improvement of the overall mission performance using the selected technologies.
- quantitative measures (metrics) of the gain for the selected mission families demonstrated an medium/low improvement of the overall mission performance using not selected technologies (i.e. in qualitative way)
- the not selected technologies show, in general, an higher complexity, an higher costs (sum of the development costs, personnel costs and ground contact frequency) and engineering risk (Consequence of Engineering Failure * Failure Likelihood)
- as a consequence, the not selected technologies show a resulting ROI lower than the selected technologies one.
- costs vs mission category considerations:
  - in case of enabling new missions, the cost should not play a remarkable role
  - in case of “classical” missions, the benefits have to be balanced against the increased development costs and complexity
- all the proposed AI technologies have been analyzed with respect to ESA Technology Readiness Levels. All the proposed advanced AI technologies can indeed be classified as TRL 4 (i.e., "Component and/or breadboard validation in

laboratory environment"). This means that they can be used to design space application prototypes.

Strategic roadmap

The strategic roadmap for the deployment of Intelligent and highly autonomous space platforms together with new generation ground systems should be implemented in multiple phases. However, even if the request is to focus on the ESA missions to be performed after the 2015, the analysis has to start the current approach of the European Space Agency on the operation automation and the already planned evolution. *Smart-1, Envisat, MEX, VEX* and *Rosetta* missions confirmed the validity of the several systems and concepts (OBCP, OBQM, MPS, GOAS). All the above automation systems are currently in a prototype/demonstration version still showing a lack of standardization and mission interoperability. It is ESA intention to go toward a standardization & integration process via the implementation of the ESA Ground Operation Software System (EGOS).
On the basis of the above consideration, it is possible to propose a three phases strategic roadmap for the infusion of the identified technologies in the ESA missions.

PHASE1 (next 5 years horizon, up to 2015): the identified advanced technologies can be used to design the general architecture of an autonomous system which can be used to create advanced control systems both on ground (e.g., control centers) and on board (autonomous spacecrafts and robots).
The first step should be the creation of a set of prototypes (based on real specifications for space applications and using the proposed AI technologies) integrated and evaluated in a generic ground simulator. This ground simulator based on the SIMSAT infrastructure should allow to verify and validate a mission scenario of a mission in different environments and operating conditions.
Rule-based systems can be used to design a general architecture for high-level, context-based, declarative control. The related prototype would be the cornerstone for the adoption of all the other advanced technologies.
Timeline-based integrated planning and scheduling can be used to design a general framework for automated planning and scheduling systems. Advanced planning and scheduling capabilities are the main requirements when building an autonomous system
After the design and development of these two prototypes, the second step would be designing and developing a prototype based on the integration of these two technologies (i.e., the integration of the planning subsystem in the rule-based high-level control architecture). Such a prototype will prove the advantages of the adoption of the autonomous architecture based on advanced AI technologies, with respect to real specifications for space applications.
At this point, the analysis of other requirements for innovative mission concepts should highlight the need to design and develop a set of prototypes for the following technologies:

- Ontology-based knowledge engineering to be used to design collaborative environments for knowledge-sharing applications.
- Constraint logic programming can be used to solve difficult configuration problems.
- Inductive logic programming can be used to solve complex diagnosis problems.
- Instance-based learning can be employed to enhance sensor data acquisition and analysis.

All these technologies would be integrated in the already defined general architecture for autonomous systems. Experiments and tests should show the advantage of adding these technologies to the architecture, when dealing with specific problems (e.g., complex sensor data analysis).

The last step would be the design of a prototype (again, based on real specifications for space applications) for the Distributed multi-agent technology extended all the capabilities designed and developed in the previous prototypes to the multi-agent context.

PHASE2 (2015 - 2025): this phase involves the injection of new technologies in the basic engineering and mission accomplishment functions of the space platforms and related ground segment. The relevant capabilities include mission planning and resource management, health management and fault protection, and guidance, navigation and control. Also in this phase, the first elements of science-directed autonomy will appear. However, the decision-making capacity to determine how mission priorities should change and what new mission goals should be added in the light of intermediate results, discoveries and other events would still reside with scientists and other analysts on the ground.
The ESA approach could be oriented in the implementation of several "decisional" or "intelligent" functions directly on the spacecraft and therefore to move from the current "automatic" approach to the "autonomy" approach. The Goal-Based Operation (GBO) concept could play a relevant role for all the ESA missions after the 2015, since the new operation scenarios cannot be modelled robustly or safely with existing PUS services such as the OBCP's. It is worth to note that the moving toward goal-based operations will involve changes and opportunities not only in the onboard systems but also in several ground functionalities like operational processes and tools, human interface design, ground P&S, data processing techniques, ground fault verification and validation.

PHASE3 (after 2025): in a very long term perspective the innovative capabilities injected into unmanned missions will be instrumental in manned exploration of the Solar System (e.g. of the Moon and Mars). Within the framework of the long-term roadmap for space exploration developed in the Aurora programme, these exploration activities have been divided into three distinct phases: Human arrival imminent, Human arrival, Long-term human presence. Clearly in the first phase, robots will be the only actors as no humans will be present (a part few ground controllers). In the later phases, a cooperative presence of humans and robots is foreseen. In general after the 2025 it is possible to imagine the utilization of the robotics capabilities in three different scenarios:

1. Robotics for Solar System Exploration
2. Robotics for Lunar and Planetary Habitation
3. Robotics for In Space Operations

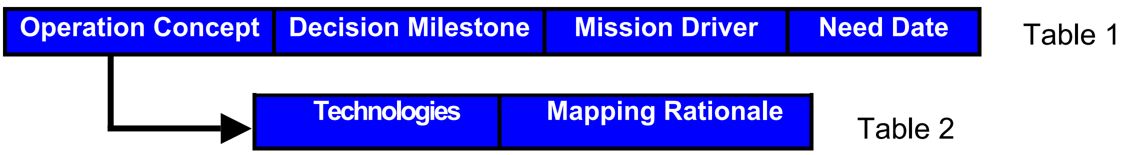
Next 15 years implementation tactical plan

Starting from the strategic plan, it has been elaborated a more detailed tactical plan for effectively and efficiently introducing the identified technology during the next 15 years from the 2010 to 2025 imposing a certain number of rules that can be summarized as the following:

Rule 1	A ground simulator is considered necessary for the future advanced technology developments and validation.
Rule 2	The ground simulator should be designed modular and used as a benchmark for specific operations concept and the related technologies development & validation.
Rule 3	The ground simulator should be operative starting from the 2011/2012.
Rule 4	All the concepts/prototypes tested on ground simulator should be injected in a real time environment (both ground and flight) in the context of the selected target missions.
Rule 5	All the concepts/prototypes should be tested in the ground simulator at leas two years before of the injection in a real time environment
Rule 6	This process can be reiterated with successive prototype refinement, allowing eventually

	the validation of both the prototype, or the technology behind it, and the operations concepts themselves.
Rule 7	Where applicable, the injection of new operative concepts in the flight segment will be always tested and validated in a real-time ground segment.
Rule 8	Enhanced autonomy induces a new repartition of processes between Ground and Space. Ground segment architecture has to evolve.
Rule 9	A staggered approach should be chosen for the implementation of the different Levels of Autonomy (LoA) with a CRL for all the requested domains ≥ 7 starting from 2025.
Rule 10	A CRL = 5/6 value must be taken as major decision milestone to assess the feasibility of a concept and related technologies application.
Rule 11	A LoA=4 should be ready from the 2015/2016 with the specific operation concepts and the related technologies infusion in the PROBA-IP and LISA-Pathfinder missions (demonstrator mission type), where ESA would demonstrate the key technologies to be used in the future Solar System's exploration missions and Observatory mission class.
Rule 12	A LoA=5 should be ready from the 2016/2017 with the specific operations concept and the related technologies infusion at least in the NEXT moon lander mission, where ESA would enhance and complement the capabilities to be applied during the EXOMARS while preparing Europe for the MSR mission.

Each operation concept has been linked to a decision milestone step where is indicated a Capability Readiness Level (CRL). A CRL can be assigned at a specific operational concept associated to one o more AI technologies. The CRL related to a specific operation concept must be intended reflected in all the technologies necessary to implement that concept. For each operation concept, a mission target that can be a driver for new technologies development is suggested as well. Of course the mission driver is intended as the mission where the validity of one or more concepts are confirmed (CRL=7).
The mapping provides, for each innovative mission concept, the set of the most suitable AI technologies, by describing the correlation between the functionalities required by the concept and the features and applications of the chosen technologies (mapping rationale).



Application prototyping activities have been identified as well as potential reference missions (current and near future coming missions) to be used to demonstrate and validate, in an operational environment, the viability of the technology for supporting the corresponding operations concept.

Mission scenarios (enabled by autonomy) mapped against long term future ESA Missions

A set of mission scenarios have been elaborated, each one characterized by a specific Level of Autonomy and including one or more identified operational concepts. The mission scenarios are mapped against the long term future ESA missions.

Mission Scenario	Future ESA Missions	Main Rationale
Science Missions Enabled by Onboard Autonomy	PROBA-IP	Demonstration mission
	Don Quijote, NEXT Lunar lander + rover Marco Polo, EXOMARS, MSR LAPLACE/EJSM	Science quality and quantity improvement; Transient opportunities capturing; Single command cycle
Beacon Scenario	PROBA-IP	Demonstration mission
	Don Quijote, Marco Polo, EXOMARS, MSR LAPLACE/EJSM	Long cruise phase Less ground contacts
Visual Navigation Scenario	PROBA-IP	Demonstration mission
	Don Quijote, Marco Polo,	Asteroid rendezvous and orbit insertion, Asteroid orbit operations improvement
Visual Landing Scenario	NEXT Lunar lander (+rover),	Demonstration mission
	Marco Polo, EXOMARS MSL	Safe and precise landing
New Rover Navigation concept enabled by Onboard Autonomy.	NEXT Lunar rover EXOMARS	Single command cycle; Science quantity improvement;
Autonomy Architectures for a Constellation/Formation of Spacecraft	LISA Pathfinder	Demonstration mission
	DARWIN LISA XEUS	Multiple spacecraft missions working in a cooperation fashion
Earth Observation global network scenario	None	No Earth Observation Missions have been selected because currently all planned to be launched before the 2015 and/or in an advanced development phase
Collaborative Monitoring and Control on Ground	ALL	Environment where inject the ground prototypes

Conclusions and Recommendations

The need for Autonomy in ESA has been anticipated by the ECCS Space Segment Operability standard ECSS-E-70-11 which defines three levels of autonomy: the execution of pre-planned missions operations on-board, the execution of adaptive mission operations on-board and the execution of goal-based mission operations on-board. The first important consideration is that the main strategic value of the current ESA approach is the operation costs reduction via an augmented efficiency by means of both on-board and on-ground operations automation. This is unfortunately not sufficient in a medium/long term perspective where the enabling of new kind of missions is a mandatory requirement

The basic categories identified where autonomy can be applied to space system functions are: On board Diagnosis and Reconfiguration (FDIR), Planning/Scheduling and Intelligent Execution, Command Sequence Generation, Data handling and processing, Navigation AOCS, Ground Segment and Mission Applications/Tools

In almost above domains, mature technologies are already available, and the main problem does not seems to be the technologies capabilities but rather the technology transfer from the research teams to the space industry (manufacturers and operators) which is not effective. In order for a research line to be productive an investment is needed on a medium term (5-10 years). While the Agency program for innovation in science initiatives is quite clear, the policy for innovation in technological innovation is not. In order to have a fruitful interaction with research labs is beneficial to create roadmaps that clarify the open points that need innovation, to make available test cases of open problems, even make available software simulators for certain scenario (e.g., for the EXOMARS rover). The proposed prototypes should be integrated and evaluated in a ground simulator first and after in a real-size demonstrator missions. If a simulator is highly desiderable, one or more demonstrator missions must be instead considered necessary for future technology developments.

Restricting the discussion on the autonomy concept, the impact of on-board autonomy on the ground segment has to be considered early enough. On board autonomy is not only a transfer of ground activities on board, but is also a mutation of the tasks of ground controllers which will have to interact/coordinate with the on board. The role of the Ground Segment should not fundamentally change when the spacecraft gets more autonomous. Ground Segment must remain in charge of commanding and monitoring the platform and the payload (define the mission, maintain the platform, monitor spacecraft health and performance) and of receiving, processing and dispatching to users mission data.

Although at first glance it is expected that functions usually performed on ground and now performed onboard will simply disappear from the ground, a more close look shows that autonomy should induce an evolution in the role of the Ground Segment.

What will be the needs for the ground segment of the future? Aspects of mission operations that are today merely troublesome or inconvenient will be disabling in 10 years given the dramatically more sophisticated and difficult mission objectives of the future. Multi-month planning timelines will be untenable, and therefore tools to plan mission activities and resolve resource usage or objective conflicts rapidly will be necessary. Onboard autonomous systems will need methods of control and monitoring that are currently unprecedented. Testing of the complex commands that enable onboard autonomy will require new methodologies that rapidly probe a nearly infinite space of possible autonomous actions and converge on a best plan while testing for fault paths. New software testing strategies will be necessary to test these autonomy software systems in the development phase. New tools for mission analysis will be required to readily visualize onboard behaviour and analyze and correct it if necessary. Science teams will need to respond to the mission environment as rapidly as engineers, quickly evaluating the fidelity of the onboard systems' adherence to their plans and objectives.

From the analysis conducted in this study, it is clearly highlighted that the automated planning, scheduling, resource management and execution will be, arguably, the core of system-level autonomy. These capabilities, when integrated, provide the basis for a space platform to perform engineering functions in closed-loop fashion onboard and for the development of the kernel of the new generation ground systems.
Goal-oriented, or otherwise dynamically responsive, sequence and commanding systems will be necessary to form the structures in which this autonomous GN&C, science acquisition, fault identification and recovery, surface roving, and generalized onboard activity programming takes place. Therefore it is recommended a strong effort on P&S technology area.

In particular, one of the first recommendations is the need of ground planning software and users to generate plans in a mixed-initiative (cooperative) fashion. Users need to explore and negotiate which goals to remove rather than having the planner decide. Also the user needs to examine infeasible plans, view plan flaws, and determine which activities to remove or what other repair strategy to consider. Another recommendation is helping operators to manage and evaluate contingencies, in the spirit of "If the plan completes early or fails at this step, do these useful low risk activities". This might be a popular evolution, and more in line with the careful way spacecraft are operated than the familiar formulation of automatically choosing contingencies to ensure the primary goal is achieved. In order to achieve these two recommendations, knowledge engineering techniques must be used.

In parallel it would be useful to adopt data processing techniques on-ground to sort through the large quantity of data received from the mission and pick up the relevant information. With concomitant advances in knowledge engineering techniques the improved science data-processing functionality could be first implemented on ground, enabling after the very real possibility of performing some forms of science-data analysis onboard the spacecraft in the next phases

In a more long-term perspective, the ESA approach could be oriented in the implementation of several "decisional" or "intelligent" functions directly on the spacecraft and therefore to move from the current "automatic" approach to the "autonomy" approach. Also here, the main assumption is that operator would be always able, by running the correct mechanisms, to take over the control of the system.

Finally, for all the ESA future missions, autonomy on-board and on-ground must be considered always complementary and the mission should be treated from this point of view as a system. Even if several decisions could be taken on-board, it is still valuable that part of them are performed on ground This point is particularly valuable for reducing the risk associated to on-board autonomy. It is bound that the on-board decisional process must be overwhelmed in some circumstances. All combinations of unexpected contexts cannot be tested before launch, and on-board constraints usually do not allow embarking the most capable software. In that case, the ground segment will provide functions to handle extreme situations.