P&S Requirements for *e*Partner-supported Astronaut-Rover Teams during Planetary Surface Operations

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Abstract

In the Mission Execution Crew Assistant (MECA) project, an industrial team has been compiling the Requirements Baseline document for a future manned planetary surface exploration mission to Mars. The project assumes that, by the time such a mission launches, astronauts will routinely work together as a team with autonomous rovers. The MECA system will form a network in which each MECA unit is an *e*Partner, capable of sensing and effecting the physical, cognitive, and affective status of its user. This paper presents the current MECA requirements for planning and scheduling for astronaut-rover teams supported by *e*Partners during planetary surface operations.

1. Introduction

1.1 Motivation

Advanced planning and scheduling (P&S) technologies are finding increasing application in space and other demanding domains. A common characteristic of such domains is that they tend to be conservative. For this reason, advanced technologies must first prove that they are safe, reliable, and beneficial in applications where the risk is limited. In the space domain, we have seen advanced P&S applied initially to ground station scheduling, to spacecraft assembly, integration, and testing (AIT), and then to offline, ground-based planning of unmanned space missions. Onboard applications were first limited to technology demonstrators (Jonsson et al, 2000), but have now migrated to unmanned scientific missions (Chien et al, 2005).

The ultimate risk is human life. At some point in the development of advanced P&S technologies they must be applied to manned space missions. Inevitably, this will bring with it unique requirements, making it necessary to reduce risk at each step in the development process. We may expect this process to echo that for unmanned missions. First, the new technologies will be applied to ground-based systems that support manned spaceflight operations. Then they will be applied to ground-based processing of manned spacecraft. Next, they will be applied to offline, ground-based planning. Initial onboard applications will be in supporting systems that are not (immediately) life-critical, then to scientific payloads, and finally to life-critical systems.

The P&S community is already embarked along this development path, whether or not it is aware of it. Ground station scheduling using advanced P&S technologies, developed for unmanned missions, can be used unchanged for supporting manned missions. Advanced P&S technologies are already used operationally for the ground processing of the US Space Shuttle. Research is in hand to apply P&S technologies to International Space Station (ISS) systems, such as electrical power planning (Knight et al, 2009), but this is not yet operational.

If we project this development process to its conclusion, then advanced P&S technologies will have migrated onboard manned missions where they will be used by astronauts to generate and execute plans autonomously

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(Grant et al, 2006). The ability to plan autonomously is essential when the communication link back to an Earth-based mission control centre is unreliable or when the light-travel time is long. This is the case for surface operations at Mars, where the round-trip time is at least six minutes and can be as long as 44 minutes. This means that if an astronaut on Mars is confronted with a problem that must be solved in lesser time, then the astronaut can no longer obtain the advice of mission control. The astronaut has no other choice but to act autonomously.

Under European Space Agency (ESA) contract number 19149/05/NL/JA, an industrial consortium led by TNO Human Factors (Netherlands) have been working on the Mission Execution Crew Assistant (MECA) project since 2005. The overall objective of the MECA project is to enhance the capabilities of human-machine teams during planetary exploration missions to cope autonomously with unexpected, complex, and potentially hazardous situations. MECA takes the approach that humans and machines (e.g. vehicles, rovers, and habitats) will be supported by a network of electronic partners (*e*Partners) incorporating P&S technologies. As well as providing information and communication support, *e*Partners will monitor and act on their users' physical, cognitive and affective state (Neerincx, 2003a/b).

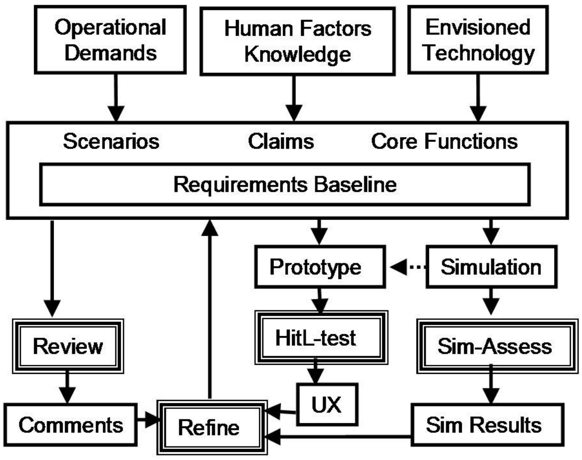

Figure 1. MECA development process

Figure 1 shows the MECA development process. The sole formal deliverable from the MECA project is the Requirements Baseline (RB) document shown in the middle. This RB is compliant with the European Cooperation for Space Standardization (ECSS) standard for software engineering (ECSS-E-40a).

MECA Phase 1 involved literature study and technology research into the operational demands, human factors knowledge, and the foreseeable technology for the likely date of the first manned mission to Mars (around 2027). The Phase 1 inputs are shown in the upper part of Figure 1. The initial RB document created from these inputs was reviewed both scientifically by presenting papers at relevant conferences and formally by ESA subject matter experts using the standard ECSS review process. This review and refinement process is shown at the lower left of Figure 1. Phase 1 was completed in 2006.

MECA Phase 2 involved three iterations of human-in-the-loop (HitL) testing of prototype demonstrators within a virtual-reality simulation representing the Martian environment. The focus was on defining and validating the MECA architecture and on incorporating health and resource management. The prototyping, simulation, and refinement process is shown at the lower right of Figure 1. The demonstrators were necessarily implemented using available technology. This impacted the demonstrators' capability for measuring its users' cognitive and affective state. Instead of monitoring the user's state continuously using skin resistance, brainwaves, or facial expressions (all technologies currently under development), users had to fill in questionnaires at pre-planned moments. Phase 2 was completed in 2007.

MECA is now in Phase 3. The emphasis is on steadily increasing the fidelity of the simulated environment. Simulation has progressed from using virtual reality to HitL testing within terrestrial analogues of Martian terrain (e.g. in the Eiffel mountains) and isolation (e.g. in the Mars105 and (currently) Mars520 laboratory experiments). In the near future, an experiment will be done in the Concordia location (Antarctica), and we hope that orbital testing on the ISS will follow.

1.2 Purpose and contribution

The purpose of this paper is to present the current MECA requirements for planning and scheduling for human-machine teams supported by *e*Partners during planetary surface operations. We compare these requirements to those developed by similar research projects reported in the International Workshop for Planning and Scheduling in Space (IWPSS), the International Symposium on Artificial Intelligence, Robotics, and Automation in Space (iSAIRAS), and the International Conference on Automated Planning and Scheduling (ICAPS).

We believe that this paper will benefit the IWPSS community in the following ways:

- It presents the results of identifying the requirements (including planning and scheduling) for manned planetary surface operations.
- These requirements have been developed by an industrial team driven by scientific inputs, but following the ECSS software engineering standards.

- It introduces the *e*Partner concept, a model of cognitive workload, and affective computing in supporting astronaut-rover teams.

At the same time, inputs from the IWPSS community are welcomed in helping the MECA team refine the Requirements Baseline document.

1.3 Paper structure

This paper has six sections. Section 1 is introductory. Section 2 outlines manned operations on the Martian surface, highlighting key environmental determinants. Section 3 describes the past, present, and future of MECA and related projects. The *e*Partner concept, the application of cognitive workload and affective computing, and the situated cognitive engineering process are described in Section 4. Section 5 summarizes the planning and scheduling requirements in the current MECA Requirements Baseline document, comparing these against related research in the AI planning and scheduling literature. Finally, Section 6 draws conclusions and makes recommendations.

2. Planetary Surface Operations

In Phase 1 of the MECA project we compared a variety of studies of manned planetary missions. These included the NASA Reference Mission (Hoffman & Kaplan, 1997), a lunar exploration study performed in ESA's Concurrent Design Facility in 2003, the three scenarios in ESA's HUMEX study (Harris, 2003), retrospective study of the Apollo 13 and EuroMir95 missions, and Nobel Prize-winner Professor 't Hooft's (2005) proposal for planetary exploration using private-public partnerships. These studies showed that the limiting factors for human health and performance during such missions are:

- Radiation exposure.
- Micro-gravity and reduced gravity.
- General human health issues.
- Psychological issues.

The NASA Mars Exploration Study Team developed a reference mission for the human exploration of Mars (Hoffman & Kaplan, 1997). Their baseline scenario consisted of the following phases:

- Pre-launch.
- Earth launch.
- Trans-Mars.
- Mars landing.
- Mars surface operations.
- Mars launch.
- Trans-Earth.
- Earth landing.
- Post-landing.

MECA will have a role to play in most – if not all – of these phases. With the exception of the Mars surface phase, MECA's operating environment will be similar to that of present-day crew workstations in use on the International Space Station (ISS). The crew will work most of the time inside the spacecraft, using the MECA to operate payloads, robot arms, and possible subsystems, with occasional EVAs.

Some differences with ISS operations will appear gradually. For example, at some point during the Trans-Mars phase the transmission delay to Earth, plus possible interruptions in communications, will begin to assert itself. This will remain an influence until the mission nears Earth during the Trans-Earth phase. Other differences will be apparent immediately. For example, the altered organisational relationship between the crew and ground-based support whereby the crew is assigned the responsibility for operations planning and execution is like to be in force from Earth launch to Earth landing, and possibly also in the Pre-launch and Post landing phases.

The big differences will appear during the Mars surface phase. Using MECA, the crew will assume control of the facilities pre-positioned there before their departure from Earth. Habitats, rovers, and Mars Exploration Vehicle(s) (MEV) will have been deployed two or more years beforehand. The crew will leave their lander, split up into smaller groups, operate and maintain the pre-positioned facilities, go on exploratory traverses, and work together with the rovers. This implies that MECA will have to a distributed system, and some elements of MECA will have to be mobile.

Moreover, the MECA and its astronaut users will be confronted with the issue of operating and maintaining entities with well-developed autonomous capabilities, such as the pre-positioned facilities and the rovers. The MEV(s), together with the astronauts they carry, should also be regarded as highly autonomous systems. It is obvious that each astronaut, too, can be regarded as an autonomous system.

Given the differences with current experience, the MECA project focuses on the Mars surface operations phase and on human factors.

3. MECA Project

This section describes what MECA and its related projects have achieved to date, emphasising the simulations in analogue environments. It also outlines the activities that MECA plans to address.

3.1 Statement of Work

In the Statement of Work (SOW), ESA envisages the MECA as a software-based system to provide the crew of long-duration, manned, planetary missions with optimal support for the scheduling and execution of corrective maintenance and troubleshooting tasks for equipment and facilities. This support must fit in with the given mission constraints, most notably:

- Long duration mission without resupply or rescue.
- Crew responsibility for execution level planning and mission execution.
- Transmission delays and interruptions in the communications link to Earth.

The SOW provides an initial list of MECA functions, as follows:

- Short- and mid-term scheduling and decision-making.
- Health and status monitoring of equipment and facilities.
- Adjustment of monitoring and supervision algorithms and data as equipment and facilities evolve over time.
- Human-to-human collaboration.
- "What-if" scenario evaluation.
- Provision to crew of procedural knowledge, updated as and when required.
- Provision to crew of advice about alternatives and their effects on resources.
- Execution of crew-delegated tasks.

In addition, there are functions implicit in other parts of the SOW, such as:

- MECA-crew interaction driven by crew workload, task urgency, and skill level, and configurable for operations or training.
- Event logging and play-back.

This list of functions identified from the SOW formed the starting point for Phase 1 of the MECA project.

3.2 Past

The MECA project envisages that manned operations on Mars will be performed in cooperation with automated systems that themselves have a high degree of autonomy. The most obvious such system is the rover, so that exploration will be done by astronaut-rover teams. Less obviously, we believe that space vehicles and habitats will also have advanced capabilities, not least because they must be able to operate autonomously before the astronauts arrive.

Another assumption made in the MECA project is that the mission control system will be distributed across all the mission elements, linking them together in a network. Each astronaut, rover, vehicle, and habitat will be provided with at least one node providing communication and decision support. Such nodes are termed "MECA units". Precisely what form a MECA unit will take is difficult to foresee. In terms of today's technology it would look like a PDA or a smart-phone. However, the MECA project is looking ahead some 20 years. Since it is difficult to imagine how current technology will develop over a period of 20 years, we do not make the attempt. Instead, we regard the MECA unit and the MECA system of which it forms part at a conceptual level. At this level, the MECA system will be ubiquitous, and the relationship between MECA units and their (human and synthetic) users will be one of partnership. In AI terms, MECA units will be intelligent agents. Both units and users will be able to inform each other, to support each other, to learn, and to teach each other (Neerincx & Grant, 2010). Moreover, support will not be limited to physical action, but will also be cognitive and affective.

In Phase 1, we developed the conceptual architecture of a MECA unit as shown in Figure 2. This architecture was originally based on Rasmussen's (1983) Skills-Rule-Knowledge model of human supervisory control. The requirements were identified with this architecture in mind. In Phase 2, the MECA prototype demonstrators were implemented using today's advanced technology: web services and ontologies (Breebaart et al, 2008).

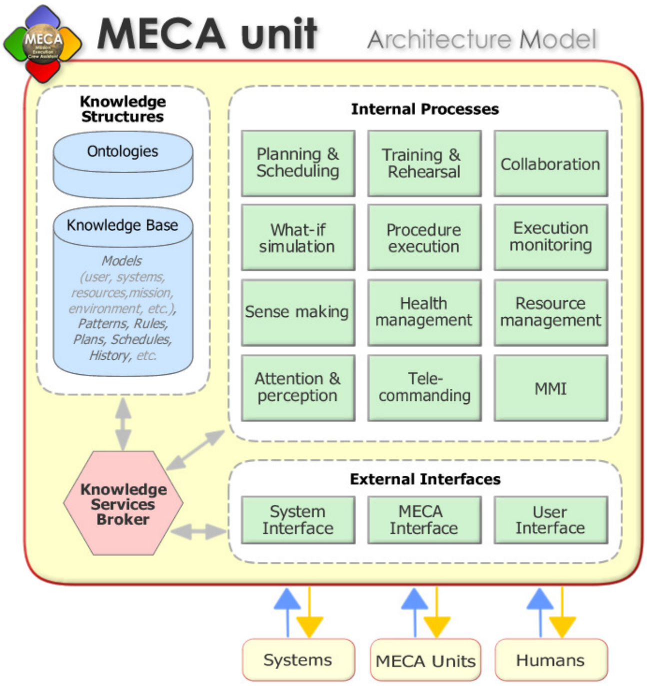

Figure 2. Architecture of MECA unit

In 2008, demonstrator prototypes participated in the Mars105 project to study the psychological effects of long-term isolation, with a focus on the user interface and collaboration. The MECA-T1 prototype[1] participated in the ESTEC Eiffel campaign in 2009, with a focus on

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[1] The "T" indicates terrestrial simulation of the Martian environment. "O" prototypes will be designed for orbital simulation.

procedure execution and monitoring, planning and scheduling, collaboration, and science support. The MECA-T2 prototype is currently participating in the Mars-500 project, with a focus on cognitive workload evaluation.

In Mars-500, pairs of astronauts perform procedure training, one as the instructor and the other as the trainee. The MECA demonstrator guides the training session, while assessing the astronauts' interpersonal communication in terms of cognitive and affective state. Based on this state, MECA suggests changes to the astronauts' work schedule, e.g. to include individual computer gaming sessions for relaxation (Van Diggelen & Neerincx, 2010).

3.3 Future

In the near future, the MECA-T3 prototype will participate in the Concordia Antarctic campaign, as a part of the ongoing Phase 3 of the MECA project. The Mars-500 demonstrator will be enhanced to suggest changes in the scheduling of physical exercise, which is known to improve mental health (Van Diggelen & Neerincx, 2010) . In addition, the Concordia demonstrator will provide social interaction games and new gaming concepts requiring joint resource supervision and tit-for-tat collaboration.

In the longer term, the intention is to progress from terrestrial to orbital simulation. While the eventual aim is to test MECA prototypes on the ISS, this will most likely be preceded by testing in the Columbus mock-up at ESTEC, in the European Astronaut Facilities, and in the Columbus Control Centre. A suitable focus for simulated and real orbital environments would be the use of MECA units working with real rovers and robotic devices.

3.4 Related projects

Several related projects have been spawned from MECA. Some are also ESA-funded. The Expert Tool for Enhanced Crew Autonomy (ETECA) project emphasizes system health management using the MECA diagnostic services. The Crew Expert Tool "Eye-Opener" (CETIO) investigates how to support the crew in solving unanticipated problems, i.e. the MECA unit's sensemaking function. The Advanced Payload Laptop Application (APLA) project is developing a payload proficiency trainer for onboard, just-in-time crew training. APLA will integrated into the MECA unit as its training and rehearsal function.

In other related research, TNO, Delft University of Technology, and the Institute for Human and Machine Cognition (IHMC) are collaborating in using the Brahms agent-based environment to simulate the MECA scenarios (Smets et al, 2010). The emphasis is on the social abilities and communication within the simulated astronaut-rover team, rather than on individuals' cognitive and affective state. The simulated individuals' behaviour is constrained by Knowledgeable Agent-oriented Systems (KAoS) policies representing social and organizational norms.

Requirements generated by these related projects will be incorporated into the MECA RB.

4. The *e*Partner Concept

This section describes the *e*Partner concept and the application of cognitive workload and affective computing. MECA units are regarded as instantiations of the *e*Partner concept.

4.1 Concept

In the human social domain, partners are comrades or companions who share experiences and carry out activities jointly. Their roles are established, the actions are entrusted to one another, the workload is divided, advice may be given to one another without the other having to ask for it, and the results are mutually satisfying. Their interaction progresses in a natural way. Through sharing experiences, partners come to know each other's qualities and foibles. With this knowledge, each partner can adjust its support for the other to the current situation, anticipate the other partner's needs and behaviour, and detect and correct or mitigate the other partner's errors. A set of partners can be regarded as a Complex Adaptive System (CAS) (Morowitz & Singer, 1995).

By contrast, the relationship between human users and present-day computer systems is – at best – one of supervisor and subordinate[2]. Current space mission control systems are a form of human supervisory control (Sheridan, 1992), an outgrowth of automated control in which human users are continually programming and receiving information from a computer system that interconnects to a controlled process or task environment through sensors and effectors. Researchers have recognized that this paradigm limits the assistance that a computer can give its users because it can only do as it is told. Under the heading of adaptive user interfaces (Schneider-Hufschmidt et al, 1993), they have attempted to develop systems that can adapt the way in which they interact with their human users according to the situation. For example, they could be designed to provide only the information that the human user needs for the current situation. Unfortunately, adaptive user interfaces have failed to result in working real-world applications, largely because of a lack of a theoretical and empirical foundation to the proposed human-machine collaboration.

Neerincx (2003a) argues that developing computer systems that can adapt their user interfaces does not go far enough.

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[2] At worst, it is a master-slave relationship. Humans think nothing of making computers wait endlessly or of switching them off without warning. Between humans this would be regarded as bad manners or even as a cause for breaking off the relationship.

Based on current developments in mental state sensing, context sensing, capacity modelling, and multimodal communication, the computer system must become an electronic partner. Such an *e*Partner has knowledge of its human partner with respect to his or her permanent characteristics (e.g., personality), dynamic characteristics (e.g., experience), base-line state (e.g., "normal" heart rate), and momentary state (e.g., current momentary heart rate). Based on this knowledge, the *e*Partner maintains a model of the task demands that are critical for its human partner, e.g., the risk of its human partner suffering cognitive lock-up in a complex task situation (Neerincx, 2003b). The *e*Partner will have a repertoire of mitigation strategies to prevent or to diminish negative effects of human operations in such critical situations by taking over tasks, guiding task performance, requesting the assistance of other partners, or subtle actions to keep the human in an adequate mental state (e.g., open-mindedness, alertness). Technologies that will be applied for the implementation of this partnership are facial expression analysis, voice analysis, physiological measurements, context recording, and task tracking (Grootjen et al, 2006).

An *e*Partner and its human user is more than a CAS, i.e., "a dynamic network of many agents … acting in parallel, constantly acting and reacting to what the other agents are doing" (Waldrop, 1992). The *e*Partner and its human user must each know the characteristics and state of the other partner, not just how the other behaves. To really collaborate with such a sensing *e*Partner, the human user must trust it[3]. He or she needs to know what the "*e*Partner knows about him or her", setting a requirement for the scrutability of the models. Human users should be able to inspect and control the details of the information held about them, the processes used to gather it, and the way that it is used. It may be possible to change some values according to his or her view (or according to the view of another partner of the team). There is "natural or intuitive" human-machine communication by expressing and interpreting communicative acts based on a common reference.

4.2 Cognitive workload

Adequate management of human and machine resources over time will be one of the crucial general problems to solve for the Mars space missions. Neerincx et al. (2004) developed a design method for human-computer collaboration based on models of Cognitive Task Load (CTL) and cognitive support. The CTL model describes load in terms of three behavioural factors: the percentage time occupied, the level of information processing, and the number of task-set switches. The higher the value of each factor, the higher the load will be. Figure 3 presents the three-dimensional "load" space—*the task design space*—in which human activities can be projected with critical regions indicating the cognitive demands that the activity imposes on the crewmember.

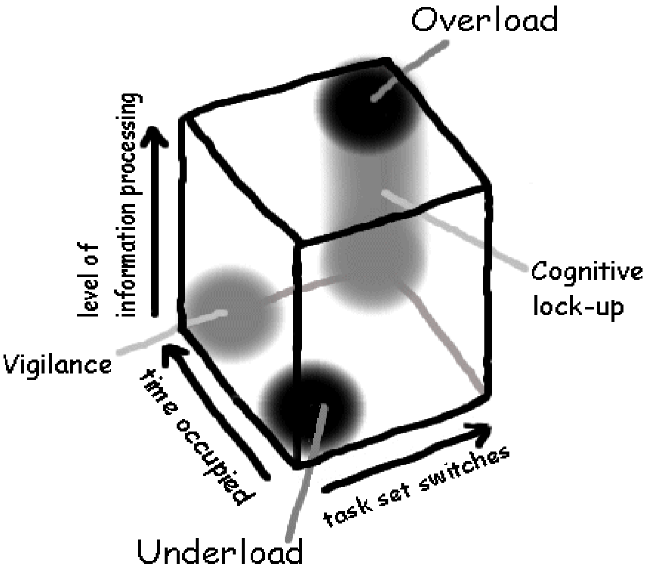

Figure 3. Cognitive Task Load model

The first load factor, percentage time occupied, has been used to assess workload in practice for time-line assessments. Such assessments are often based on the notion that people should not be occupied more than 70 to 80 percent of the total time available.

To address the cognitive task demands, the cognitive load model incorporates the Skill-Rule-Knowledge framework of Rasmussen (1983) as an indication of the level of information processing. At the skill-based level, information is processed automatically resulting into actions that are hardly cognitively demanding. At the rule-based level, input information triggers routine solutions (i.e. procedures with rules of the type 'if <event/state> then <action>') resulting into efficient problem solving in terms of required cognitive capacities. At the knowledge-based level, the problem is analyzed and solution(s) are planned, in particular to deal with new situations. This type of information processing can involve a high load on the limited capacity of working memory.

Task-set switching is a third load factor. Complex task situations consist of several different tasks, with different goals. These tasks appeal to different sources of human knowledge and capacities and refer to different objects in the environment. We use the term task set to denote the human resources and environmental objects with the momentary states, which are involved in the task performance.

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[3] For a review of the research literature on trust in automated systems see Madsen & Gregor (2000).

The combination of the three load factors determines the cognitive task load: the load is high when the percentage time occupied, the level of information processing and the number of task-set switches are high. Figure 3 presents a 3-dimensional “load” space in which human activities can be projected with regions indicating the cognitive demands that the activity imposes on the operator. In the middle area, task load matches the operator’s mental capacity.

According to the CTL method, task design—including allocation and scheduling—aims at a cube that is “empty” for the critical regions distinguished above. For remaining critical situations, it aims at empowering the crew members with computer support and training, so that they can meet the specific demands. Therefore, the method distinguishes specific cognitive support functions that affect these values. For example, procedural support will diminish the level of information processing if it complies with a number of guidelines. A second example is task management support that will diminish the task-set switching demands if it fulfils a compound set of user requirements.

4.3 Affective computing

Affect, emotion, and mood are concepts that can have many interpretations. We use affect and emotion interchangeably to reflect a momentary state, and mood to describe a state with a longer duration. Affect comprises a broad range of feelings that humans can have and which can influence humans in their behaviour.

For characterising the affective load, we focus on the underlying, often physiologically correlated factors, such as arousal, and map these onto distinct dimensions. Such dimensional models are helpful for recognition and expression, as well as in models of emotion generation. Based on Bradley and Lang’s (1994) Pleasure-Arousal-Dominance (PAD) model, we distinguish two dimensions to define the MECA user’s emotional state: the arousal level (low versus high) and the valence (positive versus negative). We omit dominance in MECA because research has shown that this explained the least variance and had the highest variability in terms of its inferred meaning.

5. P&S Requirements

This section gives an overview of the RB, describes the P&S-related requirements in detail, and compares the MECA requirements to related AI P&S research.

5.1 Requirements Baseline

At the time of writing (February 2011), the latest version of the MECA Requirements Baseline (RB) is version 3, dated 27 August 2009. This document was the main formal deliverable from Work Package 600, MECA Phase 2. Although in Phase 3 two working documents have been produced suggesting refinements of requirements specific to the Mars520 and Concordia experiments, this paper will focus on the version 3 baseline. Version 3 does not yet incorporate the requirements generated by the ETECA, CETIO, APLA, and other related projects.

Under the European Cooperation for Space Standardization (ECSS) standard for software engineering (ECSS-E-40a), the RB document expresses the customer’s requirements. The RB document requirement description covers:

- Functions and performance requirements of the system.
- Operations and maintenance requirements.
- Design constraints and verification and validation requirements.
- Identification of lower level software engineering standards.
- Overall safety and reliability requirements.
- Critical function identification and analysis.
- System partition with definition of items.
- System configuration items list.
- V&V process requirements.
- Software observability requirements.
- Development constraints.
- Customer approval of RB.
- Documentation standards.
- Design standards.
- V&V standards.
- Interface management procedures.
- Configuration management plan.
- Technical budget and margin philosophy for the project.

In addition, there is a separate Interface Requirement Document (IRD) that expresses the customer’s interface requirements. The IRD is required when the software is intended to be integrated into the customer’s hardware and software products. The IRD may be integrated into the RB.

For the MECA project, most of these aspects are irrelevant because the operational software will not be developed until 2027 at the earliest. By that time, the standards and technologies available will have undergone several evolutions. An example is the *e*Partner hardware. If the hardware requirements had been frozen in Phase 1, then the *e*Partner would have taken the form of a netbook. In Phase 2 it would have been a smartphone, and in Phase 3 a tablet computer. So it is impossible to say what the hardware will actually look like two decades from now. Therefore, the definition of the MECA requirements focuses on generic tasks, on *e*Partner functions, and on abstract user and system interfaces, based on scenarios and use-cases. Technical and operational requirements were added specifically to implement the Proof-of-Concept (PoC) MECA demonstrators using the then-current technologies, but these are separate from the RB. ECSS-standard Technical Specification and Design Justification File documents have also been produced for the same reason.

The requirements in the MECA RB document are currently divided into the following six groups:

- RG: Generic task-level requirements.
- RF: Functional requirements.
- UI: User interface requirements.
- RT: Technical requirements.
- RO: Operational requirements.
- RI: Interface requirements.

For the purposes of this paper, we will limit our description to the requirements expressing the MECA mission characteristics (to be found in the RG group) and the requirements relating to planning and scheduling (mostly to be found in the RF group).

5.2 Requirements relating to MECA mission

The RG (generic task-level) requirements express the following characteristics of the MECA mission:

- *Autonomy*. Requirement RG5010 states that "MECA shall support crew to survive and operate without continuous and direct support from Earth".
- *Distributed system*. Requirement RG1094 states that "MECA shall support a distributed set of agents to reach a common objective by sharing information and dividing tasks".
- *Generalist agents*. Requirement RG2093 states that any MECA unit should be potentially capable of performing any function, as follows: "MECA shall be generalist so that migration of functionality can be achieved dynamically by activating dormant functions".
- *Collaboration*. Requirement RG1106 states that "MECA shall support collaboration by sharing new knowledge automatically with other MECA units, crew members, or other systems". Similarly, requirements RG1091, 1092, and 1093 state that MECA shall also support collaboration among crew members and between crew members and Earth, vehicles, payloads and other equipment.
- *Cognitive support*. Requirement RG1100 states that "MECA shall manage [the] cognitive task load among [the] human actors".
- *Affective support*. Requirement RG1110 states that "MECA shall be able to provide emotional support to the human actors".

5.3 Detailed P&S requirements

Most of the MECA requirements relating to planning and scheduling can be found in the RF group. This group is sub-divided into the following elements of the classic control loop:

- *Gathering and maintaining information*. This includes proactively collecting, storing, filtering, and combining information from different sources (RF2022) to detect needs for operations and training (RF2021). Information gathered includes information about human users' physical, cognitive, and emotional status (RF2090). MECA integrates current and projected status information into plans (RG3091).
- *Setting goals*. Crew safety is MECA's foremost goal (RF2520). Crew members can set or change goals and priorities (RF2510). Together with the crew, MECA evaluates the impact of new goals, identifying conflicts, reassigning priorities, and, if necessary, rejecting them (RF2512).
- *Generating plans*. MECA generates plans incorporating a sequence of tasks (RF2110) for operations or for training (RF2101), including identifying (RF2120) and scheduling (RF2140) the resources needed, as well as alternatives (RF2150). Plan generation can be distributed (RF2164), and MECA shall be able to explain proposed plans by providing qualitative indicators (RF2165). Information on the user's status can be used to optimize plans (RF2163).
- *Evaluating plans*. MECA shall evaluate operational and training plans (RF2161), using rehearsal to validate their feasibility (RF2185) and considering the utility and risks associated with the resources (RF2190). Logged information can be played back and review to assist evaluation (RF2180). The crew can introduce hypothetical models of the state of facilities, equipment, and resources and how that changes over time (RF2170) and simulate the consequences (RF2175). MECA shall provide the facility for editing plans (RI3075) and procedures (RI3050).
- *Preparing for plan execution*. Preparation includes training the crew using simulation and rehearsal (RF2135), selecting or producing the procedures involved (RF2133), and editing the operations products needed for plan execution (RF2134). It also includes (RF2130) assigning, producing, configuring, reallocating, and (RF2131) preparing the resources needed. MECA shall generate predictions of future states for presentation during execution (RU4220).
- *Executing plans*. MECA shall support the execution of operational and training plans (RF2210), autonomously when delegated to do so by the crew (RF2290). It shall provide procedural knowledge to support execution by the crew (RF2260). Execution shall be monitored (RF2230), and all information generated shall be logged (RF2240). Monitoring algorithms and data will be optimized as equipment and facilities change over time (RF2300), and support will be provided to the crew to make sense of information and to represent the world correctly (RF2250). Related events shall be visualized and analysed (RF2298). Procedures can be shared between

actors (RF2294) and executed in parallel (RF2295), with rule-checking (RF2280).

- *Processing and evaluating the results of execution*. MECA shall evaluate the execution results (RF2401), detecting possible risks following execution (RF2430), checking the status of resources (RF2420), and comparing actual events against the plan (RF2410). MECA shall be able to learn from experience by analysing past actions and their results (RF2440).

5.4 P&S requirements relating to users' state

At present, RB version 3 only includes P&S requirements relating to the users' physical (health) state. In the related ETECA, CETIO, and APLA projects, requirements are being generated relating to cognitive and affective state. These requirements will be merged into the RB, probably in June 2011.

5.5 Related AI P&S research

There is substantial related AI P&S research. There are numerous operational ground-based AI P&S systems supporting mission planning for unmanned spacecraft. A handful of systems have flown. Jonsson et al (2000) draws lessons from the Remote Agent Experiment, flown on the Deep Space One unmanned spacecraft. Chien et al (2005) have done the same for the Autonomous Sciencecraft Experiment onboard the unmanned EO-1 spacecraft. None have flown in manned missions. Kortenkamp (2001) presents a roadmap for autonomy for crew-tended systems, such as the Space Shuttle, ISS, and a future Mars base. This roadmap includes a line of development for P&S technology that emphasizes the expressiveness of the planning representation. Allen and Ferguson (2002) describes the design of a computer agent that can collaborate with a human user in planning. However, this does not cover teaming. Sierhuis et al (2003) outline a perspective on teamwork in groups involving a mix of humans and autonomous agents, showing how their Mobile Agent Architecture could be applied to a Martian surface exploration scenario. Martin et al (2004) describes the Distributed Collaboration and Interaction (DCI) environment which supports interaction between humans and automated software systems. A DCI prototype has been applied to the advanced Water Recovery System for manned spacecraft. However, none of these projects have extracted detailed requirements for astronaut-rover teams during planetary surface operations.

6. Conclusions and Recommendations

This paper has described the European Space Agency's Mission Execution Crew Assistant (MECA) project. The overall objective is to enhance the capabilities of human-machine teams during planetary exploration missions to cope autonomously with unexpected, complex, and potentially hazardous situations. MECA takes the approach that humans and machines (e.g. vehicles, rovers, and habitats) will be supported by a network of electronic partners (*e*Partners) incorporating P&S technologies. As well as providing information and communication support, *e*Partners will monitor and act on their users' physical, cognitive and affective state.

The paper describes a reference mission for the human exploration of Mars. The MECA project focuses on the surface operations phase and on human factors aspects. The MECA development process is described, including the situated cognitive engineering methodology used. The activities performed in the completed Phases 1 and 2 are outlined. Currently, Phase 3 is evaluating MECA demonstrators in terrestrial simulated environments, and the intention is to progress to orbital simulations. Measurements of the user's cognitive and affective state are used to suggest changes in their work schedule.

Finally, the paper describes the MECA Requirements baseline document in detail, summarizing the requirements relating to planning and scheduling. Comparing these requirements to related AI P&S research shows that the MECA requirements lack an emphasis on collaboration between units and their users. Experimentation on collaboration has been limited to trainers and trainees. In the MECA project there has been an under-emphasis on MECA unit support for sensing and perception and for physical and communicative action.

Based on these conclusions, we recommend that the MECA project should incorporate selected results from AI P&S research, particularly those relating to human-machine teamwork. MECA demonstrations should place more emphasis on collaboration (and especially collaborative planning), on support for sensing and acting, and on interaction with automated space systems such as robots and rovers. Moreover, we recommend that additional MECA demonstrations should be done in terrestrial analogue missions where the autonomous astronaut-rover team is responsible for operating real hardware. These should be followed by Mars-analogue demonstrations onboard the ISS.

Finally, since future planetary surface missions are likely to be man-tended, we recommend that designers of automated elements (such as vehicles, habitats, and rovers) should make provision for later team-working with humans.

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