Cognitive Engineering for Long Duration Missions: Human-Machine Collaboration on the Moon and Mars

M.A. Neerincx, J. Lindenberg, N. Smets
TNO /DUT, The Netherlands
mark.neerincx@tno.nl

T. Grant, A. Bos
S&T BV /NDA
The Netherlands
tgrant@cs.up.ac.za
bos@science-and-technology.nl

A. Olmedo-Soler
OKS
Spain
aos@olmedo.com

U. Brauer
EADS-ST
Germany
uwe.brauer@space.eads.net

M. Wolff
ESA-ESTEC
The Netherlands
mikael.wolff@esa.int

Abstract

For manned long-duration missions to the Moon and Mars, there is a need for a Mission Execution Crew Assistant (MECA) that empowers the cognitive capacities of human-machine teams during planetary exploration missions in order to cope autonomously with unexpected, complex and potentially hazardous situations. MECA requirements are being derived via a cognitive engineering method, which addresses operational, human factors and technological aspects with their mutual dependencies. This method follows an iterative process of specification, evaluation and refinement to establish a sound—theoretical and empirical founded—set of requirements. It distinguishes three types of iterations: system-design review, scientific discourse and simulation-based evaluation. The first two iterations provided a set of requirements for distributed human-machine collaboration on the Moon or Mars.

1. Introduction

Future manned missions to the Moon or Mars should be supported by intelligent machines that cooperate with the astronauts in such a way that operations can be scheduled and executed effectively and safely in a hostile and complex environment. Such human-machine collaboration (HMC) involves the accommodation of user characteristics, tasks and contexts to provide the “right” information, services and functions at the “right” time and in the “right” way. To take care of the long duration of the missions and delays in communication, the HMC should support rather autonomous operation for the astronauts (compared to current mission profiles; cf. [1]).

The MECA project develops a theoretical and empirical founded set of requirements for a Mission Execution Crew Assistant (MECA) that will be used on future planetary exploration missions to support the collaboration between intelligent machines and human explorers (e.g. on the Moon or Mars). The general objective of MECA is to support the mission goals—without injury or loss of life—by empowering the cognitive capacities of human-machine teams during planetary exploration missions in order to cope autonomously with unexpected, complex and potentially hazardous situations. The HMC design gives rise to various human factors and technological challenges. This paper presents the cognitive engineering method taken in the ‘Mission Execution Crew Assistant’ (MECA) project to identify the most critical operational and human factors requirements, to attune the upcoming technologies to these requirements and to provide a first prototype. Furthermore, it discusses the results of the first cycle of requirements specification and refinement.

1.1. Design of human-machine collaboration

Cognitive engineering (CE) approaches originated from the fields of cognitive science, human-computer interaction and artificial intelligence to improve computer-supported task performance. These approaches follow an iterative development process in which an artifact is specified in more-and-more detail and specifications are assessed more or less regularly to refine the specification, to test it, and to adjust or extend it (e.g., [2], [3]). For adaptive and collaborative systems, human and machine task design should be developed and tested jointly for two reasons [4]. First, the technological design space sets a focus in the process of specification and generation of task support.

Second, the reciprocal adaptive behavior of both machine and human actor can only be specified and tested jointly; i.e., this behavior will only appear in the joint human-machine collaborative activity [5].

1.2. Tailoring to the space domain

Using the HMC design method for projects in various domains identified a need for tailoring the human factors knowledge and technological design space to a certain domain [3]. A recent human-computer interaction project developed a tool kit to guide the design of operation support for payload interfaces; the tool kit was called “Situated Usability engineering for Interactive Task Environments” (SUITE). SUITE consists of both (i) a Human Factors Engineering (HFE) method and (ii) a generic task support and dialogue framework, called Supporting Crew OPErations (SCOPE). SCOPE can be viewed as an implementation of human-factors methods and guidelines, and an instance of current interaction and AI technology for Human-Machine Collaboration (HMC; cf. [6]). We extended and refined the HFE method and SCOPE framework for the development of MECA.

2. MECA as electronic partner

Figure 1 provides an overview of the general cognitive engineering method for the generation, evaluation and refinement of MECA requirements. The analysis of the operational demands, human factors knowledge and envisioned technology resulted first in the definition of the MECA concept, the corresponding scenarios, and the human-machine role allocations.

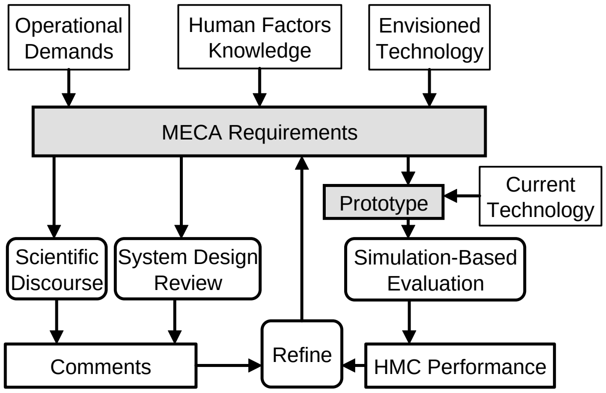

Figure 1. The iterative process of requirements analysis (HMC = Human-Machine Collaboration).

This section will summarize these results; section 3 will discuss the requirements that are being derived from this concept, scenarios and role allocations.

2.1. The MECA concept

The MECA concept comprises crew operation support that acts in a ubiquitous computing environment as electronic partner, helping the crew to assess the situation, to determine a suitable course of actions to solve a problem, and to safeguard the astronaut from failures (for a more extensive description of the MECA concept, see [7]). This concept comprises a collection of distributed and connected personal *e*Partners to support the (distributed) crew members during exploration missions. A personal *e*Partner predicts its crew members momentary support needs by on-line gathering and modelling of human, machine, task and context information. Based on these models, it attunes the user interface to these needs in order to establish optimal human-machine performance. The user interface of the *e*Partner is “natural or intuitive” by expressing and interpreting communicative acts based on a common reference of the human and machine actors.

2.2. Scenario analyses

Operational demands can be analyzed for specific, concrete task contexts by scenario analyses [8]. Scenarios presuppose a certain setting. Within the setting, roles are played by actors. In complex scenarios different actors can be involved, possible interacting with each other. Actors have specific goals or tasks. To achieve this goal actions have to be taken. We analyzed a rich set of scenarios and defined use cases to extend, refine and clarify these scenarios.

One of the scenarios centered on the collaboration processes to solve a failure in an astronaut suit. The scenario starts with two human-machine teams, team A and B, exploring the surface at different locations. Team B is working at a large distance from the habitat, and has a relatively large rover that can carry an astronaut. At the habitat, one astronaut is doing her exercises following her “self-care program”. For one member of team A, Charles, the spacesuit heater fails (figure 2). Team A, i.e. the crew and MECA units, starts a fault detection and diagnosis process. MECA predicts hypothermia and calls for help. In parallel, the following actions are started:

- Habitat prepares to receive astronaut (goal resetting)
- Rover in other team offers help & starts out
- MECA informs astronaut (& others) of plan
- Astronaut faints earlier than predicted
- MECA & rover devise way to pick up astronaut
- Rover transports astronaut to habitat

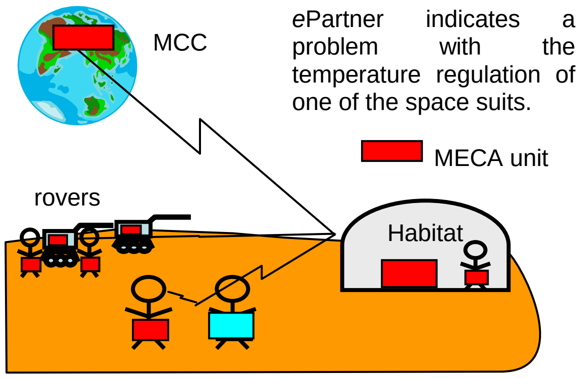

Figure 2: Example scenario state for the suit failure (MCC = Mission Control Center).

Table 1. Example mappings of roles on actors.

Role	Role description	Actor
Short term planner	Make plans to execute on short term	MECA, crew
Procedure author	Write new procedures or add to existing procedures	MECA, crew, MCC
Status provider	Provide health, status, speed, direction and location of system or other information concerning system	MECA, crew, orbiter, facility, rover, habitat
Simulator	Train actor with simulations	MECA, crew
What-if simulator	Evaluate possible alternative recovery actions	MECA, crew
Doctor	Examine and treat ill patients	MECA, crew
…	…	…

2.3. Human-machine role allocation

Based on the scenario definitions, several actor roles for exploration missions were distinguished and allocated to human or machine actors. Table 1 provides some example mappings of roles on actors.

3. Requirements framework

Section 2 described the definition of MECA as an *e*Partner, and the corresponding scenarios and role allocations, which were derived from the analyses of the operational demands, the human factors knowledge and envisioned technology. The present section contains a further operational, human-factors and technological analysis, which provided a first set of MECA requirements, distinguishing key parameters and specific requirements (i.e., task-level, functional, user interface and technical interface).

3.1. Parameter identification

For the identification of key parameters to be addressed by the MECA requirements, we conducted an extensive study of operational demands, human-factors knowledge and envisioned technology (see figure 1).

Table 2: Use case template.

ID	78
Title	Hypothermic astronaut
Level	Level 0
Goal	Treat hypothermic astronaut that is on EVA, arrange that doctor is in medical facility to treat astronaut
Actor	Personal MECA, MECA habitat, astronaut in habitat, rover, astronauts on EVA, hypothermic astronaut
Pre-condition	Astronaut on EVA is hypothermic
Post-condition	Hypothermic astronaut is in medical facility being treated
Frequency	Not frequent
Main success scenario	• Personal MECA detects hypothermia in astronaut on EVA • Personal MECA communicates to hypothermic astronaut …
Alternative scenario	• .. • Doctor is not in habitat, MECA will ask astronaut_1 to prepare…
Comment	Derived from RefDoc3 …

First, an analysis of the *operational demands* of surface explorations provided a set of use cases and list of parameters. For the elicitation, validation and refinement of the requirements use cases were generated and linked to the requirements. Table 2 gives an overview of the use case template. Three types of parameters were identified, MECA shall take account of: the high-level operation goals (e.g., provide operational conditions for scientific research tasks), the environment (e.g., radiation and social monotony) and task performance (e.g., people will get seriously ill).

Second, via an analysis of current *human-factors knowledge* on crew behavior in high-demand and dangerous situations, the following parameters were identified that MECA shall take account of:

- Cognitive task load. Due to required combination and possibly complexity of different supervision and control tasks, the momentary mental load of the astronauts can be suboptimal. MECA should support an adequate load scheduling over time and available human-machine resources based on a model of cognitive task load that distinguishes three load factors: percentage time occupied, number of task switches and task complexity [9].
- Situation awareness and sense making. If severe, unexpected and time-critical problems occur, time may be limited to communicate with experts at the earth-based Mission Control Center (MCC). In these cases the astronaut and MECA will have to be self-sufficient as a team in their problem-solving capabilities. MECA will have to provide situation awareness and sense making support by helping the astronauts in collecting relevant data, interpreting the data and the generation and testing of hypotheses [10], [11].
- Diversity of cognitive capacities. The astronauts have different expertise and experiences, and will perform their various tasks in different environments. This causes differences in the momentary capabilities, levels of attention and available modalities. MECA needs to be aware of these factors to be able to support the astronaut effectively by tailoring the communication to the available attentional resources and modalities [9], [12].
- Trust and emotion. Given the dependency of the astronauts on MECA and the ways the human-machine collaboration will be shaped, a high level of trust is required. Such a level of trust can be realized with explanatory user interfaces that provide information of the inner workings of MECA [13]. Furthermore, MECA should take into account the user's emotional state and possible effects of the human-computer interaction on these states.
- Collaboration. MECA shall help to avoid gaps and overlap in individuals' assigned work (i.e. support coordination), to obtain mutual benefits of human and machine actors by sharing or partitioning work (i.e. support cooperation) and to achieve collective results that the participants would be incapable of working alone. Furthermore, it shall help to support the generation and maintenance of a shared mental model within human-machine teams, which contains both team knowledge as well as situation knowledge. By mediating between actors, insight will be provided into the other actors' goals, intentions behavior and needs [14].
- Crew resource management (CRM) is a combination of techniques used to train crew to operate in complex environments where teams interact with technology, aiming to minimize the effects of errors related with human factors (including communication and cultural aspects) and to maximize the crew effectiveness. MECA should manage the skills and task performance of the crew, and plan and support training to keep performance to a level required by operational demands [15].
- Decision making. Rational decision making shall be supported by exhaustive evaluation of options, collecting and providing an overview, ranking the options, and possibly proposing the best. Naturalistic decision-making is supported by functions that assess the situation based on patterns capturing experience and preference of the crew, recommend actions based on the patterns, check that the execution of the course of actions is according to expectancies, and test assumption underlying human naturalistic decision-making [16].

Third, there is one essential assumption for MECA derived from an analysis of the *envisioned technology*, i.e., there is an infrastructure for automatic distribution of data, software en reference documents. MECA shall make use of this infrastructure, but shall be able to cope with possible failures of this infrastructure such as loss of connection. The assessment of the future situated design space is difficult to attain. Based on an analysis and extrapolation of emerging technologies, e.g. multi-agent systems, automatic planning and scheduling and model-based health management we set a road map. The goal is to identify technologies that are relevant for the operational and human-factors problems mentioned above. On the other there are technical requirements on maturity, graceful degradation, maintainability and fault tolerance. Also the technology will be performing in a hostile environment with a limited infrastructure. All these requirements set the boundaries for the situated technological design space.

3.2. Current set of requirements

The current framework distinguishes task level, functional, user interface, technical interface, operational and technical requirements. To provide a coherent set of functional requirements, we specified an outline that is based on a general process model for human-machine interaction (cf. [17]). Table 3 gives an overview of this outline.

Table 3: Outline of functional requirements.

Process	**MECA function**
Information Gathering	detect needs for operations and training
Goal Setting	select and prioritize goals for operations and training
Plan Generation or Selection	generate plans, or select pre-generated plans and procedures, for operations and training
Plan Evaluation	evaluate operational and training plans
Prepare for Execution	prepare the resources for executing operational and training plans.
Execution	execute operational and training plans
Processing Evaluation of Results	evaluate execution results for operational and/or training purposes

4. Refinement processes

It is important to note that this study focuses on a future MECA system that is in a very early development stage, in which human factors aspects, operational demands and technology are systematically explored. This study follows an iterative human-centered development process corresponding to recent human-factors engineering methods and standards (e.g. ISO 13407 “Human-centred design processes for interactive systems”), and it anticipates for relevant methods and standards that are being developed (e.g. by the “ECSS Human-Factors Engineering” working group). In particular, the MECA project builds on the results of the “Advanced Human Computer Interaction Informatics project” that provided an operability-centered design method in which requirements are assessed and refined from rather high-level specifications in early development stages to detailed definitions in late development stages [18]. Consequently, the present requirements baseline contains relatively abstract specifications that will be assessed and refined further, i.e., the requirements will be further selected, worked out, assessed and validated via prototyping. We foresee that future ECSS standards will support iterative human-centered processes as currently applied in the MECA project.

4.1. Three cycles

Figure 1 presents an overview of the iterative process of requirements definition, extension, evaluation and refinement. It shows three types of refinement cycles: system design review, scientific discourse and simulation-based evaluation.

System design review: Based on an analysis of operational demands, human factors aspects and technology, an initial set of requirements was defined and assessed in an “official” System Requirements Review (SRR).

Scientific discourse: The operational, human factors and technological foundation has been established. Via publications and conference participations, comments of peers will be acquired and processed to improve this foundation. New insights will lead to refinements of the requirements.

Simulation-based evaluation: Starting from the initial set of requirements, a first MECA prototype will be built and tested for its effects on the human-machine collaboration (HMC). Astronauts and representatives of the end-users will participate in this process. This will result in a refinement of the requirements and corresponding design of an improved prototype.

4.2. Criteria for evaluation

MECA functions will be included in the prototype incrementally. The use case descriptions will be enriched with claims to explicate the expected positive effects of these functions. Evaluation should include long-term human in the loop effects with standard usability measures (i.e. effectiveness, efficiency, satisfaction and learnability, see [19]), and human experience measures, such as situation awareness, trust and emotion (incl. motivation). *Situation awareness* is defined by three levels or dimension: the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future [10]. For *emotion*, we distinguish two dimensions to define the emotional state: the arousal level—low versus high—and the valence—positive versus negative. For *trust*, we distinguish four dimensions: the experience, the persistence and competence of system behaviour, the perceived servitude of the system, and the understanding of the system's content and operations [7]. Evaluations should capture all dimensions of these three user experience measures.

Recently, game-based simulation environments are being used for research in professional domains, because of their flexibility, high quality and relatively low costs. Such an environment can be an adequate platform for human-in-the-loop evaluations of adaptive task support in (simulated) dangerous situations [20]. Such evaluations can provide subjective and objective measures for human-machine collaboration on the criteria distinguished above.

5. Conclusions

The MECA project defines the requirements for a Mission Execution Crew Assistant that will be used on future planetary exploration missions to the Moon or Mars. MECA shall assist the crew during the execution of the mission thereby taking into account that the crew (i) will be prepared to operate autonomously as communication with Earth will be severely restricted, (ii) will be faced with a complex, harsh, and uncertain environment consisting of complex equipment necessary for the crew's survival and the hostile environment of the outer terrestrial soil, and (iii) will have to cope with the knowledge that a wrong decision, or even a late decision, potential has drastic consequences that may lead to the loss of the life of the crew or to failure of the mission. This paper presented a cognitive engineering method to realize an adequate Human-Machine Collaboration (HMC) performance during such missions, in which generic human-factors knowledge and HMC solutions are refined, contextualized and tested within the application domain, as part of an iterative development process. It distinguishes three types of iterations: system-design review, scientific discourse and simulation-based evaluation. The first two iterations provided a set of requirements for MECA and a first specification of the required technology. Subsequently, via simulation-based evaluations of prototypes the most crucial human-factors issues, such as trust and situation awareness, will be assessed with the corresponding support functions.

Acknowledgements

MECA is a development funded by the European Space Agency (Contract Number 19149/05/NL/JA).

10. References

[1] T.J. Grant, A. Bos, M. Neerincx, A. Olmedo Soler, U. Brauer, and M. Wolff, Space autonomy as migration of functionality: The Mars case, *Proceedings of the 2nd Space Mission Challenges for Information Technology (SMC-IT 2006)*, Pasadena, California, USA, 2006.

[2] Maguire, M., Methods to support human-centred design. *International Journal of Human-Computer Studies*, 55, 2001, pp. 587-634.

[3] Neerincx, M.A., Lindenberg, J, Situated cognitive engineering for complex task environments. In: J.M.C. Schraagen (Ed.) *Proceedings of the Seventh International Naturalistic Decision Making Conference (NDM7)*, Amsterdam, The Netherlands, 2005.

[4] Maanen, P.P. van, Lindenberg, J., and Neerincx, M.A., Integrating Human Factors and Artificial Intelligence in the Development of Human-Machine Cooperation. *Proc. of the 2005 International Conference on Artificial Intelligence (ICAI'05)*, CSREA Press, Las Vegas, NV, 2005.

[5] Hoc, J.-M., Towards a cognitive approach to human-machine cooperation in dynamic situations, *International Journal of Human-Computer Studies*, vol. 54, no. 4, 2001, pp. 509–540.

[6] A. Bos, L. Breebart, T.J. Grant, M. Neerincx, A. Olmedo Soler, U. Brauer, and M. Wolff, Supporting Complex Astronaut Tasks: The right advice at the right time, *Proceedings of the 2nd Space Mission Challenges for Information Technology (SMC-IT 2006)*, Pasadena, California, USA, 2006.

[7] Neerincx, M.A., Bos, B. Grant, T., Brauer, U., Olmedo Soler, A,. Lindenberg, J., Smets, N., Wolff, M. Human-machine collaboration for long duration missions: Crew assistant concept. *Proceedings of the 16th Triennial Congress of the the International Ergonomics Association*. Maastricht, The Netherlands, 2006.

[8] Carroll, J.M.. *Making use – scenario-based design of human-computer interactions*. Cambridge: MIT press, 2000.

[9] Neerincx, M.A.. Cognitive task load design: model, methods and examples. In: E. Hollnagel (ed.), *Handbook of Cognitive Task Design*. Chapter 13. Mahwah, NJ: Lawrence Erlbaum Associates, 2003, pp. 283-305.

[10] Endsley, M.R.. Theoretical Underpinnings of Situation Awareness. In M.R. Endsley & D.J. Garland (eds). Situation Awareness Analysis and Measurement. LEA, Mahwah, NJ, USA, 2000.

[11] Weick, K. Sense-making in Organisations. Sage, Thousand Oaks, CA, USA, 1995.

[12] Streefkerk, J.W., van Esch-Bussemakers, M.P. & Neerincx, M.A. Personal attentive user interfaces in mobile settings. *Computers in Human Behavior*. 22, 2006., pp. 749-770.

[13] Paymans, T.F., Lindenberg J., Neerincx, M.A.. Usability trade-offs for adaptive user interfaces: ease of use and learnability. Proceedings of the IUI conference 2004. New York, NY: ACM Press, 2004.

[14] Mohammed, S. & Dumville, B.C.. Team mental models in a team knowledge framework: Expanding theory and measurement across disciplinary boundaries. *Journal of Organizational Behaviour*, 22(2), 2001, pp. 89-106.

[15] Helmreich, R.L., Merritt, A.C., & Wilhelm, J.A.. The evolution of Crew Resource Management training in commercial aviation. *International Journal of Aviation Psychology*, 9(1), 1999, pp. 19-32.

[16] Klein, G.. *Sources of power: How people make decisions*. Cambridge, MA: MIT Press, 1998.

[17] Rasmussen, J.. *Information processing and human-machine interaction: An approach to cognitive engineering*. Amsterdam, The Netherlands: Elsevier, 1986.

[18] Neerincx, M.A., Cremers, A.H.M., Bos, A. & Ruijsendaal, M.. *A tool kit for the design of crew procedures and user interfaces in space stations* (Report TM-04-C026). Soesterberg, The Netherlands: TNO Human Factors, 2004.

[19] Neerincx, M.A., Ruijsendaal, M. & Wolff, M.. Usability Engineering Guide for Integrated Operation Support in Space Station Payloads, *International Journal of Cognitive Ergonomics*, 5(3), 2001, 187-198.

[20] Te Brake, G., de Greef, T., Lindenberg, J., Rypkema, J. & Smets, N.. Developing adaptive user interfaces using a game-based simulation environment. *Proceedings of the 3rd Int. ISCRAM Conference*, Newark, JN (USA), May 2006.