HUMAN MISSION TO MARS: Designing a Crew Expert Tool for a Safety Critical Environment

Dr Olga Bogatyreva (1) ; Dr Iya Whiteley (2) ; Prof Chris Johnson (2) ; Mikael Wolff (3) ; Martin Townend (1)

(1) Dept. Of Computing Science, University of Glasgow, UK, Email: johnson@dcs.gla.ac.uk
(2) SEA, Bristol Business Park, Coldharbour Lane, Bristol, BS16 1EJ, UK, Email: iya.whiteley@sea.co.uk
(3) ESA, ESTEC, Noordwijk, Netherlands, Email: Mikael.Wolff@esa.int

Abstract

On a mission to other planets, the crew would come across situations and challenges that have not been foreseen even by experienced engineers, designers, scientists and previous explorers. This paper considers existing problem solving approaches that can help structure the development of 'troubleshooting support tools' for autonomous crews during long-duration missions. It also considers the suitability of these problem solving techniques for crew autonomous operations.

1. Context of long-duration missions

Pursuing the endeavour of a long-duration human space exploration mission would be challenging even for the most technically trained and mentally prepared future space flight crews and planetary explorers. The crew would no longer be able to depend on the mission control crew to support them in real time as they monitor and support the operation of complex spacecraft systems. They would be required to operate autonomously, while travelling through the hostile environment of space, independently resolving a host of dynamic safety-critical situations of varied urgency, some of which cannot have been foreseen before departure. Hence, it can be argued that there is a need for expert tools to support crews deal with complex system failures for autonomous operation in future long duration space missions.

The crew would be mentally and physically stretched on long-duration missions. The challenges would range from missing a loved one to losing concentration; from having high workload to dealing with boredom and anxiety; from dealing with the loss of a crew member, for example from an accident, suicide or other illness to coping with the loss of critical systems. The environment would also contribute to the motivation and performance of the astronaut, such as the comfort level of the habitat (e.g. temperature), personal space (e.g. access to equipment) and lighting conditions.

Given previous studies of failure in safety-critical systems through accident and incident analysis of hazardous environments [1], experience gained on human performance on the International and Mir Space Stations [2; 3] and hypothetical scenarios, the crew problem solving tools would need to be designed to enhance human capability, accounting for human limitations and designing out the likelihood of a multitude of potential human errors.

Human space exploration is a test of human abilities, in the mission control centre (e.g. designers and mission support personnel), and in space (e.g. astronauts). Future missions will extend our knowledge and understanding of human capabilities and limitations while interacting with the systems that we design to help us explore the universe. The challenge extends to scientists and industry to devise expert problem solving tools that can support and help the crew on exploration missions.

2. Crew autonomous operation

The crew would be operating autonomously, independently of the mission control, at most times due to long communication delays where to send a message one way could take many minutes. If the crew is to request help from the mission control about the unforeseen problem, they would need to follow several steps, where each step could take a few minutes to several hours, days or even weeks (Tab. 1).

Table 1. *Steps and time required to communicate the problem and the solution between the crew and the Mission Control Centre on Earth.*

Steps	Time	Circumstances
1. Crew would compose the message stating the problem	A couple of minutes to several hours	Length & time of message composition would depend on difficulty of the problem & whether the crew have isolated & understood the cause of the problem.
2. Crew would send the message	Minutes to several hours	Depending on how far away the ship is from Earth and the relative position of the planets to the spaceship's location.
3. Earth would receive & interpret the content of the message	Minutes to several hours	The appropriate personnel would need to be in the control centre to interpret the message, e.g. the control centre may not have personnel knowledgeable in all systems 24 hours a day, but have people on-call.
4. Earth would alert & gather suitable experts to address the problem	Hours to a couple of days	On-call experts may require travelling to a designated location to meet or to establish telecommunication; some experts may not be reachable in the first instance.
5. Expert team on Earth would be troubleshooting & problem solving	Hours to a couple of days or even weeks	It may take time to replicate the problem on test equipment on Earth or it may not be possible.
6. Expert team sends a message to acquire additional data from the crew or test the proposed solution	Minutes to several hours	Depending on how far away the ship is from Earth and the relative position of the planets to the spaceship's location.
7. Crew would receive the message for additional data or a test procedure or a procedure for solving the problem	A couple of minutes to several hours	The crew that is required to respond, test, acquire data or test a solution may be resting; The data requested may need

		not be readily available; The crew may require minutes to several hours to implement the test procedure & gather the data to send back; To implement the procedure to solve the problem and see if it solved the problem may require hours; The conditions under which the problem has occurred may not repeat for several days.
8. Crew would compose & send the reply back	Minutes to several hours	Depending on how far away the ship is from Earth and the relative position of the planets to the spaceship's location; The reply data package is too large & is required to be sent in separate messages.
Steps 5 through 8 may need to be repeated a number of times		
Additional steps or repetition of steps may be required	TOTAL: Hours, weeks or months	A number of other circumstances can be considered which would lengthen the communication exchange

As an example, the steps provided in Tab. 1 draw a picture of a scenario that could take days or weeks to communicative the nature of the problem to the mission control and potentially weeks to receive the correct procedure back to implement it on-board the ship. The crew may not have the luxury of time to wait for an answer from the mission control on Earth. The crew would need to be able to operate, troubleshoot and problem solve autonomously from the mission control centre on a long-duration mission to Mars.

Of course, some of these steps could be automated – for example, by increasing the level of telemetry that would provide ground support with direct access to information about the changing status of the ship. This would reduce the demands on the crew to identify potential problems before making a request for support. However, given the communication delays this would imply a minimum time to respond to any failure that would be bounded by the time needed for mission control to receive those signals and then notify the crew that they had identified a problem. In consequence, unless we look at ways of improving the response to technical failures by the crew then there is a danger that we will create delays that could have significant consequences for safety and for the success of any mission.

3. Crew problem solving tasks

Crew problem solving tasks may be, on the one hand, a simple replacement of a light filament, where the crew would either be conducting a regular maintenance of the spaceships systems. This could also include the need to detect that the annunciator light is not working or be alerted by the system of a faulty circuit. On the other extreme, the crew may come across a significant problem that is not included in malfunction procedures and was not anticipated. Due to delayed or potential absence of the communication with the mission control, the crew would need to identify the nature of the problem themselves as early as possible to have sufficient time to resolve it. They would have to use available resources to resolve it, hopefully without effecting life support systems and systems critical to the success of the mission, e.g. equipment for experiments.

To detect the problems early the crew would monitor the ship's systems. Additionally, the ship itself can be programmed to perform periodic self-diagnostic routines to alert the crew of any system performance deviations. To keep the systems healthy, crew would conduct regular maintenance. These monitoring and maintenance activities would help the crew to detect arising problems, and, at least to a certain degree, predict and prevent sudden failures of monitored and maintained systems. When the problem is detected the crew would require access to sufficient monitoring and maintenance data to trace the origins of the problem and help find a lasting working solution for the duration of the trip.

Fig. 1 shows example activities the crew would need to perform to uncover the problem and to start addressing it. We will use these activities to help us to describe the developing concept of the crew expert tool and consider existing problem solving tools and techniques that may help define the tool.

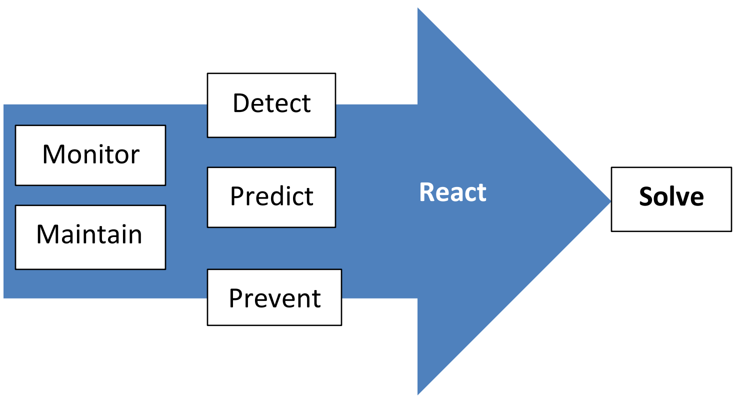

Figure 1. Crew problem solving related activities.

All is well if the ship's systems are predictable and problems are preventable. However, considerable uncertainty exists both for the crew – as a result of the inherent complexity of any future mission; but also for designers – we do not know the detailed architecture for all of the applications that would be required to support such a mission. In consequence, we must develop the design for support tools in a modular and generic way so that it might help the crew resolve potential problems with an array of systems that will become increasingly defined the closer we get to launch.

Any support tool would need to have information about all on-board systems, their components, functions and performance parameters. It would also need to account for critical interactions between those systems. In the event of an unpredictable malfunction, it would need to help the crew to interpret and manage already collected data. The tool would also need to help the crew to step through stages of a systematic problem solving activity and resolve the malfunction without compromising the rest of the systems. Meta-level issues must also be considered when, for instance, the crew disagree with the suggestions provided by any on-board expert system. As the ship would age and the crew would fix malfunctions, the tool would need to help the crew to keep track of the changes to the ship's systems and update ship systems' performance parameters. As with every change to the ship during the mission, the ship may no longer be able to perform to initial specification and withstand the stresses that is was originally designed for. The most obvious previous example of this scenario is Apollo 13; where a fault in an oxygen tank forced the crew to abandon their plans for a landing. However, mission planning would have to consider a far wider range of abort modes that would vary for each stage of the mission, similar to the multiple variations in the Shuttle ascent abort scenarios.

4. Problem solving techniques

The crew would need to do problem solving activities (Fig. 1) efficiently, preferably using one tool, to avoid transferring data from tool to tool, and to trace potential modifications and their effects on the whole system. Using various tools to conduct individual tasks can be time consuming and errors may occur during transfer of data from one system to another. To find a suitable tool (or tools) several existing problem solving techniques have been initially compared against the types of tasks the crew would need to conduct.

Tab. 2 lists the sample of existing problem so techniques and on the cross-section shows which of the crew activities it would support. In the rows of tab. 2 existing techniques are listed that would have the crew to conduct crew activities. The table offers a preliminary list of problem solving and decision making techniques through the initial literature review. The majority of literature on problem-solving techniques focuses around techniques developed for resolving managerial issues (e.g. [4]) or in the field of mathematics (e.g. [5]). The other body of research focuses on studying the mechanism of how people solve problems in various domains (e.g. [6] & [7]). Modest amount of research is published in the area of creative and systematic approaches to technical problem solving method and tools that can be applied in the context of crew autonomous operation during long-duration missions to the Moon and Mars.

Table 2. *A selection of problem solving techniques relevant to various crew activities.*

PROBLEM SOLVING TECHNIQUES -->>>>>>>		Monitor	Maintain	Detect	Solve	Predict	Prevent
↓ INSTANCES WHEN TECHNIQUES CAN HELP THE CREW TO...							
A selection of Problem Solving techniques							
Means-end analysis	It allows setting sub-goals based on the process of getting from the initial state to the goal state when solving a problem.						
Trial-and-error	The solution to the problem is identified through trial-and-error cycles until the solution is found.						
Brainstorming	It is used by a group to generate a large number of ideas to solve the problem.						
Morphological analysis	It allows exploring all possible solutions to a multi-dimensional, non-quantified complex problem.						
Method of focal objects	It allows synthesing the seemingly non-matching characteristics of different objects, creating something new.						
Lateral thinking	A method of thinking that changes concepts & perception, envoking reasoning that is not immediately obvious.						
George Pólya's techniques	Pólya provides general heuristics for solving problems of all kinds..						
Analogy	It allows choosing a similar problem & considering the suitablity of its solution.						
Hypothesis testing	It allows setting the hypothesis & trying to prove the assumption.						

Constraint examination	It considers various constraints on the system.						
Incubation	It allows time to contemplate about the problem & in time to hatch a solution.						
Methods of mathematical logic	It allows examining a problem through application of mathematical rules, e.g. if the conjunction A & B is true, then A is true, & B is true.						
Risk analysis & decision support techniques		**Monitor**	**Maintain**	**Detect**	**Solve**	**Predict**	**Prevent**
AZard& Operability Studies (HAZOPs)	Studies that are used to identify hazards & potential problems in industrial processes, focusing on problems that could create a hazardous situation or severely impair the process.						
Critical Path Analysis	Helps to plan all tasks that must be completed as part of a project; helps to act as the basis both for preparation of a schedule, & of resource planning.						
Causal Probabilistic Networks Analysis	A technique that helps to model, measure & manage the operational risk using prior knowledge of the causal risk factors & probabilistic reasoning.						
Defect/Failure Reporting Analysis & Corrective Action System	Helps to identify a closed-loop feedback path in which the user & the supplier work together to collect, record, & analyse failures of both hardware & software data sets.						
External Events Analysis	Provides an analysis of events external to the system which can occur during normal & emergency operations; it helps to identify some external events that may pose a significant threat of a severe accident.						
Ishikawa Diagrams	Provides a systematic way of looking at effects & the causes that create or contribute to those effects. The hierarchy of functions helps to see the cause of failure.						
Scenario-Based Requirements Analysis (SCRAM)	The method uses two types of scenario, structure models of the system context & scripts of system usage to define early systems requirements.						
Root Cause Analysis (RCA)	A group of methods that is aimed at identifying the root cause of the problem or events, which are aimed to improve the performance of a system or a process through elimination of the root cause rather than a removal of a symptom of the problem						

TRIZ techniques		**Monitor**	**Maintain**	**Detect**	**Solve**	**Predict**	**Prevent**
System Operator	Helps define the context of a problem & monitor a system during its lifetime.	✓	✓				✓
Resources finder	Helps identify the resources that are already in a system.				✓		✓
Functional Analysis	Helps define useful & harmful functions; identifies the origin of a conflict.	✓	✓	✓			✓
Contradiction Matrix	Helps resolve the issues suggesting non-compromising win-win solutions for conflicting parameters.				✓		
ARIZ & Sabotage analysis	Step by step procedure of problem solving & prevention.	✓	✓	✓	✓	✓	✓
Su-Field Analysis & 76 standard solutions	Used when the source of the problem does not have an obvious conflict, but can be resolved by a simple improvement. Su-fields then make a recommendation to the point in the process, which needs to be changed, & how to make that change.			✓	✓		
Knowledge Database	It is a classification of causes & effects generalised in a catalogue of working problem solving principles.				✓		
Technology evolution trends	It allows predicting the pattern of the technical systems development.	✓				✓	✓
Laws of system development (S-curves)	Each system passes four distinct stages of development, which helps predict & prevent development problem	✓				✓	✓

The list in Tab. 2 starts with well-established problem solving and decision support techniques, followed by innovative problem solving techniques, called TRIZ. TRIZ was designed as a method for identifying potential engineering problems and elucidating their recommended solutions [8] and offers a versatile range of techniques to systematically identify the problem and resolve it using existing resources. This last characteristic of the TRIZ techniques has potential advantages for autonomous operation by the crew during long-duration missions.

The initial search suggests no single technique or tool would allow the crew to transition from monitoring to solving the problem. However, the combined set of innovative problem solving techniques offered by the TRIZ method [8] does include techniques that can be applied across all crew problem solving activities (Fig. 1). Suitable techniques from this method can be turned in a set of tools. As the TRIZ method uses similar principles throughout its techniques, it would allow passing information from one technique to another. It could help the crew to synthesise the information throughout the tasks, and step them through to identify the most suitable solution using existing resources.

However, these techniques are not yet computerised and would need to be adapted to become a set of integrated tools for autonomous operations of the crew, such as during Mars missions.

5. Designing the crew expert tool

During a future emergency or degraded mode of operation, we foresee scenarios where the crew would need to monitor, maintain, detect, predict, prevent, troubleshoot and solve the problem autonomously. They would have to make do only with available resources within the spacecraft, habitat and the environment. To perform these tasks it would be critical for the crew to know the components of the systems, their operational performance, what parts of the system's components can be disassembled and used; or what materials they are composed of; what physical properties they possess; and how they can be assembled into something useful to resolve the problem or instead help the crew to mitigate the adverse consequences of any failure for as long as it takes until more detailed technical support could be provided over the telecommunications links back to earth.

As one example of such a crew expert tool it is possible to consider designing, even with the level of current technology, a handheld device that can scan (e.g. using smart tagging) anything the crew can access. The device would contain all the resources, i.e. elements and components with their respective transformational and performance characteristics. It would help the crew to locate the appropriate components or elements, as it would not only hold the information about the spacecraft systems, habitat structure, environmental composition, but also the schematic of the spacecraft and how to access all systems within and outside the habitat. It would be able to direct the crew from their current position to the location of the item. As practice shows with the International Space Station, systems are often moved to new locations during long duration missions. Tracking the location of components would be essential within the spacecraft and while on the surface moving between the habitat, laboratory and transport vehicles. Conversely, it is critical to develop a tool that can be taken to the best position at which any fault can be worked on rather than expecting crew members to shuffle between a failing component and a static display unit.

For example, the Apollo 13 crew lost oxygen and electrical power and had to come up with the mechanism to filter module air to reduce the CO2 levels. Although the crew had the canisters to filter the air, they were for the Command Module and not the Lunar Module in which they had to spend the remainder of the trip. Mission control had to design an adapter to fit the canisters from the materials at the crew disposal. Then the mission control had to relay the instructions to the crew to construct the adapter. In a similar situation the Martian crew may not have time to request help from the mission control crew. The crew expert tool may help the crew to troubleshoot and locate the components in time for the crew to build the required device with minimal help from mission control or at least help the crew to mitigate the adverse consequences of any failure for as long as it takes until more detailed technical support could be provided over the telecommunications links back from earth.

In our preliminary design, we envisage that the crew would navigate through a number of scenarios, which the crew may have to deal with, e.g. related to “LIFE- SUPPORT”, “POWER” or “MEDICAL”. The crew would then be guided through a number of questions to narrow the scenario or a problem, or even let the crew enter the question by voice or written command; or even by scanning the faulty system and locating a problem in a diagnostic function. The device would then show the crew where spare parts can be found or what can be disassembled (without taking major systems down in the process) for a suitable component; and how it can be adapted to suit and fix the faulty system.

Instead of suggesting one option or one part to replace or assemble a new component, it can suggest several through the use of modified TRIZ techniques (Tab. 2). All the composition elements and components of the systems can be recorded and provided by the manufacturers during the design and delivery of the products. The components would range from ship systems (i.e. wires, how conductive they are; composition of the metal), to extra-vehicular activity (EVA) suits (i.e. properties of materials that make up the layers; amount and type of fuel), food, all elements of missions experiments, to medical supplies.

6. Future work

Travelling and exploring other planets is an ambitious endeavour. The space crew and the engineers on Earth who undertake this challenge would need a systematic approach to design tools to resolve unexpected problems along the way. This paper outlines the initial steps taken under the European Space Agency study, to develop an “Expert Tool to support crew autonomous operations in complex human spacecraft”. The objective is to adapt and integrate TRIZ techniques to provide the crew of planetary explorers with a systematic approach to problem solving during autonomous operations. The initial prototype of the human computer interface of the crew expert tool will follow next year.

7. Acknowledgment

This work was performed under ESA Contract 21584/08/NL/HE

8. References

1. Johnson, C. (2003). *Failure in Safety-Critical Systems: A Handbook of Accident and Incident Reporting*, University of Glasgow Press, Glasgow, Scotland.

2. Manzey, D., Lorenz, and Polyakov, V. (1998). *Mental performance in extreme environments: results from a performance monitoring study during a 438-day spaceflight*. Ergonomics, 41: 537-559

3. Kanas, N. and Manzey, D. (2003). *Space Psychology and Psychiatry*, Kluwer Academic Publishers, ISBN 1-4020-1341-8

4. Proctor, P. (2005). *Creative Problem Solving for Managers: Developing Skills for Decision Making and Innovation*. Routledge, London.

5. Silver, E. (1985). *Teaching and Learning Mathematical Problem Solving: Multiple Research Perspectives*. Lawrence Erlbaum Associates, Mahwah, NJ.

6. Sternberg, J. and Frensch, A. (Eds). (1991). *Complex problem solving: Principles and mechanisms*. Lawrence Erlbaum Associates, Hillsdale, NJ.

7. Halpern, D. (2003). *Thought and Knowledge: An Introduction to Critical Thinking*. Lawrence Erlbaum Associates, Mahwah, NJ.

8. Altshuller, G. (1999). *The innovation algorithm, TRIZ, systematic innovation and technical creativity*. Technical Innovation Center Inc, Worcester, Massachusetts, USA.