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ESA STUDY CONTRACT REPORT		
ESA Contract No 21584/08/NL/HE	**SUBJECT** CET IO: Expert Tool to Support Crew Autonomous Operations in Complex Human Spacecraft (Final Report)	**CONTRACTOR** Systems Engineering & Assessment Ltd (SEA)
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ABSTRACT:

This summary report provides a technical overview of the work conducted leading to the definition of a Crew Expert Tool (CET) to support autonomous crew problem solving activities during long-duration exploration missions, where space crew reliance on mission control needs to be reduced substantially. The proposed CET has been named IO - 'Eye' Opener on an infinite number of problems. The study consisted of four parts:

- The first part provides a deeper understanding of existing long-duration mission scenarios and reviews literature on problem-solving support methods.
- The second part defines the Iterative Design and Lifecycle Process of the CET IO, including approaches for the validation of assumptions about the problem-solving process through expert user involvement to ensure efficient design process.
- The third part of the study consolidates information from previous parts of the study and defines preliminary functional and user requirements for the CET IO.
- The final part describes a proof-of-concept demonstrator, documents expert users' feedback during evaluation, and provides recommendations for the next stage in the design and development of the CET IO.

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1 OBJECTIVE

The work outlined in this Executive Summary was conducted as a European Space Agency (ESA) study to meet the requirement of Contract 21584/08/NL/HE – Expert Tool to Support Crew Autonomous Operations in Complex Human Spacecraft. The study has been conducted by Systems Engineering & Assessment Ltd. (SEA). It provides the foundations for the development of a Crew Expert Tool (CET) that supports crew problem solving activities. The proposed CET has been named IO - 'Eye' Opener for an infinite number of problems as illustrated diagrammatically in Figure 1.

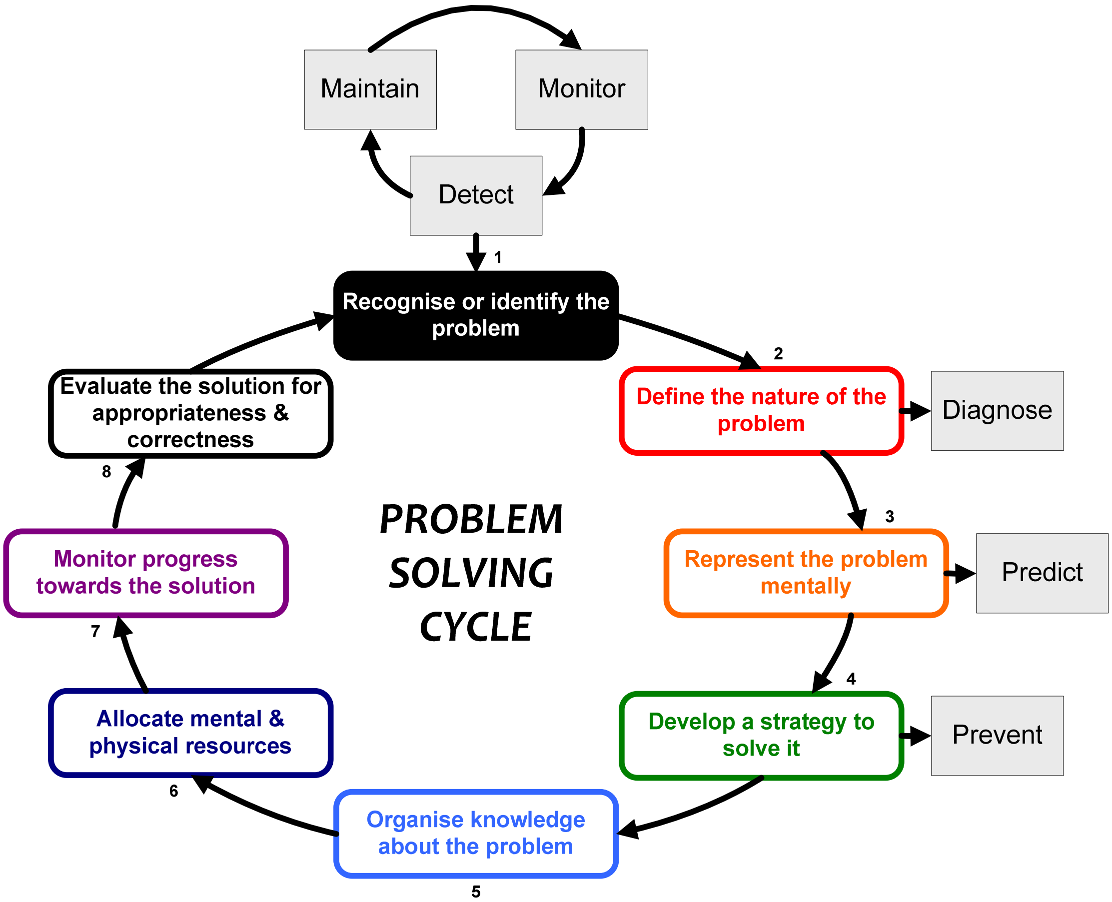

Figure 1. Problem Solving Cycle,
including both the generic process (in the coloured rounded boxes)
and the anticipated crew activities (in the grey shaded boxes).

2 PURPOSE

On an exploration mission beyond low earth orbit (LEO), the space flight crew would come across situations and challenges that have not been foreseen even by experienced engineers, designers, scientists and previous explorers. Pursuing the endeavour of a long-duration human space mission would be challenging even for the most technically trained and mentally prepared future planetary explorers.

The crew would no longer be able to depend on the flight controllers, who currently monitor and support them in operation of complex spacecraft systems in Low-Earth-Orbit (LEO). In the future, the crew would be required to operate autonomously, while travelling through the hostile environment of space. They will be required to independently resolve a host of dynamic safety-critical situations of varied urgency, some of which cannot have been anticipated before departure. The demands for autonomous operation are also created because of the anticipated communications delays with mission support and also to provide a degree of resilience in the face of systems failure.

Hence, it can be argued that there is a need for expert tools as technologically advanced companions to help crews in dealing with complex spacecraft system failures autonomously during long-duration exploration missions to the Moon and Mars.

3 STUDY CONTENTS

The results of the study have been captured through four Technical Notes (TNs):

- TN1 defines *problem-solving concepts*. It provides a deeper understanding of existing long-duration mission scenarios and reviews existing problem-solving approaches.
- TN2 defines the *Iterative Design Process* for the CET IO, based on a lifecycle model enabling frequent expert user involvement.
- TN3 defines a set of *formalised* preliminary user *requirements* and functional requirements for the CET IO.
- TN4 describes a *proof-of-concept demonstrator* for expert user evaluations, documents *expert users' feedback* during the evaluation using the prototype, and provides *recommendations* for future CET IO developments.

A summary report highlights key content from TN1, TN2, TN3 and TN4 and provides an extract of the findings.

4 PROBLEM-SOLVING CONCEPTS

TN1 laid the conceptual foundations for the tool. It analysed problem-solving activities in current and future mission scenarios and assessed the suitability of problem solving techniques for crew autonomous operations. This was based on an analysis of the literature but was also informed by a number of interviews with astronauts.

Current procedures, training approaches, data access (e.g. access to sensor telemetry data), and operational collaboration with flight controllers are likely to require adaptations where flight crew reliability on ground crew resources needs to be reduced.

The general problem-solving process to be taken as the basis for the tool development consists of eight steps: (1) Recognise the problem; (2) Define the nature of the problem; (3) Represent the problem mentally; (4) Develop an strategy to solve it; (5) Organise knowledge about the problem; (6) Allocate mental and physical resources; (7) Monitor progress towards the solution; (8) Evaluate the solution. It can be aligned well with the anticipated crew problem-solving activities including Monitor; Detect; Predict; Maintain; Diagnose; Prevent. The tool has the flexibility to support a subset of the general 8-step problem-solving process where the starting point can be from any of the steps in the problem-solving cycle and, when appropriate, take shortcuts to other steps in the cycle and if necessary steps backwards in the cycle.

The tool needs to support the characteristics of how experts solve problems, including, for example, the use of mental 'shortcuts'; reliance on developing believable scenarios (through mental successive representation of how the event will unfold); the use of creative thinking; and having to adapt expertise highly specific to one context.

Following a review of problem-solving techniques it was concluded that the approach offered by the TRIZ method, which is as yet unavailable in a computerised format, should be used and adapted to form the basis of the problem-solving support tool. TRIZ stands for Theory of inventive problem solving (Russian acronym of Теория решения изобретательских задач). It is an innovative collection of problem solving techniques and inventive principles. Typically, TRIZ would guide the problem solver through a set of techniques and questions, in order to utilise and maximise the users' own expertise and creativity. The rationale for the selection of the TRIZ method developed from an assessment of existing problem-solving theories and how they can help understand and inform the cognitive processes of the crew that can be supported by the design of a Crew Expert Tool. The maturity of TRIZ and its versatile range of techniques to systematically identify potential problems and resolve those problems using existing resources makes it a natural candidate for the expert tool design. In addition, it can include other techniques within its process which has potential advantages for autonomous operation by the crew during long-duration missions. The initial searches suggested that no single technique or tool would allow the crew to make the transition from monitoring to solving the problem. However, the combined set of innovative problem solving techniques offered by the TRIZ method does include techniques that can be applied across all crew problem solving activities.

5 THE ITERATIVE DESIGN AND LIFECYCLE PROCESS

The Iterative Design and Life Cycle for CET IO defined in TN2 is based on an analysis of design processes in aviation, military and space domain practice. It describes eight phases grounded in Systems Engineering perspectives, reaching from concept definition to the incorporation of lessons learned after a mission into defining future concepts. It enables detailed consideration of user needs throughout all lifecycle stages, and establishes an approach to requirements specification and assurance.

An important objective in defining the lifecycle was the alignment of the lifecycle activities with Cognitive Systems Engineering (CSE) methods and principles. CSE has been chosen as an overarching perspective on Human Factors, Human-Computer Interaction, and Ergonomics. The lifecycle, as described, facilitates User-Centred Design practice. TN2 describes the process which has then been applied during a first design iteration (resulting in TN3 and TN4), and to be used for subsequent CET iterations.

Key approaches outlined include (1) the need for establishing a CET IO Working Group to continuously incorporate expert user/stakeholder feedback early; (2) keeping track of the design reasoning and design progress through the CSE Design Decisions and Issues Log; (3) the use of the Cued-Recall-Debrief technique for both operational analysis and evaluation; (4) the systematic generation of scenarios; (5) the application of Enterprise Architecture principles and approaches to requirements specification; (6) the support of an iterative approach through rapid prototyping including the use of low-cost demonstrators early in the design process; (7) the integration of training and procedure design considerations with the software design as well as combining tool evaluation activities with mission preparation.

6 FORMALISED REQUIREMENTS

TN3 provides a preliminary requirements specification based on information collected during the previous two phases of the study, for example, problem-solving literature review, mission scenarios, interviews with astronauts. First, it describes the scope of the problem-solving tool, the CET IO. Second, it provides the full set of requirements envisaged at this stage of the development process. It also captures the requirements for related to CET IO systems to indicate the dependencies.

The scope of CET IO is illustrated using UML diagrams including Usage Scenario, Context, Use Case, Composite Structure, and Sequence Diagrams. The formalised requirements statements are separated into individual tables. Each table describes one of four types of requirements (1) Capability Requirements (CRQs); (2) User Requirements (URQs); (3) System Requirements (SRQs); (4) Subsystem Requirements (SSRQs).

Requirements statements are organised through a series of the topical sub-groups and also contain additional notes such as examples and justifications. Each follows a strict format. A first list of Human Computer Interface requirements are included. However, a full interface specification (including a style guide and an interface design philosophy) is envisaged for the next phase in line with more detailed prototype designs. An initial list of assumptions and design constraints is included, as well as an example Traceability Matrix (user requirements to system requirements).

7 ASSESSMENT AND RECOMMENDATIONS

TN4 provides details of an initial design implementation of the CET IO concept through a proof-of-concept demonstrator, and its evaluation by potential future users. It provides a first solution for how the tool functionality and interface of the CET IO may be implemented. The design is based on the initial requirements specification described in TN3, as well as the concepts outlined in TN1. The process of implementation and assessment of the concept has drawn on the design process outlined in TN2.

The user interface is divided into three panels as shown in Figure 2:

- The top panel provides buttons for *navigating among the stages and steps* of the problem solving process.
- The lower left panel displays *the cues and questions* for the current step.
- The lower right panel displays *the electronic sketchpad*. It records the cues and questions as they appear, captures the user's responses, and allows the user to make ad hoc notes relating to the problem description and potential solutions.

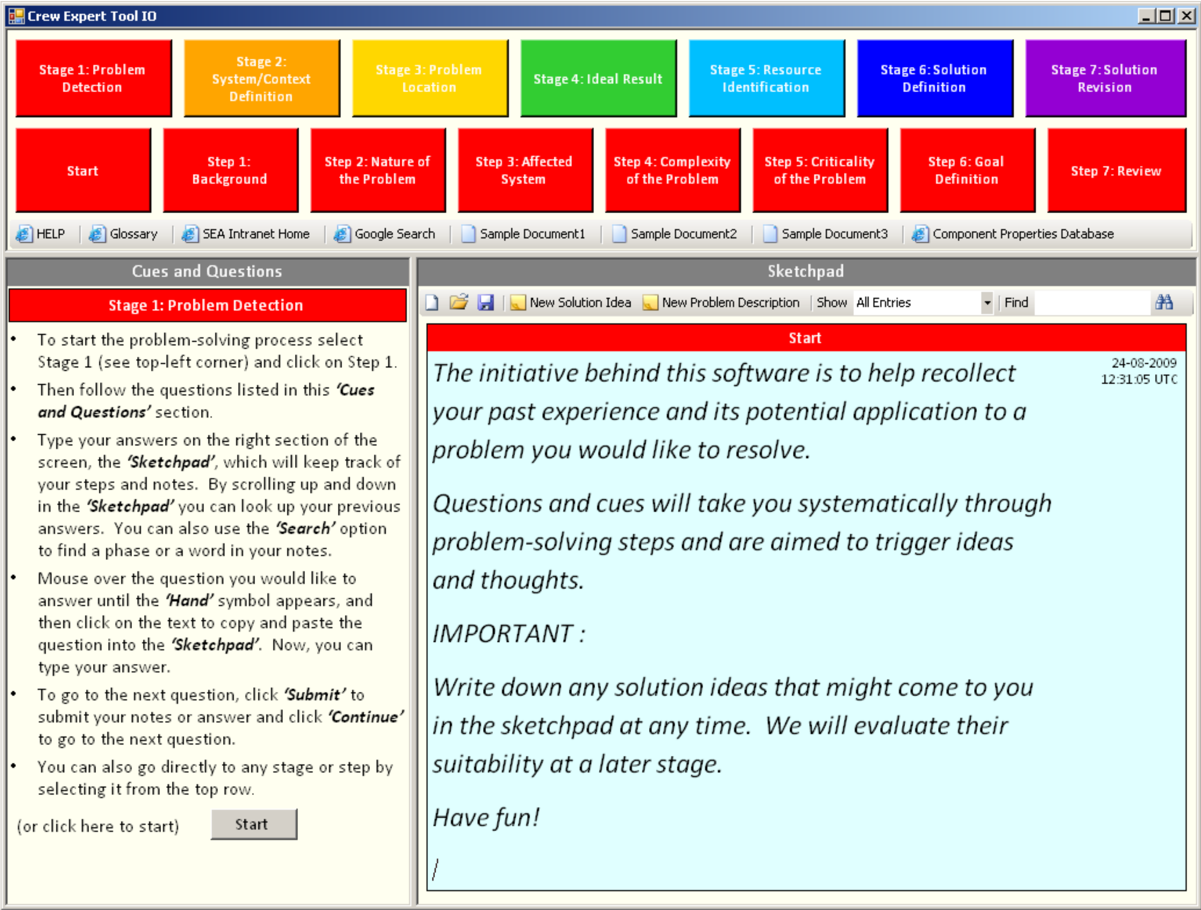

Figure 2. CET IO initial display.

Observational studies were carried out with astronauts during a two-day workshop:

- On the first day, astronauts' problem solving strategies and approaches were observed while working in a team on a given problem (without the demonstrator), as a means of collecting data supporting the tool concept refinement.
- On the second day, the objective was to observe astronauts solving problems using the CET IO proof-of-concept demonstrator based on the TRIZ methodology, and to retrieve their feedback to evaluate the tool concept.

This process involved three astronauts. On both days, the Cued-Recall-Debrief method was used, which helped the crew recollect accurately their thought processes, in order for the concept developer to capture the information demand on the crew. The problem-solving task involved exploring the possibilities of dealing with a broken smoke alarm, which could not be replaced as there were no spares on the spacecraft.

The study of astronaut teams' problem-solving approaches revealed that the concept behind the tool has made the appropriate assumptions regarding the approaches chosen and the techniques to be supported. While the proof-of-concept demonstrator has at this point only been implemented to help an individual problem-solve, it can be anticipated that the concept will also support a team of problem-solvers, by making their process more efficient and systematic.

The user feedback on the CET IO demonstrator has been classified into three areas, (1) user interface evaluation, (2) concept development suggestion, and (3) general recommendations. Feedback included, for example: a recommendation to give the CET IO some personality and character traits to make the interaction engaging and fun; the provisions of a good overview and understanding of the TRIZ approach and tool structure to enable flexible use including shortcuts; the ability of the tool to show initiative when its assistance might be helpful.

Further improvement and extension of the concept include, for example: development and refinement of the cues, questions, and terminology used; streamlining of the problem-solving process; enabling team use; providing additional functionality regarding the start of the problem solving process; improvements on the functionality of the user interface to provide fast and effortless data entry and ease of access to all tool functions.

For future tool iterations, it was recommended, for example, to conduct observations of problem-solving activities with two collaborating teams; to allow for longer studies; to also conduct studies with 'paper based' mock-ups or Power Point-like screenshots to avoid that users may become fixated on commenting on specific user interface shortcomings while the main study focus is still on refining the functionality and underlying concepts. The immediate next steps recommended for the development of the concept are:

- tool concept refinement and development;
- scenario generation matrix;
- development of the database taxonomy suitable for the tool.

The scenario matrix is used to help establish the breadth and depth of the potential technical problems that the crew is likely to come across and to help predict and prevent potential failures, while considering *what-if* scenarios explored through the use of the tool.

Database taxonomy is used as a method of classifying/categorising the databases required for using the tool and is necessary due to the numerous and potentially very large databases required.