A STRUCTURED APPROACH TO SCENARIO GENERATION FOR THE DESIGN OF A CREW EXPERT TOOL

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ABSTRACT

It is often difficult to identify the ways in which innovative systems can be used to support the crews on long duration space missions over the coming decades. This paper presents a structured approach towards scenario generation for crew autonomous operations during these future missions. The proposed approach will help to systematically generate scenarios that help define the design requirements for mission related equipment. A *crew expert tool* is used to illustrate our approach. This system is intended to help crewmembers identify and then resolve complex system failures in situations where it may not be possible to call upon immediate technical assistance from ground support staff. Our approach to scenario design helps to identify ways in which such an application may support crew tasks during the initial development of the application.

1. CONTEXT OF LONG-DURATION MISSIONS

A long-duration human space exploration mission is challenging even for most technically trained and mentally prepared space flight crews and planetary explorers. Communication delays will ensure that the crew cannot depend on the ground crew to support them in real-time. The crew will be required to operate the spacecraft semi-autonomously, while travelling through the hostile environment of space. They must independently resolve a broad range of safety-critical situations, some of which are likely to be unforeseen. The difficulty of predicting every possible system problem that might arise on a mission of this nature makes it important to provide flexible support that does not rely on an instantaneous response from ground support. Hence, there is a need for many different stakeholders, including but not limited to, mission planners, designers and human factors experts, to consider the range of safety-critical scenarios that crews might encounter before embarking on the detailed development of any system(s) that will support the crew of an exploration mission to other planets.

2. A STRUCTURED APPROACH TO SCENARIO GENERATION

The structured approach to scenario generation is based on retrieving and methodically uniting specialists experience and expertise in specific systems to enrich a matrix for systematic generation of mission scenarios. It accounts for lessons learned from accident and incidents. In particular, it accounts for the impact of both time and safety-critical tasks; it investigates the mitigating actions taken by crews in similar existing systems and situations. As a result the generated scenarios can be help to guide the design process. It can be used in the development of potential future mission profiles and in the requirements definition for problem solving, troubleshooting and training tools for a future crew.

2.1. Contradiction Matrix

This approach was inspired by a contradiction matrix, used in the TRIZ approach [1]. TRIZ was originally designed as a method for identifying potential engineering problems and elucidating their recommended solutions. The contradiction matrix allows the traceability of systems and their components potential interactions. It can be used to identify potential hazardous scenarios and help develop ways to avoid them.

According to TRIZ philosophy in the core of any problem there is a conflict or a contradiction. There are three types of contradictions described in TRIZ: physical, technical and administrative. We will be using *physical* contradiction, which is related to specific functions or components, but they are not required to be used or operated at the same time; and a *technical* contradiction, which refers to improving one parameter, while another parameter becomes affected and becomes worse.

There are also a number of contradiction matrixes that have been defined. The matrix used in this approach is constructed to show conflicting parameters within systems and their interaction within the environment. The matrix would be presented in a form of a table, where conflicting parameters will be listed in rows (those that can be improved or changed) and columns (those that can become worse). On the intersection of contradicting parameters, a source to potential problem scenarios will emerge. At the later stage each individual cell will be populated with inventive principles that would help model possible solutions. However, for the purpose of this paper we will stop at showing how the sources of the potential problem scenarios are generated.

Recently, this matrix generating scenario has been developed for an ESA study, the Psy-Matrix, to generate scenarios for potential psychological challenges that the crews may encounter during missions to the Moon and Mars [2]. The Psy-Matrix has helped to identify 2278 individual issues that the crew may face during missions to the Moon and Mars. Roughly, only a quarter of these issues are currently identified in the literature.

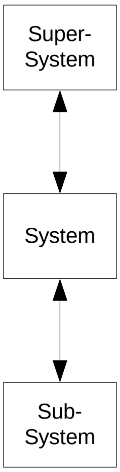
First, techniques are used to analyse factors in existing systems that can contribute to future mission problems; second, the matrix of interfering factors that can contribute to the development of the problem is generated; third, existing similar systems are analysed to identify malfunction procedures and to check or refine factors within the matrix; fourth, the existing failures in existing systems are examined; further additional steps require the use of a range of expertise to refine the matrix and extend it to enrich initial scenarios with further details.

2.2 Generating initial list

First, a hierarchical architecture of the environment and the system is generated that demonstrates the relationship of systems. The initial list of systems is composed to have the space or the environment at the top of the list, followed by the overarching system, namely, a *super-system*, followed by the smaller *systems* and components. These are illustrated by the *sub-systems* in Fig. 1.

The hierarchical architecture can be broken down into as many levels as necessary to develop increasingly more detailed scenarios. As a demonstration example, we use a Columbus laboratory [3], which is the principal European contribution to the International Space Station, designed and manufactured by an industrial consortium lead by Astrium, Bremen. The Columbus External Architecture (Fig. 2) could be broken down further into subsystems. Systems engineers, knowledgeable in a specific system, can continue to populate the scenario matrix by adding and subdividing systems into subsystems and its components, as the system is being defined and refined during initial stages of the design and development process.

The hierarchical architecture represents layers or *protective shells* that guard the crew from hostile external environments. These layers provide the crew with a habitable spacecraft or a habitat on the surface of the planet. Breakdown of any of these shells can cause a mission failure if the problem is not resolved with sufficient resources, including time. The protective shells, i.e. super-system, systems and sub-systems, can be further broken down into system components, i.e. *shell layers* (Fig. 2).



- Space
- Low Earth Orbit
- International Space Station
- ISS Modules, e.g. Columbus
- Columbus External Architecture
- Columbus Internal Architecture
- Basic Habitability and Outfitting for IVA and EVA
- Mechanical / Structural Architecture
- Environmental and Thermal Architecture

Figure 1. A hierarchical architecture of the environment and the system [3].

Columbus External Architecture

- Port End
- Starboard End
- EVA transition path
- External Payload Facility
- Mechanical interconnections
- Electrical Interconnections
- Data Interconnections

Figure 2. Shell layers [3].

3. GENERATING THE SCENARIO MATRIX

After developing the hierarchical models, the second stage of our approach identifies those systems parameters or factors that might lead to specific incidents or accidents for the systems at each level within the protective decomposition. These parameters or factors represent elements or components of the system that can trigger potential problems and lead to incident and accidents. Within our matrix they are referred to as *interfering* factors (Fig. 4). The parameters or factors for each system can be identified through a range of techniques, including the use of a manual from an existing system (e.g. Columbus Module Manual [3]) and interviews with system experts. These elicitation techniques may also include the post-mission accounts and informal observations that play a significant role in understanding the ways in which failures can develop in complex space missions.

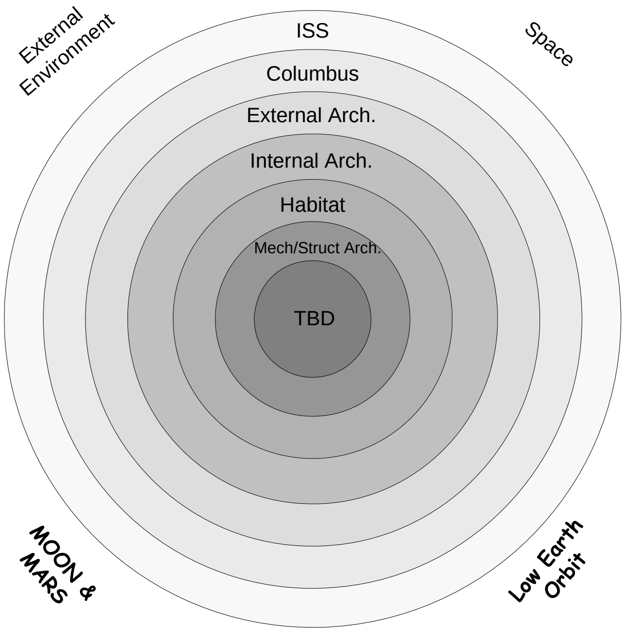


Figure 3. Environment and Protective Shells

Interfering factors are generated using context-defining dimensions of the matrix (Fig. 5). These dimensions provide the necessary elements to model potential situations, e.g. Columbus Module protective panels (i.e. *substance*), which is part of a larger hierarchical *structure, e.g. Columbus External Architecture* that happens in a specific place (i.e. *space*), and changes over *time* with *information* and *energy (e.g. energy of a moving space debris)* input.

The scenarios are generated on the cross section of the *contradicting factors*, which can be also called as *interfering* or *triggering factors* within the matrix, such as described in the above example where the interaction of two factors (see greyed out cell in the Matrix, Fig. 4) can help develop the potential problem scenario.

In order to demonstrate the application of our approach, we have begun to develop an example scenario matrix based on the Columbus Manual [3]. This has already enabled us to identify hundreds of potential problem scenarios, which are increasing with every new element, or layer that we consider in the functional decomposition. Incident and accident scenarios could be triggered by more than two factors and over a period of time affecting more and more systems. Hence the number of potential situations is increasing exponentially as the analysis continues. Hence, we are using the multi-stakeholder approach advocated in the opening paragraphs of this paper to help prune the space of possible problem scenarios that are being considered. We would rather generate too many potential problem descriptions that can then be discarded than develop a method that adopts a less systematic approach to scenario generation; where there is a risk that important failure modes may not be identified.

Once the matrix is established the scenarios can be tailored for specific operations, by changing and defining the environment dimension within the matrix for example:

- Orbital station operations;
- Crew transportation vehicle;
- Planetary surface habitat.

This methodology of generating scenarios out of a matrix provides a systematic method of capturing the information required for the design of the crew support tool. However, for the matrix to work efficiently and to provide a more systematic output, it would benefit from being a computer-based tool, which initially can be used by designers and later by the crew as a means of brainstorming for potential problematic scenarios.

The following steps would help populate the matrix further to allow generation of more genuine long-duration mission scenarios.

4. USING EXISTING PROCEDURES TO POPULATE THE MATRIX

The next stage in our approach is to populate the cells in the matrix of Fig. 4 through the analysis of existing malfunction procedures to generate more accurate case studies. This analysis is guided by comparisons between the proposed system and the procedures that are already followed in similar, existing systems. Of course, for many long-duration space missions it can be difficult to identify similar applications. However, it is important to establish some ‘base case’ scenarios to ground scenario identification, in order for the design not to become too far divorced from existing practice. Without this stage of the process there is a danger that developers may fail to benefit from the insights and expertise that have been gained in the development of previous generations of on-board interactive applications.

The list of malfunction procedures can be examined against created categories of problems within the matrix, which are developed on intersections of interfering systems and their factors. If the procedure cannot be fitted in any of the categories, either a new category can be created or additional new factors are required to be added to the existing list.

System Architecture / Shells	Shell Dimensions	Interfering/Developing Factors & Existing Factors	Physical/chemical property (min density -max density)	Landscape diversity (low --- high)	Resource distribution (rare --- dense)	Weather cycles (short --- long)	Light cycles (short --- long)	Gravitation level (micro ---- hypo)	Light; spectrum, luminosity level (low --- high)	Radiation level (low --- high)	Information load level (low ---high)	To be determined	Thermal protection properties	Radiation protection properties	Shielding protection properties	Welded shell panels	Cylindrical shells	Wear and tear	Pressure containment	Thermal conductivity	Feedback system	Detection system	To be determined
Space environment	Substance	Physical/chemical property (min density - max density)																					
	Structure	Landscape diversity (low --- high)																					
	Space	Resource distribution (rare --- dense)																					
	Time	Weather cycles (short --- long)																					
		Light cycles (short --- long)																					
	Energy	Gravitation level (micro ---- hypo)																					
		Light; spectrum, luminosity level (low --- high)																					
		Radiation level (low --- high)																					
	Information	Information load level (low --- high)																					
ISS	Substance	To be determined																					
	Structure	To be determined																					
	Space	To be determined																					
	Time	To be determined																					
	Energy	To be determined																					
	Information	To be determined																					
Columbus Module	Substance	Thermal protection properties																					
		Radiation protection properties																					
		Shielding protection properties	▨																				
	Structure	Welded shell panels																					
	Space	Cylindrical shells																					
	Time	Wear and tear																					
	Energy	Pressure containment																					
		Thermal conductivity																					
	Information	Feedback system																					
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Figure 4. Scenario Generating Matrix

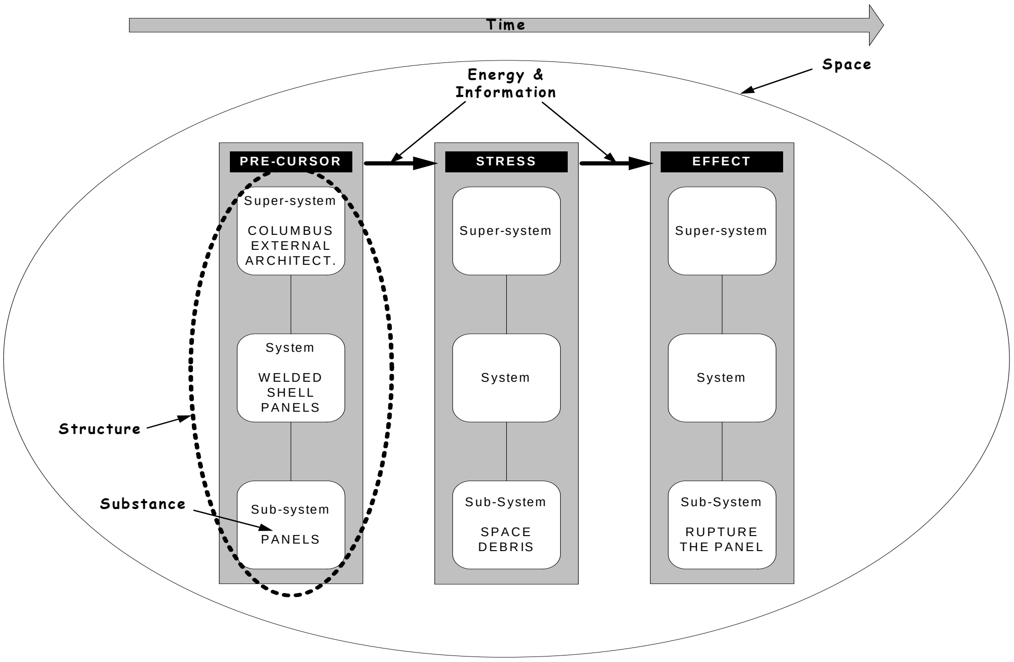

Figure 5. Shell Dimensions.

5. USING ACCIDENT AND INCIDENT ANALYSIS TO POPULATE THE MATRIX

Having used existing procedures to identify potential responses to system ‘failures’; it is possible to identify a range of further influences that may compound or exacerbate the crews response. In particular, previous mishap investigations illustrate the dangers that can arise when crewmembers fail to carefully consider the knock-effects of their actions on safety-related systems. These accident and incident reports provide a means of establishing the completeness of the scenario matrix by comparison to mishap databases of previous relevant case studies.

The scenario matrix identifies those factors that may trigger an accident or incident. Previous accounts of mishaps help to identify the ways in which those faults may develop or may be compounded by other system failures and human ‘error’ over the duration of a mission. Accident investigators can be used to extrapolate from these previous events to propose an analogous flow of events for a newly defined system using other similar systems or components to the systems described in an accident or an incident. Additionally, this step can be informed by experience gained on the ISS and Mir Space Stations (e.g. mission reports, published scientific paper [4, 5], anecdotes [6]).

Mishap analysis, therefore, provides means of further populating the scenario matrix. It helps to propose case studies to help further refine the design of the system. This range of experience and expertise involved in the development of the matrix can also guide requirements elicitation for computer-based tools that will be used to support the crew on future space missions, including experience gained from failures in other safety-critical systems [7]. This ‘real world’ evidence helps to identify and refine hypothetical scenarios that can be systematically developed. Throughout all of this the common concern is to identify future failure scenarios but also to ensure that those scenarios make the best possible use of available ‘lessons’ from previous missions.

6. FURTHER ADDITIONAL STEPS

The number of scenarios that can be generated by the matrix will be in the thousands. The scenario generating matrix will have them grouped in categories of hundreds. There may still be a need to prioritise the scenarios, for example in terms of safety or regarding their level of importance in design.

7. SUMMARY

This matrix system helps teams of different stakeholders to predict or forecast potential problem situations as well as eventually providing a framework that can help to identify ways of resolving those problems. Most of our present work is focused in applying this matrix to inform the design of a crew expert tool to address potential problem scenarios in long-duration space missions, where it is particularly difficult to hypothesise all of the challenges that will lay ahead of the crew. This matrix is a first step in providing a methodological approach that can aid early-design processes for support tools for complex missions. The advantage of this classification is that it allows placement of potential situations, problems and solutions into the same framework.

7. FUTURE WORK

This study is in its initial research and development stages. The proposed approach relies upon close interaction with a range of domain experts. The framework and matrix provides a forum for the exchange of information and ideas during the initial stages of development and planning for support tools against potential problem scenarios. For instance, the scenario matrix would benefit from a review by specialist engineers for each specific system, from a re-examination by an accident and incident expert to generate case scenarios and sequence of events developments. There are also a number of traditional methods that are used in safety analysis, for example a fault tree analysis, which could be added into the analysis framework.

This systematic and multi-disciplinary approach is important to find innovative, but systematic and robust engineering solutions for the next generation of human-flight in space.

8. ACKNOWLEDGEMENT

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