A Systems Engineering Process for the Development of Analog Missions for the Vision for Space Exploration

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Throughout human exploration of space, analog missions have proven to be a critical aspect in reducing risk while increasing technical and operational experience. In light of the new goals associated with the Vision for Space Exploration (VSE), the prior processes and procedures for analog missions are not adequate to meet the objectives of the VSE. To solve this problem, previous analog work was analyzed to uncover gaps in the current system of creating and running analog missions. Then, a Systems Engineering approach to the design process of analogs was created, which includes outlining the analog, documenting it in NASA's Analogs Database, using checklists to ensure all elements of the analog are being considered, and creating a quantitative trade study with consistent metrics. A trade study can be used to compare the fidelity of analog missions and to ensure that the analog missions closely match the actual spaceflight mission. Overall, the Systems Engineering approach can be applied to analog missions so that the analog missions meet the objectives of the Vision for Space Exploration through high fidelity, consistency, and collaboration.

I. Introduction

AN analog mission is an "activity that simulates multiple features of the target mission in an integrated fashion to gain an understanding of system-level interactions."[1] NASA and other agencies have acknowledged the usefulness of analog missions for decades to prepare for space missions. The current NASA Analog Missions Initiative that lays down rationale and objectives for future analog missions is:

> "To create a cross-cutting Earth-based program to minimize cost and risk while maximizing the productivity of planetary exploration missions, by supporting precursor system development and carrying out system integration, testing, training, and public engagement as an integral part of the Vision for Space Exploration." [1]

The Initiative includes[1,2]:

- Learning: system of systems, driving requirements, concept of operations, etc.
- Testing and Developing: Requirements, hardware, software, and countermeasures
- Training: mitigate risk, develop procedures, train all crew
- Engaging: Excite the public in the VSE and educate the next generation of explorers

Considering NASA's Analog Missions Initiative, the underlying reason for performing analog missions in the context of the VSE is to reduce risk related to projected human exploration missions by identifying risks and developing risk mitigation strategies to reduce the risk early in the design cycle. High-fidelity analogs will help with training and technology development, uncovering issues with systems integration and testing, and demonstrating system performance during nominal and off-nominal situations.

It is important to note that prior to the Vision for Space Exploration (VSE) announcement in 2004, analog missions did not have a direct and unified mission statement because the missions were not on the critical path of NASA's prior goals. Now, the VSE gives the analog missions a distinct purpose of reducing the risk of returning to the Moon and traveling to Mars. Looking through this new lens of the Vision for Space Exploration and its Constellation program, we must analyze the current analog missions system and determine the best course to take.

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II. Previous Analog Work

Two different facets of analog missions are discussed in this section. First, the analog missions that have actually been carried out are investigated to see how they were operated, what has been documented, and what was learned (i.e. the Mission Aspect). Second, the processes that were used to design analog missions are presented and evaluated (i.e. the Process Aspect).

A. Mission Aspect

Agencies around the world are performing a wide variety of analog missions, from testing rovers and spacesuits, to full-scale life support simulations with human subjects in extended studies. The following list includes major analog missions that have been completed or are currently underway:

- NASA
    - Full-mission simulators: Lunar-Mars Life Support Test Project (LMLSTP), BIO-Plex, Integrated Human Exploration Mission Simulation Facility (INTEGRITY), NASA Extreme Environment Mission Operations (NEEMO) (underwater)
    - Technology demonstrator
        - Rover and spacesuit tests: Astronaut Rover, Desert Research and Technology Studies (RATS), Field Integrated Design and Operations Rover (FIDO)
        - Drills: Drilling Automation for Mars Exploration (DAME), Mars Analog Rio Tinto Experiment (MARTE), Mars Drill
- European Space Agency (ESA)
    - Life support simulator: Facility for Integrated Planetary Exploration Simulation, Micro-Ecological Life Support System Alternative, Concordia
    - Full-mission simulator: Mars500 (with Russia)
- Russia
    - Life support simulator: Bios-3
    - Full-mission simulator: Mars500 (with ESA)
- Private/Other:
    - Scientific study: Haughton-Mars Project (Mars Institute)
    - Full-mission simulator: Mars Desert Research Station (MDRS), Flashline Mars Arctic Research Station (FMARS) (Mars Society)
    - Life support simulator: Biosphere-2 (Space Biosphere Ventures)

Most of these analog missions were carried out successfully, meeting the goals they set forth – to inspire the public, sharpen team skills, and perform space-analog tasks. However, the analogs listed above are not meeting the Exploration Systems Mission Directorate's goals because these analogs were created before the VSE, and the VSE changed the objectives for analog missions.

B. Process Aspect

Previously, analog missions have been independently developed by multiple groups around the world without apparent horizontal integration or consistency of the development process. Some groups are beginning to correct for these oversights by outlining a Systems Engineering approach for creating and carrying out analogs, using principles and methods which would be recognizable to members of the Systems Engineering community.

Analog missions can be split up into three different categories: scientific, technology, and operational.[3,4] Scientific analogs aim to simulate physical aspects of the landscape, including morphological, chemical, biological, and geological similarities. These missions will investigate questions such as how the astronauts perform science, what science they want to and can perform, and what and how many instruments will be necessary.

Technology development and demonstration analogs must simulate both the environment and the use or application of the technology under evaluation, making temperature, precipitation, rock abundance, availability and type of technology, hardware, etc. important when performing this type of analog. These analogs will also examine, for example, how astronauts use technology, how the technology will actually perform in a variety of different conditions, what types of supporting hardware will be necessary, and so on.

Lastly, operational/human factors/training analogs focus on situational, behavioral and logistical parameters (remoteness, isolation, confinement, limited communication, etc.). These analogs study what training and planning is necessary, how people will respond to the physical and psychological realities of the mission, how the mission will operate, etc. In order to carry out the VSE and to best learn how to reduce risk, the three different types of analogs should, at some point, be combined into an integrated full mission simulation.

One group has created a Fidelity Evaluation Framework (FEF) to compare the fidelity of different analogs.[2,3] There are three components to this framework.

First, Mohanty, et al, as well as other sources, created checklists to list elements and subsystems that are important for accurate simulations of analogs. The problem, though, is that these lists are all separate and are not yet complete. (See Table 1 for a new, complete checklist.) A checklist may be recognized as the aspect of Systems Engineering practice associated with defining and organizing the elements of the system, frequently referred to as "architecting" or developing system architecture.

The second step in the FEF is to create mission visualization schematics. This component may be seen as another aspect of Systems Engineering, associated with identifying and characterizing the "functional flow" produced by the system by visualizing the interactions and relationships between the different elements of the system.

Third, trade studies are done to review the architecture and operations in terms of important metrics. This component is most easily seen as being closely associated with the system analysis aspects of Systems Engineering practice, developing what INCOSE references as a "baseline" for the system.

As the FEF suggests, there will not be just one analog mission performed prior to the launch of the VSE missions. Therefore, it would be best to structure a series of related analog missions in a stepwise, systematic approach applying a more complete Systems Engineering process and treating the set of analog missions as the system under development. [5]

III. Gaps in Analog Work

Before analog missions continue or new analog missions are created, further objectives within NASA's Analog Missions Initiative may be needed to guide analog missions along the VSE lines. Then, given these objectives, an organized Systems Engineering process is needed to fill gaps relating to the creation of analogs, collaboration, and documentation of objectives and lessons learned.

C. Mission Aspect

There are gaps in a number of fundamental aspects of analog missions. Of primary concern is the sparse and unspecified VSE Concept of Operations. Analog missions can serve two purposes here. NASA can use analog missions to detail out objectives and to relate those objectives to the space mission. Or, once the objectives and concept of operations are outlined, the analog missions can test to determine whether the operations concepts can be fulfilled. For example, part of the current VSE plan is to send four people to the lunar surface, but there is no operations concept for how to safely make a habitat.

Documentation is a large problem in current analog missions. Both pre-mission documentation on objectives and the concept of operations, and post-mission documentation on how the analog performed in relation to its intended objectives are needed, but neither is well documented. To develop better analogs in the future, it is critical to understand what the goals were, and what was done well and what was not in the simulation.

One method of learning what went wrong in analog missions is to look at what was unrealistic in relation to the space mission. The list below is not exhaustive, but it was gathered from the documentation available. Additional unrealistic aspects are also added to the end of the list that were true of many missions but were not documented in their reports.

<u>NEEMO</u>[6]

- Incorrect role sharing: Maintenance/housekeeping crew separate from aquanauts
- More one-on-one time between engineers and crew with NEEMO than with ISS
- Divers could refill oxygen at waystations during a dive

<u>LMLSTP</u>[7]

- Tools supplied to the crew members from outside during the simulation
- Unscheduled and unnecessary transfers of supplies (not isolated)
- No time lag on communications
- No simulation of Extravehicular Activity
- Easier rescue and low-risk mission could affect judgment, engineering, etc.
- Were able to talk to family every day with videoconferencing

<u>MDRS and FMARS</u>[7]

- Had to break simulation: repair, unsuited safety person for protection from bears
- Limited (and not strict) exercise regime
- Face-to-face contact with press and locals (MDRS) during simulation
- Food system: regular groceries, fresh goods (not freeze dried)
- Non-strict mass limits and more frequent re-supplies than a space mission
- No team building prior to some missions
- Training occurs on-site before simulation starts
- Life support systems 'open'
- Living conditions more comfortable – large areas of personal space
- Living design was not extensively traded or studied – just one possible design

Rovers (Fido and Desert RATS)[8,9]

- Worked with rovers first in field while not in simulation to test them and set them up

General Analogs

- Insufficient training and procedures
- The mission did not start right away when the team arrived at the analog location
- Amount, type, and cooking methods of consumables not as restricted
- Clothing (material and functions) not as restricted and not same as space mission
- Mission length too short
- Schedule not based off of those for space missions
- No simulation of launch, microgravity, entry into atmosphere
- Setup, expansion, and buildup of habitat not as constrained (time, personnel, etc.)

It would be impossible to make an analog mission on Earth the exact replica of the space mission. Therefore, there will always be aspects of the analog mission that do not exactly match the analogous space mission, but those aspects should be listed out so that it is understood what areas of the analog do not have high fidelity.

Risk mitigation is mentioned as one of the main objectives of performing analog missions, and risk management in a project is one of the most important aspects of Systems Engineering practice. However, there is nearly no discussion of how analog missions have helped manage risk. Groups do not lay out risk objectives, actively measure risk, or discuss it in their reports after the mission. This lack of a consistent and systematic approach to risk management is a huge gap in the objectives of analog missions and must be fixed as analog missions continue.

Cooperation is another major area of analog missions that needs improvement. The horizontal integration of analog elements can be considered interface management in Systems Engineering practice – in this case, the interfaces are between the external elements running the analogs. In this case, the agencies are not interfacing and are independently running simulations and studies, meaning few groups combine resources such as funding and experience. While separately run missions can increase the amount of knowledge gained, that knowledge must be shared in an effective way for the space missions to benefit.

One method for collaboration that NASA is implementing is the NASA Analogs Database.[1] The purpose of the website is to provide a source of information on and a collaboration tool for analog activities that are relevant to NASA's exploration program. This website has two databases – the Surface Exploration Lessons Learned Database, and the Analogs Database, where users can list contacts, descriptions, objectives, results, sources, and links to show how one analog is connected to another.

D. Process Aspect

Before laying out an approach to developing analog mission systems using Systems Engineering practices and principles, the gaps in the current definition process must be noted.

To make the list of analog elements helpful in the system design and development process, it is necessary to combine, complete, and categorize the elements of the analogs – to develop an archetype of the analog mission system that can be used as an intellectual frame. Engineers can use this list of analog elements to ensure that all necessary exploration issues are included in any analog mission being developed, and to architect specific analog missions.

To compare the fidelity of analog missions both to other analog missions as well as to the real space mission, consistent metrics are needed within quantitative trade studies. The Fidelity Evaluation Framework[2] began the discussion and implementation of trade studies and metrics to compare analogs, but the metrics were inconsistent across comparisons, which could bias results and take a long time to implement. Therefore, consistent metrics (both qualitative and quantitative) would make certain that analogs could be compared and contrasted quickly and fairly, providing effective support for design decisions.

IV. How to Fill the Gaps

Agencies performing analog missions have started off well in terms of basic mission design and simulation. However, a few steps need to be taken to refine the process of designing analog missions so that the objectives of NASA's Analog Missions Initiative and the Vision for Space Exploration can be accomplished. One way to combine both the previous and the new techniques for analog missions is to apply a Systems Engineering process that treats analog missions as the system under development, and considers the physical, process, and human aspects of the analogs.

A. Mission Aspect

To improve the next set of analog missions, better communication and collaboration is needed, and one way to do that is to better utilize NASA's Analogs Database. This site should furnish designers with complete information on past missions, including each mission's purpose, concept of operations, lessons learned, risks, assumptions, etc. Gathering information on analogs could be made more systematic through use of a comprehensive electronic fill-in form and by making the searchable site accessible throughout NASA, perhaps using some portal such as Polaris.

The Analogs Database site could also help in the area of risk management by designating a specific area for risk management feedback and risk discussions. This area could even include access to risk tools such as those used within the Constellation program, and instructions on their use. In addition to the risk page, the database should include a searchable lessons learned section from all missions, including components that were realistic and ones that were unrealistic.

B. Process Aspect

1. Documentation

Consistent with Systems Engineering practice and prior to any design work, the mission must go through a definition phase so that the mission objectives and purpose are clear. First, the team must define the purpose of the analog mission, including all research, operational, and technological objectives. Next, the baseline mission should be identified in order to determine the operational requirements of the analog. Then, the concept of operations can be tied back to the purpose of the analog mission. Finally, assumptions and unique factors that are unchangeable for this mission must be analyzed for their appropriateness and their affect on mission fidelity.

The outcome of this definition phase must then be discussed to make sure that the resulting mission and its operations concept answers the questions that the analog mission was intended to address. Clearly documenting and publishing this work will lead to better collaboration and cooperation among missions.

2. Checklists

The next step in creating a Systems Engineering process for analog missions is to refine the FEF tool. First, the checklists provided[2] are incomplete and are inconsistent. Second, a method for identifying the types of trade studies needed for developing mission baselines should be included. Third, the types of metrics used in the trade studies[2] should be broader and more consistent to provide a base set of similar measures for better analog comparison and contrast. And finally, the metrics should be appropriate to quantitative, not only qualitative, trade studies.

The checklist shown in Table 1 was combined from multiple sources and then expanded upon to create a complete list of elements that must be considered when designing an analog mission. Then, the elements were categorized into four categories – chronological, operational, behavioral, and functional – to make designing an analog easier because it is apparent what could be applicable to the analog.

Chronological elements are mission events or phases that occur at different times throughout the space mission. The Operational checklist covers the actions of the people and the system, while the Behavioral checklist relates to human factors issues. Finally, Functional subsystems identify the physical architectural and environmental aspects of the analog – i.e. the system, the people, and where they interact.

After their categorization, the applicability of each element to each of the analog types (operational (O), technological (T), and scientific (S)) was noted (see Table 1) to show whether the fidelity of that element is important to the three different types of general analog missions. Nearly every element is important to an Operations mission because of the large scope of the Operations analogs.

Table 1. Checklist of Elements of Analog Missions[2, 5, 10-13] (Legend: O = Operational, T = Technological, S = Scientific)

Phases and Elements			O	T	S
Chronological					
	Earth Launch, Docking, Cruise, Orbital Insertion, Entry Descent, Landing, Surface Stay, Launch from another planetary body		O	T	
	Surface Exploration		O	T	S
Operational					
	Crew Selection Process, Onboard Training, Group Dynamics, Housekeeping, Opportunities for: crew meetings, meaningful work, recreational activities, and physical exercise		O		
	Emergency Response, Caution and Warning System, Extra-vehicular activity (EVA), Food Preparation, Personal hygiene and waste management, Personal Time, Construction, Maintenance, Technology experiments		O	T	
	Communication: To other remote analog locations, To local mission control, To remote mission control, To internal/external crewmembers, To internal/external equipment, and Restrictions (type, duration, and delay)		O	T	
	Pre-Mission Training, Documentation, Crew Protection, Integration of humans with hardware and software, Displays and Controls, Autonomy/Degree of User Control, Pre-event Planning, Science experiments and planning, Logistics Difficulty: placement & re-supply, Quantity of Resources		O	T	S
	Science experiments and opportunity		O		S
Behavioral					
	Crew characteristics and compatibility, Inter-team dynamics (Group roles and leadership), Mission management/crew dynamics, Behavioral emergency procedures, Mission Mentality (Meaningful work and Realistic Schedule), Crew health, Sleep, Clothing style and amount, Exercise, Personal hygiene, Personal time, Privacy, Communication with family, Food preparation, Recreational opportunities, Personal space, Habitat Aesthetics, Perception of external environment, Sense of temporal and physical isolation		O		
	Habitat Environment (temperature, humidity, etc.)		O	T	
Functional					
	General Stowage, Crew quarters and privacy, Internal design of habitat, Internal volume (space) considerations, Facilities for: crew meetings, meaningful work, recreational activities, and physical exercise;		O		
	Food stowage and preparation, Water System, Safety systems and emergency equipment, Vibration and acoustic isolation, Health Care Facility (Monitoring, Countermeasures, Medical care), Life Support (Air, closed-loop simulation, other Human Systems Integration Requirements), EVA preparation location		O	T	
	Hardware Elements		O	T	
		Transportation Elements (Launch Vehicle, Transit Vehicle, Lander), Core Planetary Base Elements (Habitation modules, Lander, Portals, Greenhouses, Medical Facilities, Cargo), Exploration Elements (EVA suits, IVA suits, Pressurized rovers, Un-pressurized rovers, Robotic assistants), ISRU elements,	O	T	
		Simulation (Missions) Support Elements	O	T	S
	Subsystems				
		Medical Support, Food Management, Lighting, Thermal environment control, Waste management/personal hygiene facilities, Communication, Propulsion, Attitude Determination and Control, Guidance Navigation and Control, Restraint and mobility aids	O	T	
		Information Management	O	T	S
		Electrical power storage, distribution, and control	O	T	S
	Physical aspects of the external environment		O	T	
		Hostility, Susceptibility to disruption, Morphological similarity	O	T	S
		Chemical similarity, Biological similarity, Geological similarity		T	S
	External area: sufficient floor size, volume		O	T	S

3. Metrics and Trade Studies

Trade studies should be used to compare multiple analogs to each other, as well as to compare analog designs to the space mission to determine which analog has the highest fidelity. In order to determine fidelity, a consistent set of metrics is needed. The metrics below (see Figure 1, across the top) were created by compiling, editing, and filling out existing analog trade study metrics[3,4], and then the metrics were categorized. Since the list of metrics covers a wide range of topics, it can be used for all analogs, which makes the process of setting up a trade study much faster.

The metrics to compare analog missions are primarily categorized in the same manner as the analog elements (functional, operational, and behavioral) to make the transition from working with elements to working with metrics as smooth as possible. There are a few metrics that only apply to science or technology analogs, and these are given separate categories so that performing the trade study is easier.

A trade study tool was developed that can compare multiple analog missions to the space mission while being quicker and easier to implement (Figure 1) than the more common Analytical Hierarchy Process (AHP). Figure 1 shows a partly completed quantitative trade study example.

	Overall			Functional								
	Mission Realistic	Mission Duration	Low Cost	Ease of Construction	Low Maintenance	Flexibility	Control over external environment	Control over internal environment	Habitable Living Space - Sufficient size/volume	Internal Environment Fidelity	External Environmental Fidelity	Meets HSIR Requirements
Weighting, Person 1 (0-9)	9	5	3	2	5	3	3	3	7			
Option 1, Person 1	2	1	2	-2	-1	2	-1	2	-1			
Option 2, Person 1	-1	1	0	1	2	-1	1	0	0			
Weighting, Person 2 (0-9)	7	7	5	1	5	5	2	5	3			
Option 1, Person 2	1	2	1	-1	0	1	0	1	0			
Option 2, Person 2	0	1	0	0	2	-2	1	0	0			
Option 1 Results	25	19	11	-5	-5	11	-3	11	-7			
Option 2 Results	-9	12	0	2	20	-13	5	0	0			

	Operational											Behavioral		
	Overall Integration	Mission Operations	Ease of access for engineers & personnel	Safety	Contamination Mitigation Potential	Integration of humans and system	Potential to develop procedures	Autonomy and self-sufficiency	Crew/Ground Team Training	Fidelity of Resources	Risk Level Similarity	Sense of isolation and danger	Psychological Fidelity (impact on crew)	Correct mental model for crew
Weighting, Person 1 (0-9)														
Option 1, Person 1														
Option 2, Person 1														
Weighting, Person 2 (0-9)														
Option 1, Person 2														
Option 2, Person 2														
Option 1 Results														
Option 2 Results														

	Science & Tech					Science		Tech			Total Score
	Research Potential	External Environment Fidelity - Morphological	External Environment Fidelity - Chemical	External Environment Fidelity - Biological	External Environment Fidelity - Geological	Science Return	Science Support and Remote Science	Technology Development	Technology Fidelity	Technology Integration	
Weighting, Person 1 (0-9)											
Option 1, Person 1											22
Option 2, Person 1											8
Weighting, Person 2 (0-9)											
Option 1, Person 2											35
Option 2, Person 2											9
											Final Score
Option 1 Results											57
Option 2 Results											17

Figure 1. Quantitative Analog Comparison Spreadsheet Tool

In this trade study, the metrics are listed across the top. Each metric can be weighted in the first row depending on its relevance to the analog mission being studied (0 for no relevance, 9 for high relevance). The analogs/space missions/design decisions/etc. that will be compared are listed in the left column. The users can then compare the analogs on the left to the metric in that column. The ratings scale from 2 (very good), 1 (good), 0 (neutral), -1 (poor), and -2 (very poor). The metrics are written such that receiving a high score is good. This comparison and rating process can be done for multiple people to get an average opinion.

In the body of the matrix, the weightings are multiplied by the score the user gave for each metric, and the weighted scores are added up by the row to give a total score, located on the right hand side. The total scores for each analog and each user are added to get the final score (the bottom right corner). A high score means that the analog is closer to the target conditions (has higher fidelity), while a low score means that the analog is not as close to the target conditions. The spreadsheet highlights the winner in yellow.

V. Future Work

In addition to advancing well-planned, high-fidelity analog missions in NASA, this systems engineering process should be developed further in conjunction with an analog mission in the non-NASA sector. One potential area of development is with the PolAres program, which is an Austrian follow-up to the AustroMars mission conducted at the Mars Desert Research Station. The AustroMars program included many realistic aspects in their mission, including using freeze-dried food, having a realistic background mission scenario, a time-delayed 24/7 mission control, a human-robotic component etc. The Systems Engineering Process for Analog Missions could be tested, benchmarked, and developed further in conjunction with the PolAres program.

VI. Conclusion

Analog missions have already made a contribution in how engineers and managers are thinking about the implementation of the Vision for Space Exploration. Valuable work is being performed in science, engineering, and operations. To continue making analogs that are more closely tailored to the needs of the VSE, both the process of designing analogs and process of how the analogs are carried out must be improved through a well-structured and consistent Systems Engineering process. This Systems Engineering process involves outlining the mission and its purposes and objectives, tying in the Concept of Operations, improving upon the Fidelity Framework with complete checklists and quantitative trade studies with consistent metrics, and documenting all the work to share with other missions. Through the new Systems Engineering process, analog missions will be able to meet the needs of the VSE while better sharing data and collaborating on both current and future projects.

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