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Systems Modeling of Space Medical Support Architecture: Topological Mapping of High Level Characteristics and Constraints

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Abstract— **The challenges associated with providing medical support to astronauts on long duration lunar or planetary missions are significant. Experience to date in space has included short duration missions to the lunar surface and both short and long duration stays on board spacecraft and space stations in low Earth orbit. Live actor, terrestrial analogue setting simulation provides a means of studying multiple aspects of the medical challenges of exploration class space missions, though few if any published models exist upon which to construct systems-simulation test beds. Current proposed and projected moon mission scenarios were analyzed from a systems perspective to construct such a model. A resulting topological mapping of high-level architecture for a reference lunar mission with presumed EVA excursion and international mission partners is presented. High-level descriptions of crew operational autonomy, medical support related to crewmember status, and communication characteristics within and between multiple teams are presented. It is hoped this modeling will help guide future efforts to simulate medical support operations for research purposes, such as in the use of live actor simulations in terrestrial analogue environments.**

I. INTRODUCTION

The challenges of medically supporting astronaut crews on long duration missions are significant [1]. In addition to the routine health and medical issues faced by all humans, astronauts face additional threats to health due to the hazardous environments in which they work. A critical difference from previous missions however will be the need for enhanced medical autonomy on long duration expedition-class flights. The ability of the crew to function independently will be critical as distances from Earth become so great as to preclude immediate or effective medical evacuation. This need for autonomy drives consideration of numerous factors including not only delivery of health care, but also access to consultant advice and training for maintenance of competence, particularly in the case of skills-based training. Thus the degree of autonomy required of crews increases with increasing distances and the resultant time delays in communication. Medical support for long duration missions, such as the one presented herein will entail a complex network of systems, and significant work will be required to maximize the effectiveness of such systems. Ensuring redundancy, failure recovery, and optimal performance will be critical.

This paper presents an initial systems-level analysis of medical support operations for a manned lunar long duration lunar surface mission. Through reviewing current proposals for future mission parameters, a topological system map can be defined, and key constraints and enablers can be projected for each region on this map. In addition, characteristics of required crew autonomy and general medical support levels for crewmember health states can be described. This paper represents a first step for this research teamat creating such a model, with a primary objective being to help inform and design future live actor simulation exercises in terrestrial settings.

II. BACKGROUND

A. Biomedical challenges of spaceflight

Biological and medical challenges associated with spaceflight have been identified since the earliest missions in space. Both American and Soviet space programs have long and productive histories of space biomedical research, aimed at increasing our understanding of the biomedical risks posed by spaceflight. Thorough reviews by NASA in recent years include the comprehensive Bioastronautics Critical Path Roadmap [2] released in 2004, and the more recently restructured Human Research Program (HRP) [3] provide detailed analysis of the current understanding of risks and knowledge gaps related to human spaceflight. Among the highest identified risks are: radiation impact on human biology, the impact of microgravity on bone mass and muscle mass, and the impact of psychological stresses on crewmembers. In the HRP specific risks are stratified by mission type and duration, with short orbital flights having generally the lowest impact, and long duration missions to Mars having the greatest. The maintenance of crewmember health, the prevention of disease, and the treating of disease processes in spaceflight are crosscutting priorities that impact on all areas of biomedical health for space crews.

B. Simulating medical Concepts of Operations (CONOPS)

The impetus for the analysis presented in this paper (an admittedly preliminary analysis) follows attempts by the authors and others to model medical operations in spaceflight using live actors, high-fidelity patient simulators, and scenario-based simulations. Although simulation has been used in many industries for a number of years for both training and system evaluation, these are relatively new concepts in medicine generally and space medicine more specifically. High fidelity patient simulators have been widely available since the late 1990s, and their uptake by medical educators has been gradual. The use of simulators to evaluate medical support systems was virtually unknown in

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healthcare until very recently [4]. The work by the authors to use high fidelity simulation to study complex support operations is a relatively undeveloped practice in healthcare, and guidelines are non-existent. Furthermore, the system being modeled - in this case, medical support for long duration missions - has no currently established definitive structure on which to build such a model. Thus, clearly mapping out the structure of medical supporting spaceflight has value for future efforts to model such systems, and through such modeling, could conceivably increase understanding and improve the design of spaceflight medical support. For the authors' purposes, this attempt at formal modeling serves as a framework on which to construct field simulations of space tele-medical support.

III. METHOD

The authors reviewed recent and currently proposed mission designs and comprehensive medical reviews to identify mission design parameters and biomedical challenges. Sources reviewed to establish reference design scenarios included the Human Research Program [3] and the Canadian Space Agency's Exploration Mission overview Technology Assessment 2011 [5]. Bioastronautic and medical support requirements for long duration missions have been a major focus in the space medicine community and for several national agencies for many years. Resources reviewed to determine these medical requirements include the above resources, along with several CSA commissioned studies: Needs and Capacity Study: Provision of Medical Care Solutions for Long Duration Human Space Flight Missions [6], Advanced Medical Technologies for Spaceflight Beyond Earth Orbit [7] and Development of a Training and Maintenance of Competency Program for Remote Health Care Providers [8].

Based on the above materials, the primary task for the authors was to develop a topological mapping of high-level elements of a proposed medical *concept of operations* (CONOPS), and once defined, identify and describe major constraints and requirements for this system. The mapping is aimed to identify functional units with the recognition that specific mission design scenarios would determine unit specifics.

IV. RESULTS

A. Reference Mission Determination

After reviewing potential mission designs, the authors agreed upon on a 60-90 day extended duration lunar stay as the most appropriate reference mission for this analysis. Short and long duration low Earth orbit (LEO) missions represent the current scope of activities in the manned international space community at the present time. It was felt to be impractical to work towards recommendations for changing existing support architecture of these missions, as these are already well established. Long duration missions to Mars, while intriguing from a systems design perspective, where felt to be too distant a possibility to be the focus of current modeling efforts, and any resulting research findings would therefore be of minimal use in the foreseeable future. In addition, it seemed apparent that any long duration mission

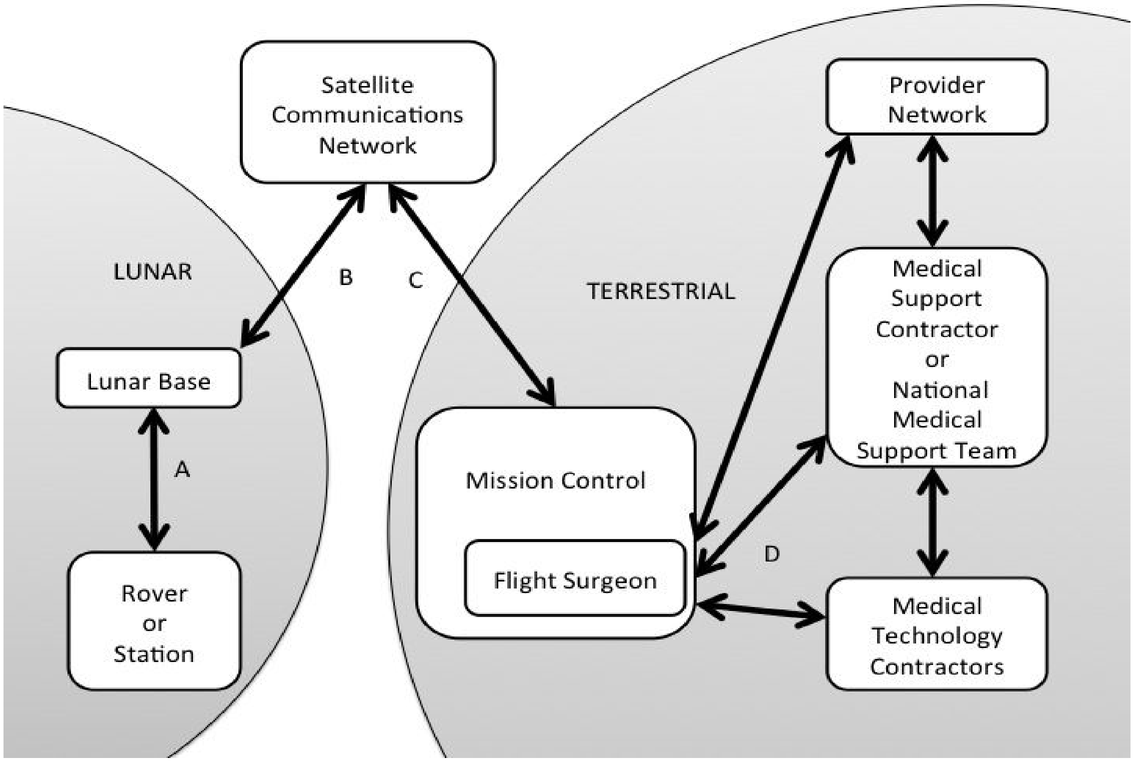

Figure 1. Topological map of high-level architectural elements of lunar medical support system.

to destinations farther than the moon would likely be informed by lunar or asteroid surface experiences.

The resulting mission design to be selected as the Reference Mission Design (RMD) for this analysis is a 60-90 day lunar surface exploration mission, with an estimated crew size of 6 individuals, and with architecture that includes both a lunar base station and extended mobile surface activity (likely rover-based). Consistent with current space program activity and stated international space agency intentions, this extended lunar surface mission would be expected to be international in nature, and modeled on a similar mission control model to current International Space Station (ISS) operations.

B. *Topological Mapping*

A review of current space medical support and proposed plans for a medium duration lunar mission produces the functional model shown in Fig. 1. This model is high-level, and does not include detailed technologies, specific biomedical telemetry requirements (EEG, ECG, SpO2, etc.) or crewmember numbers and roles. Furthermore, this model is architectural in nature, with specific elements determined by a given mission design scenario or medical contingency management model. Identified units within the model are geographically specific or functional operating units of both humans and technology. On the lunar surface, we have defined both a base station and a mobile human presence (extended extravehicular activity, or EVA). On the terrestrial side, we define a central mission control (although functionally there could be more than one), with an embedded flight surgeon presence. The flight surgeon serves as the key medical support and contact individual within mission control. Mission control, through the flight surgeon, will interact with technology partners (typically external contractors who design, build and serve as technological experts for flown systems); medical support for international partners; and a broader, and perhaps more loosely defined network for secondary and tertiary level medical support providers. Primarily channels of communication between these functional units are also defined, and are labeled as A, B, C, D. Channel A represents on surface communication between extended EVA and the lunar base station. B and C represent communications between the lunar base and satellite relays, and between satellite relays and mission control, respectively. Distances for channels B and C are vast, on the order of 400,000km. Channel D represents the extensive ground based communications between mission control and the various terrestrial support units described above. It is possible to subdivide this and other channels into multiple subcomponents. Table 1 lists the basic technical and human characteristics of each communication channel. It is important to recognize that each channel includes human-to-human communication (voice, audio), biomedical telemetry (ECG, SpO2, Respiratory rate, BP, etc depending on the scenario and the technological capabilities of any on board suite), as well as non-biomedical data.

C. *Units and Teams*

Medical support for spaceflight involves large numbers of individuals, and requires the efforts of many distinct, interactive, and interdependent teams. From the perspective of a sick or injured crewmember, however, 3 separate levels of teams or systems are identified. The first level relates to the crew itself. Astronaut crews are very tightly defined teams; they are highly interdependent in nature, and to some extent will function in any mission design with some degree of autonomy (though this level may vary both between and within a mission). The second level of team involves the

Figure reference	**Communications channel**	**Technical Characteristics**	**Human characteristics**
A	**Lunar Surface Communication**	• Low power • Bandwidth undefined • Minimal signal delay	• Protocol-driven in nature • At times informal • Face to face and audio/visual
B	**Lunar to Satellite Communication**	• Low power • Limited bandwidth (comparative) • Signal delay 1-3 s	• Protocol-driven • Typically formal • Both scheduled and unscheduled • Complicated by signal delay (1-3 s) • Both open channel and secure channel modes
C	**Satellite to Mission Control Communication**	• Low power (satellite to ground) • High power (ground to satellite) • Moderate bandwidth (comparative) • Minimal signal delay	
D	**Ground Support Network Communication**	• Power unlimited • High Bandwidth • Minimal signal delay • Highly variable in architecture (particularly extended network)	• Variable in nature • Protocol-driven in nature • At times informal • Face to face and audio/visual

Table 1. Communications channels (from the topological map) and their basic characteristics.

relationship between the crew and mission control; this is also a very tightly coupled team, though anecdotal reports of challenges within this relationship are not rare. This team is slightly less well circumscribed, as mission control personnel may rotate in and out on a continual basis, and since ongoing involvement of external parties may blur lines of membership on the terrestrial side of this human system. The third level of medical team (again, from the crew perspective) includes parties outside of mission control. This is the largest, and least clearly defined team of the three. A fourth level of team, System IV is also shown – this being the broader team of crew, ground, and medical support. These systems are listed in Table 2.

System No.	**Composition**
System I	Lunar Crew
System II	Crew-Ground
System III	Ground-Medical Support
System IV	Crew-Ground-Medical Support

Table 2: Four distinctly identified human-human systems

A. Aspects of medical support and crew status

Three distinct areas of medical support were identified for the defined reference mission. The first is that of routine physiologic and psychological monitoring, without specific involvement of pathology, diagnostics or treatment. The second involves medical diagnostic activities; the third involves active treatment of illness or injury. These are laid out in Table 3 .

B. Autonomy and Medical Operations

The issue of medical autonomy, or the degree to which the crew will manage medical monitoring and discrete events independently of mission control is part of a broader discussion of crew autonomy. Historically, the activities of astronaut crews have been actively and tightly managed by mission control. There is a growing awareness that for long duration missions beyond low Earth orbit (LEO) that this may not be an ideal mission management model. Indeed, for interplanetary missions, the time delay alone will necessitate a higher degree of autonomous operations. On a Mars mission, for example, communications may be delayed up to 45 minutes by distance alone. For extended-duration lunar missions, there is no universally agreed upon model of how autonomy should be defined, nor to what degree crews should function autonomously. Indeed, this would appear to

		Medical Support		
		Physiologic Monitoring	**Diagnostic Testing**	**Treatment**
Crewmember Status	**Healthy State** **No identified injury or illness**	• Intermittent, particularly during EVA	• As participant in biomedical studies • Preventative medicine health assessments (disease screening)	• Prophylaxis • Preventative medicine interventions
	Acute Illness or Injury	• Continuous	• Continuous	• Immediate • Acute
	Chronic Illness, injury, or Debilitation	• Frequent or Continuous	• Frequent or Continuous	• Immediate and ongoing

Table 3. Medical support activity in health state, acute illness, and chronic illness.

	Autonomy Level	
	Low	**High**
Enabling or Precipitating Mission Conditions	• Continuous communications with Mission Control • Minimal time delay in signal transmission	• Intermittent or loss of communications with Mission Control • Increased signal transmission durations
Medical Support Characteristics	• Mission control in-the-loop • Medical expertise immediately available • Real time supervision possible • Medical evacuation variable	• Crew unsupervised • Reliance on on-site expertise and technology • Real time supervision constrained or impossible • Medical evacuation variable, but unlikely

Table 4. Enabling/precipitating conditions and medical support characteristics of low and high medical autonomy scenarios.

be an important research objective. High and low crew autonomy operations, along with both precipitating/enabling factors and medical considerations for each are detailed in table 4, above.

V. CONCLUSION

In summary, this project presents a first attempt by the authors to model lunar medical CONOPS for the purposes of building an operational simulation test-bed model, and as such, the model is both high-level and incomplete. We have attempted to define the topology of such a system so that it may be replicated in laboratory and field settings.

This work grew out of our efforts to model lunar tele-medical support in field settings in remote terrestrial settings. Physical simulation we constructed, using live actors and high fidelity patient simulators, were based up discussions with colleagues at both the Canadian Space Agency (CSA) and the National Aeronautics and Space Administration (NASA) and its subcontractors working in this area. Our initial efforts highlighted the need to physically map out the various processes were attempting to simulate. We would expect this modeling to evolve over time as our experience in building these simulations grows, and as agency and contractor personnel provide ongoing input and feedback.

How this model may be used can be illustrated through a case example. Imagine an astronaut crew of two, traveling across the lunar surface in a pressurized rover. If one astronaut were to develop symptoms of chest pain, care would be rendered in the rover by his/her crewmate. They would contact the established lunar base where the medical officer and more definitive facilities would be located. Depending on the mission parameters, Mission Control may or may not be monitoring the detailed rover excursion, and medical support at Mission Control may or may not be monitoring the real time health status of the astronauts in the rover. If not already the case, communication would need to be quickly established between the rover, the lunar base medical officer, and mission control. Basic vital signs and other data would be transmitted from the rover to the lunar base; the medical officer would likely oversee management of the ill astronaut. Medical support at Mission Control would likely enact protocols to engage a medical expert provider system and bring high-level expertise in the relevant medical field into the situation. It will not be possible nor advisable to have so many individuals in direct contact with the affected individual. A clear history, along with biometric data will be transmitted from the rover, to the lunar base, to mission control, to additional individuals in the provider support network. Patient management decisions will need to be made, including any pharmacotherapy and plans for possible evacuation. Managing this situation obviously becomes very complicated very quickly. An initial assumption is that all of the biometric sensors, supporting equipment, and drug formulary are optimal for the likely conditions that crews will encounter. Physical, live simulation will likely play an increasingly important role in defining technological requirements, pharmacologic selection, and operational management strategies. The topological mapping presented herein will assist in the construction of such simulations, and help clarify which questions are being addressed at any given time.

It is important note that any one element of the model presented can be defined in terms of its own systems, subsystems and interactions. Indeed, this represents next-steps in the development of this model. It is also important to note that this model is specific to the mission design that we identified as most relevant to our purposes. While we believe this model may be useful for these purposes, it is, like all models, imperfect. Any shortcomings in this model become more pronounced as the mission plan in question strays from our chosen design. We do believe, however, that a medium-duration lunar mission, similar to the reference mission we have chosen, is the most likely next-stage manned exploration class mission to be undertaken by the international space community (following ISS).

We believe that there is tremendous value in continually revising and updating this model as the international space communities modify and adjust mission planning in response to economic realities, new technologies, and changing priorities. However, we also strongly feel that it is important to look beyond what sometimes may be shortsightedness in international space mission planning. Striking a balance between what is politically and financially most likely in the short run and what is desirable from an exploration perspective in the long run may be difficult, but it will help ensure that the best systems to ensure crew health and well being are designed into these systems.

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