AIAA 2017-5270
AIAA SPACE Forum
12 - 14 Sep 2017, Orlando, FL
AIAA SPACE and Astronautics Forum and Exposition

Envisioned Concept of Operations for Beyond Low-Earth Orbit: The Collaborative Decision Making Between Human and Cognitive Assistant

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This study discusses the envisioned concept of future space operations that includes the collaborative decision-making between humans and automation. Future mission objectives include flying beyond Low-Earth Orbit (LEO). Two major challenges for such operations include communication delays and off-nominal situations, where no procedures exist for the situation. Current space operations rely heavily on communication between Mission Control and space crew, but missions beyond LEO introduces communication delays that impact collaboration. To respond to off-nominal situations, the space crew will need real-time guidance and support to develop new procedural steps. However, communication delay will prevent Mission Control from providing real-time assistance. A Cognitive Assistant (CA) system could be developed to assist the space crew in these situations. A systematic approach was used to ground the development of envisioned collaboration between humans and an adaptive CA for space operations. This new approach extrapolates the domain knowledge of current space operations to future operations in the presence of communication delays. In the first phase of study, interviews with astronauts were performed to generate an Abstraction Hierarchy (AH) and a Decision Action Diagram (DAD) to define the cognitive functions performed by the space crew, Mission Control and on-board automation during the current operations. Functions that would be interrupted due to communications delay were identified as the breakpoints on DAD. This paper presents the envisioned concept of operations and the role of CA in space crew, based on the domain knowledge models developed under the first phase of this study.

Nomenclature

CA	=	Cognitive Assistant
WDA	=	Work Domain Analysis
DAD	=	Decision Action Diagram
AH	=	Abstraction Hierarchy
LEO	=	Low Earth Orbit
ConOps	=	Concept of Operations

I. Introduction

THIS paper presents an envisioned concept of operation (ConOps) for future space operations beyond Low-Earth Orbit (LEO). As future space operations move beyond LEO, this will introduce challenges, including communication delays and off-nominal situations[1]. These challenges will be particularly acute for off-nominal situations. For this study, an *off-nominal situation* is defined as a situation where no procedures have been developed prior to the mission to support the space crew's decision making under time pressure. Current practice in handling any situation during space operations relies heavily on the collaboration between Mission Control and space crew, and requires maintaining clear communications to collaboratively generate and choose between alternative solutions.

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However, flying beyond LEO affects the utility of communication to produce solution alternatives. Therefore, the majority of the negative impacts would probably be on the use of operational procedures due to the increased communication lag[3].

In nominal operations, the communication lag can be managed with the use of established procedures and adaptations to communication protocols. On the other hand, non-normal situations can be anticipated in the design of the mission, and procedures developed *a priori* to mitigate the effect of the situation. In off-nominal situations where immediate action is required, however, space crew must detect, diagnose and develop responses in a timely manner[4].

Unlike LEO missions, off-nominal situations in long distance missions are situations where the space crew does not have support from established procedures or Mission Control's guidance to support their decision-making effort[5]. The increased communication delay would limit Mission Control's ability to provide support and guidance in generating a solution for off-nominal situations. Besides the lack of Mission Control's guidance or established procedures, the space crew will have limited access to information needed to assess the situation and to produce decision alternatives. Therefore, the majority of the negative impacts of time delay will be in situations without pre-established operational procedures[3]. In this condition, the crew will heavily rely on their expertise gained with training or from their experience of previous mission(s), but this may not be enough to deal with off-nominal situations.

The inability to provide sufficient guidance to the crew will require more capable automation systems to assist the crew. These systems must be capable of performing cognitive tasks with space crew in the decision-making process to detect and diagnose problems, and to develop responses. However, current automation systems are not designed to perform collaborative decision-making with humans [6,7].

A Cognitive Assistant (CA) is defined, for this study, as the intelligent agent that can serve as crew assistant to monitor systems, recognize situations, and collaborate and exchange information with the space crew to support decision making. This system must be able to assist space crew in dealing with an off-nominal situation in a timely manner when Mission Control support is lacking. To develop this type of system, the essential functions which must be allocated from humans to the CA system must be determined. A starting point would be to identify functions in the current process that would be interrupted in space missions beyond LEO. Thus, the design requirements and functionality matrix for a CA system have been developed, using Work Domain Analysis (WDA) techniques.

WDA techniques were used to capture the negative effects of increased communication delay on current space operations. Functions from current operations were extrapolated to future space operations to identify the major impacts and technological requirements in off-nominal situations under long communication delays. Previous work developed a functionality matrix and design requirements of a CA system[5]. Based on the previous work, this paper discusses a future collaborative decision-making process for a proposed ConOps for space missions beyond LEO.

This paper is organized as follows: The *Current Concept of Operations for Space Missions* section summarizes the collaborative work between space crew and Mission Control during current space operations and the impact of communication delays and off-nominal situations on this collaborative work. The *Development of Domain Knowledge Models* section explains the approach, and the WDA techniques used to develop the domain knowledge models of current space operations, and the breakpoints within the current space decision-making process when future space operations are extrapolated. The *Future Concept of Operations for Space Missions beyond LEO* section presents the proposed concept of operation and the role of CA within space crew for future space operations beyond LEO that explains how the envisioned operation would be performed by Mission Control, space crew and a Cognitive Assistant. Finally, the future work of research is introduced.

II. Current Concept of Operations for Space Missions

A generic decision-making process includes the following functions: (1) detection and assessment of the situation; (2) generation of decision alternatives; (3) definition of the criteria for evaluating alternatives; (4) selection of evaluation methods and tools; (5) assessment of the decision alternatives with the risk trade-off criteria (prioritization); (6) analysis results report with recommendations, impacts and corrective actions; and (7) choice of the best decision (process of elimination)[15, 16, 17]. This process ends with the selection of appropriate procedure for space crew from the range of procedures that have been developed to respond to known or predicted situations. In current space operations, Mission Control and space crew collaborate closely to make a decision.

While the collaborative decision-making process between Mission Control and space crew follows the generic decision-making process for all type of situations, the sub-functions of the functions listed above may differ between nominal conditions and off-nominal conditions. Under *off-nominal situations,* no procedures exist, and so new procedures have to be generated, assessed, and rapidly tested by Mission Control for the use by space crew[14]. Thus, off-nominal situations rely more on collaborative problem solving effort, where the decision-making process between

Mission Control and space crew involves detecting and assessing problems, defining the evaluation criteria for alternative decisions, evaluating alternatives based on risk trade-off, and selecting the best alternative decision[15, 16, 17].

Real-time (or near real-time) communication for this collaborative effort between Mission Control and space crew is key to the success and safety of space operations[13]. Maintaining real-time communication is major requirement for Mission Control to support the mission, enabling a tightly-coupled collaborative decision-making process between Mission Control and space crew[12, 13, 18]. When near real-time communication enables data sharing between the space vehicle and the Earth, Mission Control processes the information and data of the flight phases[13]. Much of the data generated and collected by onboard sensors are displayed to the flight controllers and subject matter experts at the mission control center. Information exchange enables the collaboration between space crew and Mission Control to monitor the data stream, detect and diagnose any off-nominal condition, and make decisions regarding the situations[13]. The onboard computer systems observe data to detect whether any parameter is out of the range of normal value. If any parameter is out of its normal range, this condition is detected by the warning systems, and its cause is diagnosed. Other than computer systems, data is also monitored by two members of space crew and Mission Control[13]. A problem can be detected by either Mission Control or onboard sensors. Once the out-of-limit condition is detected, the space crew has to find the information for troubleshooting from a large number of paper flight documents, and one crew member has to search for any off-limit information via computer systems. The troubleshooting not only requires space crew to detect and then follow the procedure, it also requires managing multiple steps of decision-making in real time with limited information access and poorly designed displayed information[13].

The communication delays would impede information exchange between Mission Control and space crew. The limited or delayed information exchange between Mission Control and space crew would interfere in the generation of possible alternative solutions[12]. This interruption on the collaborative work can be manageable by adapting established procedures regarding the changes in communication protocols during nominal operations in contrast to off-nominal operations. Since off-nominal situations requires more effort on the collaborative work than nominal conditions (e.g. detection and diagnosis to develop responses in real-time[4]), the interruption would not be easily manageable as in nominal conditions.

Because the time delay increases from an order of seconds for near-Earth distances to an order of tens of minutes beyond LEO distances[2], the space crew will increasingly be reliant on themselves and the on-board systems to respond to a situation. A communication delay of greater than 50 seconds for one-way disrupts nominal operations, and limits the ability to achieve mission success under current operational procedures[3]. The collaboration between Mission Control and space crew will be interrupted with a 5- and 10-minute communication delay during emergency. With a communication delay more than 20-minute, the operations and decision-making process must be modified, and the collaboration is limited to daily reports, recorded video streams, and daily crew/Mission Control coordination[3].

Under delayed-communication for long distance space operations, the collaborative decision-making process would be adapted to develop new procedures and protocols of communication. Therefore, the presence of CA system would fill the need of real-time collaboration during space operations to generate new procedures and simulate possible outcomes. Developing mixed-agent teams with automation and astronauts for space missions beyond LEO would be beneficial to maintain the collaborative work.

III. Development of Domain Knowledge Models

A. Methods

A systematic approach was used to ground the development of proposed collaborative decision making process between humans and an adaptive CA for space operations. This approach helps to extrapolate the concept of future operations from the domain knowledge of current space operations to future space operations with the condition of communication delays. In the first phase of the study, interviews were performed to capture the functions performed by the space crew, Mission Control and on-board automation during current operations in off-nominal events. The first phase is described in deatil in Tokadlı and Dorneich[5], and is summarized in this section. The understanding was augmented with a document analysis. Results of the interviews and document analysis captured the domain knowledge in Abstraction Hierarchies (AHs) and a Decision Action Diagram (DAD). From these domain knowledge models, a functionality matrix and the design requirements were developed for the design of CA[5]. Building upon this work, this paper presents the proposed concept of operation to propose the collaborative decision making process for future space operations. Figure 1 summarizes the approach used to develop the concept of operation. The gray-colored boxes were completed in the first phase and are summarized in this paper. A more detailed description of the first phase can be found in Tokadlı and Dorneich[5].

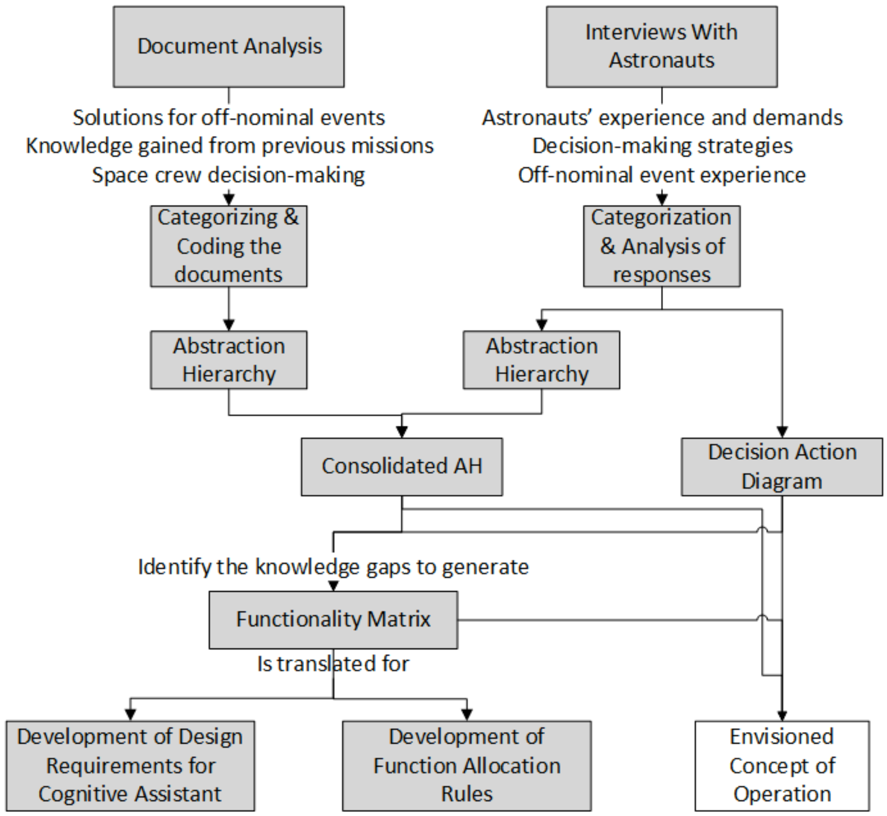

Figure 1: Approach on the development of CA design. Functionality matrix and design requirements were not the scope of this paper.

Document analysis and *Interviews* were performed to document current space operations and decision making processes, guidelines developed for each operation, the support systems used to respond to off-nominal events, and astronauts previous experiences in space operations. For document analysis, forty-three documents were gathered from NASA Technical Reports Server (NTRS). For interviews, two former NASA astronauts whose duration in space each exceeded 60 days, and a subject matter expert who is a former NASA Flight Director completed the interview. Interviews with astronauts had two parts: discussion of a case study, and discussions based on particpants' experience. For case study discussion, astronauts were asked to explain what actions they would perform, how they would have made a decision to proceed, the decision alternatives chosen, and what type of support they would have needed throughout the situation provided with the case. For experience-based discussion, they were asked to share their experience with any challenging situations from their time in space. Both discussions followed a similar flow to capture the same level of information.

Datasets of both document analysis and interviews with astronauts were analysed using Qualitative Data Analysis method to extract the cognitive functions of decision-making process. With this method, the documents and interview responses were examined in a systematic way to develop domain knowledge of current decision-making process in space missions. The knowledge of the work domain, available resources for crew decision-making, considerations for an off-nominal event, and the decision-making process of the crew were captured with in Abstraction Hierarchy (AH) and Decision Action Diagram (DAD) as *Domain Knowledge Models*. The DAD was reviewed by the SME and was updated accordingly. These models represent the functional structure and process of work domain[8,9] and portray the activity process (e.g. a storyboard, flow of an activity, and a process) in terms of decisions required to accomplish any task[11]. The categorization of cognitive functions on domain knowledge models was performed with the guide of modified prompting questions (developed by Naikar et al.[10]). This categorized information was then used to represent the decision-making process as a functional workflow by identifying the functions and actions taken, the decision points and the questions the crew asks to make a decision. Potential disruptions (labeled as breakpoints) of the space decision making process due to communication delay were identified.

B. Domain Knowledge Model of Space Operations

The domain knowledge models represent the domain knowledge of current operations, and the assessment of the impact of communication delay in off-nominal situations on collaborative decision-making process. This resulted in the identification of potential breakpoints in the collaboration between Mission Control and space crew[5].

Figure 2 represents the the functions of the decision making process for LEO missions, where Mission Control and the space crew collaborate in real time to address off-nominal situations. It can be used to evaluate current operations as well as to inform system design and procedure development[11]. The model describes the current interaction between Mission Control and space crew, and demonstrates the importance of real-time (or close to real-time) communication in order to maintain the information exchange and to support Mission Control guidance to the space crew during any task or operation. Mission Control has the major responsibility to develop decisions and solutions to deal with any situation. Each decision has to be assessed by Mission Control and simulated to understand the consequences before sharing with space crew. Under the condition of an off-nominal situation (t_{delay}<1.3 minutes), space crew proceeds based on Mission Control instructions. Mission Control diagnoses the situation, assesses the risks, and develops decision alternatives. If the established procedures do not meet the needs for the solution, Mission Control has to generate new procedure and test it in a timely manner to deliver it to space crew. Each action the space crew takes is reported to Mission Control for feedback to ensure that the new procedure is the correct solution for the off-nominal situation.

When the current decision-making process was assessed under the conditions of increased communication delay in an off-nominal situation, either space crew or Mission Control will not be able to or will be limited in their ability to perform some functions. Beyond LEO, the collaborative work between Mission Control and space crew will be interrupted in space missions. The interrupted functions shown in **Figure 2** have been marked with a lightning bolt and a dashed line. The impact of delay will start with the information exchange between space crew and Mission Control. Therefore, Mission Control will not be able to successfully assess the situation and the condition of space crew. This would cause operational difficulties for both space crew and Mission Control. For example, space crew will not be able to get the guidance of Mission Control in a timely manner. Space crew would have to diagnose the situation with the limited sources and equipment, to predict the risks for each alternative solution they consider, and to generate new procedure when established procedures cannot support them anymore. On Earth, Mission Control would have hard time to diagnose the situation, to develop alternative solutions, to assess the risks, to run prognoses, to generate new procedure, and to provide effective and timely guidance for space crew.

The interruption within the process may have negative impact on mission success and the safety of space missions. For example, in space missions beyond LEO, Mission Control may no longer play the primary role in problem detection. Thus it is porposed that a higher level of automated assistance may be needed to fill this gap, in the from of intelligent Cognitive Assistant to support the decision-making process. Understanding where current operations would breakdown under long communicaton delays will informs how to design a Cognitive Assistant to assist the space crew, and identify the responsibilities and functions of a CA. The next section will describe the development of a ConOps where a CA works the space crew and Mission Control in space missions beyond LEO.

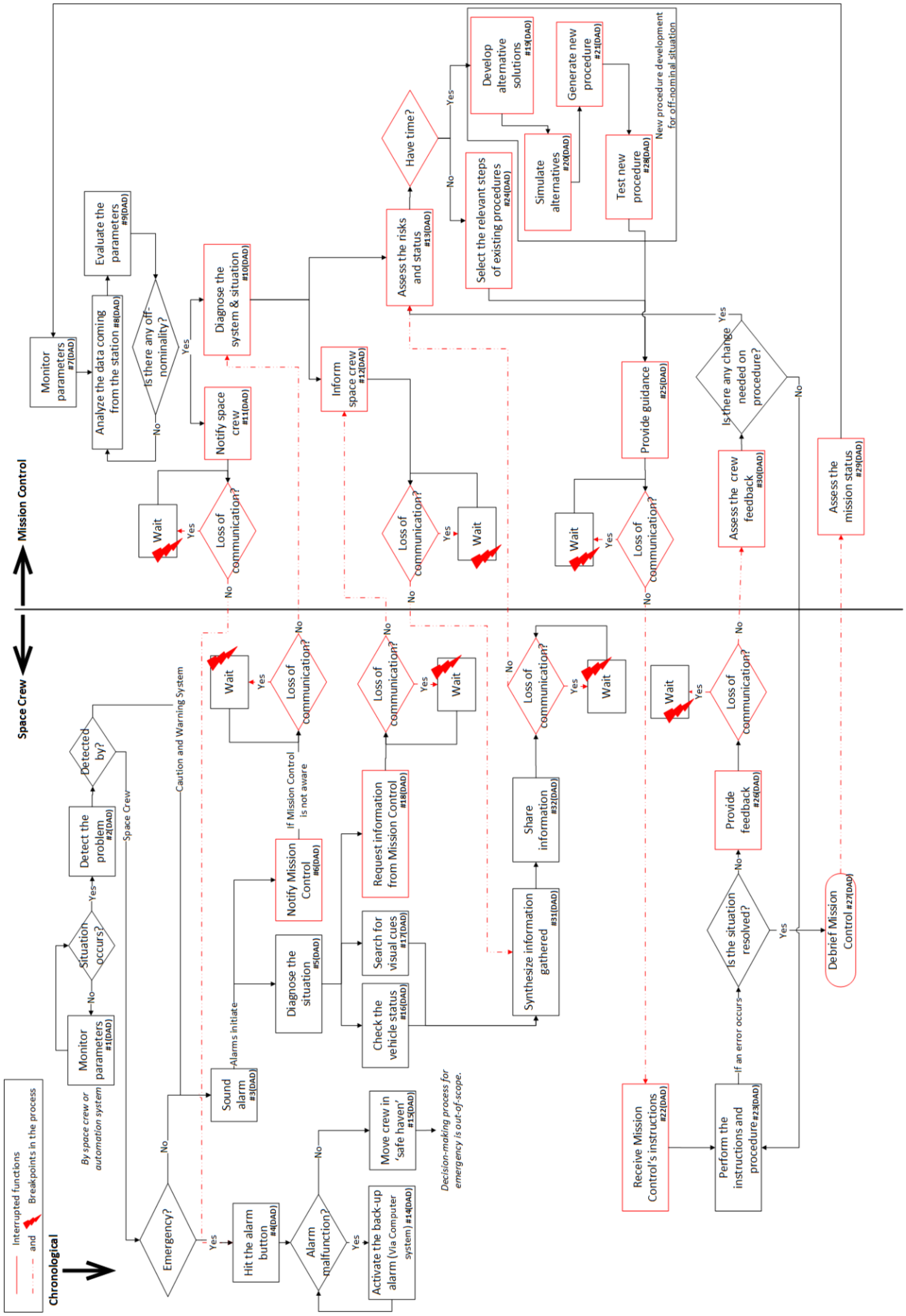

Figure 2: The current collaborative decision-making process of space operations (Decision-Action Diagram)[5].

IV. Future Concept of Operations for Space Missions beyond LEO

The increase on communication delays would cause limited ability to the collaborative decision-making process during space missions. Therefore, this project proposes the participation of an on-board adaptive cognitive assistant to support space crew while making a decision, specifically during off-nominal situations. With the participation of a Cognitive Assistant into the space operations, the current ConOps would need to be changed.

A. Methods

Future concept of operation were developed to improve new guidelines for Mission Control, space crew and CA interaction using the Domain Knowledge Models. These models informed the potential responsibilities and the role allocation between Mission Control, space crew and CA, as well as the processes they would perform. From the domain knowledge of current space operations, the future space operation were extrapolated by examining the impact of communication delay and off-nominal situations. Elements of the models were identified to highlight the interrupted functions (labeled as "breakpoints") on the current decision-making process under the condition of communication delay (t_{delay}>1.3 minutes). The process was then reviewed step-by-step to discover how the functions with breakpoints could be enhanced with a CA to provide essential mission guidance and support for the space crew. The process would be adapted by introducing an adaptive on-board Cognitive Assistant.

The presence of the CA on-board would change the current concept of operations. A diagram was developed to identify the authoritiy and major responsibilities of Mission Control, space crew and CA. The diagram also represents the proposed operational organization.

B. Concept of Operations

Figure 3 demonstrates the changes between current and future concept for space operations, and Table 1 lists the key numbers on the figure. For current operations, Mission Control performs the major amount of decision-making functions when an off-nominal situation occurs. They are responsible to develop and test alternative decisions for assisting space crew. Then, space crew can follow the newly established procedure to resolve an off-nominal situation. Nonetheless, the communication delay will interrupt this effort of Mission Control on decision-making process, and Mission Control would no longer have the complete authority. Consequently, space crew would seek guidance to make a decision to develop new procedure to cope with any off-nominal situations. To support the effort of space crew during space missions beyond LEO, a CA system would collaborate with space crew to perform cognitive functions (e.g. situation diagnosis, alternative decisions generation, risk trade-off, alternative decisions evaluation and assessment). An adapted collaborative decision-making process between space crew and CA would mitigate the impact of Mission Control guidance latency or absence in future space operations.

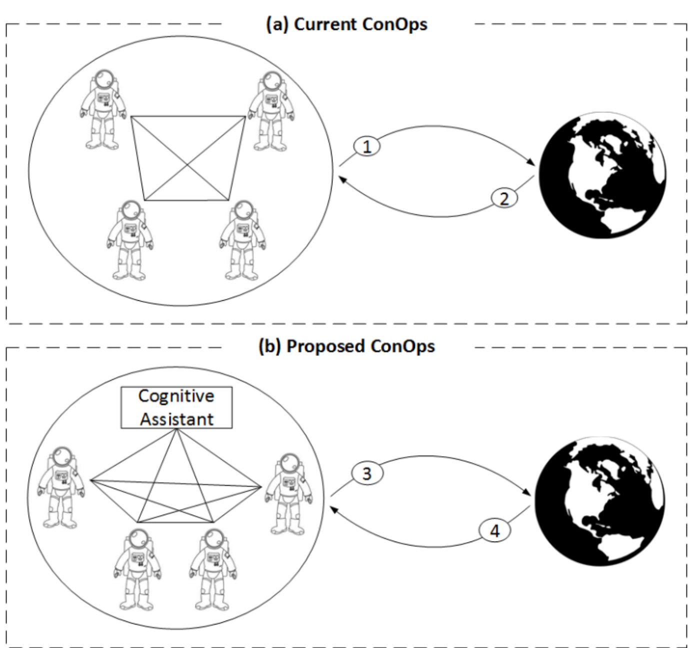

Figure 3: Current (a) vs. proposed (b) ConOps (see Table 1 for the key numbers).

Table 1: Functions that would change or be modified in the move from the current to a proposed future concept of operations.

	#	Mission Control	Space crew	Cognitive Assistant
Current Process (real-time collaboration)	1		Have the ability to - request the Mission Control's guidance, - share the situational information for Mission Control to make a decision together.	
	2	Have full authority to - monitor and analyze the data, - evaluate the mission status, - provide the guidance on challenging situations.		
Future Process (delayed communication)	3		Would have the authority to make final decision as the result of CA collaboration. Would collaborate with the CA to - analyze, diagnose and evaluate off-nominal situation, - develop alternative decisions, and - establish procedural steps.	Would collaborate with space crew to perform - situation detection, and - diagnoses, - notification of space crew (in real-time) and Mission Control (with latency). Would be able to - evaluate the situation data with space crew, - offers alternative decisions, - simulate the potential outcomes of alternatives, - establish the procedural steps with space crew, and - inform Mission Control by sending report of action.
	4	Would not have the authority to make the final decision during off-nominal situations. Would be able to monitor – analyze – evaluate mission data with latency.		

It should be noted that Mission Control and space crew will be able to maintain communication with a latency in space missions beyond LEO. Mission Control would be still capable of performing some functions of decision-making process (e.g. simulating alternative solutions (see #4 in Table 1)). But the latency involved with Mission Control's effort would impact the depth and timeliness of their contribution to the decision-making process. Additionally, off-nominal situations might include time pressure. Having time pressure in addition to communication delay would influence the role that Mission Control is able to play. Thus this proposed ConOps describes how the current ConOps would change the level of authority between Mission Control and space crew. The goals of changes in the ConOps are (1) mitigating the impact of communication delays on collaborative decision-making, (2) investigating the future needs on decision-making effort to deal with off-nominal situations, and (3) understanding the participation of Cognitive Assistant in team composition. The goal is for the effectiveness of real-time problem-solving process to be maintained with the collaboration of CA in space. For example, CA must be able to establish alternative solutions based on the information exchange with space crew as well as would be responsible to share operational information as a result of off-nominal situation with Mission Control. Thus, CA would be able to make risk trade-off by getting critical parameters from space crew, and to run prognoses to result the evaluation. According to the results of prognoses, space crew can select the best alternative solution.

Along with the proposed ConOps for space missions beyond LEO, the role of CA within space crew is also demonstrated in Figure 3.b. CA is considered to be a member of space crew that creates mixed-agent team for space missions. This team arrangement would enable space crew to consider the CA as an active partner while changing the team organization for future missions.

V. Conclusion

This overall research investigates how to mitigate the effect of communication delay and off-nominal situation for future space operations. An onboard adaptive CA system can be designed to collaborate with space crew to support decision-making efforts. It should be noted that the purpose of CA design is not to exclude Mission Control from the operational organization. Instead, it is to mitigate the negative impact of delayed Mission Control guidance, and enable the space crew to cope with off-nominal situations.

As the results of the development of domain knowledge models, it has been found that the current ConOps of space operations must be modified for space missions beyond LEO. This leads the changes on the level of Mission Control's authority and the team structure of space crew. The proposed ConOps in this paper shows the potential changes on Mission Control's role and responsibilities when supported by a CA. This concept was designed to describe the operational organization, and the adaptivity on Mission Control's authority level.

The mixed-agent team introduces the issues on the function allocation to define the system components and interface, and the design guidelines of human-automation interactions to perform efficient[19, 20]. To resolve this issue, the rules of function allocation and the validation methods must be developed. As future work of this research, the interaction and responsibility sharing between CA and astronauts will be developed and evaluated with CA prototypes.

Acknowledgments

We would like to thank our participants for their open discussion and information they provided. Any opinions, recommendations, findings, or conclusions expressed herein are those of the authors.

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