Control Authority Network Analysis Applied to Lunar Outpost Deployment

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Abstract—In order to return humans to the Moon, the Constellation Program will be required to operate a complex network of humans and spacecraft in several locations. This requires an early look at how decision-making authority will be allocated and transferred between humans and computers, for each of the many decision steps required for the various mission phases. This paper presents an overview of such a control authority analysis, along with an example based upon a lunar outpost deployment scenario. The results illustrate how choosing an optimal control authority architecture can serve to significantly reduce overall mission risk, when applied early in the design process. * †

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1. INTRODUCTION

In order for the Constellation Program to fulfill the President's Vision for Space Exploration, NASA will be required to simultaneously operate an increasingly complex network of humans and machines in several locations around the solar system, including Earth orbit, in-transit to/from the Moon, on the lunar surface, and eventually in transit to/from Mars and on the surface of Mars. Humans in all of these locations will depend on computers and robots to provide data, information, life support, and a variety of other critical functions. Managing this complex multi-mission and multi-element network represents a new challenge for NASA, which will have to leverage its experience in multi-mission robotic operations and single-mission human operations.

Advances in technology since the Apollo and Shuttle eras open up a large trade space regarding possible roles of humans and automation in the upcoming lunar missions. Therefore, it will be necessary to define a control authority architecture that defines the allocation and transfer of control authority among Constellation elements, between these elements and other space and ground assets, and between humans and machines. In this context, control authority is defined as *the allocation and transfer of operational control decision-making and control action initiation*. In other words, control authority refers to a definition of whom or what has decision-making authority during each mission phase, and under what circumstances that authority is transferred to another entity. The chosen control authority architecture can significantly impact the design of Constellation elements and missions, Constellation operations cost, and overall mission and program risk.

Control Authority Analysis (CAA) models the operations process from a control authority viewpoint, which includes: (1) Assigning functions, and the control thereof, to mission elements by mission type and operational phase; (2) Determining criteria, hierarchies, and processes for transfer of control authority among machines and humans in various mission elements; (3) Finding optimal architectures for the above. This study applies CAA to the deployment of a lunar outpost, modeling three simultaneous missions occurring at three distinct locations: one crew at an outpost on the lunar surface, a replacement crew in transit from Earth to the Moon, and a teleoperated/autonomous rover on the lunar surface conducting remote-site prospecting and science. Candidate control authority architectures are analyzed based on their impact on the probability of various mission outcomes (e.g., Loss of Crew, Loss of Mission, Degraded Science, etc.). Important in this analysis are the conditions under which the ground-based Mission Control Center or Moon-based outpost crew become saturated when multiple events occur simultaneously, particularly if these events are off-nominal. Finally, issues relating to crew sickness and fatigue are taken into account, due to the extended duration of the outpost missions. The result is an approach for determining an optimal control strategy for the example outpost scenario, along with sensitivities to various factors, which illustrate the benefit of a control authority modeling approach applied early in the design process.

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2. MOTIVATION

The Constellation program, in order to return people to the Moon, requires a number of different systems operating in several different locations. These elements include, but are not limited to, the Crew Exploration Vehicle (CEV), the Lunar Surface Access Module (LSAM), a Crew Launch Vehicle (CLV), a Cargo Launch Vehicle (CaLV), and several propulsive stages. Additionally, there are ground based systems, such as the Mission Control Center. Other existing elements may interface with the Constellation Program, such the Deep Space Network and the International Space Station. Finally, the destination surface systems include a habitat, surface mobility systems, power systems, robotic systems, and in situ resource utilization systems. Figure 1, from the Exploration Systems Architecture Study [1], illustrates graphically the number of different elements that may be operating simultaneously. From its inception, the Constellation program will be operating more robotic and human missions than any program ever before.

Communications and commands links will have to exist between these vehicles and with mission control establishments on the Earth, creating a network with a large number of possible telecommunications and command links. This situation multiplies complexity in several ways. The links will create multiple possible communications paths between any two vehicles, with different data rate capability, availability, reliability, and data latency. With humans and advanced computing resources available at a variety of locations, situation analysis and decision making can also occur at multiple locations, providing several potential sources of control authority. The trade space of control authority origins is multiplied by the number of possible network paths. The complexity of future operations also suggests the likelihood of states where one or more nodes would be subject to overload, creating chokepoints that could slow down the whole network. Finally, with many operating systems, the likelihood increases that at least one will be in an off nominal state.

Thus, for each spacecraft function or troubleshooting activity, there must be a primary and one or more back-up sources of control authority with multiple potential communications paths between them. This potential redundancy in control authority points represents not only a complex trade space, but also a control authority hierarchy problem. Careful trade analyses are required to realize the potential offered by the combination of resources.

In addition to the increased number of vehicles and locations, a significant number of other factors have changed since the Apollo program. First, the importance of crew safety and reliability has increased tremendously, along with an added emphasis on crew comfort [2]. Additionally, there is a desire for extensibility of current systems towards long-duration missions on the Moon and eventually on Mars [3]. It is therefore important to design early missions with these long-term goals in mind, in order

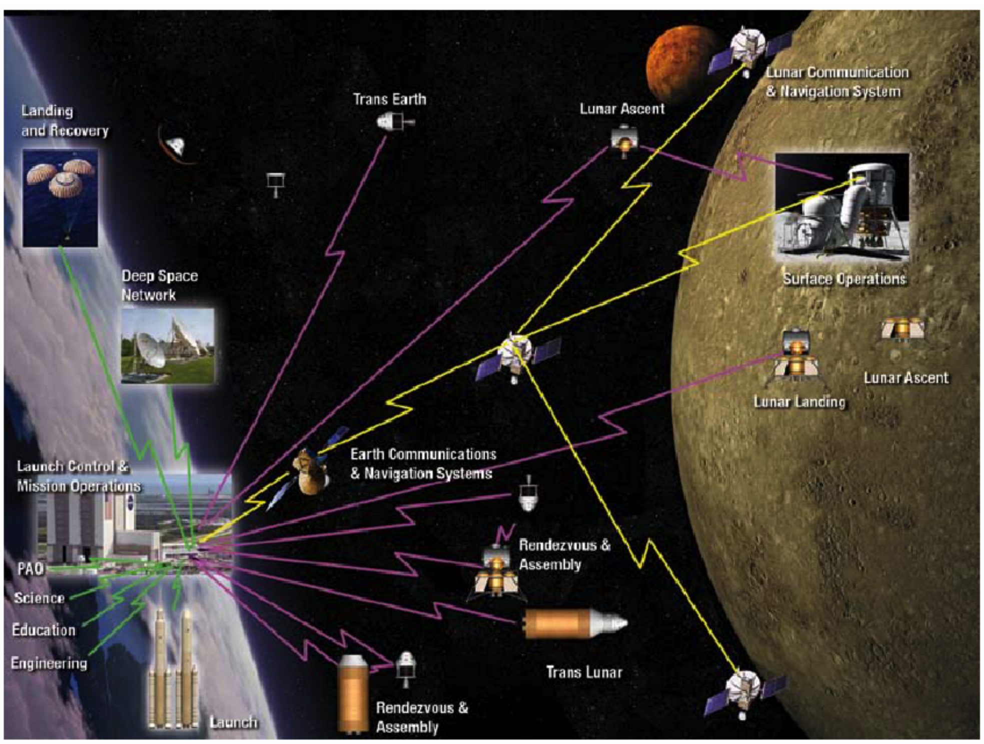


Figure 1: Constellation program mission operations communications overview.

to avoid major system redesigns down the road. Finally, there have been significant improvements in technology since the Apollo and Shuttle eras. While these improvements can result in increased reliability and decreased mass and cost, they also open up a large trade space of possible levels of autonomy and automation [4].

This set of new challenges therefore warrants a look at the system aspects of transfer of control authority among multiple Constellation program elements from an operational perspective early on in the system development life cycle. The resulting findings and recommendations can be employed to mitigate and manage operations related risks, develop effective and efficient operational requirements on the system design, guide implementation to address overall operations costs, and facilitate system verification and validation. The amplitude of what is at stake can be inferred from the fact that the Shuttle program saved 40% in yearly operations costs ($1.25B/yr) by careful redesign of its operations, including better use of new technologies [5]. The magnitude of the potential savings would only be multiplied for a multi-mission, multi-system network such as Constellation.

3. MODELING APPROACH

The purpose of this work is to demonstrate the importance of analyzing and optimizing the Control Authority Architecture early in the design process in order to mitigate risk and reduce overall program costs. A Control Authority Architecture embodies the set of rules that determine who or what is responsible for decision making during a mission, broken down by mission phase and operational element, and at what point that decision-making authority is transferred to another entity. The analysis presented here attempts to optimize the Control Authority Architecture to reduce overall mission risk. There are ten steps required to accomplish this analysis, as discussed below.

Step 1 – Operations Concept Framework

The Control Authority Analysis begins with the Operations Concept (OpsCon) Framework, illustrated in Figure 2, which provides an organized structure for development of the operations scenario. Each cell in the OpsCon framework represents a particular mission phase for a particular mission type involving a specific actor. These actors represent both humans and computers, such as the Mission Control crew, Mission Control computers, Flight Element on-board computers, Flight Element crew(s), and the telecom links between them. For example, in Figure 2, the highlighted cell represents the "Trans-lunar Cruise" Operations Phase, for a lunar sortie mission type, involving the Crew Exploration Vehicle (CEV). Other possible mission phases would include Earth ascent, Low Earth Orbit operations, and lunar descent/landing. Other possible mission types would include crew and cargo missions to the International Space Station, or cargo mission to the lunar surface. Each of the cells in the OpsCon framework would have to be analyzed to develop an overall mission-level Control Authority Architecture.

Step 2 – Functional Event Tree

Functional Analysis of a particular OpsCon cell leads to functional block diagrams representing the nominal sequence of events during a particular mission phase. As part of the requirements development process, the Constellation Program is currently developing Functional Analysis documents that describe the nominal functional steps to be carried out during each mission phase. The Functional Event Trees contained within Control Authority Analysis contain two types of failures. The first is what is

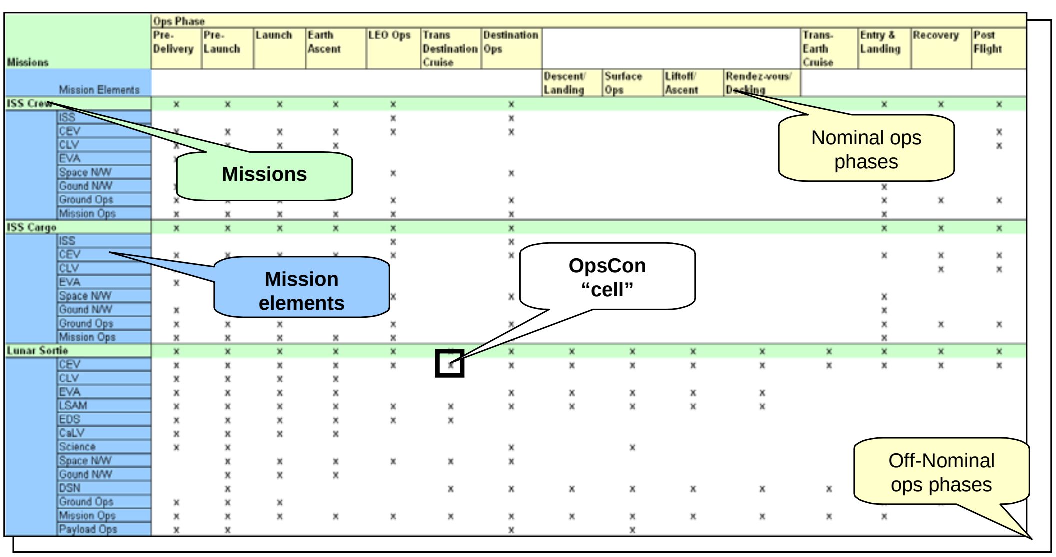


Figure 2: Example Constellation OpsCon Framework

generally found in Probabalistic Risk Assessment (PRA), which is due to hardware and software failures, with each possible type of failure having a corresponding probability of failure associated with it. The second, which is at the heart of Control Authority Analysis, is due to an incorrect decision being made. The probability of such a failure is specific to the chosen Control Authority Architecture, and will be explained in more detail in subsequent steps. Additionally, the Functional Event Trees capture the off-nominal function and events that occur as the result of a possible failure.

Figure 3 illustrates an example of a Functional Event Tree, again for the Trans-lunar Cruise OpsCon cell highlighted in Figure 2. The sequence of events is based on the current Constellation Program's Functional Analysis documents. In the event tree, the circles represent hardware/software failure events, with probabilities of success drawn from PRA. The rectangles represent decision events, with the probability of a correct decision being made dependent on the chosen CA Architecture. These can represent either nominal (NF) or off-nominal (ONF) events. Each of the decisions represents a function type, listed in the white boxes, such as "Navigation" or "Create Strategy." Each of the diamonds then represents a possible mission outcome, such as Loss of Crew (LOC), Loss of Mission (LOM), Degraded Science (DS), Loss of Science (LOS), etc. The total probability of a single path through the tree is the product of the probabilities of each event along the path. Therefore, the total probability of a given mission outcome is the sum of the probabilities of all the paths ending with that outcome.

Step 3 – Information Processing Network (IPN)

As can be seen from Figure 3, there are numerous decision events contained within a single mission phase. These decisions can be made by any of the actors listed above, or some combination thereof: computer or crew on the ground or on any of the flight elements. For the Trans-lunar cruise example, the possible actors are the ground crew, ground computer, flight (TLI) crew and flight (TLI) computer. Additionally, all of the possible nodes must be considered, where information is passed between actors and where the quantity and quality of that information may be affected. This includes the telecom links (data and/or voice) between the spacecraft and ground, as well as computer/human interfaces, such as displays and controls.

Each decision can be viewed as an information processing task, with distinct steps that rely on different types of information processing skills. These steps are the same regardless of the actual decision event in question. Observe, Orient, Decide, and Act (OODA) is a common framework used to describe the decision process when both humans and computers may be in the loop [7]. For this analysis, the decision process is broken up into seven steps [6], to better characterize the difference between humans and computers, and to include a confirming step, which is critical in human spaceflight operations:

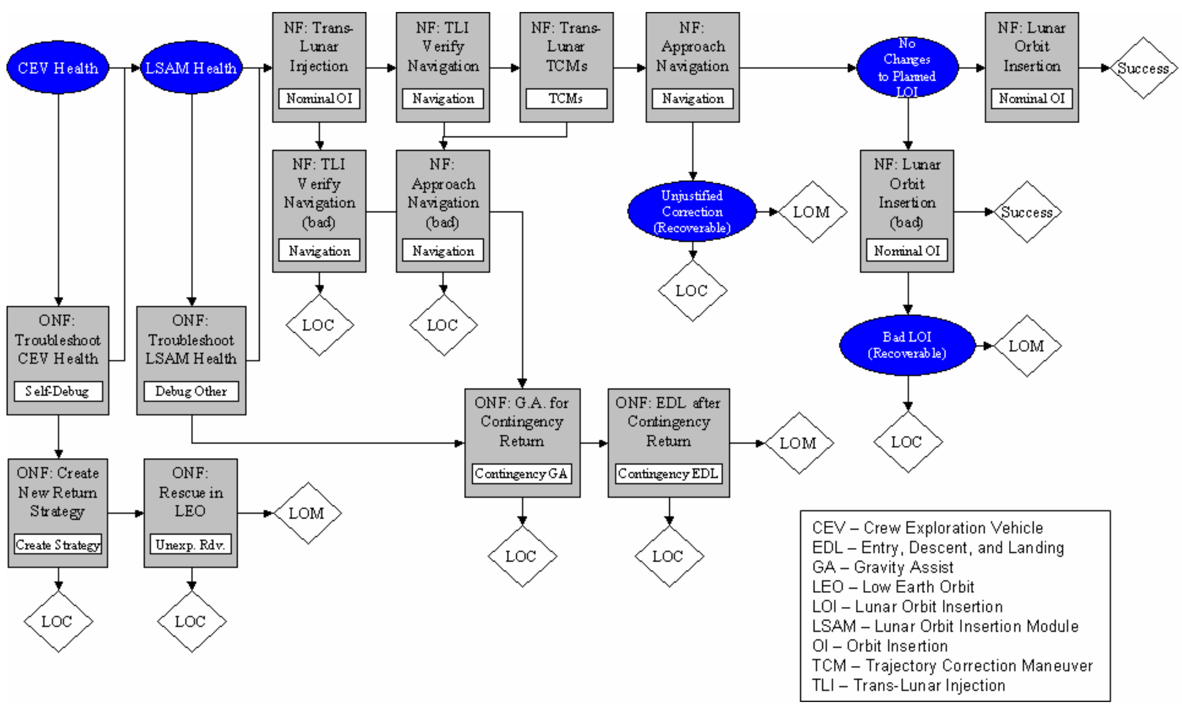


Figure 3: Functional Event Tree for Trans-lunar cruise example.

(1) *Sensing* information. This is a characteristic of the spacecraft design (sensors on board and their reliability). For some functions, the crew on board can sense some of the information.

(2) *Summarizing* the information, i.e. “number crunching”. This is an example of a step that computers perform very well and very quickly; by summarizing the information they can help reduce the amount of information that humans have to process.

(3) *Analyzing* the summarized information to extract trends and decision-support information. This task is different from summarizing as it requires trend-analysis, inferring and other “intelligent” deduction skills. Diagnosis algorithms might perform this well, but given sufficient time, humans are typically better at such tasks.

(4) *Deciding* on the course of action to take. This step could be merged with analysis. However, psychological factors could influence a human being in making the wrong decision even after properly analyzing the situation.

(5) *Confirming* the decision. For critical functions, operational concepts typically include a back-up decision maker. In particular, computer decisions often need to be confirmed by the human crew.

(6) *Commanding* the action. This step is mostly useful in modeling the control interface, e.g, the possibility of an error in the uplink command from ground to spacecraft, or of an inadequate design of the “joystick” a human crew could use to maneuver the spacecraft.

(7) *Executing* the action. This final step acknowledges that the information flow needs to end back at the spacecraft for action.

This sequence of decision steps makes up an Information Processing Network (IPN). Most of these decision steps can be performed by any of the actors, which leads to a very large number of possible paths through the IPN. Figure 4 illustrates the IPN for the Trans-lunar cruise example, with each of the possible actors, represented by circles (humans) and squares (computers), and each of the possible nodes, represented by triangles. One particular path has been highlighted in bold, beginning with the flight computer sensing some form of information, perhaps telemetry data. The raw data is then passed to the ground computer via a telecom relay. The ground computer then summarizes and

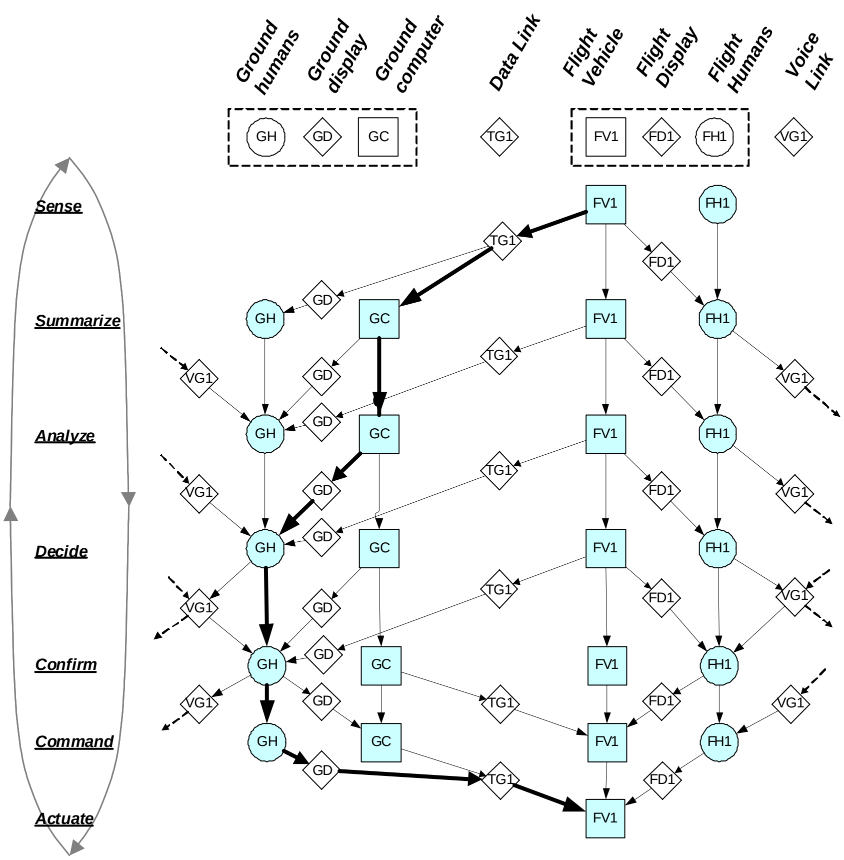


Figure 4: Possible paths through the Information Processing Network (IPN).

analyzes this data. The resulting information is displayed to the ground humans through a computer display, and the ground crew decides what action to take. In this example, no back-up confirmation step is shown, so the ground crew confirms its own decision. Finally, the ground crew sends the appropriate command, which is passed through the computer interface and data link to the flight computer. Finally, the flight computer acts on the specified command. Obviously, this is just one of many possible paths through the IPN, each of which will result in a different probability of making the correct decision depending on the time available to make that decision.

A detailed explanation of how these probabilities are calculated can be found in previous work by Morse et al [6]. In general, however, the following metrics are considered in calculating the probability of making a correct decision:

(1) *Information*. This includes the amount of information required for a specific function, the amount that is sensed by either the computer or human, how much the data is compressed during each decision step, and the amount of information needed to transmit the decision.

(2) *Computers as information processors*. The maximum data processing rate of computers depends on the technology generation, based on a Moore's Law equivalent. Additionally, the probability of a computer hardware failure increases with time.

(3) *Humans as information processors*. The maximum data processing rate of humans depends primarily on the level of training. Additionally, if humans do not perform a task or similar task, they will "forget" their training over time. The physical and psychological health of the crew also degrades over time, which decreases their data processing rate and ability to make correct decisions. Teamwork will increase the data processing rate, but will incur a team decision-making delay time. Finally, humans are better than computers at making decisions with incomplete information.

(4) *Data Transmission*. Telecom voice and data links have a maximum data rate for each link between any two elements. There is also a time delay per pair of elements, due to the light travel time between them. There is also some probability that an error can appear in either transmission, especially with voice links, or in displaying the data. As with humans and computers, there is also a failure rate for these elements as a function of time, due to hardware failure.

Step 4 – Find an optimal path in the IPN for each function

For each function type found in the Functional Event Tree (i.e., "Navigation" or "Create a New Return Strategy"), the process described in Step 3 allows each path through the IPN to be evaluated. This results in a probability of making the correct decision as a function of time available to make that decision. Figure 5 illustrates these results for five different paths for the two functions mentioned above. It is apparent from these examples that each path has a maximum probability of making a correct decision. Even with infinite time available, 100% probability of a correct decision is not possible. Each path, however, processes information at a different rate, so the optimal path is greatly dependent on the time available to make a decision, not on the maximum possible probability. Additionally, the two functions shown represent a nominal function ("Navigation") and an off-nominal function ("Create New Return Strategy"). It is expected that computers would outperform humans for nominal functions, while humans (with computer help) outperform computers in off-nominal situations.

It is also important to note that the time units are presented as "arbitrary time units" in both Figure 5 and subsequent figures. One of the current weaknesses of Control Authority Analysis is the difficulty in locating required data. Therefore, for the examples presented in this analysis, numerical assumptions are best estimates, determined mostly by the expected relative performance of each of the

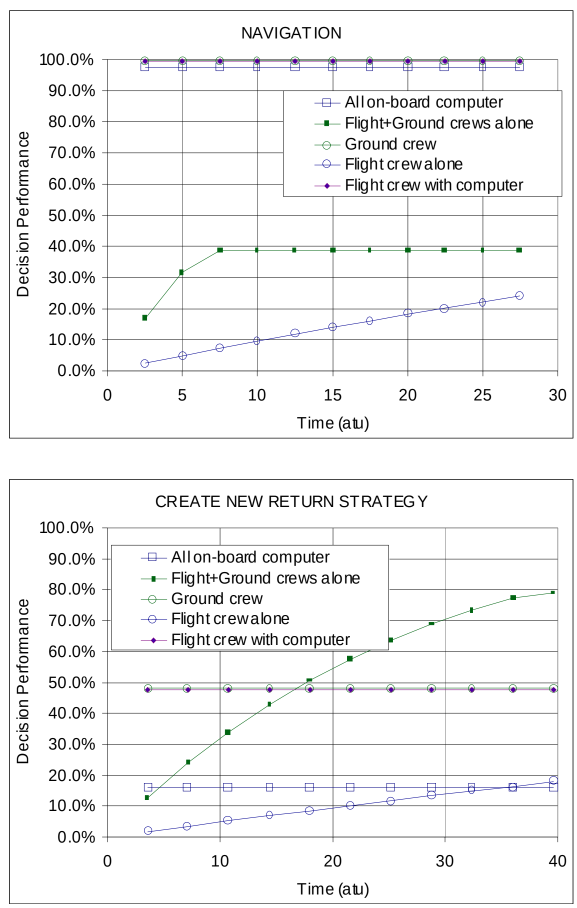


Figure 5: Example results of path analysis for two different functions.

actors and elements under consideration, as opposed to absolute performance values.

Step 5 – Narrow the set of optimal paths into candidate rule sets for each function

Results generated from Step 4 would indicate which control authority path would be optimal for each possible decision event within the Functional Event Tree. However, not all actors are 100% available, so back-up paths must also be considered. Additionally, the analysis will often result in multiple paths with similar performance, but this analysis does not consider any penalties due to transferring control authority too often between actors. Therefore, the evaluation of the individual paths should determine the best set of paths, instead of a single best option. These are termed *candidate rule sets*, which for each decision event in the functional event tree, allocate a *hierarchy* at each decision step, i.e. a nominal path and a set of back-up paths through the IPN. For the trans-lunar cruise example, four candidate hierarchies that form different rule sets are as follows:

(1) *"Ground Crew"*: Data is sent to the ground computer, summarized and analyzed for the ground crew, who makes the decision and sends the command.

(2) *"Flight Crew"*: The flight computer summarizes and analyzes the data, and the flight crew makes the decision and sends the command.

(3) *"No Computer"*: The flight crew transmits observations to the ground crew, who does the analysis and makes the decision; the flight crew actuates the command.

(4) *"Computer Only"*: The flight computer proposes the decision to the flight crew, who confirms.

Each of these candidate rule sets represents a different path through the IPN. The short-hand names have been given simply for clarity. Figure 6 illustrates the probability of a correct decision being made for each decision event during trans-lunar cruise, for each of the candidate rule sets. The probabilities shaded in green represent the best probability across all rule sets for that particular decision event. The four candidate rule sets encompass all of the highest probabilities for all of the decision events. Therefore, the optimal control authority strategy for this particular OpsCon cell would be to use the candidate rule set shaded in green for each decision event as the nominal choice.

Step 6 – Analyze candidate control authority rule sets across the whole mission phase

The probability of each possible mission outcome must now be summed by following all of the possible paths in the functional event tree from Step 2. Again the probability of success for each decision step is calculated based on Step 4, assuming a candidate rule set from Step 5. Figure 7 shows a portion of the functional event tree, with the probabilities overlaid based on the "Ground Crew" rule set. For the simple trans-lunar cruise example, only three mission outcomes are possible: Loss of Crew (LOC), Loss of Mission (LOM), and Mission Success (MS). Other mission phases may include other possible outcomes, such as Degraded Science or Loss of Science.

Figure 9 illustrates the nominal analysis results in terms of overall probability of the various mission outcomes. In this case, this represents the probablity of the mission resulting in a Loss of Crew (LOC) or Loss of Mission (LOM) outcome. The first four bars correspond to the given rule set used across all decision events. Both the "Ground Crew" and "No Computer" rule sets perform poorly due to the extra time required to transmit data, as well as data losses in the transmission. The "Flight Crew" rule set outperforms the "Computer Only" rule set due to humans' better

Function	Ground Crew	Flight Crew	No Computer	Computer only	Rule Set 5	Rule Set 6	Rule Set 7	Rule Set 8	Rule Set 9	Rule Set 10
Trans-Lunar Injection	99.6%	99.3%	38.9%	98.3%	99.6%	47.1%	94.6%	97.5%	98.4%	97.4%
TLI Verify Navigation (good TLI)	99.6%	99.3%	38.9%	98.3%	99.6%	21.4%	22.5%	97.5%	98.4%	97.4%
Trans-Lunar TCMs	99.6%	99.3%	38.9%	98.3%	99.6%	45.6%	47.9%	97.5%	98.4%	97
Approach Navigation (good approach)	99.6%	99.3%	37.2%	98.3%	99.6%	5.8%	6.1%	97.5%	98.4%	97.4
Lunar Orbit Insertion (good plan)	99.6%	99.3%	0.0%	98.3%	99.6%	9.3%	9.8%	97.5%	98.4%	97.4%
Approach Navigation (bad approach)	99.6%	99.3%	13.7%	98.3%	99.5%	2.0%	2.1%	69.5%	98.4%	97.4
Gravity Assist for Contingency return	99.6%	99.1%	38.9%	97.2%	99.5%	7.7%	8.1%	60.5%	98.2%	96.
EDL after Contingency return	0.0%	22.3%	0.0%	97.3%	96.6%	0.2%	0.2%	1.9%	22.1%	96.4%
TLI Verify Navigation (bad TLI)	99.6%	99.3%	38.9%	98.3%	99.6%	21.4%	22.5%	97.5%	98.4%	97.4%
Troubleshoot CEV Health	48.2%	47.6%	79.6%	22.3%	80.4%	21.2%	22.3%	46.8%	47.2%	22.1
Create new Return strategy	48.2%	47.6%	62.2%	19.8%	62.8%	11.2%	11.8%	46.8%	47.2%	19.6%
RdV for unplanned rescue in LEO	0.0%	91.0%	0.0%	59.4%	90.6%	0.2%	0.2%	12.2%	90.2%	58.9%
Lunar Orbit Insertion (bad plan)	0.0%	99.3%	0.0%	98.3%	98.4%	2.3%	2.4%	75.7%	98.4%	97.4%
Toubleshoot LSAM Health	48.2%	47.6%	38.9%	22.3%	48.2%	21.2%	22.3%	46.8%	47.2%	22.

Figure 6: Probabilities of correct decision being made for each decision event, for the candidate rule sets.

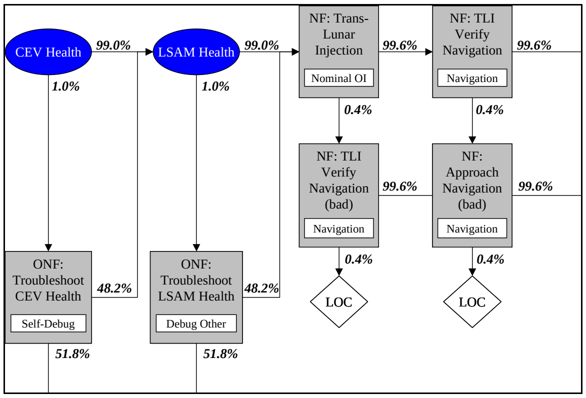


Figure 7: Trans-lunar cruise event tree with probabilities based on "Ground Crew" rule set.

performance in handling off-nominal situations. The last bar in Figure 9, however, illustrates that choosing the optimal rule set for each decision event can improve the probability of mission success, but more importantly, decrease the probability of loss of crew. This simple result begins to point at the importance of modeling and understanding the transfer of control authority throughout a mission.

Step 7 – Sensitivity Analysis

Once the optimal rule set for each function is determined, additional information can be gathered by conducting sensitivity or "what if" studies. Some examples of these sensitivity studies would be the level of computer technology and display quality, the availability and reliability of telecom relays, or the presence of crew on various flight system elements.

Figure 8 plots two sample sensitivity studies for the trans-lunar cruise example.Again, the plotted probability represents the probability of having a LOC or LOM mission outcome. Both plots represent the optimal rule set for each function in the event tree. The top plot illustrates how operational requirements could be derived by examining these "what if" scenarios. The first two bars compare

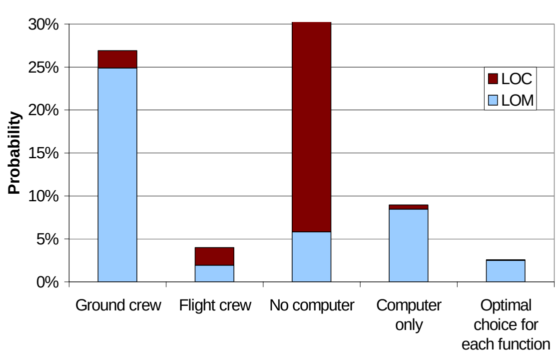


Figure 9: Results indicate optimal control authority rule set for the trans-lunar cruise mission phase.

whether the crew is in the lunar lander (LSAM) or the CEV during trans-lunar injection. Each of these spacecraft have different computing, display, and telecom capabilities, which result in a lower Loss of Mission probability if the crew are stationed in the CEV. Furthermore, from this study one could determine if the crew should be active or passive during trans-lunar injection and what the best use of ground personnel would be. The bottom plot illustrates the effect of technology advances on the overall probability of mission success. The results indicate that advancing technology is beneficial, but only up to a certain point, since other sources or error are still present that can not be addressed by improving technology.

Step 8 – Conclusions for each cell

After concluding the full analysis for a particular mission phase, as described in the above steps, an optimal control authority architecture can be defined. This architecture includes a primary rule set for each of functions in the event tree, along with a hierarchy of back-up rule sets. Additionally, it should provide criteria for transfer of control authority between the various actors.

Step 9 – Model a whole mission

Considering all mission phases in the analysis and

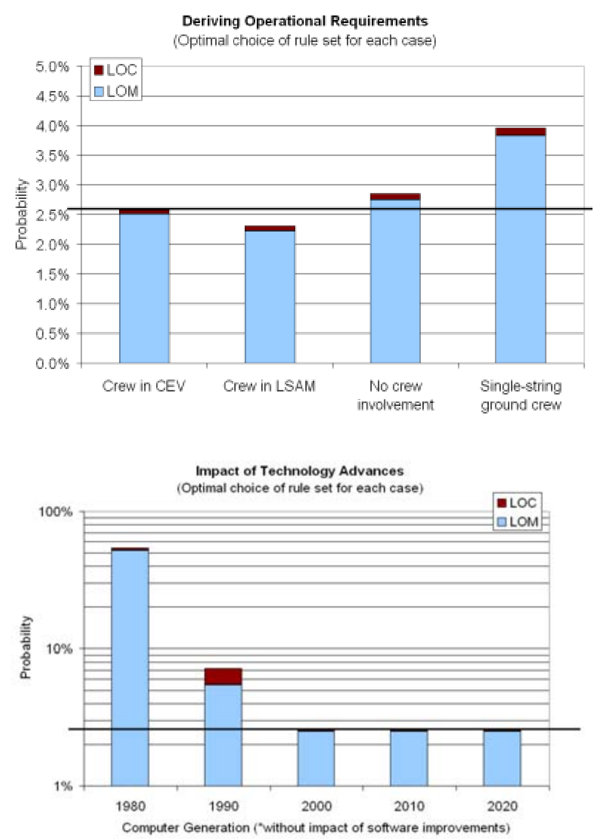


Figure 8: Sensitivity analysis helps determine effects of changes in ground personnel and technology.

accounting for time elapsed during the mission could result in a different answer than the one arrived at in Step 8. Previous work done on control authority analysis (CAA) has focused on analyzing single mission phases without the consideration to their place within the overall mission [6], similar to the results presented for the trans-lunar cruise example. This analysis, however, will expand these results to include some of the aspects that must be dealt with when considering an overall mission. When an entire mission is analyzed, there are certain mission phases that could occur simultaneously, which would make some of the actors either unavailable or overloaded with multiple tasks, thereby degrading their ability to arrive at a correct decision. Additionally, failures and degradations over time can increase the likelihood of failure. The flight crew in particular is susceptible to having their physiological and psychological health degrade. Humans also will tend to "forget" how to accomplish tasks if they have not been carried out for some time. Because of these factors, the optimal solution when considering an independent single mission phase may be different when it is considered within the mission context as a whole. Eventually, a full analysis would require a Monte Carlo (or similar) analysis.

Step 10 – Develop operational requirements

Ultimately, an analysis similar to the one described above would provide a means to develop cost-effective operational requirements that can flow down into vehicle design requirements, based on a solid understanding of the operational trade-offs, and of the mission risk impacts of the chosen architecture.

4. RESULTS

As mentioned above, the focus of this analysis is to expand the Control Authority Analysis to multiple simultaneous mission phases, while also considering "real" effects such as time elapsed and random failures. The mission under consideration is the build-up of a lunar outpost using migrating lander habitats, based on a concept proposed at NASA's Jet Propulsion Laboratory. The lunar outpost will nominally be constructed using mobile lander/habitats, which have the ability to migrate thousands of kilometers from their original landing sites to the outpost location near the lunar South Pole. Once four landers have been assembled at the outpost site, six month crew rotations will begin. A crew of four will be located at the outpost, while the replacement crew is in-transit from Earth. Simultaneously, other landers will be conducted prospecting and science at diverse locations on the lunar surface. The three mission phases under consideration are as follows:

(1) *Outbound cruise from Earth to the Moon*. Trans-lunar injection will take place using the EDS propulsive stage. During trans-lunar coast, the CEV and LSAM are required to perform navigation and guidance functions, attitude control, and mid-course correction burns. Health status will be monitored and reported for both the CEV and LSAM. Finally, the LSAM will conduct the Lunar Orbit Insertion (LOI) burn.

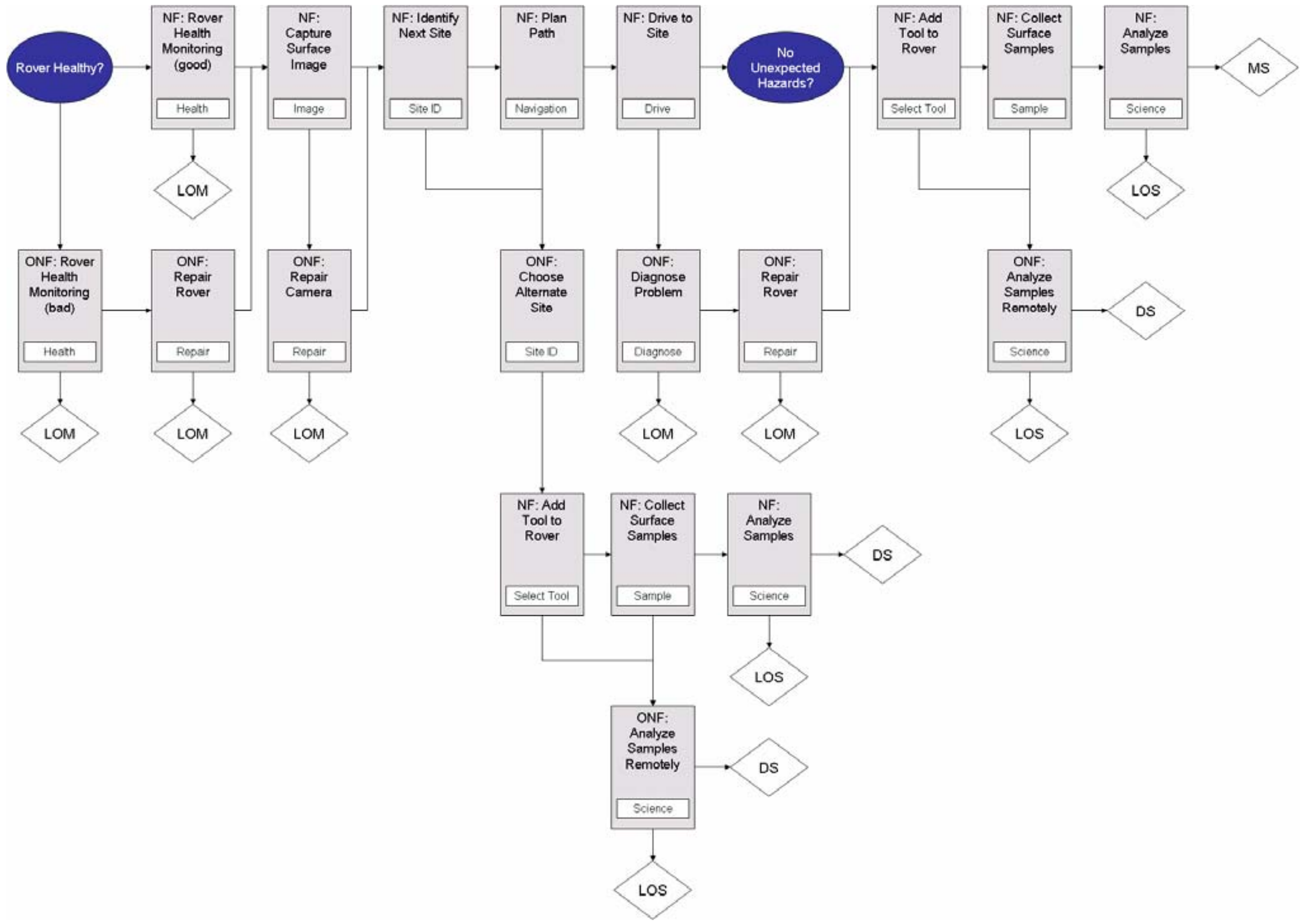
(2) *Crew surface operations at outpost site.* The crew will be responsible for a number of daily functions at the outpost site, including outpost maintenance and repair; crew health monitoring; monitoring, planning, and conducting science activities; and preparing for and conducting extra-vehicular activities (EVAs). For this analysis, the EVAs will use long-distance rovers to conduct science at sites far from the outpost.

(3) *Remote site prospecting by autonomous/teleoperated rovers*. An unmanned lander located at a remote site will conduct surface science and prospecting at sites of interest, either pre-determined or chosen en route. During nominal operation, the mobile lander must be able to plan its path, evaluate its progress, and re-plan its path in order to avoid obstacles and arrive safely at its desired science site.

The outbound cruise from the Earth to the Moon is the same as the example presented in the Methodology section. For the other two mission phases, analysis was also conducted on these phases independently, by creating an event tree and determining candidate rule sets for each, using the same method explained above. As was the case for the outbound cruise example, numerical assumptions are placeholders based on the best available estimates. Again, arbitrary time and data units were used.

The event trees for the mobile rover and the crewed outpost operations are presented in Figure 10. The events were also based off of the Constellation Program's Functional Analysis documents, with events added as needed (particularly for the off-nominal cases). Nominally, the rover examines its health status, selects a science site, plans and executes its path, and conducts science on surface samples. Off-nominal functions include repairing the rover, choosing an alternate science site or path, or analyzing surface samples remotely. The crew at the lunar outpost nominally monitors the habitat and crew health, prepares for EVAs, and conducts EVAs using lunar rovers. Off-nominal cases would include diagnosing and fixing problems with the crew health or habitat, rescuing stranded EVA crews, or aborting from the lunar surface.

For each function found in the event trees, possible paths through the Control Authority Network were then analyzed. Figure 11 illustrates the performance of four candidate paths for the off-nominal rover function *Repair Rover,* as an example. The chosen paths correspond to the same four paths that were analyzed previously for trans-lunar cruise mission phase, which were also among the top-performing candidate paths for the additional two mission phases being



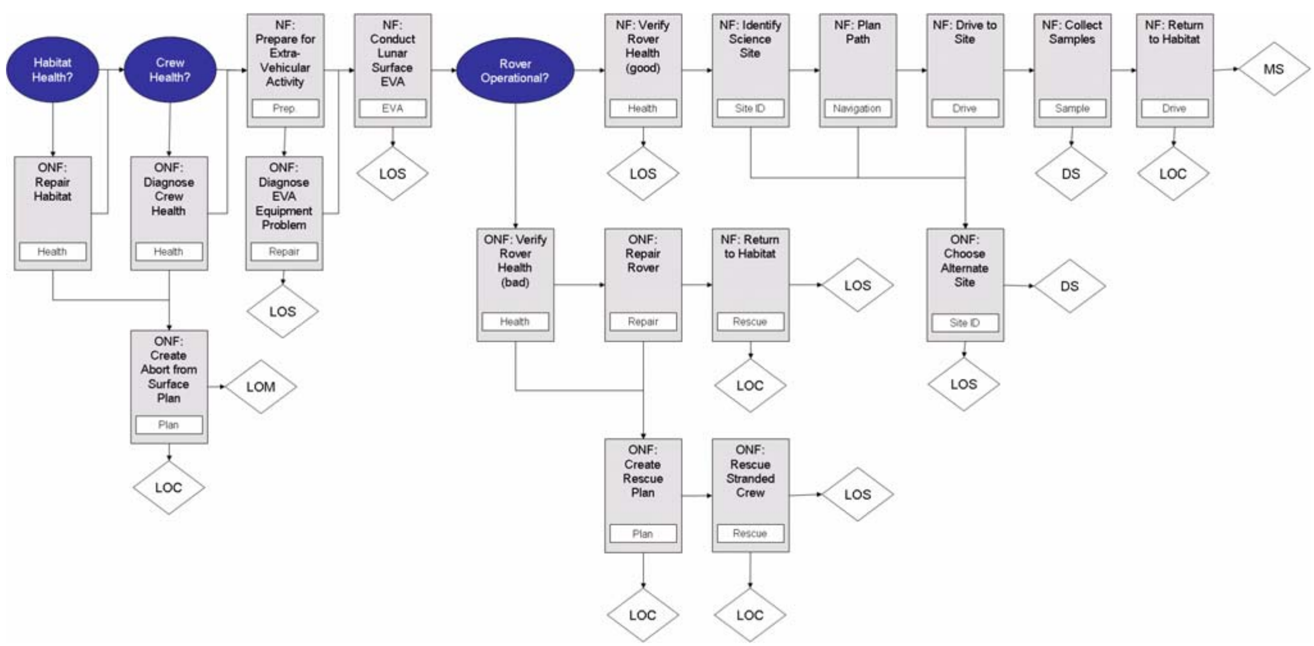


Figure 10: Functional Event Tree for remote rover operations (top) and crewed outpost operations (bottom).

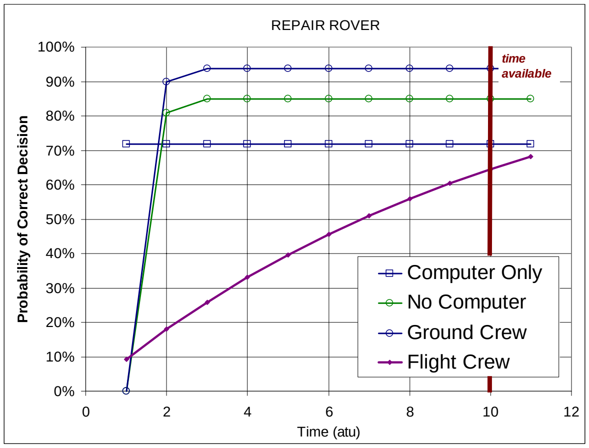
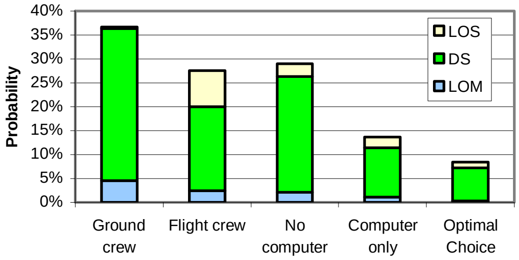


Figure 11: Performance of various CAN paths for "Repair Rover" function.

analyzed. For the rover mission phase, because there is no rover crew, the flight crew refers to the crew at the lunar outpost, while the flight computer refers to the rover computer. While there is also a lunar outpost computer, it was not considered as a possible actor in this example. The ground crew still refers to the crew on the Earth. As expected for an off-nominal function, humans have better performance at successfully arriving at a correct decision, if given sufficient time. The "Computer Only" rule set has essentially constant performance over time, but the maximum performance capability of the various crews exceeds that of the computer.

Based on analyzing the performance of the chosen paths for each of the functions in both mission phases, the overall probabilities of various mission outcomes could be determined. Figure 12 illustrates these resulting probabilities for the remote rover and outpost crew mission phases, if each is considered independently. As can be seen, there are now two new possible mission outcome: Loss of Science (LOS) and Degraded Science (DS) for the rover and outpost operations. Obviously, there is no potential for loss of crew for the autonomous/teleoperated unmanned rover. Surprisingly, the best single rule set for the outpost operations is the "Flight Crew" rule set, not the "Computer Only" as with the other two mission phases. This is due to humans handling off-nominal situations better than computers, as has been seen several times.

The results in Figure 12, however, were generated by analyzing a single OpsCon cell independently and without considering its place within the overall mission timeline and framework. One of the key drivers for an actual outpost mission is the significant time that a crew spends on the lunar surface, which can lead to fatigue, sickness, and "forgetting" their skills. Therefore, the longer a crew goes without conducting certain tasks, the greater probability there is of a particular task resulting in a failure. For the



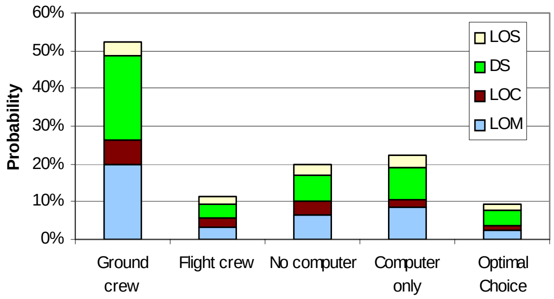
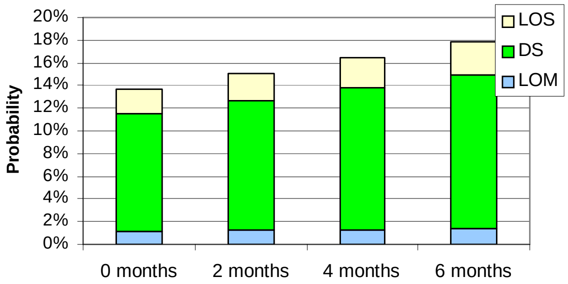


Figure 12: Control authority rule sets applied to lunar rover (top) and lunar outpost crew (bottom).

lunar rover, the probability of mission failure will also increase over time, even though a computer does not "forget" its training and skills. This increased failure rate is not due to an increased probablity of making an incorrect decision, but instead is a result of the hardware failure rate.

Figure 13 illustrates how the probability of failure increases over time for the lunar rover mission phase for two different rule sets. In the top plot, the "Computer Only" rule set is considered. The failure rate of the rover computer is approximately linear, thereby resulting in a constant, steady decrease in mission reliability. In the bottom plot, the "Flight Crew" rule set is considered, to illustrate how the performance of the crew's decision-making capabilites degrades over time, up to the full six months at the lunar outpost. Unlike the "Computer Only" rule set, the decrease in reliability is no longer linear. This degradation is due to several factors. First, human health and psychology tends to deteriorate over time (although this is not the case for the ground crew). Second, humans tend to "forget" some of their skills and training if not practiced often. The time elapsed in Figure 13 assumes that amount of time has passed since the last time the flight crew operated the rover. Otherwise, the decreased reliability would not be as dramatic. Finally, there is a natural degradation in the reliability of the telecom relays and displays that the crew must use to remotely operate the rover. All of these factors combine to result in a significant decrease in reliability for the flight crew-operated rover over time. When the same analysis is conducted on the lunar outpost mission phase, however, the decrease in reliability for the "Flight Crew"



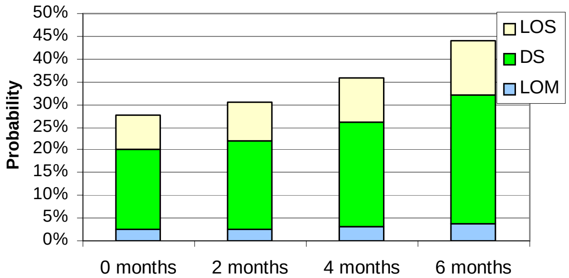


Figure 13: Degradation in reliability over time for the lunar rover mission phase, based on the "Computer Only" rule set (top) and the "Flight Crew" rule set (bottom).

rule set is not nearly as significant. This is because the flight crew is likely to be conducting the same tasks on a daily basis. Therefore, the only degradation is due to health reasons instead of "forgetting" their skill sets.

These results point to the importance of keeping the skill sets of the flight crew up to date, in case off-nominal situations require them to conduct tasks that they normally would not be responsible for. Therefore, even if a computer only rule set appears optimal for a single instance in time, it may be beneficial to keep the crew in the loop so that later in the mission they will be prepared to take over operational control if necessary. After a long duration mission, however, the crew will still suffer from physical and psychological degradation, implying that the "Flight Crew" rule set should be lower on the control authority hierarchy later in the mission. For example, the lunar outpost crew should have little involvement during the trans-lunar operations of their replacement crew, since they will already be six months into their lunar mission. The control authority architecture must therefore be dynamic in time, to account for different failure and degradation rates of the various actors within the architecture.

Finally, the possibility of saturation must be addressed, if several decision events must occur simultaneously using the same rule set. This is where the control authority hierarchies become important. If just a single rule set were used for each decision event, there would be instances where the ground crew, for example, would be required to

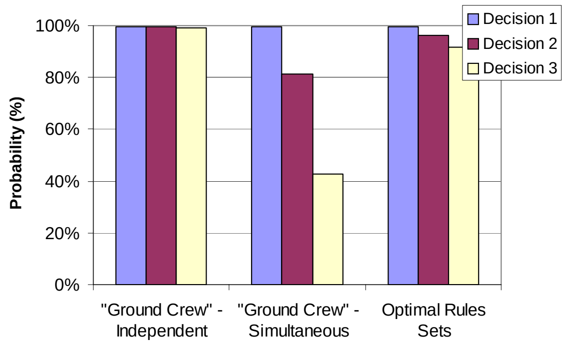


Figure 14: Probability of correct decision being made for three simultaneous decision events under three different analysis scenarios.

tackle three decisions simultaneously. This would be a daunting, if not impossible task, particularly for off-nominal decision events. Additionally, the decision events must be given priority if all of the resources were to become saturated. Therefore, a decision event that could lead to loss of crew if an incorrect decision were made must be given priority over a decision event that may only lead to degraded science on the lunar surface. Figure 14 illustrates the importance of establishing control authority hierarchies when multiple decision events are occurring simultaneously. In this case, the following decision events are considered, listed in priority order:

(1) TLI Verify Navigation (*outbound cruise*)

(2) Diagnose EVA Equipment Problem (*outpost crew*)

(3) Select Path (*rover migration*)

The first set of bars in Figure 14 - labeled "Ground Crew" Independent - illustrates the overall performance of the three decision events using the "Ground Crew" rule set, when each event is considered independently. Each decision event is analyzed separately, and using the "Ground Crew" rule set, the probability of making a correct decision is nearly 100%. This would be the correct analysis approach if each event actually occurred at distinct moments in time, and the ground crew could devote their full attention to making the correct decision for each particular event.

The next set of results - labeled "Ground Crew" Simultaneous - indicates the performance of the decision events when all three decisions occur simultaneously, again using just the "Ground Crew" rule set for all decisions. Therefore, the decision event with the highest priority uses all of the ground crew resources necessary to make a correct decision with the highest probability. The remaining resources are then allocated to the next highest priority decision event, and then finally to the third highest priority decision event. The "TLI Verify Navigation" decision event still has the same probability of success as when considered independently, because it uses as many resources as needed. The probablity of success of the remaining decision events decreases, however, since the necessary resources on the ground are no longer available, and these decisions must be made with a limited set of available actors and information processing capability. Furthermore, the telecommunications links can only handle a certain data rate, so data for the second and third decision events may be incomplete or take longer to reach the ground. This set of results illustrates the importance of having multiple rule sets for each decision event. Although a back-up rule set for the "Diagnose EVA Equipment Problem" decision event may have a slightly lower probability of success than the "Ground Crew" rule set (when considered independently), it will likely have a higher probability of success than using a partially saturated ground crew that is busy with a more important decision event.

The last set of results in Figure 14 - labeled "Optimal Rule Sets" - illustrates the rule sets for each decision event that maximizes the overall reliability of each decision, when all three decisions occur simultaneously. The "Ground Crew" rule set is still used for the first decision, but control authority has now been transferred to back-up rule sets for the other two functions. This serves to significantly increase the overall probability of success for the three decision events over using just the ground crew, by preventing saturation of any one resource. These results further emphasize the need for dynamic rule sets, as presented earlier. Each actor must be able to communicate when they are becoming saturated with a more critical decision event, so that transfer to another rule set can occur. Furthermore, the procedures must be in place so that this transfer can occur quickly, so as not to jeopordize mission success.

5. Conclusions

This work has illustrated the importance of considering control authority rule sets, hierarchies, and architectures early in the design process to significantly mitigate risk. These optimal rule sets must be determined early on, in order to establish the operational requirements that influence the design of the spacecraft, as well as ground and telecommunications assets. Money can be saved by making these decisions before significant spacecraft and architecture redesign would be required. Therefore, the Constellation Program should adopt such a design and analysis approach, as was presented in this paper, which integrates traditional system-centered techniques with early introduction of human factors and operations perspectives via operational scenarios. This will help the program address and meet the inherent system complexities and the constraints and opportunities it faces. This will be critical as more infrastructure elements are added to the architecture and more spacecraft must be operated simultaneously throughout the solar system.

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Biography

Kristina Alemany is a graduate research assistant in the Space Systems Design Lab at Georgia Tech. Her research while at Georgia Tech has focused on the conceptual-level modeling and simulation of lunar transportation architectures, and on Mars entry, descent, and landing. She is currently working on her PhD in Aerospace Engineering, focusing on low-thrust trajectory optimization. She received her M.S. in Aerospace Engineering from Georgia Tech in 2005 and her B.S.E. in Mechanical and Aerospace Engineering from Princeton University in 2003.