Active Mission Success Estimation through PHM-Informed Probabilistic Modelling

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ABSTRACT

Prognostics and Health Management (**PHM**) techniques have traditionally been used to analyze electrical and mechanical systems, but similar techniques can be adapted for less mechatronically-focused processes such as crewed space missions. By applying failure analysis techniques taken from PHM, the probability of success for missions can be calculated. Extensive work has been conducted to predict space mission failure, but many existing methods do not take full advantage of modern computing power and the potential for real-time calculation of mission failure probabilities. The Active Mission Success Estimation (**AMSE**) method is developed in this paper to track and calculate the probability of mission failure as the mission progresses, and is intentionally adaptable for shifting mission objectives and parameters. This form of mission modelling takes a broader view of the mission and objectives, and develops statistical probability models of success or failure for multiple possible choice combinations that is used to inform real-time decisions and maximize probability of mission success. A case study of a generalized crewed Mars mission that has turned into a survival scenario is considered where an astronaut has been left behind on the surface and must survive for an extended period of time before undertaking a long-distance journey to a new launch site for rescue and return to Earth. The AMSE method presented here aims to establish real-time probabilistic modeling of decision outcomes during an active mission and can be used to inform mission decisions.

1. INTRODUCTION

Risk analysis and space exploration have a long and intertwined history of development. With initial modern rocket efforts of Goddard (Goddard 1920) and others, and the start of the Second World War, the space exploration era and risk analysis of complex systems both began. During the space race between the Soviet Union and the United States of America, tools such as Probabilistic Risk Assessment (**PRA**) (Kumamoto, Henley, and J 1996) were developed to closely examine complex system risk in a probabilistic and quantitative manner. Recently, a renewed focus on understanding risk during the early design phases of complex systems has received special attention (Douglas Lee Van Bossuyt 2015; Douglas L Van Bossuyt 2013; Douglas Van Bossuyt 2012; Van Bossuyt, Tumer, and Wall 2013). However, relatively little work has been done to develop real-time risk-informed decision support tools for missions that are actively occurring. Current risk modeling and analysis methods require significant adjustment and reanalysis when an unforeseen event occurs that can delay critical risk information during a rapidly developing scenario.

By changing the way the mission is modelled and analyzed to be more modular and actively recalculating risk as the mission progresses, the probability of success can be more accurately estimated and decision points with many multiple options can be analyzed to help inform mission command decisions to increase probability of mission success. This paper presents the Active Mission Success Estimation (**AMSE**) method that provides timely risk information to inform decisions being made in crisis situations with rapidly evolving circumstances.

Performing AMSE requires that all critical components of the mission be modelled thoroughly and modularly to enable rapid rearranging of model elements to evaluate potential decision outcomes to estimate mission success probabilities. To effectively represent the mission, a novel form of functional modelling was developed where environments nest around the system of interest and are used to determine what hazards are present in the environment that can damage the system. Mission tasks are then developed and analyzed by configuring tasks to represent both internal and external system risks including the effects of the nested functional modeling environment. For the purpose of this paper, a case study is considered of a

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single astronaut attempting to survive alone on Mars until rescue can arrive (Weir 2011), where the single astronaut is the system of interest.

1.1. Specific Contributions

This paper contributes the novel AMSE method for real-time assessment of risk during a mission using PHM techniques and functional modelling to provide decision-makers with immediate and up-to-date risk information during critical decision points. The AMSE method utilizes a novel form of nested functional modelling to analyze the effects of various layers of environmental protections. These protections could either protect the subject directly or be layered around each other. In the case study the effects of various environmental protections such as a permanent base, a passenger rover, or an Extravehicular Mobility Unit (**EMU**) were considered. AMSE provides quick and active estimation of current mission success, as well as projecting probable success based upon potential decision options. Through the active analysis of mission success probability during important decision points, the probability of success for the mission can be maximized. Additionally, the modular nature of AMSE allows for quick adaption to unexpected mission parameters. While AMSE was developed with space mission applications in mind, it could easily be adapted to analyze any complex system.

2. BACKGROUND

AMSE relies upon several topics including PHM techniques, decision theory, and functional modeling. Traditional mission success estimation relies upon difficult to configure methods such as Probabilistic Risk Assessment (**PRA**) (Modarres, Kaminskiy, and Krivtsov 2011), (Mohaghegh, Kazemi, and Mosleh 2009) or Worst Case Analysis (**WCA**) (Ye 1997), (Nassif, Strojwas, and Director 1986). PRA, WCA, and related techniques are very successful in analyzing potential foreseeable failure scenarios but have difficulty in situations where rapid reconfiguration of the model is necessary in unanticipated rapidly changing situations, such as those faced by the astronaut in the hypothetical case study presented in this paper.

2.1. Space Mission Engineering

Space mission engineering is the process of establishing and refining mission parameters in order to reach broadly defined mission objectives (Wertz, Everett, and Puschell 2011b). Generally, space mission engineering aims to reduce time, cost, and risk associated with a space mission. One long-standing issue facing space mission engineering is the Space Spiral phenomenon where increasing cost of missions leads to longer mission schedules and reduced new mission frequency that leads to a higher demand for mission reliability that in turn leads back to a higher mission cost. This leads to ever-increasing expenses and timeline delays for many space missions. One way that the Space Spiral can be combatted is by reducing the amount of time and energy that goes into the space mission engineering process through development of new techniques that can reduce time and decrease risk, leading to lower costs.

2.2. Functional Modelling

Functional modelling describes a variety of techniques used to represent the function of a system, often including many sub-functions representing work done in the system on flows that represent energy, material, or information passing between and being transformed by functions and sub-functions. In addition to internal flows, input and output flows enter and exit the system boundaries. One popular form of functional modelling is Flow Block Diagrams or Functional Flow Diagrams (**FFD**) (Blanchard, Fabrycky, and Fabrycky 1990), (Böhm and Jacopini 1966). FFD is very good at modelling systems where there are direct linear flows between various functions and a clear system input and output exists. However, many existing methods of functional modelling suffer when the system is less linear, leading to tangled networks of flows and functions that are impractical to analyze or provide an inaccurate representation of the reality of a situation. Recently work has been done on the development and modelling of systems to model failure propagation through uncoupled systems (O'Halloran, Papakonstantinou, and Van Bossuyt 2015). Uncoupled failure propagation refers to systems where failure can be exported from one sub-system to another sub-system through three-dimensional space instead of being limited to propagation along system flows.

2.3. Space Mission Risk and Success Assessment

Space mission risk assessment can take many different forms, each having its own advantages and disadvantages, but generally risk assessment techniques tend to build on a foundation of probabilistic modelling. One method for risk estimation is the use of a hazard rate, λ, in an exponential distribution, Eq. (1), to calculate the expected survivability rate of a space mission (Wertz, Everett, and Puschell 2011a).

$$S(t) = e^{-\lambda t} \qquad (1)$$

The expected survival can then be determined to find the expected failure rate function, Eq. (2).

$$F(t) = 1 - S(t) = 1 - e^{-\lambda t} \qquad (2)$$

While the failure rate or a related function appears in many risk assessment methods, many additional complex techniques for evaluating risk of failure to a system exist. One example is the Failure Flow Identification and Propagation (**FFIP**) method (Kurtoglu, Tumer, and Jensen 2010; Kurtoglu and Tumer 2008) that uses a function block diagram (Stone and Wood 2000) structure and analyzes how failure flows through a system. This technique can be enhanced to enable mission control and autonomous decision making through the application of Failure Flow Decision Functions (**FFDF**) (Short and Van Bossuyt 2015c) that determine what the best a worst ways for a failure to propagate through a system are. Space mission risk assessment can also be applied to control of autonomous systems in order to maximize mission success while minimizing human work hours (Short and Van Bossuyt 2015a), (Short and Van Bossuyt 2015b). Many of the existing methods, while generally robust, have a lengthy setup analysis process. The lengthy and resource-intensive setup of existing methods makes active assessment of dynamic situations infeasible when relying on established methods.

2.4. Prognostics and Health Management

Prognostics and Health Management (**PHM**) is used to predict and prevent failures in mechatronic systems (Sheppard, Kaufman, and Wilmering 2014). Many methods exist for PHM analysis, each with their own strengths and weaknesses, making them more or less advantageous for particular applications (Hutcheson et al. 2015), (Balaban et al. 2013). The process of making decisions based on PHM information is referred to as Prognostic-Enabled Decision Making (**PDM**) (Sweet et al. 2014) and can be used to decide which act presents the optimal level of risk and reward within a system. This can be an incredibly useful tool in analysis with PHM because it can be used to calculate the potential damage that could be caused to a system by one component failing.

An essential element of PHM analysis is the development of mathematic models of physical systems such as mobility, control systems, structures, or power as well as the hazards that face the systems. These models are a necessary piece of PHM because they offer a prediction of the results of taking an action on the physical state of the system. The application of PHM techniques could be further extended by considering their effects on the wellbeing on a person in the system. In this case, a person can be treated similarly to traditional hardware with equations estimating the probability of survival based on a variety of mission-specific factors.

2.5. Human Exploration of Mars

Recently there has been resurgence in interest in sending human explorers on a mission to Mars. This has taken the form of planned missions from leading organizations such as the National Aeronautics and Space Administration (**NASA**) (Daines 2015), increased interest in popular culture (Weir 2011), (Sneider 2015), and combinations of the two ("Mars One" 2015). While autonomous rovers and satellites have gathered a large amount of information on Mars, there are still many unknowns to discover and a large number of serious problems remain to be solved. One such problem is the lengthy flight time between Earth and Mars that not only presents psychological risks from extended isolation (Gushin et al. 1998), but also presents danger from the large amount of radiation exposure along the way (Hellweg and Baumstark-Khan 2007). Once the astronauts have arrived, radiation on the surface has shown to be present, but at less hazardous levels than some earlier estimates. However, there are still environmental risks from extreme weather (B. A. Cantor 2007), (B. Cantor, Malin, and Edgett 2002), potentially unexpected hazardous terrain (Lakdawalla 2015), health effects from reduced gravity (Horneck et al. 2003), (Marty et al. 2009), difficulty of communication with Earth due to signal delay, and various other hazards. The hazards are all compounded by external rescue or repair being exceptionally difficult in the case of an emergency.

3. METHODOLOGY

The AMSE method is based on an object-oriented form of functional modelling, risk assessment techniques derived from FFIP and related methods, and concepts from decision theory to evaluate a mission's current state and potential for success. The core of AMSE is a Survival Rate function for the system of interest that examines a number of variables to determine the probability of the system's survival. These variables can be greatly affected by the performance of tasks, which in this context refer to actions that affect resources and sub-systems health and often take up some amount of time. The definition of tasks in the context of AMSE will be expanded upon later in this section.

To have a structure to build the analysis upon, a modified form of FDF is developed and implemented where instead of functions being lined up and having flows pass from one to another, systems of interest are nested within each other, with each later augmenting flows passing through their barriers. The system can be visualized as a series of nested shapes, each representing a different sub-system/environment. At the center of the system is the critical system which represents a system (or systems) that are critical to mission success. For the case study presented in the next section, the critical subsystem is an astronaut stranded on Mars. The AMSE nested functional model is shown in Figure 1.

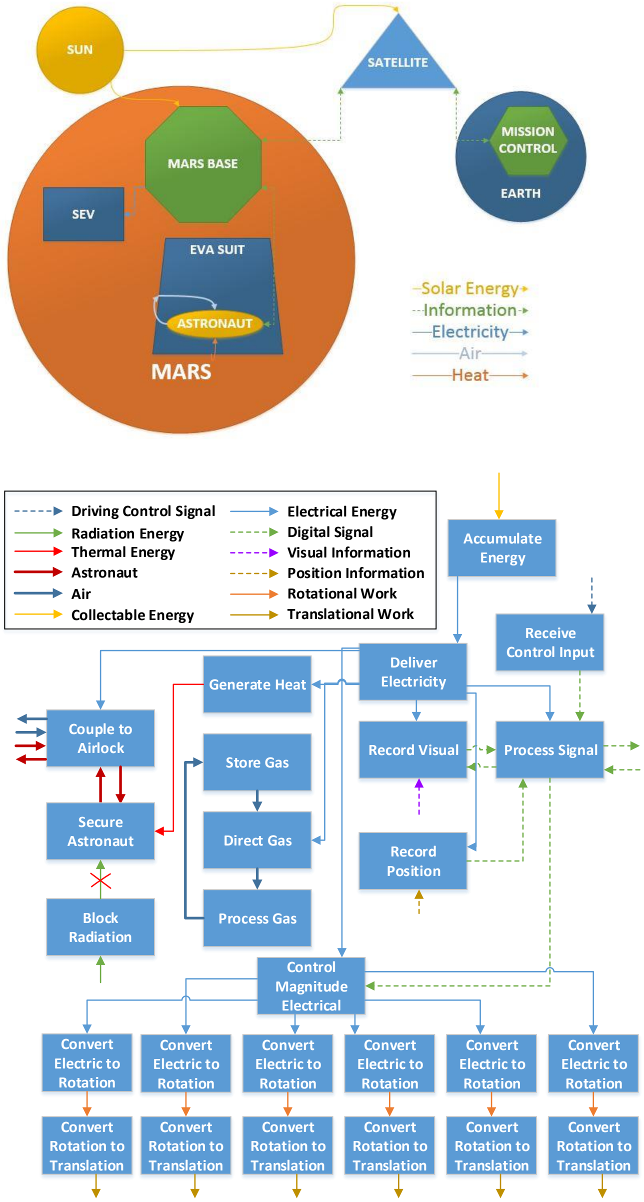

Figure 1. Simplified functional diagram of the system focusing on the astronaut (top). Simplified functional model of the Surface Exploration Vehicle (bottom).

The primary flows between the sub-systems are resources and energy. Some examples include food, heat, physical forces, or information. These flows are used to calculate the current and future states of the sub-systems. When passing through a sub-system, a flow can be affected by that sub-system to either be increased, reduced, or transformed before being passed on to the next layer of sub-system. Eventually the magnitude of the flows, health of sub-systems, and current time are used to calculate the health of the system.

In addition to the sub-systems' effect on the flows, tasks can also affect the flows and the state of external resources. Tasks are actions that can be taken to control the system in a way that is either desirable or undesirable. For the purpose of the case study discussed in the next section, many tasks are actions taken by the astronaut to increase their probability of survival and mitigate risk. Tasks can be combined in order to create a Task Plan for a length of time that can be used modularly to reduce the amount of work necessary to represent a series of actions. The Task Plans are then put into chronological order to create the Mission Plan, which represents all of the tasks that will be taken over the course of the mission including driving, eating, working, sleeping, and downtime. An example of the Mission Plan structure can be seen below.

- Mission Plan
    - Task Plan Week 1
        - Task A
        - Task B
        - Task C
    - Task Plan Week 2
        - Task A
        - Task D
    - Task Plan Week 3
        - Task C
        - Task D
        - Task A

An overview of setting up AMSE analysis is now presented: 1) A nested functional model of the mission system must be developed. 2) A mathematic model is developed to represent the flows and sub-systems from the visual functional model representation. 3) The critical sub-systems or flows must be identified. The critical sub-systems will be the primary focus of the mission analysis so models associated closely with them should be thoroughly developed to ensure accuracy. 4) The general mission plan should be define clearly. This includes a general mission objective, as well as any major secondary objectives, or necessary actions. 4) Task Modules should be developed that are necessary to complete all of the mission objectives, as well as account for downtime as necessary. 5) Task Modules are then used to construct the Task Plans which represent periods of time, such as a few hours, a day, a few weeks, years, or any other desirable amount of time. All necessary tasks must be included in the Task Plan and all time must be accounted for. The resolution of the Task Plan however can be either very detailed or very broad depending on the circumstances of the analysis. 6) Organize the Task Plans into a final Mission Plan. Finally analysis can be performed on the mission. Figure 2 graphically shows the AMSE method. The AMSE method has been implemented into a MATLAB environment.

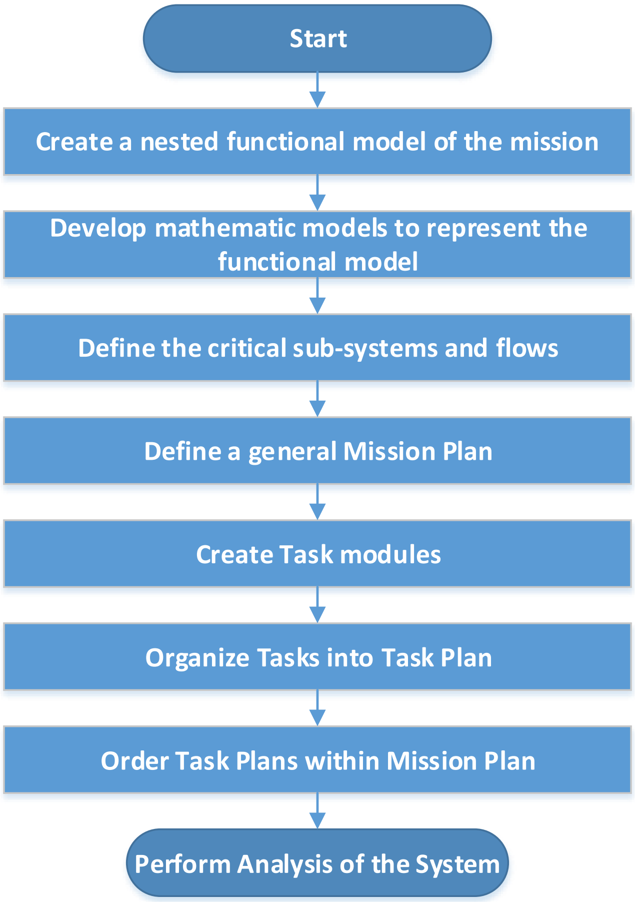

Figure 2. AMSE Process Flow.

4. CASE STUDY

To demonstrate the effectiveness of AMSE for space mission assessment, a case study is presented of an astronaut in a solo survival scenario on Mars. The astronaut has been left behind by their crew due to unforeseen circumstances, and now must survive for 550 Martian days (Martian days or sols are approximated to be 24.6 hours) until a rescue vehicle can arrive. Additionally, over the last 45 sols of the mission, the astronaut must travel approximately 4200 km to reach the extraction point and be rescued. An ideal mission plan will be considered, as well as an adapted mission plan selected from several possible options after an unexpected event.

At the beginning of the mission, the astronaut has access to 1 Martian base, 2 surface exploration vehicles (**SEV**) (Bagdigian and Stambaugh 2015), 4 extra-vehicular activity suits (Boyle et al. 2012), 400 sols' worth of meal rations, and several raw potatoes capable of growth.

The model of the astronaut takes into account radiation exposure, caloric intake and usage, time since sleep, physical injury, and exposure to extreme temperatures. While this list is not a comprehensive list of all of the dangers that face the astronaut, it does account for hazards identified to have a substantial effect on survival. At the beginning of the mission, the astronaut weighs 85 kg and is considered to be 180 cm tall for the purpose of modelling caloric intake needed and energy stored on their body.

Mars has temperatures ranging between -143 °C and 35 °C, an air pressure of 0.6 kPa (0.006 atm), surface radiation around 215vμGy/day, and an atmosphere that is approximately 96% carbon dioxide (Mahaffy et al. 2013). The astronaut must depend upon the available protection of existing equipment to avoid several forms of mission ending fatalities.

The Martian base protects from most radiation and provides breathable air at a comfortable temperature. However the base is immobile and at one point in the mission will need to be abandoned when the astronaut transits across Mars to an extraction point for rescue from the surface. The Martian base is powered by solar cells on its exterior surface.

The EVA suit has a suit port that acts as an airlock and allows for the astronaut to get in and out of the suit through the SEV which in turn docks to the Martian base. The suit can regulate temperature and offers approximately 8 hours of breathable air. While the suit protects to a small degree from radiation, it does not protect from large amounts of radiation which increases the health risk of using the EVA suit on missions. Additionally, it is harder to perform tasks in the suit thus causing caloric use while in the suit to increase.

The SEV is a 6-wheeled vehicle that can reach speeds of up to 25 km/h and can dock with the Martian Base (NASA.org 2015). The SEV has a rechargeable battery for power and can be charged from the Martian base's power or solar cells directly. The two SEVs have parts that are interchangeable if necessary and can carry up to 1000 kg each. Driving the SEV burns approximately 170 kilocalories per hour.

At the Martian base there is enough food for 400 sols of 1500 calorie meals. Since 1500 calories does not allow for a very large amount of activity and rescue cannot arrive until sol 550, more food will have to be cultivated. Using the potatoes, the astronaut will grow additional food to extend food stores in an attempt to avoid starvation ending the mission. After initial setup time, the potato farm will produce 850 calories of food per day. However, the potatoes will have to be tended which also expends calories.

While much sleep and rest will be necessary to conserve energy and reduce risk due to starvation, scientific work will still be performed by the astronaut over the course of the mission. The time spent in the Martian environment is incredibly valuable and while the astronaut is stranded there, they should attempt to collect as much scientific information and perform as many experiments as possible. The physical intensity of this work will remain low to reduce energy expenditure, but two hours of work will be performed per day when possible.

An overview of the Mission Plan is shown below.

- Sol 1-5
  - Start Potato farm
- Sol 6-14
  - Assess current situation for survival
- Sol 15
  - Test drive rover
- Sol 16 – 500
  - Establish routine
    - Farm potatoes
    - Perform Experiments
  - Perform extended EVAs every eight weeks
    - Maintain equipment
    - Perform external experiments
  - Perform extended SEV missions every eight weeks
    - Test modifications to SEV
    - Prepare for long drive
  - Eat extra meals and rest once every four weeks
    - Replenish lost nutrients
    - Conserve energy
- Sol 500-545
  - Drive to extraction point in SEV
    - Drive 4 hours a day
    - Stop to recharge batteries using solar cells
- Sol 546-550
  - Prepare for rescue
  - Conserve energy when possible

In addition to the planned mission analysis, this case study is run on a scenario where half the food is lost at sol 350. AMSE is then used to determine how to properly re-ration food in order to achieve acceptable probabilities of survival which is defined as a mean instantaneous survival rate of 0.95 or higher. A survival rate of 0.95 is chosen for the minimum survival rate, because it is known to be achievable as the rate is below the control mission plan’s mean instantaneous survival rate, but is still high enough that many Mission Plans would fail to reach the rate if Mission Plans are not constructed carefully.

A loss of food is chosen as a focus for the case study because it presents a very direct risk to the system (astronaut) and there are multiple actions that can be taken to address the problem.

5. RESULTS AND DISCUSSION

AMSE is able to model the mission scenario described in Section 4 and provide an assessment of probability of success, as well as allow for rapid assessment of problems as they arise and allow for expedient information to be generated that can inform mission command decisions. General mission tasks are modelled for an astronaut attempting to survive alone on Mars while awaiting rescue. The astronaut is required to survive 550 sols and travel over 4200 km. The biggest risk that arises in the system is the risk due to starvation, because food supplies are very limited. The survival rates for the control mission are show below in Figure 3.

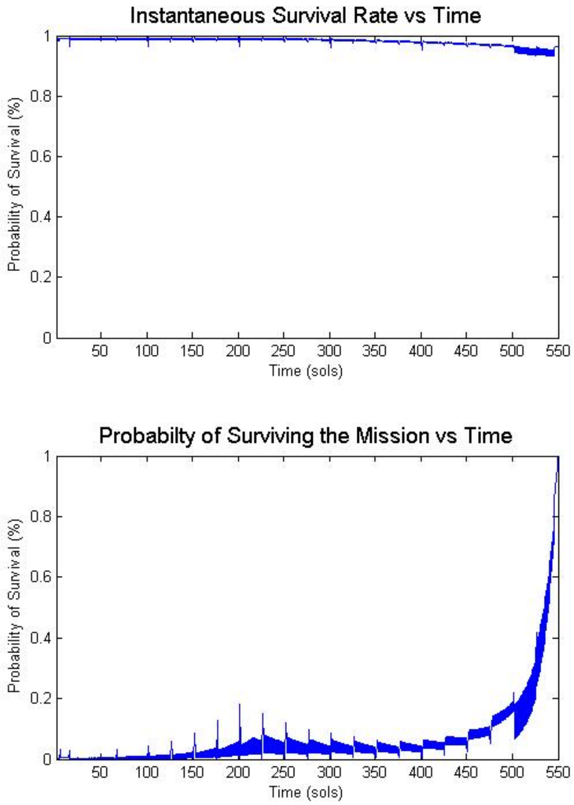

Figure 3. Instantaneous Survival Rate vs Time shows the probability of survival at a particular moment (top). Probability of Surviving the Mission, shows the probability that the astronaut will survive the entire mission as related to time in the mission (bottom).

One notable feature of the plots in Figure 3 is that there are spikes in the probability of mission survival, especially around 225 sols where a local maximum is present. This is unexpected because it was assumed going into the analysis that the rate of survival would only go up over time. The cause of this phenomenon is dangerous driving and EVA tasks that momentarily increase the risk presented to the astronaut, leading to the characteristic spikes in the second plot. There are similar spikes in the Instantaneous survival rate plot also occurring in line with EVA and SEV missions.

The real test of AMSE is in the food loss section of the case study analysis. In this case, half of the current food supplies are lost on sol 350. If no mitigating action is taken, the astronaut will likely begin to run out of food by sol 503 and will starve to death within seven to fourteen sols with near guaranteed death by starvation by sol 543. The survival rates for the potato loss scenario with no rationing are shown below in Figure 4. The Probability of Surviving the Mission vs Time is shown in the bottom plot of Figure 4. This plot represents the calculated rate of surviving the rest of the mission at a given time. If the astronaut is likely to survive the mission, the probability of survival should approach 1 as the mission time runs out. This is a result of there being less potentially hazardous events between the astronaut and the end of the mission.

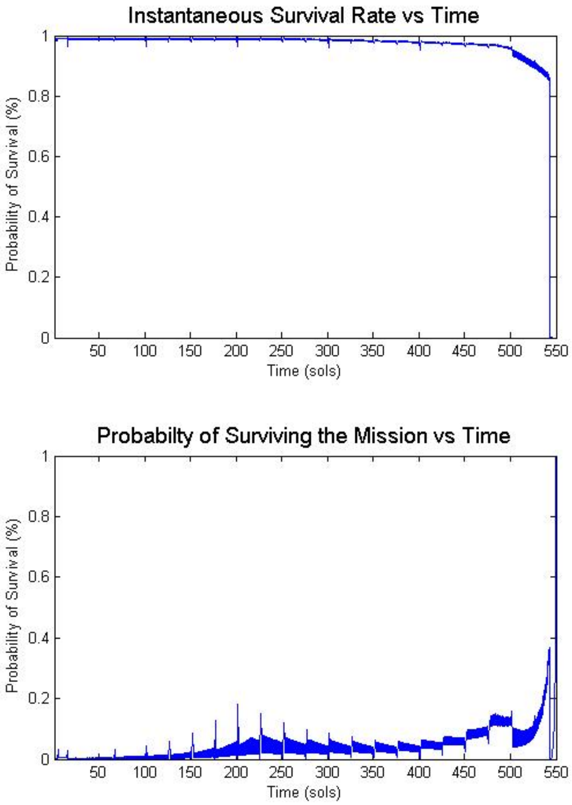

Figure 4. Instantaneous Survival Rate (top) and Mission Survival Rate (bottom) after losing half of the food on sol 350. No food rationing occurs. Mission failure is assured by Sol 543.

By reducing the rations to 1115 calories per day and spending a few weeks resting and reducing physical work tasks, the food can be stretched through the end of the mission. The results are shown in Figure 5.

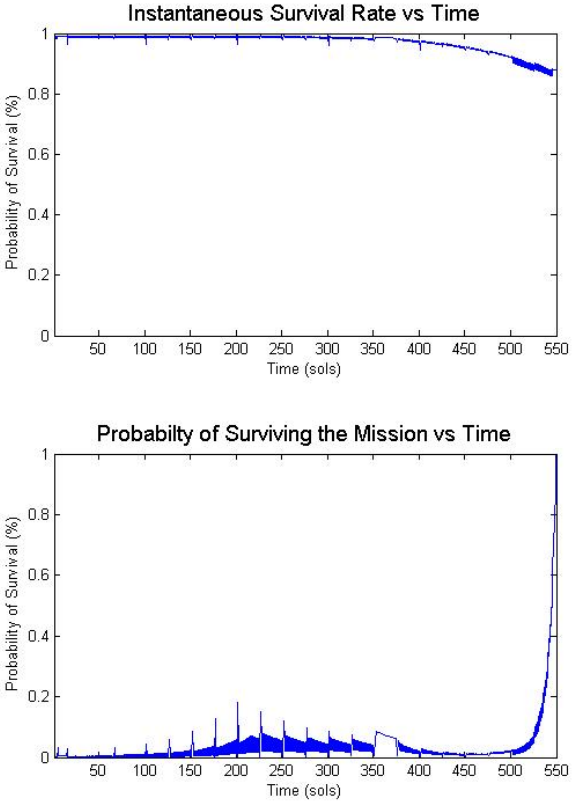

Figure 5. Instantaneous Survival Rate (top) and Mission Survival Rate (bottom) after losing half of the food on sol 350. Food is rationed to 1115 calories per day.

While the astronaut can survive through a 1150 kilocalorie diet and by limiting the amount of physical work the astronaut does for two weeks, the astronaut will still lose a dangerous amount of weight. The 85 kg astronaut that started the mission will drop down to approximately 50 kg in this scenario. Half of the weight lost is lost in the final 150 sols of the mission. For comparison, under the conditions of the control scenario the astronaut only loses 23 kg, dropping down to 62 kg. The astronaut is very likely to starve to death at around 48 kg under these conditions. Figure 6 shows a plot of the astronaut’s estimated weight over time.

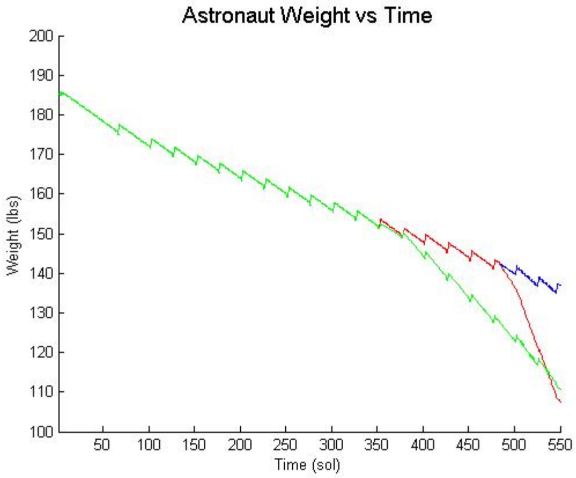

Figure 6. Blue: Control, Red: No rationed food after loss, Green: Rationed food after loss.

A final piece of the results that deserve attention is the mission survival rate near the beginning of the mission vs the end. Near the beginning of the mission the survival rate was much lower in general and near the end the survival rate should approach 1. The general trend results from the fact that the beginning of the mission still has many potential problems that may arise and lead to the loss of the astronaut and subsequent mission failure. The mean mission success value for the control mission is found to be around 0.06 which means a 6% rate of astronauts in this scenario being successfully rescued.

6. CONCLUSION AND FUTURE WORK

The AMSE method is shown to be a viable tool for mission success estimation. The method is much more dynamic than existing methods due to its object-oriented approach to mission design and assessment, and is able to accurately model complex mechatronic systems and their interactions with a human sub-system through the application of PHM techniques and methodology.

While the current revision of the AMSE method is fast and effective, there is still room for improvement. To make the method more accessible, software should be developed for AMSE that has an improved user interface and leads the user more directly through the method to ensure that the analysis is performed completely and correctly. Additionally, a future AMSE case study should be applied to large missions with more individuals and equipment as well as a higher degree of model fidelity. While the analysis presented in the case study tracks the use of multiple SEVs and EVA suits, there is only one human component to consider. Modelling a mission team dynamic may be very interesting and improve upon the model as a tool for mission planning and assessment. The resolution of the models themselves may also be increased to give a better understanding of the nuances of a mission from emergent system behavior. Currently the Martian base, SEV, EVA, and astronaut all have between four and 12 parameters that affect their state, but these can be increased and linked more complexly to allow for methods such as FFIP and FFDF to be built directly into the analysis to determine what factors may more directly affect critical sub-systems. A final expansion of AMSE is a built-in optimization toolkit for hassle-free solving of problems such as food and resource rationing over the course of the mission.

AMSE has shown to be an effective tool for rapid and effective mission planning and assessment. The object oriented structure of the method allows for rapid construction and analysis of mission alternatives. This will enable more dynamic and informed mission planning to be performed. Additionally the AMSE method shows a great deal of potential for future improvement and development.

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