

Proposed Standards and Tools for Risk Analysis and Allocation of Robotic Systems to Enhance Crew Safety during Planetary Surface Exploration

Lealem Mulugeta

Universities Space Research Association, Division of Space Life Sciences

David Bodkin

Orbital Sciences Corp

Romain Chasseigne, Michael Demel and Dexter Jagula

Matthew Turnock

McMaster University

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ABSTRACT

Several space agencies have announced plans to return humans to the Moon in the near future. The objectives of these missions include using the Moon as a stepping-stone towards crewed missions to Mars, to test advanced technology, and to further exploration of the Moon for scientific research and in-situ resource utilization. To meet these objectives, it will be necessary to establish and operate a lunar base. As a result, a wide variety of tasks that may pose a number of crew health and safety risks will need to be performed on the surface of the Moon. Therefore, to ensure sustainable human presence on the Moon and beyond, it is essential to anticipate potential risks, assess the impact of each risk, and devise mitigation strategies. To address this, a nine-week intensive investigation was performed by an international, interdisciplinary and intercultural team on how to maximize crew safety on the lunar surface through a symbiotic relationship between astronauts and robots.

To identify if and how robotic systems may be employed to enhance safety, it was necessary to establish a

standardized risk assessment criteria. Risk assessment criteria used by space agencies and health and safety institutions from around the world were combined and integrated to meet this requirement. In addition, a decision tree was developed to rapidly identify robotic platforms that will enhance crew safety during tasks that require astronaut participation. Using these tools it was possible to appropriately identify the impact of each risk on crew safety in terms of the probability of occurrence (likelihood) and consequence (severity), and generate a list of robotic platforms to improve crew safety. Furthermore, the risk assessment criteria and robotic decision tree are extensible to lunar and Mars exploration missions regardless of mission architecture.

INTRODUCTION

History has demonstrated that exploration is a risky endeavor. In the early exploration age, loss of life was considered acceptable risk, and to be expected. A good example of this is when Zhang Qian and 100 men, in 138 B.C., ventured into the unknown land beyond the Great Wall. Thirteen years later, only Qian and his slave returned; which by today's standards is considered

unacceptable loss. However, in light of the wealth of information acquired about the unknown territories, the two men received great honors for the successful completion of their mission (Quian, 1993). Over time, however, our perception of acceptable risk has become more stringent.

During Europe's colonization period, significant progress was made in exploration technology, such as ships and navigation tools, to ensure mission success as well as crew safety (Sandrone and Wagner, 2007). In the late 19th and early 20th century, at the peak of polar exploration, standards for acceptable risk and value of human life became more stringent. This is demonstrated best by the works of three prominent polar explorers: Fridtjof Nansen, Roland Amundsen, and Ernest Shackleton. All three explorers worked diligently to ensure the safety and comfort of their crew through the provision of well tested and reliable equipment, careful crew selection, and expedition simulation training similar to today's space mission training requirements. Nansen even suffered cost overruns due to the increased crew safety margins, while Shackleton's attentiveness for his crew's safety made him well known for having never lost a crewmember during his expeditions (Stuster, 2005; Stuster, 1996).

Even in the mid-twentieth century, when political agenda was the main driver for space exploration, human safety was a high priority. President John F. Kennedy clearly stated this in his address to congress: "...this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the earth" (Kennedy, 1961). As a result, new technologies and risk mitigation techniques were developed and tested under enormous time constraints to maximize the safety of the men who bravely ventured into the unknown.

Today, any accident or event that threatens the health of a crewmember can have enormous consequences on public opinion of current and future human spaceflight missions. The loss of the space shuttle Columbia during re-entry is a tragic reminder of the effect that human loss during space exploration can have on the mission, economy, and public opinion (Kauffman, 2005). Returning to the Moon and traveling beyond will hold the public's attention, and for this reason the experience and lessons learned from past human space missions are vital to the success of planetary exploration and maintenance of positive public opinion. Additionally, a high level of astronaut-robotic synergy can be extremely beneficial for ensuring astronaut safety and mission efficiency (Mendell, 2004). Consequently, the authors believe astronaut safety is best achieved through standardized systematic decision making tools and robotic systems. Furthermore, standardized risk assessment and mitigation strategies can reduce the complexities associated with international collaboration during lunar and Mars exploration.

The ideas proposed in this paper can be applied to increase crew safety during planetary exploration missions through two distinct products: 1) a universal safety risk assessment criteria, and 2) a robotics decision tree (ISU, 2008). Although the nine-week study completed by the international, interdisciplinary and intercultural team (ALERTS study) focused on lunar base operations, the two products are also applicable to Mars exploration.

During the ALERTS study, a list of tasks common to all lunar bases, irrespective of mission architecture, was generated through research and consultation with industry experts. Some tasks in particular were adopted from Gies (1996). The list excludes any tasks that do not occur directly on the lunar surface, such as transport from the Earth to the Moon and spacecraft landings or takeoffs. Ultimately, 66 tasks were identified and grouped into ten different classifications (ISU, 2008). These tasks were then used as the basis for identifying risks that astronauts will be exposed to during their stay on the lunar surface.

The complexity of a single lunar or Mars manned mission requires clearly defined risk mitigation strategies throughout its lifetime (NASA, 2005a). Although all risks and hazards of a lunar base can threaten the crew's safety, the scope of this study was limited to potential risks associated with tasks astronauts would perform on a planetary surface in the early development phases of a base. Based on the level of risk and complexity associated with each task, it was possible to assess if and how robotic systems can be employed to enhance crew safety.

RISK ANALYSIS AND CREW SAFETY

During the ALERTS study, risk identification posed a significant challenge since there is currently no universally accepted definition of risk among the different space agencies. Instead, space agencies seem to adopt their own definitions. For NASA, "risk is characterized by the combination of the probability that a program or project will experience an undesired event... and the consequences, impact, or severity of the undesired event, were it to occur" (NASA, 2007). ESA defines risk as "an undesirable situation or circumstance that has both likelihood of occurring and a potential negative consequence on a project" (Reid and Romero, 2003; ECSS, 2007). These definitions are used by space agencies for projects or missions, and can be applied to analyze cost, schedule, safety, or environmental impact. However, they do not specifically address the aspect of crew safety. Therefore a more suitable definition was adopted from the Institution of Occupational Safety and Health (IOSH); an internationally recognized institution dedicated to safety and health in high-risk activities.

According to IOSH, a risk is simply a "combination of likelihood and consequences of a specified hazardous

event" (IOSH, 2002). Though this definition may not be as complete as those cited above, it is a concise definition that can be applied more effectively to crew safety on a planetary surface. Additionally, in conjunction with the European Agency for Safety and Health at Work (EU-OSHA), IOSH further defines an accident as "an unplanned event leading to damage, injury/illness, death or loss"; and defines an incident as "an event causing damage, injury/illness, death or loss, or that has the potential to lead to such" (IOSH, 2002).

By using these definitions, the ALERTS team was able to generate a preliminary list of safety risks associated with the 66 tasks to be performed by astronauts on the lunar surface. The impact of each risk was evaluated by rating the probability of occurrence (likelihood) and the magnitude of its effect (severity) (Preyssl et al., 1999).

Determining likelihood and severity, also posed difficulty due to the lack of a universal standard for crew safety risk assessment. Additionally, most of the risk assessment criteria within the space sector were established to assess entire projects or missions, and not for assessing crew safety or specific task-associated risks. Risk assessment is a difficult process in general since it involves many uncertainties and assumptions influenced by the perception and level of acceptance of risk among different populations and organizations, resulting in variations in risk estimation and assessment (Department of Health and Ageing, 2007). This was especially evident during the ALERTS study due to the team's diverse composition in nationality, cultures and professional backgrounds or expertise, introducing not only interpersonal subjective assumptions, but also intercultural and interdisciplinary variety in the perception of risk. Therefore, standardization of risk classification and criteria is required to effectively assess the different risks encountered, especially within an international and interdisciplinary context.

With this in mind, risk assessment criteria from the space sector, as well as the health and safety profession were reviewed and adapted to construct a comprehensive crew risk assessment standard. Statistical data from space analogue studies were also used to ensure the validity of the standard established.

LIKELIHOOD

Currently, there is no common standard amongst space agencies regarding the likelihood of task-associated astronaut health and safety risks that could potentially result in accidents or emergencies while on the lunar or Martian surface.

Submarine and Antarctic missions, and various remote expeditions, are good analogues to planetary exploratory missions, and could provide valuable information on the possible occurrence of hazardous events. As a result, data from such expeditions are widely used by space

agencies to evaluate risk probabilities and develop mitigation strategies (Cermack, 2000; Thomas et al., 2000; National Research Council, 2002; Ball and Evans, 2001; Thomas et al., 2003; Horneck and Comet, 2006; Davis et al., 2008; NASA, 2008a)

For example, the incidence of certain types of illnesses during extended submarine missions are similar to the rate of incidence encountered during spaceflights (Ball and Evans, 2001). The occurrence of health concerns among crewmembers aboard 136 submarine patrols between 1997 and 1998 were analyzed and their occurrences were estimated. One study estimated the occurrence of illness to be 119.8/100,000 person-days, and the occurrence of accidents to be 37.2/100,000 person-days within a population in an isolated environment. The occurrence of injuries was found to be 48.8/100,000 person-days, where open wounds were 21.0/100,000 person-days (Thomas et al., 2000; Ball and Evans, 2001; Thomas et al., 2003). In analogue environments the annual occurrence of surgical diseases requiring evacuation or invasive intervention is approximately 1/10,000 person-days; this means that for a crew of six, the probability will be approximately once in four years (Cermack, 2000).

The ESA HUMEX study in particular analyzed the probability of diseases, injuries, and death on lunar and Mars missions. This study characterized a lunar mission as one involving 4 crewmembers that would last 180 days on the surface of the Moon with 60 EVAs, each composed of 2 astronauts for a maximum of 8 hours. A Mars surface mission was characterized with 4 crewmembers for 525 days with 175 EVAs conducted in pairs for 8 hours. Using the two mission characteristics, it evaluated health and safety statistics from the general population, as well as from professionals exposed to greater hazards on a more regular basis such as fire fighters, pilots and astronauts. The applicable results to this paper are summarized in Table 1 (Horneck and Comet, 2006).

Based on estimates from the HUMEX study and statistics from space analogues, it is possible to conclude that some classifications of likelihood proposed by space agencies are not appropriate to assess risks related to planetary surface exploration. For instance, the NASA's Bioastronautics Strategy (NASA, 2003) used to generate the Bioastronautics Roadmap uses probability percentages that are much higher than the probabilities of incidents or accidents likely to occur on a lunar base. In addition, the acceptable level of risk in this standard would not be adequate for some of the potential risks of each task. For example, according to the Bioastronautics Strategy, an estimated probability of 1% mortality would be classified as acceptable, but would be very high for the safety targets identified in the HUMEX study. This issue is also evident in the NASA Risk Management Guidelines (NASA, 2008b) where the classification cannot be compared with the statistics presented

previously. On the other hand, some of ESA's criteria for likelihood (Schroeter, 2001) do not include percentages, but use subjective, non-numerical categories that can include a large range of probabilities. This allows for large variations in interpretation due to a lack of reliable quantitative data and the subjective perception of risk by each evaluator. For instance, an event could be considered "likely" by one member of the team may be "unlikely" to another. Finally, in another ESA classification described by Preyssl et al. (1999), the highest classification of likelihood only corresponds to an event with a 100% probability of occurring. This is not acceptable or applicable in the case of accidents on a planetary base, and therefore could not be employed for the ALERTS study.

Type of Injury	Per Man-Year	Per Mission	
		Moon	Mars
Fracture of the skull	0.002	0.004	0.011
Fracture of spine and trunk	0.002	0.004	0.011
Fracture of upper limb	0.006	0.012	0.034
Fracture of lower limb	0.003	0.006	0.017
Dislocations	0.005	0.001	0.029
Sprains / Strains	0.07	0.138	0.403
Head injury	0.002	0.004	0.012
Internal injury	0.0005	0.001	0.003
Open wounds	0.01	0.02	0.058
Contusions	0.02	0.039	0.115
Crushing injury	0.01	0.020	0.058
Burns	0.01	0.020	0.058
Radiation short term disease (standard limits respected)	0.00001	0.00002	0.00006
Radiation long-term disease (standard limits respected)	0.0008	0.0016	0.0046
Mortality by injury (excluding S/C failure)	0.0004	0.0008	0.0023
Mortality by illness / injury (excluding S/C failure)	0.0024	0.0047	0.0138

Table 1: HUMEX estimated probabilities for incidences of injuries during Moon and Mars surface missions (Horneck and Comet, 2006).

The rating of likelihood involves subjectivity and uncertainties; however, numerical classifications for the different levels of likelihood provide a common rating system that may be used by different people performing the assessment. A classification with numerical categories applied by ESA (Preyssl et al., 1999) could be one tool to effectively compare probabilities found in HUMEX. However, even though that classification is proposed for missions and projects, it does not consider health and safety, and it is not clear if manned space missions were included as part of its original objective. Although the Emergency Preparedness Guidelines in the United Kingdom (UK Resilience, 2008) were intended for

non-space activities, its classification of risk probability provides a better definition of the levels to be applied to the safety objectives of the HUMEX study than any other classification considered. Furthermore, it was also designed to assess emergency situations that are similar to what would be expected on a planetary base. Despite its terrestrial application origin, it seems to be the best classification to estimate the probability of risks related to tasks on the lunar surface with regards to crew safety. Therefore, it was applied throughout the ALERTS study. Minor modifications were made to the scale to make the probability ranges between each classification level more explicit. The latest version of the likelihood scoring scale developed by the ALERTS study is presented in Table 2.

Score	Classification	Probability
E	Probable	>50% (>1:2)
D	Possible	5 - 50% (1:20 - 1:2)
C	Unlikely	0.5 - 5% (1:200 - 1:20)
B	Rare	0.05 - 0.5% (1:2000 - 1:200)
A	Negligible	<0.05% (<1:2000)

Table 2: ALERTS classification of risk likelihood. (Adapted from: Schroeter, 2001; NASA, 2003; UK Resilience, 2008)

SEVERITY

Although the criteria of the Emergency Preparedness Guidelines in the United Kingdom (UK Resilience, 2008) can be applied to rate likelihood, it cannot be applied to rate the severity of risks present on a planetary surface. Its classification divides severity according to the impact of the emergency on large populations. For example, according to this classification a moderate number of fatalities can be accepted as a moderate risk. The Risk Analysis Framework established by the Australian Department of Health and Ageing cannot be used either since it also assesses severity for large populations (Department of Health and Ageing, 2007). Exploratory missions to the surface of the Moon and Mars are expected to initially be crewed by only 4-6 people, as outlined in the NASA Bioastronautics Roadmap reference missions (NASA, 2005a). Therefore, severity ranking system established for large populations would not be applicable for planetary missions.

Space agencies, on the other hand, have developed classifications to rate severity relating to cost, schedule, performance, mission, safety or science. For instance, for assessing risk impact, the NASA Bioastronautics Roadmap considers "engineering technology and system performance risks" combined with "health and medical risks", where the human is considered to be a "critical