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AN INTERDISCIPLINARY APPROACH TO HUMAN-ROBOT COOPERATION IN NEAR-TERM EXPLORATION SCENARIOS

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This paper will present a model for collaborative space exploration through effective and efficient cooperation of humans and robots — an extension to the Cooperation of Humans and Robots Model (CHARM) developed by the Human-Robotic Cooperation (HRC) team at the International Space University's 2011 Space Studies Program held in Graz, Austria. The HRC team integrated international, intercultural, and interdisciplinary perspectives to develop a decision-making model — CHARM — capable of selecting a mission scenario which best utilizes humans and robotics in order to accomplish a given objective.

Human and robotic capabilities differ, with each offering their own benefits and drawbacks. Robots are reliable and accurate, and can operate in hostile environments — all attributes well-suited for space exploration. However, when faced with new scenarios and unexpected events, robots pale in comparison with the intuition and creativity of humans. Future space exploration will have to intelligently balance the flexibility and ingenuity of humans with robust and sophisticated robotic systems.

Based on various space agency goals and the 2011 International Space Exploration Coordination Group (ISECG) Roadmap, this paper selects an exploration objective for the timeframe between 2015 and 2030, and drafts different scenarios to accomplish this objective. Each scenario uses different degrees of human-robot interaction. CHARM is applied to select an optimal mix of human and robotics in order to accomplish the selected objective. CHARM uses an interdisciplinary approach, scoring attributes including technical, scientific, life sciences, political, social, financial, and legal perspectives. In this iteration of CHARM, an Analytical Hierarchy Process is used to assign weighting values to each attribute and the respective categories. The weights are complemented with those collected by survey of a panel of international experts in space exploration mission planning.

The results demonstrate that CHARM can be used to select missions efficiently and rationally, thereby reducing both mission costs and risks, making space exploration more feasible and long-term space exploration sustainable. To quantify output confidence in the CHARM scenario selection, a Monte Carlo probabilistic simulation is used to analyze the uncertainty in attribute weighting, introduced by the inclusion of numerous weight value input sources.

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I. INTRODUCTION WHY AND WHAT TO EXPLORE

Historical justifications to explore space include building national prestige and advancing strategic and geopolitical priorities [1]. Taking a broader view, these justifications are supplemented by long range moral imperatives — humankind will eventually require celestial resources, and needs the ability to protect itself from dangerous asteroids [2]. Stephen Hawking has challenged mankind to become a truly space faring and multi-planetary civilization, and this will be the crucial task of humanity for the next millennium. Outer space still awaits, and our solar system is brimming with locations to explore.

> *"Humans should search Mars and find out why liquid water no longer runs on its surface; something bad happened there, and it would be important to identify any signs of something similar happening on Earth. We should visit an asteroid and learn how to deflect it—after all, if we discover one heading toward Earth, it would be rather embarrassing if big-brained, opposable-thumbed humans were to meet the same fate as the pea-brained dinosaurs. We should drill through the miles of ice on Jupiter's frozen moon Europa and explore the liquid ocean below for living organisms. We should visit Pluto and other icy bodies in the outer solar system, because they hold clues to the origin of our planet. And we should probe Venus' thick atmosphere to understand why the greenhouse effect has gone awry there, raising surface temperatures to 500 degrees Celsius. No part of the solar system should be beyond our reach, and no part of the universe should hide from our telescopes."* [3]

A wealth of possible mission objectives exist and many nations have set goals and objectives for their national space agency. Informing these goals are priorities from the scientific and academic community. In the United States, priorities for space exploration may originate from the National Academies' Astronomy and Astrophysics Decadal Survey and from its Planetary Science Decadal Survey [4].

Taking one scientific discipline, Astrobiology, we find another set of priorities. Astrobiologists are keen to investigate Mars, Europa, Enceladus, and Titan for water and organics, looking for either existing life or the evidence of previous life. However, with slashed planetary science budgets, these missions will likely require the leveraging of robotic capabilities to their fullest extent. Additionally, while Mars and the Moon can be explored using robots and human mission elements, Enceladus and the outer solar system can only be done with robots.

What considerations should be taken into account? Scientific return is not the only overriding mission requirement. We should not "go with whatever mission will give us the most science, as 'Science' is not the only end. There are other mission objectives." [5]

With an aim towards making further applications of the International Space University's (ISU) Cooperation of Humans and Robots Model (CHARM) to reflect real-world exploration goals, this paper looks to the Global Exploration Roadmap, promulgated by the International Space Exploration Coordination Group (ISECG) and reflecting the long-term, coordinated interests of fourteen of the world's leading space faring nations [6]. The work of the ISECG has allowed for the articulation of high-level commonly shared goals among the world space agencies. These goals are:

- Search for life
- Extend human presence into space
- Develop exploration technologies and capabilities
- Perform science to support human exploration
- Stimulate economic expansion into space
- Perform space, Earth, and applied science
- Engage the public in Exploration
- Enhance Earth safety

These common, high-level goals are supported by shared, supporting objectives. For example, the goal of extending human presence is supported by objectives including: testing countermeasures to maintain crew health and performance; demonstrating and testing power generation and storage systems; and developing and testing high-performance life support and habitation capabilities [7]. Some supporting objectives apply to many destinations in the solar system, while others are specific. As an objective, the search for life, for example, implicates objectives on Mars, rather than on the Moon [7]. The ISECG framework of common goals and shared objectives allow for space agencies to then develop long-range exploration mission scenarios and reference missions at destinations of interest [7].

Based on the success of the International Space Station (ISS), the ISECG Roadmap defines two different near-term mission scenarios for human exploration of the solar system after ISS: "Moon Next" and "Asteroid Next". While the ultimate destination is Mars, the Roadmap acknowledges that there are many steps to be taken beforehand, including reducing inherent risks and developing new technologies. For the purposes of this paper, objectives from the Roadmap will be used as mission inputs, with an aim of articulating an advantageous blend of human and robotic mission elements for the stated ISECG Roadmap objectives.

II. EXPLORATION OBJECTIVES

It is understood that in order to both minimize risks and enable the long-term sustainability of Martian exploration, various milestones must be accomplished beforehand. A crewed Mars mission requires proven capabilities, including the capability of living at increased distances from the Earth, and the ability to live self-sufficiently on the surface of another planet. The ISECG Roadmap identifies ways of achieving these goals, using Asteroid Next and Moon Next approaches [6].

The Moon Next approach is pushed by the need to develop the capabilities to live self-sufficiently on a planetary surface. This will entail developing capabilities for surface habitation, long-range mobility, extended operation in dusty environments, advanced surface power, robust and routine Extra-Vehicular Activities (EVAs), as well as precision landing and hazard avoidance.

Conversely, the Asteroid Next approach is to develop capabilities for extended crew missions at increased distances from the Earth. This approach will promote the development of space radiation mitigation techniques, living without a supply-chain from the Earth, as well as long-term storage and management of expendables.

For this iteration of CHARM, the focus centered around one of these exploration objective, as they rely heavily on effective human-robotic cooperation [6]. The timeframe is set to the mid-2020s, and the two objectives from the two Roadmap approaches are as follows:

- *To develop the capabilities necessary to explore and begin to understand how to live self-sufficiently on a planetary surface*
- *To develop the capabilities necessary to demonstrate crew missions in space for longer durations at increased distances from Earth*

III. EXPLORATION MISSION SCENARIOS

The scenarios presented in the Roadmap for both the Asteroid Next and Moon Next pathways are a conceptual, logical *"sequence of missions over a 25-year horizon [...] considered technically feasible and programmatically implementable"* [6]. Both the Moon next and Asteroid Next scenarios are a stepwise development and demonstration of the capabilities ultimately required for human exploration of Mars [8]. These scenarios were proposed considering the benefits to the public, providing sustained partnership opportunities, maximizing the synergy between human and robotic missions, providing for resilience to technical and programmatic challenges and ensuring the ability to meet exploration objectives. The technical capabilities required can be scaled and reused for other destinations.

Criteria considered in the decision making process for pathway selection will be driven by the science return per dollar invested, technological readiness level, availability of trajectory opportunities, and the feasibility of carrying on incrementally progressive missions [4,8]. In addition, "human-robotic partnership" has been identified as one of the key principles in mission scenario development with a special emphasis on "maximizing the synergy between human and robotic missions" [6].

Many technology demonstrations needed for a Mars mission are common to both the Asteroid Next and the Moon next scenarios, such as high subsystem reliability, repair at the lowest level, advanced EVA and robotics capabilities, power generation and storage, long-term storage and management of cryogenic fluids, and habitation in a hostile and high radiation environment.

A brief comparison of the Asteroid Next and Moon Next pathways is presented in Table 1. The Asteroid Next missions would help bridge the recognized technological gaps that stand before reaching the goal of a crewed missions to Mars, by developing "the capabilities necessary to demonstrate crewed missions in space for longer durations and at increased distances from Earth" [6]. One of the greatest challenges of the Asteroid Next Pathway is near-term technology readiness and affordability. A high technological leap is necessary to safely and successfully achieve such a mission [6].

The Moon Next pathway is seen as an ideal opportunity to learn how to live and work on another planetary surface. It is at a relatively close, safer distance and, aside from technology development and capability demonstration, there is significant scientific interest in returning to the Moon [8]. The Moon can be used as a stepping stone for a subsequent asteroid and Martian exploration missions. Following the ISS, it is considered the most suitable next step in human space exploration [6].

The model proposed in this article for optimal human-robot cooperation mission selection can be used to evaluate scenarios of either of the ISECG pathways. Considering the technology readiness level for a return to the Moon and accounting for the agency interest shown by the Roadmap, the Moon Next pathway is studied using CHARM in the following sections.

Table 1: Comparison of Asteroid Next and Moon Next pathways

Pathway	Mission Benefits	Mission Challenges
Asteroid Next	Directly stimulate new technologies: • Radiation mitigation • Life support systems • Deep space habitats • Power generation • Propulsion technologies • Cryogenic fluid handling • Closed loop autonomy and reliability	• Technology readiness • Affordability • Public interest and support • Availability for trajectory opportunities • Need for better characterization of asteroid population for destination selection
Moon Next	• Test human/robot cooperation technologies • Evaluate in-situ resource utilization • Further understanding of solar system evolution • Permits simulation of near-Earth asteroid simulation operational concepts • Utilize the Moon's importance to engage public	• Expense associated with surface activity • Demonstrate safe habitats with efficient life support and environmental control • Reliability in radiation environment • Develop health care for human explorers, including tele-medicine

IV. SCENARIO DEVELOPMENT FOR EVALUATION

Six missions were highlighted in the first iteration of the ISECG Roadmap, including

1. Robotic Precursor Mission
2. Crew-to-Low Lunar Orbit
3. Crew-to-Lunar Surface - 7 day Sortie Mission
4. Crew-to-Lunar Surface - 28 day Extended Stay Mission
5. Cargo-to-Lunar Surface (small)
6. Cargo-to-Lunar Surface (large)

Mission 4, the Crew-to-Lunar Surface – 28-day Extended Stay Mission, has been selected for effective human robotic cooperation evaluation using CHARM, as successful human robot cooperation is considered to have the greatest impact on this mission in particular [6]. The three following scenarios based on this mission are proposed for evaluation. The three scenarios proposed in this paper are based on precursor missions and current developments related to human and robotic capabilities in space exploration, and cover a wide spectrum of human-robotic cooperation levels. This evaluation method is intended as a high-level decision aid for mission design. Specific design or selection is beyond the scope of this paper.

IV.I Mission Scenario 1 - Human-Controlled Robotics

Human presence in planetary exploration provides improvements to mission resilience, as in-situ operators provide a means for more immediate responses to unpredictable events. However, long duration missions pose a variety of hazards and challenges. In order to reduce the unknown risks involved with human missions, such as radiation exposure or micrometeorite impacts, this scenario proposes a solution for minimising such challenges and improving keeping the crew safety.

Scenario 1 in-situ hardware consists of two modules: one a stationary habitat that houses the on-board crew and provides shielding from the external environment. The second is an autonomous, unmanned rover that performs sample collection missions, providing specimens for the astronauts to further investigate from the stationary habitat. The autonomous rover is sent on daily traverses to collect data and samples while the astronauts perform experiments in their stationary habitat. Throughout the day, the astronauts have the opportunity to monitor the rover performance and the quality of the samples being collected from their habitat, without being directly exposed to external hazards.

The rover has the capability of autonomous obstacle avoidance and path planning. However, astronauts or ground crew can override the path plan or manually direct the rover to a new location to collect further data. This scenario provides a more efficient method of a sample collection and return, as rover autonomy is combined with human discretion [9]. However, direct control of rover manoeuvring on-site will remain dependent upon some level of autonomous reasoning and decision-making. Extensive image processing and object identification is, therefore, required by the system. The sample collection tasks are performed entirely autonomously (*i.e.* no direct tele-operation). The rover is estimated to travel a total of 0.205 km during the 28 days mission, with a maximum speed of about 8.33 m/hour. Autonomous path planning and on-board science results in a reduced average rover speed [10,11]. The autonomous approach mitigates the direct hazards to humans performing equivalent traverses. However, the quantity of samples will be reduced when compared to a human-only mission.

The size of the rover is proportional to the cost of the mission and the size of the sample return mission. In other words, generally larger rovers can cover greater distances during a traverse. A macro-rover with an estimated mass of 900 kg could fulfil a larger sampling area in comparison to a micro-rover [12]. An example of such a rover is capable of collecting up to 500 kg of samples per mission, and is equipped with horizon navigation and a multi-sensor fusion system [13]. Its advanced image processing techniques offer multi-image correlation; while the Field Programmable Gate Array (FPGA) processors are used to enhance the operational capabilities for rapid image processing by combining multiple rover commands [14].

The rover consists of an advanced visual system for imaging and planning its mission autonomously and is equipped with seventeen cameras, as summarised in Table 2 [12]. The image processing techniques allow on-board autonomous path planning and scientific analysis [12].

Table 2: Cameras equipped on the rover

Name	Quantity	Function
Hazcam	8	Hazard and obstacle avoidance
Navcam	4	Navigation and path planning
Mastcam	2	Decipher nearby mineralogy
ChemCam	1	Laser pulses for vaporizing material layers
MAHLI	1	Close-up high-res images of surrounding rocks
MARDI	1	Natural color images

IV.II Mission Scenario 2 - Unpressurized Crew Mobility Rover

In this scenario, a multifunctional rover is used to assist human explorers during lunar surface exploration activities from a stationary habitat. The capabilities of the Lunar Roving Vehicle (LRV) of the Apollo 15, 16 and 17 missions are used for comparison, to which current and relevant capabilities are added. The rover considered in this scenario would act as a small and reliable utility vehicle. It would be capable of transporting and using different scientific payloads, and would be equipped with emergency life support systems for a crew of two.

The longest distance traveled on the Moon was approximately 36 km over the three day surface stay of the Apollo 17 mission. The distance traveled was kept within a 7.5 km range of the lunar module for safety reasons (the longest distance traveled on foot was 3.5 km during the Apollo 14 mission). The longest expected duration of lunar EVAs would be similar to the J-type Apollo missions at just over 7 hours [15]. Similar to the LRV, a 92 km travel range would be adequate for a surface mission such as that considered in this scenario, although recharging capability would also be a necessity.

The LRV was 3 m long, 2.3 m wide, had a 36 cm ground clearance. The load capacity, including astronauts and cargo, was 490 kg on the lunar surface, and the maximum speed was 13 km/h [16]. By comparison, the current All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) rover developed at JPL has a similar cargo capacity (450 kg) and similar speeds [17]. These specifications are adequate considering the travel distances, duration and safety requirements of EVA activities. A design life of ten years, in accordance with that of ATHLETE, would provide sufficient durability.

The main function of the rover is to provide mobility to crew and cargo on the lunar surface so that astronauts can effectively collect a variety of samples from a range of locations. Sampling tools developed for the ATHLETE program include a small plow and a mobile power platform for drilling operations. The functionality of such a rover could include:

- Deploying/servicing equipment at remote locations
- Crew bio-sensing and life support monitoring
- Surface mapping and crew position monitoring
- Communications to the lunar base
- Autonomous operation of certain scientific payloads (*e.g.* cameras, spectrometers, radiometers, etc.)

Figure 1: ATHLETE [18]

Semi-autonomous capabilities would be necessary for the safety of the rover as well as for scientific investigation purposes. The rover would have dual use functionality, including tele-operation from both the Earth and the lunar base. This functionality allows exploration of further locations than those permitted by an EVA alone. Furthermore, exploration of the surface can be continued remotely, prior to or in the time after human aspects of the mission. For example, as an extension of its cargo ferrying capabilities, the rover could be used to position and assemble portions of the lunar habitat prior to the arrival of the astronauts.

The use of a basic rover for transport has been demonstrated in previous manned lunar missions. Future rovers based on equivalent functionality could combine current autonomous rover capabilities with lunar transport rover capabilities demonstrated during the Apollo missions. The LRV proved to be reliable, an important requirement for the operation of a human-bearing rover. The sample quantity and quality will also be high, due to the presence of humans to aid in sample selection, and the high cargo capabilities of the rover.

IV.III Mission Scenario 3 – Pressurized Crew Mobility Rover

In this scenario, a human habitat is used as a stationary base on the lunar surface. It is capable of supporting 4 crew members for the duration of 28 days and is designed to provide a habitat environment and medical support to crew members as well as to perform sample analysis and ISS-type science in reduced gravity [19]. The mobile surface exploration is performed by a pressurized rover, with a baseline design provided by the Space Exploration Vehicle (SEV) [19,20]. The SEV has two major components, the chassis module, expected to have a mass of 1000kg, and a payload, having a mass of up to 3000kg [19]. A typical payload consists of the pressurized cabin module and cargo. The pressurized cabin module is expected to have a mass of approximately 2000kg, leaving an allowable payload, including astronaut and soil samples, of up to 1000kg [19]. The length of the SEV is 4.5m, with a wheelbase of 4m, and a combined chassis and cabin height of approximately 4m [19]. The crew interior space is approximately 10 cubic meters. Based on the latest design specifications of the SEV proposed by NASA, the range of the SEV is around 240km, traveling at a velocity of 10-19km/h [19].

The primary purpose of the SEV is to allow astronauts to work and explore a planetary surface for longer durations and at longer distances from the habitat for extended periods of time. As such, the SEV is designed to provide mobility and habitat support to two crew members for up to fourteen days. For the purpose of planetary exploration, sample return and initial analysis, sampling tools include drilling equipment, a small plow, and scientific payloads for environmental and sample analysis, including cameras, spectrometers, radiometers, altimeters, and microscopes.

The SEV is a modular system comprised of a mobile chassis and pressurized cabin, which can be docked to the human habitat to extend crew living space. The pressurized cabin module provides the following capabilities: basic life support (radiation protection, thermal protection, food, water, pressurized atmosphere, basic washroom facilities, sleeping areas), health monitoring, emergency medical supplies, advanced thermal insulation and control, emergency habitat and accommodation for crew of up to four, and radiation protection for up to 72 hours against solar particle events [19,20]. The two SEV suit ports allow for fast (under 10 minutes, equivalent Shuttle or ISS systems require several hours of preparation) egress and regress with minimal loss of pressure and gasses. This feature avoids the need for a separate airlock system. The SEV can be tele-operated for basic maneuverability in case of emergency, but it is intended for direct human operator control.

Pressurized rover concept designs such as the SEV have been proposed as far back as the 1990s, with a comprehensive lists provided in Zakrajse [21]. However, only a few designs have ever been built and tested. As such, the technology readiness for the SEV is moderate to low. Various proof-of-concept designs have been proposed and some prototypes tested in an analog environment, such as the NASA 2008[22], 2009[23], 2010[24], 2011[25] Desert RATS experiments. A number of design challenges remain before a flight-ready SEV design is implemented. These include power requirement definition, dust mitigation, electrostatic charge mitigation, thermal protection based on environmental conditions, effective protection against solar wind, cosmic rays and solar flare events, degradation of structural materials, micrometeorite protection and acceptable pressurized cabin noise levels for crew to live and work in [8,21].

V. MODEL DESCRIPTION

This section describes the decision making model, CHARM, and how it is applied to select between the three scenarios described above. CHARM is hereinafter referred to as “the model”.

The basic process of the model is to weight and score a series of attributes. Attributes are defined as a characteristic of a particular scenario (*e.g*. Mission Cost). The attributes are sorted into four categories, and the categories weighted again to determine their relative importance. The weighting for the categories (referred to as "Category Weighting") and the attributes ("Attribute Weighting") is done in two steps. The first step is to assign a relative importance ranking to the categories and attributes as per the Analytical Hierarchy Process (AHP) [26]. The second step is to survey various professional representatives of the space industry for their personal ranking of the relative importance of each category and attribute. The survey was distributed to eleven participants at the ISU ISS and Mars conference, held on April 12-13, 2012. The values obtained from the survey were averaged with those calculated via the AHP method to arrive at the overall weightings. The category and attribute weights will be discussed in the following sections.

V.I Model Categories

The attributes used to compare the scenarios are sorted into four categories: Scientific and Life Sciences, Technical, Economic, and Sociopolitical. Figure 2 illustrates the hierarchical organization of categories and their respective attributes and Table 3 shows the AHP and survey weightings.

The category weighting factors denote the relative importance of the respective categories towards successful completion of the objective. Because the pathway chosen for this investigation is Moon Next, the objective for this iteration of the model is:

“To develop the capabilities necessary to explore and begin to understand how to live self-sufficiently on a planetary surface”

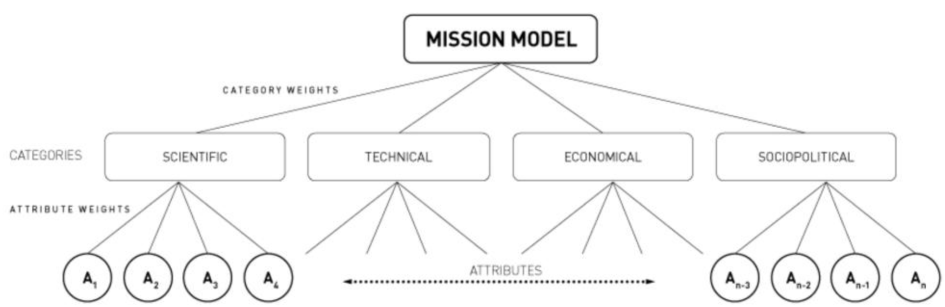

Figure 2: Scenario evaluation attributes hierarchy

Table 3: Category weightings

Category	AHP Weight (percent)	Survey Weight (percent)	Average Weight* (percent)
Science & Life Science	23	38	31 (9.8)
Technical	19	24	21 (7.5)
Economic	30	13	21 (8.6)
Sociopolitical	28	26	27 (9.5)

V.II Model Attributes

The model attributes are the main pillars used to trade-off scenarios with different degrees of human-robot cooperation. The Attribute Weightings given in this section denote the relative importance of the attribute in its respective category. The influence of an attribute in the model is determined by multiplying the Attribute Weighting with its corresponding Category Weighting. The final product of this is the "Total Weight." These attributes are considered to be independent of one another and cover all important areas of each category.

The breakdown of the attributes in each category, including the respective weighting values, is as follows (note that values in brackets represent the Attribute Weight, not the Total Weight):

Scientific

1. *Scientific Relevance* (Weight: 23%): As it is necessary to establish a common evaluation criterion for different scientific mission scenarios, the number of scientific questions that can be answered by any specific mission has to be investigated. In the case of a mission to learn to live sustainably on the Moon, this would reflect the diversity of experiments necessary to understand how to live on another planetary surface (*e.g*. experiments regarding the lunar environment, or the diversity of rock samples that could be gathered for analysis)
2. *Quantity of Data* (Weight: 18%): The quantity of data a mission can provide is an important factor that can influence the final design of a mission. In this case, technology demonstrations and the amount of samples that can be collected, brought back, and analyzed in the habitat are considered.
3. *Exogenous Short-Term Risk of Human Loss of Life* (Weight: 29%): This attribute considers the short-term risk to human life from exogenous variables (*e.g*. space debris). This attribute does not include the risk to human life from endogenous variables (*e.g*. technical malfunction) as this will be covered in the Technical Category. For this objective it would reflect the percent change of an astronaut loss-of-life from environmental phenomena.
4. *Exogenous Long-Term Risk of Human Loss of Life* (Weight: 22%): This attribute considers the long-term risk to human life from exogenous variables (*e.g*. space radiation). Similar to the previous attribute this does not include risk to human life from endogenous variables. For this objective exogenous long-term risk would reflect the percent increase in premature death for an astronaut as a direct result of the mission.
5. *Planetary Protection* (Weight: 8%): This attribute addresses the possible contamination and disruption of both the Moon and Earth's surface with foreign material brought with or back by the human explorers and their equipment. This attribute includes back-contamination of the human explorers as well as their habitat and reflects the percent chance of contamination.

Technical

1. *Impact on Technical Advancements* (Weight: 15%): Ability of the scenario to promote technological advancements. This would reflect the number of technologies that would be developed for each scenario.
2. *Ability to Demonstrate Technologies* (Weight: 21%): The capability for the scenario to demonstrate technologies necessary for the objective. In this case it would reflect the number of technologies that are tested and demonstrated for each scenario.
3. *Maintainability* (Weight: 18%): Defined as the capability within a scenario to ensure that all technologies involved in the mission are operating at an acceptable performance throughout the mission duration. This includes monitoring health of the system to predict maintenance requirements, capability to repair the system, and ease of repairs.
4. *Reliability* (Weight: 23%): Ability of the technology to perform the necessary functions for the entire duration of the mission. Considered in this attribute is the ability of the systems to adapt to multiple environments and the design lifetime. Note that endogenous risks to human health are included in this attribute (*i.e*. chance of a technology failure resulting in a loss of life).
5. *Level of Autonomy* (Weight: 24%): The capability of the technology to make decisions for themselves and achieve the tasks of the mission. The level of autonomy is dependent on the mobility of the systems, the manipulation capabilities, the intelligence of the systems, and the interaction between operating agents (such as robot-robot, human-robot, or human-human).

Economic

1. *Mission Cost* (Weight: 44%): The total required investment for the mission, including

system development, launch and operation, and end-of-life costs.

2. *Return on Investments* (Weight: 31%): Reflects the economic benefits of executing the mission. This includes job creation, economic return of spinoff technologies (note that this includes number of technologies developed that could be made into spinoffs and not the number of technologies developed), and competitive advantage gained of companies involved.
3. *Risk of Overruns* (Weight: 25%): Refers to the risk of having the mission cost or time to deployment exceed initial estimations during the development and/or mission operation phases. Note that this estimate will take into consideration the technology readiness level in the system development costs.

Sociopolitical

1. *Long-Term Political Will* (Weight: 64%): Reflects how willing policy makers are to continue funding such a mission through to its completion. This attribute includes how the mission promotes a national agenda, and does not reflect scientific gain as this has previously been accounted for. This attribute also considers the impact of the scenario in popular culture since this in turn influences public awareness and public support.
2. *Impact on Education* (Weight: 15%): Indicates the degree to which education is impacted by the mission. This refers to the percent increase in enrollment in STEM (Science, Technology, Engineering, and Mathematics) fields, as well as the addition of space-oriented curricula as a direct result of the mission
3. *International Cooperation* (Weight: 21%): This attribute refers to the degree to which international cooperation is promoted by carrying out the mission. This will reflect the number of nations that are involved in the mission.

The total weight, that is the product of the Attribute Weighting and Category Weighting was then calculated and is summarized in Table 4. Note that for simplicity the Attribute Weight column reflects the average of the AHP and survey weighting values.

Table 4: Summary of Category, Attribute, and Total Weighting

Category	Category Weight	Attribute	Attribute Weight*	Total Weight
Science & Life Science	31%	Exogeneous Short-Term Risk of Loss of Life	29% (11.2)	9%
		Scientific Relevance	23% (5.8)	7%
		Quantity of Data	18% (5.0)	5%
		Exogeneous Long-Term Risk of Loss of Life	22% (18.3)	7%
		Planetary Protection	8% (4.9)	2%
Technical	21%	Reliability	25% (8.6)	5%
		Maintainability	21% (6.1)	4%
		Ability to Demonstrate Technologies	22% (5.5)	5%
		Impact on Technical Advancements	15% (6.5)	3%
		Level of Autonomy	18% (9.2)	4%
Economic	21%	Mission Cost	47% (16.7)	10%
		Return on Investments	30% (13.7)	6%
		Risk of Overruns	22% (14.0)	5%
Sociopolitical	27%	Long-Term Political Will	68% (19.9)	18%
		International Cooperation Promotion	19% (6.9)	5%
		Impact on Education	14% (7.6)	4%

** Standard deviation shown in brackets*

Table 5: Summary of scenario scoring

Category	Attribute	Total Weight	Scenario 1	Scenario 2	Scenario 3
Science & Life Science	Exogeneous Short-Term Risk of Loss of Life	9%	10	1	4
	Scientific Relevance	7%	1	10	8
	Quantity of Data	5%	5	10	1
	Exogeneous Long-Term Risk of Loss of Life	7%	10	1	6
	Planetary Protection	2%	10	1	8
Technical	Reliability	5%	10	7	1
	Maintainability	4%	1	8	10
	Ability to Demonstrate Technologies	5%	1	7	10
	Impact on Technical Advancements	3%	7	1	10
	Level of Autonomy	4%	10	4	1
Economic	Mission Cost	10%	10	7	1
	Return on Investments	6%	6	1	10
	Risk of Overruns	5%	5	10	1
Sociopolitical	Long-Term Political Will	18%	1	10	9
	International Cooperation Promotion	5%	1	8	10
	Impact on Education	4%	1	9	10

V.III Attribute Scoring

The scoring for each scenario is summarized in Table 5. The following section explains the rationale of scoring in order to illustrate the model scenario selection mechanism.

Science and Life Sciences

In the scientific category, the Exogenous Short-Term Risk of Human Loss of Life score was chosen considering the portion of time the human explorers spend inside the habitat. It is argued that the explorers are more vulnerable during an EVA. Therefore, greater time spent inside a habitat would provide greater relative protection against natural accidents and hazards. The Exogenous Long-Term Risk of Human Loss of Life attribute was also scored according to the amount of time the human explorers spend in the habitat, which would provide improved protection from radiation.

Regarding the Scientific Relevance attribute, Scenario 2 is scored highest as it would demonstrate many of the technologies necessary for a future Martian exploration mission, where a high level of mobility and human immersion in the environment is desired. Half of the crew would stay at the habitat performing other research, such as life science experiments that, together with the EVAs, would permit a broad range of experiments. Although there is a high level of mobility in Scenario 3, the scoring is slightly lower, as it includes fewer EVAs.

With regard to the Quantity of Data attribute, the scenarios are scored according to the quantity of science and technology demonstrations they can perform. Habitats of different complexities are to be demonstrated in the three scenarios, but only Scenarios 2 and 3 demonstrate those with EVA capabilities. In each scenario, data would also be generated from scientific experiments, particularly by the astronauts in the habitats. Scenario 2 would generate large amounts of data from the selected samples. Scenario 3 can be considered as comparable to a submarine excursion. As such, it is anticipated that the lowest quantity of samples would be collected, and thus scored accordingly.

Concerning the Planetary Protection attribute, contamination is expected mainly from lunar dust sticking to spacesuits and equipment, which would subsequently be transferred to the habitat. Since the mobile habitat in Scenario 3 would have integrated suit ports, contamination of the human explorers and cross-contamination of the lunar surface is expected to be very low. Conversely, Scenario 2 is similar to the Apollo lunar missions, where contamination was found to be an issue. Although surface disruption would be high in Scenario 1 with multiple rover trips from the habitat to exploration targets, this is judged less of a concern than contamination.

Technical

The technical category described in the model is intended to showcase the competence of each scenario with respect to demonstration of the infrastructure capabilities. In the context of the model, the reliability attribute is interpreted as the ability of the technical infrastructure to support the mission goals safely and efficiently. The highest rated scenario is considered to be the one in which an unmanned rover performs the mobile planetary exploration and sample return tasks, which corresponds to Scenario 1. This decision is based on the fact that the required technology for Scenario 1 is more mature, as it has been tested in precursor missions and has a higher level of technological readiness, thus likely to be more robust. Furthermore, a catastrophic failure of the exploration rover would not incur loss of human life. Scenario 2 was rated highly as well, since a manned rover has been technically demonstrated on the surface of the Moon; however this scenario carries a risk to astronaut operators in case of failure. Scenario 3 is rated as lowest as it has the lowest technology readiness and would be tested in-situ for the first time.

Maintainability is also an important aspect in evaluating the technical infrastructure of each scenario. Direct human intervention was considered to be highly beneficial, as human operators would have the dexterity, resourcefulness, and critical thinking abilities to carry out maintenance or repair tasks. In this regard, Scenario 3 is preferred as the astronauts would be able to perform maintenance operations for longer durations, as it is assumed mobile habitat would be equipped with a larger variety of tools and supplies. Scenario 2 is highly rated because of direct human operator input and closeness to human habitat for additional support if needed.

It was considered that the level of complexity in the technical infrastructure associated with supporting astronauts on site would drive the impact on technical advancements. From this point of view, Scenario 3 is considered the most complex, and is rated as highest, as the mobile habitat would require the most technical advancements in terms of life support, radiation mitigation, power generation, and autonomy. Scenario 1 is highly rated as it would drive advancements in autonomous robotics, which can have a direct impact on spinoff technologies.

The ability to demonstrate technologies is directly related to the capability of each scenario to demonstrate technologies that would be applicable to the goal of long term human exploration of planetary surfaces. In scoring this attribute, it is assumed that the Moon Next pathway would act as an analog environment for a more complex mission to Mars. From this point of view, it is considered that Scenario 3 would be the highest rated, as it would demonstrate the most complex means for mobile planetary exploration. Scenario 2 is also scored more highly due to the level of technology necessary to support a two-person crew on the mobile exploration platform.

The level of autonomy for each scenario differs noticeably. The most autonomous platform is presented in Scenario 1, where the robotic rover is able to perform exploration and basic scientific tasks autonomously. Scenarios 2 and 3 rate poorly, as the respective rovers considered in these cases are operated primarily by direct, human control. Scenario 2 is scored moderately, as the crew-operated rover would have some autonomous components, such as basic obstacle avoidance, hazard detection and navigation. The mobile habitat described in Scenario 3 is considered too large to be efficiently used as an autonomous platform and scored poorest in this category.

Economic

The economic category has a significant impact in selecting the ideal scenario for the mission. This is because the available funding and costs involving the mission have to be balanced very delicately. Mission cost relies on the amount of foreseeable expenditures involving the mission. Scenario 1 is the least costly as it will not require additional equipment to support a human traverse such as spacesuits, additional fuel and resources to support that crew, and more. By the same reasoning, a scenario that requires an overnight stay during a traverse for astronaut excursions will receive the lowest score, as it will be the most expensive.

Return on Investments reflects the complexity of the technological requirements for the mission scenarios. As a result, scenario 3 receives the highest score as it offers the highest number of job creations and spinoff products as a result of the mission. Respectively, Scenario 1 and Scenario 2 receive the second and the lowest scoring as a result, as sample analysis robotics missions, similar to Scenario 1, are already underway, lowering the opportunities for new spinoffs or extending a new job market.

Risk of Overruns is the second most important attribute of the economic category, as it focuses on the chances of mission cost or time deployment exceeding the initial estimations during the development and mission operation phases. Considering the technology readiness level of the equipment necessary to support the mission, Scenario 3 receives the lowest score. This is because the complexity of the technology to support the onboard crew is at the lowest relative technology readiness level. This elevates the risks involved with executing the mission on time and within budget. Scenario 1 receives a mid-level score, as the majority of the technology is currently ready. However, suitable autonomous path planning and science technology remains under development. Scenario 2 receives the highest score, as all required technologies to control and manoeuvre sample return missions, with the assistance of the crew on site, currently exist.

Sociopolitical

The sociopolitical attribute category is significant when determining the model outputs, second only to the scientific category. The category has a relatively high weighting and small number of attributes, the most prominent being Long-Term Political Will. For the three scenarios, Scenario 2 is scored highest on the Long-Term Political Will attribute, as it incorporates a large degree of human activity. Furthermore, there will be a large amount of human activity on the lunar surface, as opposed to within a vehicle (for example, as seen in Scenario 3). Conversely, Scenario 3 is scored the highest in terms of the International Cooperation Promotion, as the greatest technological improvement would be needed for this scenario, which would necessitate international support and expertise. As Scenario 1 is the most technically feasible with current technology, this is scored the lowest in terms of International Cooperation Promotion. Lastly, the Impact of Education attribute was scored similarly to International Cooperation Promotion, as the most technically challenging scenario would logically be the one with the greatest impact on education.

VI. RESULTS AND DISCUSSION

CHARM is intended as a decision-making tool in evaluating the performance of scenarios designed to achieve a common global objective. In Section V it was shown that, for each scenario, the criteria for evaluation are organized in clusters called "categories" and each category contains evaluation sub-criteria called "attributes". One of the most important features of the CHARM model is the fact that it is a dynamic tool, where mission designers can decide on the rank of "categories" and pertinent "attributes" by assigning them weightings based on factors such as importance, relevance or financial considerations.

The incorporation of inputs from both the authors and those of the multiple mission designers surveyed at the ISU ISS and Mars conference introduces variation and uncertainty in the model output. To integrate the opinions of multiple mission designers into the decision-making process, CHARM been adapted by applying it in the context of a Monte Carlo probabilistic simulation to determine the influence of uncertainties in weighting inputs on the model outputs. A schematic of this approach is illustrated in Figure 3.

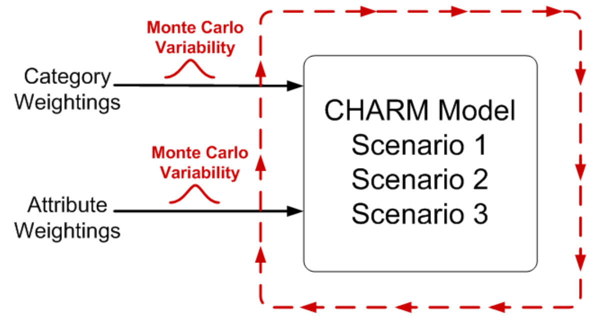

Figure 3:Schematic of Monte Carlo probabilistic simulation

In CHARM each weighting can be considered to be a probabilistic variable, described by a mean and standard deviation for each category and attribute (see Table 3 and Table 4). In a Monte Carlo simulation, each weighting is randomly sampled based on its respective mean and standard deviation. Subsequently, CHARM is applied using the sampled weightings as inputs. This process is repeated one thousand times to ensure that the sampling of inputs is statistically representative. The results from the CHARM output from each simulation are collected and summarized as a mean and standard deviation as seen in Table 4.

It is recommended that the CHARM results be interpreted based on the mean results, while the standard deviation is used as an indicative of confidence level in the results.

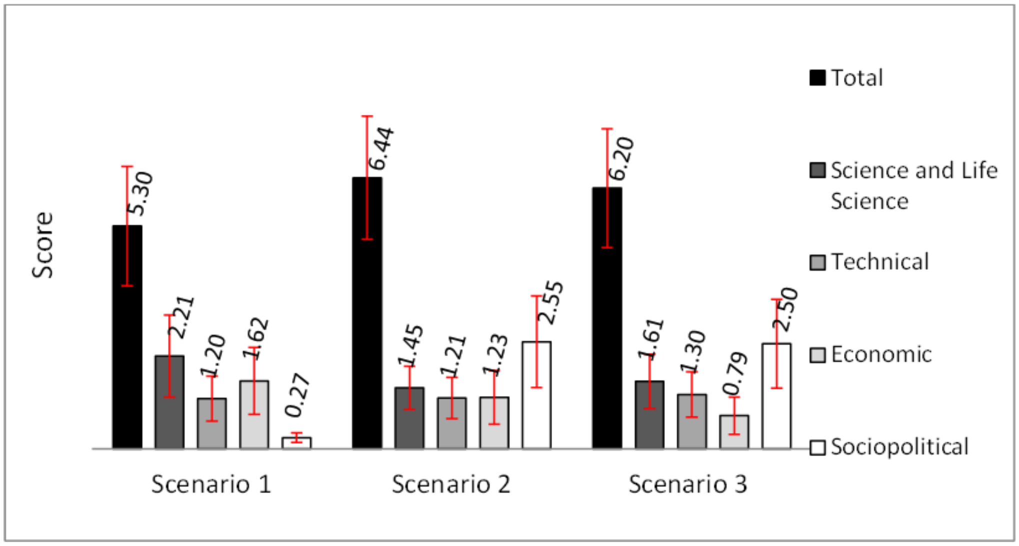

Figure 4: CHARM outputs

VI.I Statistical Interpretation of Results

It is important to note that both the combined CHARM-Monte Carlo results and a number of the scenario categories have a standard deviation equal to a significant percentage of the total score. The large standard deviation in results may be indicative of:

1. Having a small population set for collecting weighting statistics. For running this CHARM iteration, the team has used a total of eleven experts to collect data for the category and attribute weightings. This number is statistically small, therefore, to improve on the quality of inputs, it is recommended to use contribution from a larger pool of experts. This would increase the confidence in the CHARM outputs.

2. Having divergent opinions amongst the experts in assigning weightings to categories and attributes. When the experts have differences in opinion with regards to weightings, they are reflected in a large standard deviation for that particular weighting. In this case, the variability of CHARM outputs obtained through Monte Carlo probabilistic simulations would be indicative of the variability in inputs. This can be a useful tool in analysing how divergent opinions may influence scenario selection.

VI.II Practical Interpretation of Results

The CHARM-Monte Carlo approach described in this article gives the highest overall score to Scenario 2. Considering the objective of developing the capabilities necessary to explore and become self-sufficient on a planetary surface, the selection of Scenario 2 emerges as an intuitive choice. The scenario is comparatively well balanced for all considered categories, with Sociopolitical support representing a strong benefit.

Since undertaking such an ambitious mission in the near future would require strong financial support, it was assumed that it would be undertaken as a cooperative effort between several government agencies. This approach has been proven historically in the success of the ISS. This interpretation was reflected by the relatively high importance of the weighting of the Long-Term Political Will and Mission Cost attributes. However, the demonstration of the necessary technology as well as its safety remains a challenge.

The third most highly weighted attribute is that of risk to human life. Loss of human life in any scenario would result in the public perception of the mission as a failure, regardless of any scientific achievements. Scenario 2 scored poorest in the risk to human life attributes, primarily as the safety of the technology needs to be demonstrated and tested in the field. The demonstration of habitat technology along with the EVA capabilities proposed in Scenario 2 will best improve the technological flight heritage necessary for a Martian exploration mission. However, with such demonstrations, there are technical and economic hurtles to be overcome, which is coherent with a low scoring of Scenario 2 in the Technical category. In summary, Scenario 2 scores between the two other scenarios in both the Economic and Technical categories and appears as a suitable compromise.

VII. CONCLUSION

CHARM has been applied to the Moon Next pathway as an example of how its decision making model can be applied to near-term exploration objectives. This application demonstrates the ability in using CHARM to examine enabling mission scenarios for subsequent exploration objectives, such as manned missions to Mars.

Examination of internationally accepted mission structures have allowed the identification and categorization of relevant mission attributes, suitable for use in CHARM and allowing the definition of valid mission scenarios for examination. Weighting value selection has been extended and improved over previous implementations of CHARM by incorporation of independent weight selection by international experts in fields relevant to exploration mission design.

The mission outcome selected for examination, manned exploration of the lunar surface, has indicated the optimum scenario of human and robotic cooperative exploration of the lunar surface currently lies in the implementation of simpler robotics, supplemented by direct human interaction through extended EVA excursions. This is summarized by Scenario 2 above, and reflects the current state of the art in robotic autonomy and the benefits of direct human discretion in the selection of objectives in real time.

The CHARM output robustness is examined using a Monte Carlo simulation to analyze the confidence level in the total scenario scores. The results suggest that large numbers of experts must be surveyed to provide a reduced output deviations. Near term and transient global conditions, *e.g.* political unrest, economic stability, or technological breakthroughs, may easily sway the result between any of the scenarios when the outputs are close. As such, attribute selection must accurately reflect relevant global conditions in each CHARM category.

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