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AN INTERDISCIPLINARY APPROACH TO HUMAN-ROBOTIC COOPERATION IN MARS EXPLORATION

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The recent past has seen robots develop into autonomous artificial agents capable of executing complex tasks. In the near future, robots will likely develop the ability to adapt and learn from their surroundings. Robots have self-reliance, accuracy, and can operate in hostile environments - all attributes well suited for space exploration. Robots also reduce mission costs, increase design flexibility, and maximize data production. On the other hand, when faced with new scenarios and unexpected events, robots pale in comparison with their intuitive and creative human counterparts. The future of space exploration will have to intelligently balance the flexibility and ingenuity of humans with robust and sophisticated robotic systems. The Cooperation of Humans And Robots for Mars (CHARM) team at the 2011 Space Studies Program of the International Space University integrated international, intercultural, and interdisciplinary perspectives to investigate Mars exploration objectives, robotic capabilities, and the interaction between humans and robots. Based on the goals of various space agencies, this paper selects an exploration objective for the time frame between 2015 and 2035, and drafts different scenarios to accomplish this objective. Each scenario uses different degrees of human-robot interaction. A theoretical model is then developed based on discrete requirements to help create an effective combination of human and robots to achieve the mission objective. This model is used to select the most appropriate of the proposed mission scenarios. The CHARM model uses an interdisciplinary approach, including technical, societal, political, financial, and scientific perspectives. The CHARM team believes that this decision-making model can be used to select missions more efficiently and rationally, thus enabling greater feasibility to space missions.

Keywords: Model, International Space University, Space Studies Program, Human Robot Cooperation, Mars.

I. INTERNATIONAL SPACE UNIVERSITY

The International Space University (ISU) is the world's foremost educational institution devoted to fostering the development of tomorrow's global space industry workforce. It was founded in 1983 by Bob Richards, Peter Diamandis and Todd Hawley, and has a principal campus in Strasbourg, France. ISU conducts both a one year Master's Program and an intensive nine-week Space Studies Program (SSP). This year's SSP was held at the Technische Universität in Graz, Austria, from early July to mid-September 2011.

ISU 2011 Space Studies Program

This year's SSP included over 120 participants, who were divided into three team projects: one focused on space based solutions to problems of access to fresh water, another developed a guidebook on small satellite applications and the third focused on the human-robotic cooperation and interaction for space exploration and discovery. The students attended core lectures on a wide variety of space-related subjects for the first third of the program, split into smaller departmental tracks for the second part of the program, and were able to refocus on their team projects for the final third of their curriculum.

II. COOPERATION OF HUMANS AND ROBOTS FOR MARS

The team project which focused on robotic applications for space exploration named itself the Cooperation of Humans and Robots for Mars (CHARM) team. The team was comprised of 41 separate individuals from 16 countries with a variety of backgrounds and disciplines. This paper reflects a distillation of the team project final report, which may be found at http://hrc.isunet.edu (SSP2011 CHARM, 2011). This paper was drafted by the above-named authors, but could not have been accomplished without the effort of all of the CHARM participants.[*]

Additionally, the CHARM team was assisted and inspired faculty and staff of the ISU SSP[†], along with some very inspirational and helpful external experts[‡].

The CHARM Team met in small groups, and as a whole, to discuss the complex and various aspects of humans and robots exploring other celestial bodies, namely Mars, and the challenges and opportunities of these endeavors.

Motivation:

In 2004, two robotic geologists began their exploration of the Martian surface. Since that time, the Mars Exploration Rovers (MERs), Spirit and Opportunity, have transformed our perception of Mars by uncovering important evidence of the role of water in the planet's history. Yet as we recognize their great accomplishments, we must also acknowledge their great limitations.

During the first five years of their operation, they travelled a collective distance of only 21 kilometres. [1] Opportunity spent five weeks stuck in a Martian sand dune [2] while Spirit ended its operational life similarly ensnared [3]. Their operation required a large support team to plan every step in painstaking detail. Even the simple act of moving to a rock and analyzing it could take three days. [4] These limitations were best summed up by Steve Squyres, the Principal Investigator of the MER project when he said:

> *"What Spirit and Opportunity have done in 5½ years on Mars, you and I could have done in a good week. Humans have a way to deal with surprises, to improvise, to change their plans on the spot. All you've got to do is look at the latest Hubble mission to see that." [5]*

The Hubble Space Telescope servicing mission to which Squyres refers, and the missions that preceded it, could be held up as examples of the enormous benefits of having humans, rather than robots, in space. Without the ability of the astronauts to improvise solutions to unexpected problems, the Hubble telescope would have long ago ceased to provide useful data. One could argue that these examples capture a dichotomy in our approach to space exploration: either human or robot. Indeed, much of the discourse on this topic has been framed in these terms, with two camps fighting for limited resources. But this dichotomy does not bear scrutiny. Consider that the Hubble servicing missions relied on the superior reach, precision, and endurance of a robot, the *Canadarm1*, to complement the intelligence, ingenuity and dexterity of the astronauts. Moreover, to guide their exploration, the MERs did not act independently but relied on the experience and expertise of geologists on Earth who could not travel to the Martian surface in person. When we look more closely at these examples, we see that only when the strengths of humans and robots are combined do we reach optimal performance.

The CHARM team believes that it is more useful to view the above examples in terms of a continuum of human-robot cooperation. The CHARM team further contends that approaching mission design from the perspective of cooperation instead of the traditional "one or the other" approach will allow for greater achievements in future space missions. And while it is difficult to effectively and efficiently blend human and robotic mission elements, crucial decisions can be broken down into a series of smaller decisions, and with their merits weighted and rationally compared, effective mixes that maximize the benefits of human characteristics and the benefits of robotic features can be achieved.

III. MARS EXPLORATION: PAST, PRESENT AND FUTURE

Mars is only half the size of Earth and an average of 230 million kilometers away, yet we on Earth have long speculated about Mars and what we will find there, perhaps more so than about any other planet. Is there life on Mars? Flowing water? Was there ever flowing water? What is the atmosphere like, and the temperature? What minerals and resources are there - and what could we do with them? In the first half-century of spaceflight, various space agencies have sent spacecraft to explore Mars.

The CHARM team investigated the history of Mars exploration, paying particular attention to the scientific objectives of those missions. The team also investigated current and future Mars missions, as well as their objectives. Next, the CHARM team turned its attention to the history of Mars exploration policies, and the economic rationales for Mars exploration.

Summary of Mars Exploration Objectives

Through extensive research of past, present, and planned missions to Mars, and also looking to groups like the Mars Exploration Program Analysis Group (MEPAG), the CHARM team has observed that there are several key objectives common for Mars exploration. These are:

1. To search for life or evidence of past life
2. To investigate of the Martian atmosphere and weather
3. To study the Martian terrain (i.e., photography, remote sensing)
4. To study Martian geology (i.e., soil composition, seismology)
5. To test systems for future Mars exploration missions
6. To test *in-situ* resource utilization systems

Mars Exploration Policies

Historically, human exploration of space has been driven by national prestige, the apex being the race to the Moon with the National Aeronautics and Space Administration's (NASA) Apollo program and its Soviet competitor in the 1960s. After the cancellation of the Apollo program in 1972, several Mars human exploration programs have been proposed and even planned, but, to date, no governmental imperatives have spurred enough political and public desire for a sustained human Mars exploration program.

Beginning in 1972, NASA Administrator Thomas Paine constructed an exploration plan that included a human mission to Mars in 1981. Then President Richard Nixon rejected this plan in favor of the Space Transportation System.[6] A human Mars exploration program was revisited in 1989 when President George H. W. Bush announced his Space Exploration Initiative that included a human mission to Mars. This plan was abandoned after a study reported the cost of the program to be approximately USD 500 billion, an amount too expensive even with international collaboration. [7] In 2004, President George W. Bush set forth his human exploration plan, entitled The Vision for Space Exploration. This plan was similar to his father’s and ultimately was cancelled by the Obama administration in 2009, because of significant scheduling overrun and lack of funding.

The former Soviet Union had proposals for human missions to Mars in 1969, largely in response to the success of the Apollo project. Called the “Mars Expeditionary Complex,” plans for interplanetary spacecraft were created that were to fly aboard the planned N-1 rocket. However, no successful launches of the N-1 were ever accomplished; hence, the proposals were abandoned. [8]

Current Mars Exploration Policies

Currently, there are several space-faring nations that have created preliminary proposals for human exploration of Mars - such as the United States, Russia, and China, none of which have initiated such a program. There have also been various programs for robotic exploration of Mars by various nations.

The 2010 Space Policy of the United States states: “It is the goal of the US space policy to expand international cooperation, pursue human and robotic initiatives and explore the solar system and the universe beyond. It is the national space policy of the US to send humans to orbit Mars by the mid 2030s and to maintain a sustained robotic presence in the solar system.” [9]

With the retirement of the Space Shuttle in August of 2011 and the lack of concrete plans for human exploration of Mars, Russia and China remain the only countries that have the capabilities to send humans into space. Although without the technical capabilities to send humans to Mars, Russia has put forth numerous concepts and proposals for human exploration of Mars. The Russian Federal Space Agency and the European Space Agency have also been cooperatively working with the MARS500 project, an analog experiment for simulating a human flight to Mars.

While no formal plans exist for Chinese human exploration of Mars, it is likely that following the planned lunar exploration, focus will be diverted to exploration of Mars: however, any technical plan to explore Mars has yet to acquire governmental approval. [10]

Interagency Mars Plans

Human planetary exploration is extremely costly, and this type of space exploration will always be subject to budgetary constraints. Consequently, there are many reasons for national space agencies to pool their resources and knowledge, work cooperatively, and share risks of such complex projects. Cooperation allows agencies with particular competencies to play crucial parts, and allows smaller agencies with niche talents to work with larger partners to achieve what none could accomplish alone. For Mars, there are two important interagency groups currently looking at possible cooperative missions: the MEPAG and the International Space Exploration Coordination Group (ISECG). The MEPAG is a forum supported by NASA that provides an overview of its Mars exploration goals and the scientific objectives of these goals. The four goals of MEPAG[11] are:

1) Determine if life ever arose on Mars
2) Understand the process and the history of the climate on Mars
3) Determine the evolution of the surface and interior of Mars
4) Prepare for human settlement

The ISECG is an international coordination body where agencies can meet in a voluntary, non-binding manner to exchange information, interests, objectives and future projects in space exploration. The goal of the ISECG is to strengthen individual as well as collective exploration programs. The guiding principles of the ISECG are that it should be open and inclusive, flexible and evolutionary, effective, and for mutual interest. [12]

As the ISECG is largely involved with future exploration missions, their involvement in a mission to Mars will be invaluable. It is likely that any future mission to Mars cannot be done by a single country acting alone, but through a consortium of participants acting in a coordinated fashion. It will be up to the ISECG to act as a mechanism or aid in determining the distribution of costs, how capabilities are pooled, what roles each agency will play, and how scientific knowledge will be shared from a Mars exploration mission.

Review of Mars Exploration, Past and Present

Numerous national space agencies, including those of the United States, the former Soviet Union, Russia, the United Kingdom, and Japan have attempted robotic exploration of Mars with flyby, orbital, and lander missions. The full CHARM report contains an in-depth discussion of its investigation on the history of Mars exploration, past and present, along with a discussion of Mars exploration plans, including Mars Direct and the NASA Design Reference Mission. [13]

Economic & Political Aspects

The CHARM team also investigated the economic and political aspects of Mars exploration, including the budgets of large space agencies and what fraction of national gross domestic product they constitute, the rationales for investment in space exploration, and the return on investment from such exploration. The team then investigated the cost drivers for robotic and human payloads to Mars, with purely robotic missions as a baseline and the addition of crewed missions driving additional costs. The full report also includes the scaling factors applicable to launching a given mass to Mars orbit, to the surface of Mars, and of returning that mass from Mars to Earth. [16] These considerations play into a discussion of the ideal mix of human and robotic elements on a Mars mission from a financial point of view.

IV. HUMAN-ROBOT COOPERATION

The ability of humans to use their intellect, ingenuity, and intuition to complete tasks is not yet present in robotic systems. Unexpected events can easily confuse robots in widespread use today, and it is common for the failure mode in such cases to involve a halt or delay in the execution of a task. By this argument, the use of human agents in the execution of mission critical tasks is desirable. A place for robotic assistants does still exist, however, in assisting humans, commonly in situations where repetitive or strenuous tasks are necessary, or where environmental conditions are hazardous to human health. The CHARM team completed a detailed review to examine how humans and robots interact and work together, which is discussed in the following sections.

Human-Robot Interactions

At the most fundamental level, mechanical, automated, and autonomous systems are necessary to keep human occupants of spacecraft alive. A physical habitat is necessary to house human explorers, shield them from the extremes of the space environment, the radiation events, and to provide a temperate and breathable atmosphere. It provides the human necessities for day-to-day life, for exercise, sleep, and work, and is also necessary in supporting the psychological necessities of human well-being. Workloads, performance pressures, or lack of privacy are all factors known to increase stress and reduce mental stability in human space explorers.[14] The above examples of stresses on human health can be addressed through the use of robotic systems, but the reliance on these systems raises the question of how humans react to such a heavy dependence on non-human agents.

The level of exposure of a person to robotic systems has been shown to have measurable effect on how receptive they are to the use of robots in society. Perhaps counter-intuitively, greater levels of exposure appear to have a detrimental effect on the public perception of robots. [15] Theis belief would appear to be rooted in a greater level of understanding resulting in issues of trust with a robot to operate as instructed. In a space exploration situation it would not be unusual to expect a crew to develop an emotional relationship with the systems with which they both work and use to stay alive. The existence and stability of these relationships are likely to be as important as the inter-human relationships between the members of a crew.

Robotic considerations

Robotic explorers have been used throughout the history of space travel. All orbiters, landers, rovers and probes act as remote agents to aid humans in the exploration of our planet, solar system and further afield. There are several key examples, however, where robotic systems have acted in cooperation with humans in exploration missions.

One of the most basic mechanical examples of a robot is a manipulator. Used extensively in space exploration, perhaps the most apparent examples are the *Canadarm1* and *Canadarm2* robotic arms used on the Shuttle and ISS, respectively. Both were used extensively in aiding astronauts and cosmonauts in the construction and maintenance of the ISS. They provided a support platform to maneuver humans around elements of the station, relocated cargo from the Shuttle payload bay, and also utilized their own set of tools to allow operators inside the station to perform tasks. The next stage of robotic assistants is under way today, with the delivery of the humanoid robot Robonaut2 to the ISS in February 2011. Resembling a human torso, arms, hands, and head, Robonaut2 can work alongside humans using same the tools – and performing the same experiments and tasks.[16]

Sophisticated manipulators have also been used in the exploration of Mars, the most recent examples having flown on the MERs and Phoenix lander. In these cases, direct operation by humans is not possible due to the extensive radio latency incurred by the distance between Earth and Mars. The use of autonomous operation allows these systems to react to certain unknowns, including readjustment of a commanded trajectory, or autonomous approach and deployment of an instrument.[17][18]

The autonomous ability of a robotic system is of particular importance to mobile robotic platforms, or rovers, such as the MERs. Challenging terrains provide one of the most unpredictable environments in which to use a robotic system, and as a result, even the most sophisticated autonomy system depends upon a human "in-the-loop". The inherent human strength of adaptability to unknowns makes their presence in a locale highly desirable in aiding and directing robotic assistants, perhaps specialized to a given terrain. Exploration missions would benefit significantly from such cooperation between local human and robotic agents.

A final example of human robotic cooperation in a long-term mission can be found in the selection, preparation, and analysis of scientific experiments. This is exemplified in the quote by Steve Squyres in Section II, and is another example of the benefits of human adaptability. Once in place, the natural strengths of robotic systems in performing repetitive, high precision or fatiguing tasks common to certain scientific procedures compliment the human abilities.

V. MODEL ARCHITECTURE DEVELOPMENT

The CHARM model was developed with the intention of aiding mission designers in selecting an appropriate degree of human-robot cooperation for a space mission. A literature review was performed on various models that could be applied to human-robot cooperation, with the CHARM model ultimately incorporating the Vroom-Jago[19], the Analytic Hierarchy Process (AHP)[20], and the Simple Multi-Attribute Rating Technique (SMART) models[21]. The CHARM model architecture defines the mechanism by which alternative scenarios for human-robot cooperation are evaluated. Finally the CHARM team identifies the criteria on which this evaluation is based, and the weighting (relative importance) of each of these criteria.

Review of Existing Models

The Vroom-Jago decision making model is an objective means to determine who in a group makes the decisions. The decision-making process occurs on a scale that ranges from purely leader-made decisions, to purely group-made decisions. The details of the Vroom-Jago method can be found in [19]. It is important to note that this model simply provides guidance as to who should make a decision, but does not detail the means by which different alternatives can be evaluated.

The aim of the AHP decision making tool is to choose between different alternatives, hereafter called scenarios, to achieve a common goal. This is done by scoring different evaluation criteria, hereafter called attributes, as well as the relative importance of these attributes. The AHP method uses a relative scaling system to score the attributes to allow for a relative ranking of the scenarios. The full details of the AHP method can be found in [20].

The SMART method, as used in the Astra team project of the 2010 ISU SSP [21], is a trade-off analysis that consists of the following steps:

1. Determine the objectives of the mission.
2. Identify the mission designer(s).
3. Identify the different scenarios that can accomplish the mission objectives.
4. Identify the scenario attributes and assign weightings for each scenario.
5. Assign importance scores to each scenario for each attribute.

6. Sum the weighted scoring of each attribute for each scenario and determine the preferred scenario by comparison.
7. Perform a sensitivity analysis on the weightings and scores to determine the main driving factors influencing the selected scenario.

The Vroom-Jago, AHP, and SMART methods were each incorporated into the development of the CHARM model in order to evaluate different mission scenarios involving various levels of human and robot cooperation.

Model Architecture Description

The basic architecture of the CHARM model can be broken down into six steps which are detailed below.

STEP 1 - Determine the mission objective, which is the goal or desire of pursuing a mission.

STEP 2 - Determine the mission designer(s) by using the Vroom-Jago method.

STEP 3 - The mission designer(s) is/are to determine the different scenarios to accomplish the mission. These are the different ways in which the mission objective can be accomplished and all scenarios must incorporate different degrees of human-robot cooperation.

STEP 4 - The mission designer(s) determine(s) the attributes required to evaluate the scenarios, as well as the attribute weightings. The attributes are sorted into the predetermined categories Scientific & Life Sciences, Technological, Economic, and Social & Political. The attributes are sorted into categories to enable two levels of weightings: "Category weightings" which determine the importance of the respective category to achieving the mission object, and "attribute weightings" which determine the importance of the respective attribute within its category, as shown in Table 1.

Table 1: CHARM model category and attribute weighting matrix.

Category and Attribute Weightings Matrix				
Category	Category weight	Attribute	Attribute weight	Total weight
Science & Life Science	CW_1	A_{SLS1}	AW_1	$TW_1 = CW_1 \cdot AW_1$
		A_{SLS2}	AW_2	$TW_2 = CW_1 \cdot AW_2$
Technical	CW_2	A_{T1}	AW_3	$TW_3 = CW_2 \cdot AW_3$
		A_{T2}	AW_4	$TW_4 = CW_2 \cdot AW_4$
Economic	CW_3	A_{E1}	AW_5	$TW_5 = CW_3 \cdot AW_5$
		A_{E2}	AW_6	$TW_6 = CW_3 \cdot AW_6$
Social & Political	CW_4	A_{SP1}	AW_7	$TW_7 = CW_4 \cdot AW_7$
		A_{SP2}	AW_8	$TW_8 = CW_4 \cdot AW_8$

STEP 5 - The mission designer(s) determine(s) the scoring of each attribute, ranging from 1 (the worst case) to 10 (the best case) as per the AHP method. These scores are put into a decision matrix as well as the weightings as shown in Table 2.

Table 2: CHARM model scoring matrix.

Scoring Matrix				
Category	Attribute	Total weight	Scenario 1	Scenario 2
Science & Life Science	A_{SLS1}	TW_1	$S_{1,1}$	$S_{2,1}$
	A_{SLS2}	TW_2	$S_{1,2}$	$S_{2,2}$
Technical	A_{T1}	TW_3	$S_{1,3}$	$S_{2,3}$
	A_{T2}	TW_4	$S_{1,4}$	$S_{2,4}$
Economic	A_{E1}	TW_5	$S_{1,5}$	$S_{2,5}$
	A_{E2}	TW_6	$S_{1,6}$	$S_{2,6}$
Social & Political	A_{SP1}	TW_7	$S_{1,7}$	$S_{2,7}$
	A_{SP2}	TW_8	$S_{1,8}$	$S_{2,8}$

STEP 6 - The weights and scores are combined to determine the overall scenario performance using the equation shown in following Equation 1. The scenario performances are then compared to determine which scenario best accomplishes the mission objective.

Equation 1: Scenario performance estimate equation.

$$SP_j = \sum_{i=1}^{n} TW_i \bullet S_{ji}$$

where
Scenario j = 1 … 4
Attribute i = 1 … n

A sensitivity analysis can then be performed to determine the extent to which certain attributes are dominating the score and what the major factors are that are limiting a more preferred scenario.

Model Attributes and Descriptions

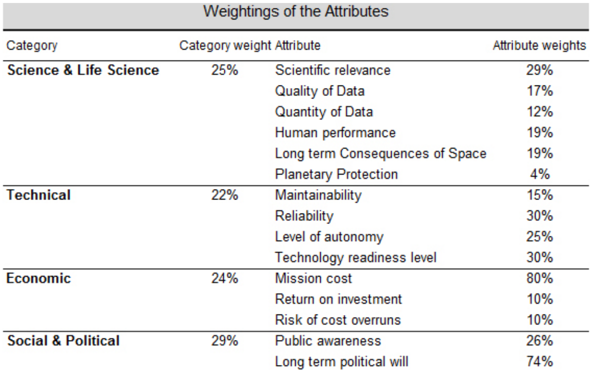
As a result of the literature review that was performed, the following category weightings were used:

1. Scientific (Weight: 25%)
2. Technical (Weight: 22%)
3. Economical (Weight: 24%)
4. Sociopolitical (Weight: 29%)

Furthermore, Table 3 shows the attributes that were used in the current mission objective analysis and their respective category and attribute weightings.

The attributes shown in Table 3 were chosen for a Mars sample return mission, but can however be modified to suit the needs of a mission designer. The details of these attributes and the rationale for the respective weightings are discussed in great detail in the CHARM full report[13].

Table 3: The weightings of the attributes used in the current analysis.



Weightings of the Attributes

Category	Category weight	Attribute	Attribute weights
Science & Life Science	25%	Scientific relevance	29%
		Quality of Data	17%
		Quantity of Data	12%
		Human performance	19%
		Long term Consequences of Space	19%
		Planetary Protection	4%
Technical	22%	Maintainability	15%
		Reliability	30%
		Level of autonomy	25%
		Technology readiness level	30%
Economic	24%	Mission cost	80%
		Return on investment	10%
		Risk of cost overruns	10%
Social & Political	29%	Public awareness	26%
		Long term political will	74%

VI. APPLICATION OF THE MODEL AND RESULTS

According to the 2010 MEPAG study, there are two main categories of rationale for Mars exploration missions; to look for evidence of life on Mars and to prepare for future human settlement. The MEPAG also outlined 55 fundamental future science investigations associated with the exploration of Mars. The MEPAG concluded that around half of the investigations "could be addressed to one degree or another by Mars sample return," making a Mars sample return "the single mission that would make the most progress towards the entire list" of investigations. [11] As such, a Mars sample return mission was chosen to be the mission objective to be examined by the CHARM model.

Once the decision maker(s) were determine as described in Section V, four scenarios were envisioned each incorporating various degrees of human-robot cooperation. These scenarios were then evaluated by the CHARM model and are summarized below.

Scenario 1 - Robotic Mars Sample Return

A composite spacecraft containing a robotic lander as well as an orbiter is to be sent to Mars. The lander collects samples and uses a Mars ascent vehicle to lift the material into low Mars orbit where it is then returned to Earth via an orbiter. This scenario does not involve human spaceflight elements and has been based on the iMARS (International Mars Architecture for Return of Samples) mission concept. [22]

Scenario 2 - Mars Orbital Outpost

The Mars Orbital Outpost scenario is a mission concept where robots on the surface of Mars are operated by humans in low Mars orbit, reducing the communication delay between operators and robots. This scenario is based on the Russian MARPOST mission concept. [22]

Scenario 3 - Human Short-Stay on Mars

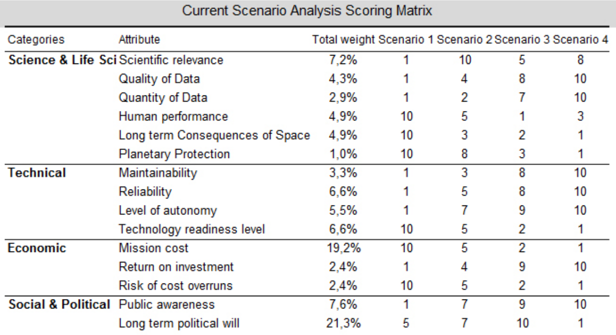
The Human Short-Stay scenario will allow for up to 40 days on the surface of Mars with a total mission time of 661 days. The scenario will place two out of the four total crew members on the surface of Mars with various rovers and robotic equipment. This scenario is based on the Mars Design Reference Architecture 5.0. [24]

Scenario 4 - Human Long-Stay on Mars

The long-duration scenario is a mission based on low energy transfers to and from Mars. For this mission, five crew members will spend 18 months on the surface of Mars and 6 months in transit to and from Mars, for total mission duration of 30 months. This scenario is based on the Mars Design Reference Architecture 5.0. [24]

Table 4 details the scores that were given to the separate attributes, as described in the previous section, for each of the four scenarios. The details for the rationale behind each of the scores can be found in the CHARM full final report. [13]

Table 4: CHARM scoring matrix used in the current analysis.



Current Scenario Analysis Scoring Matrix

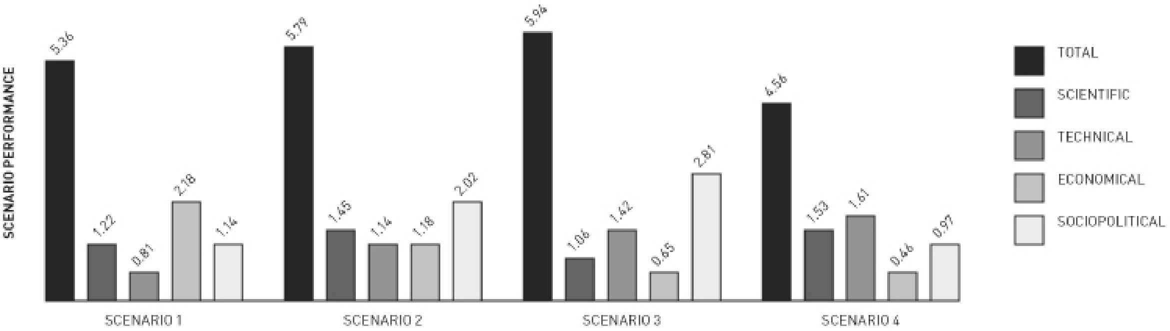
Categories	Attribute	Total weight	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Science & Life Sci	Scientific relevance	7,2%	1	10	5	8
	Quality of Data	4,3%	1	4	8	10
	Quantity of Data	2,9%	1	2	7	10
	Human performance	4,9%	10	5	1	3
	Long term Consequences of Space	4,9%	10	3	2	1
	Planetary Protection	1,0%	10	8	3	1
Technical	Maintainability	3,3%	1	3	8	10
	Reliability	6,6%	1	5	8	10
	Level of autonomy	5,5%	1	7	9	10
	Technology readiness level	6,6%	10	5	2	1
Economic	Mission cost	19,2%	10	5	2	1
	Return on investment	2,4%	1	4	9	10
	Risk of cost overruns	2,4%	10	5	2	1
Social & Political	Public awareness	7,6%	1	7	9	10
	Long term political will	21,3%	5	7	10	1

Using the scoring and total weightings as depicted in Table 4. Based on the evaluation of all the attributes, the best scenario incorporating human and robotic cooperation for a Mars sample return is the Human Short-Stay mission scenario, as shown in Figure 1. The largest driving factors leading towards the selection of the short stay on Mars are the social and political attributes, with a mission that puts a human on the surface of Mars undoubtedly provoking much more positive societal support than any other mission scenario. A full analysis of the chosen mission can be found in the CHARM full final report[13].

Model Application Conclusions

The CHARM model was application to a Mars sample return mission with four different scenarios to accomplish this objective. It was determined that the Human Short-Stay mission to Mars was the most favourable mission scenario which was largely driven by the societal and political impacts of the mission. Following this study, a sensitivity analysis of the model to various changes in weightings was performed which is detailed in full in the CHARM full report [13].

Figure 1: Scenario performance of all four scenarios as outputted by the CHARM model.



VIII. CONCLUSIONS

The main objective of the CHARM team project was to propose and apply a model for future Mars exploration missions. The research into past, present, and future missions showed that the participation of robots, and therefore the need of an understanding how humans and robots can work together is essential. Challenges involved with long-duration space missions to Mars imply the need of sophisticated robotic systems to reduce the risk to human life, and also to reduce costs. Certain tasks, such as dangerous or repetitive tasks, may be better performed by an autonomous or, at least, a remotely controlled robot. A key aspect of future long-term or Mars exploration missions will be to determine the role that both humans and robots play while considering their effectiveness to accomplish the mission tasks. Therefore, the aim should be the optimal mix of human and robotic cooperation for manned Mars exploration missions.

To create this robust and generalized model, different influences form socio-political, economic, scientific, and technical areas were considered and integrated. To test the model and to show the applicability, four scenarios were developed and evaluated. These scenarios were derived while analyzing past, present and future Mars exploration missions, using various decision making methods and intensive literature research. Once the scenarios were found and well described, the CHARM model could be applied. While developing the scenarios and the applying the model, the CHARM team also identified critical gaps in research areas, and suggestions on how to address the gaps and answer the questions that need to be addressed to successfully complete (long-term) human missions to Mars with robotic cooperation were made.

The reliability of the model and the quality of the outcome depends on two major factors. First: scenarios are highly dependent on the considered future and how the future has to be handled. Second: the identification of an appropriate set of attributes by which each scenario may be measured. Variations in the weighting, scoring, and different assumptions of the future can have a significant influence on the outcome of the model, especially with heavily weighted attributes (e.g. Long-Term Political Will or Mission Cost). To validate the model, an analysis of extreme futures was performed and a sensitivity analysis was conducted on the results. It is clear a manned Mars mission is not feasible for a single nation. Both, from a technological and financial perspective it is more efficient for nations to collaborate. Thus, future of space exploration will be driven by how well we can work together — not only in terms of our international cooperation, but also on our ability to live, work, and interact with our robotic counterparts. The answer to the question of how we best use robots remains up to us. The CHARM report hereby hopes to help mission designers who plan on envisioning and embarking on journeys to Mars and beyond, along with our robotic counterparts.

To conclude, the CHARM team has proposed a feasible model for selecting a successful scenario for space exploration. The robustness and reliability of the model has been tested. Although the attributes were chosen and weighted using rational approaches there is an associated amount of uncertainty involved. Therefore, the outcome of the model should not be used blindly. The model and its outcome is intended to be seen as a learning process for better understanding all of the individual decisions to be made when selecting a scenario. The CHARM team showed two approaches which can be used to confirm the specific scenario. These include revising the attributes, weights, and scoring of the model with other mission designers, as well as following an alternative decision-making process.

The CHARM team is confident that this model could be implemented by mission designers in the scenario selection process to reduce mission risk and costs and to make space exploration more feasible. With this knowledge, the CHARM model can be used to get a profound result after a first iteration. If necessary, more iteration can be made to get a more detailed result.

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X. ACRONYMS

AHP	Analytic Hierarchy Process
CHARM	Cooperation of Humans And Robots for Mars
GER	Global Exploration Roadmap
iMARS	International Mars Architecture for Return of Samples

ISECG	International Space Exploration Coordination Group
ISS	International Space Station
ISU	International Space University
MER	Mars Exploration Rovers
MARPOST	Mars Piloted Orbital Station
MEPAG	Mars Exploration Program Analysis Group
NASA	National Aeronautical and Space Administration
SMART	Simple Multi-Attribute Rating Technique
SSP	Space Studies Program

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