The use of robotics has opened new doors in space exploration, but what is the best blend of human and robotic elements? Should we send robots into harsh and dangerous environments and keep humans on Earth? Or will inquisitive and resourceful human explorers do a more effective job in exploring our solar system? Can humans and robots cooperatively pursue goals in better ways than either could do alone?

The Cooperation of Humans and Robots for Mars (CHARM) team at the 2011 International Space University Space Studies Program presents an interdisciplinary model that addresses these challenging questions. This report will appeal to those interested in the approaches used in the design of Mars exploration missions.

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COOPERATION OF HUMANS AND ROBOTS FOR MARS **REPORT** SSP 2011

CHARM

COOPERATION OF HUMANS AND ROBOTS FOR MARS

REPORT

INTERNATIONAL SPACE UNIVERSITY

SPACE STUDIES PROGRAM 2011
INTERNATIONAL SPACE UNIVERSITY | TU GRAZ, AUSTRIA

COOPERATION OF HUMANS AND ROBOTS FOR MARS

CHARM

Final Report

International Space University

Space Studies Program 2011

The 2011 Space Studies Program of the International Space University was convened at Technische Universität (TU) Graz, Austria

The logo of the CHARM team symbolizes the cooperation between humans (the eye) and robots (the camera lens) for Mars exploration and discovery. The cover illustrates the red planet perceived through the binary and decimal systems.

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ABSTRACT

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 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 intuitive and creative human counterparts. The future of space exploration will require that mission designers balance intelligently 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 integrates 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 report 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. The CHARM model uses an interdisciplinary approach, including technical, societal, political, legal, financial, scientific and mission risk perspectives. The results of the CHARM model are then further analyzed using these interdisciplinary aspects, with considerations to the future studies of human-robot cooperation.

The CHARM team believes that this decision-making model can be used to select missions more efficiently and rationally, thus bringing down both mission costs and risks, and making space exploration more feasible.

FACULTY PREFACE

> *"Man is the best computer we can put aboard a spacecraft, and the only one that can be mass produced with unskilled labor."*
>
> *– Commonly attributed to Wernher von Braun*

The first 50 years of space history was a deeply human story of daring pioneers, astronaut heroes, people embodying what Tom Wolfe called "the right stuff". The people of the world were captivated by stories of Russian and American heroes completing risky missions in outer space, thus demonstrating the technical and scientific superiority of their political systems. At the same time, the scientific community has often expressed skepticism to whether human spaceflight missions are the best way of accomplishing scientific goals. Parallel to the human space exploration adventure, robotic exploration missions to Mars have met with both failure and spectacular success. The exceedingly successful series of American Mars rovers in the 1990s and 2000s have generated enormous amounts of public interest, and have likely contributed to an acceptance of robot planetary explorers in the eyes of the public.

The Wernher von Braun quote, while tongue-in-cheek and perhaps wrongly attributed, expresses something more profound than cold war era machismo. In the foreseeable future, the human brain will remain the most versatile decision-making machine. The human body also remains more agile than a state-of-the-art robot. Yet, in space, the human body is infinitely fragile. Any space mission that involves human astronauts will spend a significant part of its mass budget on human life support systems. Space Agencies' willingness to accept danger to astronaut lives has decreased, leading to the design of ever more safety systems; systems added exclusively to save astronaut lives in the event of catastrophic mission failure.

Since man set foot on the Moon in 1969, human spaceflight proponents have always advocated the planet Mars as the logical next step. Considering the multiple plans for human Mars missions that have never advanced beyond the conceptual stage, the team project asked itself whether alternatives might exist between the traditional scenarios of purely robotic Mars exploration on one side, and "boots on the ground" human Mars missions on the other side: alternatives where human and robotic elements would complement each other, reducing risk and cost, while retaining most of the societal impact of a human landing on Mars.

We put the challenge of evaluating these scenarios forward as a Team Project at the International Space University's 2011 Space Studies Program. For nine weeks, an international group of 41 students and professionals from 16 countries have applied their specialist and generalist skills in a highly interdisciplinary manner to come up with a possible answer to our challenge. We hope that the reader will detect an echo of the excitement and enthusiasm that characterized our TP between the covers of this report.

Yours truly,

Dr. Reinhold Ewald, *Team Project Chair*

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AUTHOR PREFACE

The CHARM team project was to develop a model which, when fed goals and the relative importance of those goals, would articulate how humans and robots can best complement each other for any type of activity in space. The CHARM model takes into account both quantitative and qualitative inputs, and we believe that this powerful analytical tool can be used to make planetary exploration more efficient: cheaper, faster, smarter, and in a way which leverages and maximizes the public's support.

A particular strength of our model is that it takes both societal and technical factors as inputs. An example of a societal factor is the degree to which the taxpaying public cares about robotic exploration. Technical inputs to the model include the mission risk to humans in dangerous environments, and the capabilities of robots in performing tasks.

Robotic explorers can do amazing things in space and on celestial bodies, and their capabilities have the potential to change how and even why we undertake space exploration. In the years and decades ahead, the impact of robotics will be even greater.

The CHARM model is about robots serving space exploration and space science goals. It is about robots and humans working alongside each other, and even autonomous robots pursuing tasks. The output depends on what objectives the mission-designers have, what they think robots are capable of, and even what other stakeholders want space agencies to do: the model returns the optimal relative mix for a variety of space activities.

Forty-one individuals have convened in Graz, Austria for the purpose of developing this model. We have heard from experts and professionals in robotics and mission designers, toured a car assembly factory where mechatronic robots assemble cars, and reviewed and discussed the literature on robotic capabilities and past, present and planned Mars exploration. Then we met (both in small groups and as a whole), to discuss difficult topics like the roles and capabilities of robots, the relationship between humans and robots, national and international objectives on Mars, and the ways to intelligently balance human and robot mission elements in spaceflight settings.

The CHARM team participants are thankful to the faculty and staff of ISU and external experts for their guidance and leadership in this team project. Their vision and dedication for space was vital to our success. We are profoundly grateful for their contribution.

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LIST OF ACRONYMS

Acronym	Definition
BETA	Bureau d'Économie Théorique et Appliquée
CHARM	Cooperation of Humans And Robots for Mars
CHeCS	Crew Health Care System
CNES	Centre National d'Etudes Spaciales
CrIS	Cross-track Infrared Sounder
DRM	Design Reference Mission
ECLSS	Environment Control and Life Support Systems
EDL	Entry, Descent, and Landing
EDR	European Drawer Rack
EEG	Electroencephalogram
EPM	European Physiology Module
ERA	EVA Robotic Assistant
ERV	Earth Return Vehicle
ESA	European Space Agency
EU	European Union
EVA	Extra-vehicular Activity
FSL	Fluid Science Laboratory
GAP	Gas Analytic Package
GDP	Gross Domestic Product
GER	Global Exploration Roadmap
GES	Global Exploration Strategy
GESTALT	Grid-based Estimation of Surface Traversability Applied to Local Terrain
GM	General Motors
GPS	Global Positioning System
HF	High Frequency
IBMP	Institute for Biomedical Problems
IDD	Instrument Deployment Device
IMars	International Mars Architecture for Return of Samples
IMU	Inertial Measurement Unit
ISECG	International Space Exploration Coordination Group
ISRU	*In-Situ* Resource Utilization
ISS	International Space Station
ISTAR	ISS as a Testbed for Analog Research
ISU	International Space University
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LIBS	Laser Induced Breakdown Spectroscopy
LIDAR	Light Detection And Ranging
LMO	Low Mars Orbit
LOX	Liquid Oxygen
LRV	Lunar Roving Vehicle

Acronym	Definition
LSS	Life Support Systems
MADM	Multi-Attribute Decision-Making
MARPOST	Mars Piloted Orbital Station
MARTE	Mars Astrobiology Research and Technology Experiment
MAV	Mars Ascent Vehicle
MAX-C	Mars Astrobiology Explorer-Cacher
MCDM	Multi-Criteria Decision-Making
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rovers
MGS	Mars Global Surveyor
MRO	Mars Reconnaissance Orbiter
MSG	Microgravity Science Glovebox
MSL	Mars Science Laboratory
MSR	Mars Sample Return
MTV	Mars Transfer Vehicle
NASA	National Aeronautics and Space Administration
NBL	Neutral Buoyancy Laboratory
NEEMO	NASA Extreme Environment Mission Operations
NERVA	Nuclear Engine for Rocket Vehicle Application
NPP	National Polar-orbiting Operational Environmental Satellite System Preparatory Project
NTR	Nuclear Thermal Rocket
PADLES	Passive Dosimeter for Life Science Experiments in Space
PCDF	Protein Crystallization and Diagnostics Facility
PrOP-M	Device Evaluation Terrain - Mars
R&D	Research and Development
R1	Robonaut 1
R2	Robonaut 2
RA	Robotic Arm
RADAR	Radio Detection And Ranging
RIA	Russian International News Agency
ROM	Rough Orders of Magnitude
SAM	Sample Analysis at Mars
SCK	Sample Collection Kit
SCOUT	Science Crew Operations and Utility Testbed
SCUBA	Self Contained Underwater Breathing Apparatus
SHARAD	Shallow Subsurface Radar
SMART	Simple Multi-Attribute Rating Technique
SPE	Solar Particle Event
SSP	Space Studies Program
STS	Space Transportation System
SWOT	Strengths, Weaknesses, Opportunities and Threats
TRL	Technology Readiness Level
UHF	Ultra High Frequency
VCI	Vehicle Cone Index
VIKOR	Vlse Kriterijumska Optimizacija Kompromisno Resenje (Multicriteria Optimization and Compromise Solution)
VR	Virtual Reality

LIST OF DEFINITIONS

The following definitions are used by the CHARM Team in this report and included to aid the reader as a reference in understanding this report.

Attribute: An aspect of a *Mission Scenario* that can be used to evaluate it either qualitatively or quantitatively.

Attribute Scoring: A quantitative or qualitative assessment of the performance of an *attribute* for a given *scenario*.

Attribute Weighting: The relative importance of an *attribute*.

Augmented Reality: A perception of a physical environment that is enhanced by computer-generated sensory inputs such as sound and graphics.

Autonomous: Able to decide and act independently.

Back Contamination: "The contamination of the terrestrial environment, which may occur as a result of returning samples from another planetary body." (Williamson, 2003, pg. 34)

Cooperation / Interaction: Multiple parties working together to achieve a common goal.

Delta-V: Change in velocity, usually supplied by the rocket thrust.

Forward Contamination: "The contamination of a planetary body other than the Earth, which may occur as a result of landing a spacecraft on that body." (Williamson, 2003, pg. 136)

Mars Sample Return: "A concept involving the collection of a sample from another planetary body [Mars] and returning it to Earth for analysis." (Williamson, 2003, pg. 322)

Mission Design: The proposed *scenario* which contains, as evaluated by the *mission designer(s)*, the optimal mix of human and robotic cooperation.

Mission Designer(s): The person/people who will utilize the CHARM *model* to evaluate different *mission scenarios*.

Mission Objective: What the *mission designer* hopes to achieve by pursuing a mission.

Mission Scenario: A means of accomplishing a stated *mission objective*.

Model: A qualitative method by which *attributes*, weightings and scores are incorporated together to determine an optimal *scenario*.

Orbiter: A spacecraft designed to orbit a celestial body.

Robot: "Automated (or semi-automated) machines designed and programmed to perform specific mechanical functions with or without human intervention."(Williamson, 2003, pg. 316-7) "A mechanical device that sometimes resembles a human, and that is capable of performing a variety of often complex human tasks on command, or by being programmed in advance.

Rover: A manned or unmanned vehicle designed to move over the surface of a celestial body.

Performance: The sum of the weighted scores for a given *scenario*.

Sensitivity analysis: An investigation in to how the output of a *model* is affected by variations or uncertainties in its inputs.

Teleoperation: An action by which a *robot* or mechanical manipulator is controlled entirely by human intervention from a distance.

Trafficability: The capacity of terrain to be traversed by a vehicle.

Weighted Score: The product of the *attribute weightings* and *scores*.

1 INTRODUCTION

1.1 Motivation

In 2004, two robotic geologists began their exploration of the Martian surface. Since that time, the Mars Exploration Rovers 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 traveled a collective distance of only 21 kilometers (Webster and Brown, 2008). Opportunity spent five weeks stuck in a Martian sand dune (NASA, 2011d) while Spirit ended its operational life similarly ensnared (O'Neill, 2011). 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 (Kim et al., 2005). These limitations were best summed up by Steve Squyres, the Principal Investigator of the Mars Exploration Rover (MER) project when he said:

> *"What Spirit and Opportunity have done in 5 1/2 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." (Thompson, 2009).*

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 *Canadarm*, to complement the intelligence, ingenuity and dexterity of the astronauts. Moreover, to guide their exploration, the Mars Exploration Rovers 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.

1.2 Mission

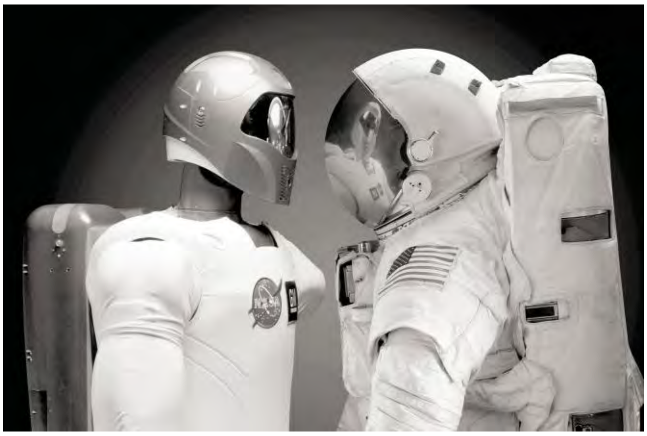
> *It is the Mission of the CHARM team to propose a model for effective human-robot cooperation and apply it to Mars exploration scenarios for the time frame between 2015 and 2035.*

1.3 Scope

To achieve our mission, we have conducted an extensive review of the literature concerning human-robot cooperation, and developed a model, the CHARM model, which seeks to advance this aspect of space missions. Our model provides a means by which vastly different designs of human-robot cooperation can be compared objectively, with the intention that this will allow an optimal scenario to be selected, given a particular mission objective. The model is broad in its scope as it captures the scientific, technical, economic, social and political dimensions of this comparison. It also represents a novel synthesis of a number of recognized tools from the fields of decision-making and multi-criteria decision analysis and is underpinned by a thorough study of the criteria by which mission scenarios should be judged. To demonstrate the CHARM model, we have used it to compare potential scenarios for a Mars exploration mission and conducted an in-depth analysis of the selected scenario. We believe that this model will be a useful tool for mission planners and researchers in human-robot cooperation for space exploration.

In the chapters ahead, the CHARM Report will first examine past missions to Mars to determine their scientific objectives, including Mars missions both successfully executed and merely planned, along with the policies driving space exploration and the economic consequences of those policies. We then look at a number of aspects of the human-robot relationship, including societal perspectives and the use of robotic and automated systems for scientific experiments. We then turn to examine decision-making models applicable to the tough decisions necessary in designing space missions to maximize the best elements of humans and robots. After choosing a particular Mars exploration scenario, we apply the CHARM Model, and discuss which human and robot elements would best suit this exploration scenario. Finally, we discuss the implications of this scenario using a multitude of interdisciplinary perspectives.

Figure 1-1: NASA's Robonaut interacting with an astronaut (NASA, 2008)



2 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. This chapter provides a brief synopsis of space missions and objectives proposed by various agencies, along with current and planned future missions, existing policies, and an economic rationale relevant to Mars exploration missions.

2.1 Mars Exploration Objectives

Figure 2-1: Meteorite ALH84001 thought to be of Martian origin

Through extensive research of past, present, and planned missions to Mars, and on extraterrestrial objects (Figure 2-1), 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 geological properties (i.e., soil composition, seismology)
5. To test systems for future Mars exploration missions
6. To test *in-situ* resource utilization systems

2.2 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. The following sections document the past and present national and international policies regarding exploration of Mars.

2.2.1 Past Mars Exploration Policies

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 (STS) (Handlin, 2005). 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 partners (Dick, 2010). 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 (Encyclopedia Astronautica, 2011).

2.2.2 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."(The White House, 2010).

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 (Roscosmos) and the European Space Agency (ESA) have also been cooperating on the MARS-500 project, an analog experiment for simulating a human flight to Mars (RIA Novosti, 2009).

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 (NDTV, 2011).

2.2.3 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 Mars Exploration Program Analysis Group (MEPAG) and the International Space Exploration Coordination Group (ISECG)

Mars Exploration Program Analysis Group

The MEPAG is a forum provided by NASA that provides an overview of its Mars exploration goals and the scientific objectives of each of these goals.

The first goal is to determine if life ever arose on Mars. The scientific objectives for this goal include:

- Habitability — What is the evidence that can point to the emergence of life on Mars?
- Bio-signature preservation potential — What evidence of life has been preserved and what has been lost?
- Long-term evolution of Mars — What are the effects of the physical and chemical environments on the habitability of Mars?

The second goal is to understand the process and the history of the climate on Mars. The scientific objectives for this goal are:

- Knowledge of the present state of the entire atmospheric system
- Investigation of the recent period of climate history, as well as the ancient climate history
- Determining if and when Mars was warmer and more hospitable than it is today

The third goal is to determine the evolution of the surface and interior of Mars. The scientific objectives for this goal are:

- Study the geological processes of the Martian crust
- Characterization of the internal structure, composition, dynamics, and evolution of the interior of Mars, as well as of its moons - Phobos and Deimos

The fourth goal is to prepare for human exploration. This goal implies a level of knowledge of Mars sufficient to design and perform a human mission with acceptable cost, risk, and performance measurements. To this end, each successive mission to Mars has to collect data to improve the current models of the Martian atmosphere and its variability, its surface climate, weather patterns, topology, geology, and available resources. The MEPAG also proposes cross-cutting strategies that could be used for the present and future exploration of Mars. For example, a proposed strategy is entitled "follow the water." Water is essential to all known forms of life, is integral to understanding climate systems, plays a crucial role in geologic processes, and also is a necessary resource for future human exploration missions (MEPAG, 2010).

International Space Exploration Coordination Group

The ISECG is an international coordination group 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. In May of 2007, fourteen space agencies established the ISECG in furtherance of the "The Global Exploration Strategy: The Framework for Coordination"; an ambitious document laying out a global vision for space exploration. Integral to the Global Exploration Strategy's framework is the use of robotic capabilities for future space exploration. Utilization of robots is essential, to reduce the risks to human life, and to gather data and information about locations for eventual human exploration. The four guiding principles of the ISECG are that it should be open and inclusive, flexible and evolutionary, effective, and for mutual interest (ISECG, 2010).

By establishing the ISECG, it was the hope of the fourteen founding space agencies (including ESA, JAXA, NASA and Roscosmos) to increase the safety, cost effectiveness, and exploration capabilities of the individual agencies. This would be done by sharing information regarding products, findings, and future recommendations that are deemed valuable to enable future exploration by any of the contributing individual agencies (ISECG, 2010b).

Within the ISECG, efforts have been made to develop a Global Exploration Roadmap (GER) to enhance global cooperation in space exploration. Included in the GER will be an overview of individual space agency future space exploration plans. Additionally, the overview will include the short-term exploration goals, as well as the role that the International Space Station (ISS) will play in the advancement of space exploration (ISECG Annual Report, 2010). The roadmap will then discuss the challenges of space exploration, and identify scenarios where the international community can meet together to overcome these challenges (ISECG, 2008b).

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 aide 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.

2.3 Review of Mars Exploration

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. Many of the planned and attempted missions have been unsuccessful for various technical reasons, with the United States executing the only fully successful missions. The following discussion details the successful missions and the objectives that were performed.

2.3.1 Past Mars Missions

Mariner Program

Since the first successful flyby of the planet Mars by Mariner 4 in 1965, NASA has been the most active player in Mars exploration (Taylor, 2010). The Mariner program included a series of robotic interplanetary probes aimed to investigate Mars, Venus, and Mercury from 1963 to 1973. Following Mariner 4, the next successful mission was Mariner 6 and Mariner 7; the first dual mission to Mars. These orbiters flew over the equator and southern polar regions, performed an analysis of the Martian atmosphere and surface with remote sensors, and recorded and relayed hundreds of pictures back to Earth. Following the Mariner 6 and 7 probes was Mariner 9, the first artificial satellite of Mars. Designed to map the Martian surface, it successfully took close-up pictures of the Martian moons, Phobos and Deimos. The main objectives of these Mariner missions were to photograph the Martian surface and analyze the Martian atmosphere (NASA JPL, 1996).

Viking Program

NASA's next big step in Mars exploration was the Viking program. Vikings 1 and 2 were spacecraft each composed of an orbiter and a lander. After reaching the Martian surface, the orbiters served as communication relays for the landers. The scientific objectives for these missions were to obtain high-resolution images of the Martian surface, to determine aerodynamic properties and composition of Martian atmosphere with changes in altitude, and to examine physical and magnetic properties of the measured Martian soil. Both Viking 1 and 2 had robotic arms to collect soil samples and examine them in an onboard laboratory (NASA JPL, 1988).

Mars Global Surveyor

After Viking, NASA returned to Mars with the Mars Global Surveyor (MGS) to study the surface, atmosphere, and interior. The satellite was launched in 1996 - a full 20 years after the Viking missions were launched. MGS visually mapped the Martian surface until the last signal was received in 2007 and the mission was ended. MGS also carried five scientific instruments such as the Mars Orbiter Camera (Albee, 2001). One of the most important observations taken by the Mars Orbital Camera was that Mars has repeating weather patterns. Also, images were collected that documented gullies and debris flows, showing that sources of liquid water might have been present on the surface (NASA JPL, 2011f).

Pathfinder and Sojourner

The Mars Pathfinder mission landed on Mars in July of 1997. It consisted of a lander and a small rover called Sojourner. The mission was designed to examine the atmosphere, climate, geology, and the soil and rock composition of Mars using a series of scientific instruments on the lander and rover. The mission was largely a demonstration mission to show how a lander and free ranging rover could be sent to the surface of Mars, but was later considered a great scientific success for the amount of data returned and the lifespan of the technology that exceeded that of the design. The lander and rover exceeded expectations by 3 and 12 times respectively (NASA, 1997).

Phoenix Lander

NASA's Mars Phoenix Mission was a collaborative effort among the University of Arizona, NASA's Jet Propulsion Laboratory (JPL), Lockheed Martin, the Canadian Space Agency (CSA), and other agencies and laboratories worldwide. Launched in late 2007, Phoenix was NASA's most northerly situated Mars lander. Phoenix landed in Mars' northern arctic region in May of 2008 to study the characteristics of it soil and search for water using a robotic arm to collect samples and bring them into an onboard laboratory (University of Arizona, 2005). By November 2008, having exceeded its design lifetime by almost 2 times, the Phoenix lander lost communications with ground control - but not before completing its stated mission objectives (Kessler, 2011).

2.3.2 Current Mars Missions

Mars Odyssey

Launched in 2001 and currently operational in Mars orbit, NASA's 2001 Mars Odyssey spacecraft has collected more than 130,000 images and consistently sends information to Earth about Martian geology, climate, and mineralogy. In the beginning of the mission, Odyssey determined radiation in low-Mars orbit, a very important finding for future human exploration. Magnetometer readings have shown that the planet does not have a global magnetic field like the Earth, but instead has magnetic fields that are localized in certain areas of the Martian crust. Odyssey has also provided crucial support to the current exploration of Mars by relaying data from surface rovers to Earth through the spacecraft's ultra-high frequency antenna (NASA JPL, 2003).

Mars Express

Mars Express is ESA's first Mars exploration mission. The main objective of this mission is global observation of the planet including the surface, subsurface, atmosphere, and ionosphere. Mars Express was launched in June of 2003 by a Soyuz-FG/Fregat rocket, and inserted into Mars orbit in December 2003, with the mission extended to December 2014. Mars Express consists of two parts, the Mars Express Orbiter and Beagle 2, a lander designed to perform exobiology and geochemistry research. The lander failed to land safely on the Martian surface, but the orbiter has been successfully performing scientific measurements since 2004. These measurements include high resolution imaging and mineralogical mapping of the surface, radar sounding of the subsurface, precise determination of atmospheric circulation, and study of the interaction of the atmosphere with the planet's surface. Mars Express is equipped with seven instruments: a high resolution stereo camera, a visible and infrared mineralogical mapping spectrometer, a subsurface sounding radar altimeter, a planetary Fourier spectrometer, an ultraviolet and infrared atmospheric spectrometer, an energetic neutral atoms analyzer and the Mars radio science experiment. The major findings from this mission indicate that water is available as ice mixed with mineral dust and as hydrated minerals (Taylor, 2010).

Mars Exploration Rovers

In the summer of 2003, NASA launched two rovers, Spirit and Opportunity, towards two different equatorial sites on the Martian surface. Their main scientific objective was to determine: the mineralogical composition of the Martian surface. To accomplish this, the MERs have the Athena Science Payload, which includes a panoramic camera, three different spectrometers, one microscopic imager, one rock abrasion tool, and magnet arrays able to analyze the magnetic dust. The main technological innovations concern the mobility system, known as a Rocker-Bogie system, and its ability to grip in rough terrain. The last signal from

Spirit was in 2010, while Opportunity has remained operational and has now arrived at the Endeavour Crater after a three year period. The MER mission has been extended five times and has exceeded planned mission length by over 25 times (Taylor, 2010), (NASA, 2004).

Mars Reconnaissance Orbiter

In August 2005, NASA launched the Mars Reconnaissance Orbiter (MRO) with the objective of finding subsurface water, identifying surface minerals and to study how dust and water are transported to the Martian atmosphere. The high-resolution camera onboard the orbiter is also to be used as a guide for future spacecraft landings to open up otherwise dangerous landing sites. The Mars Reconnaissance Orbiter is also designed to set up a communication link with the Earth, which is to provide greater signal performance while reducing power required (NASA JPL, 2011).

2.3.3 Future Mars Missions

ExoMars

ExoMars is a collaborative Mars exploration space program carried out between ESA and NASA. The main scientific objectives are to search for signs of past and present life on Mars, investigate how the water and geochemical environments vary, and investigate Martian atmospheric trace gases and their sources. The mission also aims to test flight *in-situ* technologies necessary for future exploration missions. These include technologies such as entry, descent, and landing (EDL) of a payload on the surface of Mars, rover mobility performance, as well as sample acquisition, preparation and analysis (Pratt et al., 2010).

The program is composed of two different phases: ExoMars 2016 and ExoMars 2018. The first phase consists of an orbiter and is planned for launch in 2016. The main objective of the first phase is to investigate methane and other trace atmospheric gases that can be considered signatures of active chemical, or perhaps biological, processes. In addition, the first phase acts as a support for the communication relay system of ExoMars 2018, also known as Phase two of the ExoMars mission. This second phase is planned to use two rovers: the European ExoMars and the American Mars Astrobiology Research and Technology Experiment (MAX-C) (ESA, 2011). The ExoMars rover aims to characterize the Martian subsurface, in terms of its physical structure, the presence of water or ice, and related geochemistry. NASA canceled the MAX-C program in 2011, and the ESA-NASA Joint Exploration Working Group is now redefining the architecture for a single rover mission (Svitak, 2011).

Phobos-Grunt

Phobos-Grunt is a Russian-led mission to land on the surface of the Martian moon Phobos and return samples of its soil back to Earth (CNES, 2011). The mission would focus on *in-situ* and remote studying of Mars, as well as investigating the Martian atmosphere with a focus on the search for life.

The main payloads are: the gas analytic package, gamma spectrometer, neutron spectrometer, infrared spectrometer, seismometer, long wave penetrating radar, panoramic TV cameras, visible and infrared optical spectrometer, solar occultation spectrometer, plasma science package, and solar sensor. The mission is planned to be launched on a Soyuz rocket in November 2011 and will reach its destination in 2013. It is expected that samples from Phobos will return to Earth by 2014. In addition, the Chinese probe Yinghuo-1 will be launched with Phobos-Grunt. This probe is to orbit near to the Martian equator to investigate its magnetic field, ionosphere, particle distribution, and gravity field; determine atmospheric ion escape rates; examine the surface topography, landforms, and dust storms; and imaging the planet (NASA, 2011b).

Mars Science Laboratory

Mars Science Laboratory (MSL) is NASA's next mission to land and operate a rover on the surface of Mars. If successful, MSL will be the largest mass ever to land on the surface of Mars. MSL is scheduled to launch in late 2011 and will land on the surface in August of 2012 (Figure 14). The main scientific goals of MSL are to determine the past and present habitability of Mars, study the climate and geology, and to prepare for future human exploration. Because of its large mass, MSL will also be a demonstration platform of a new EDL technology incorporating a rocket stage that lowers the rover down a cable to the surface before detaching and propelling itself far away from the rover landing site (NASA JPL, 2011d).

2.3.4 Other Mars Mission Scenarios

Mars Direct

Direct Mars Direct is a program proposed by a non-governmental advocacy group; however, parts of it have been adapted for the NASA design reference mission. The mission architecture was designed by Dr. Robert Zubrin, and features "a minimalist, live-off-the-land approach" to exploring Mars (Mars Society, 2011). The first step of the mission is to send an unmanned Earth Return Vehicle (ERV) to Mars. The ERV would contain hydrogen and a small nuclear reactor for generating fuel for the return journey. Since the return fuel would not need to be carried from Earth, the launch mass - and therefore, the cost - would be reduced. Humans would be sent later, only after successful production of fuel. Once on the surface, humans would travel using chemically powered vehicles. This would allow for a larger area of the Martian surface to be explored than by only using either humans or robots (Zubrin and Weaver, 1995).

NASA Design Reference Mission

The NASA Design Reference Mission (DRM) is a detailed study of the human exploration architecture for Mars first developed in the early to mid-1990s. Since then, it has been updated and modified on several occasions. The most recent is Version 5.0 published in 2009, which is called the Human Exploration of Mars Design Reference Architecture 5.0 (Drake et al., 2010). The mission proposal is a detailed description covering all known elements of a possible mission to Mars. It is important, however, to emphasize that it is not a formal plan for a human mission to Mars, but rather a framework for future system concepts, technology research and development, and testing. It is also intended to be a reference for robotic Mars missions, future research on the International Space Station, and future lunar missions. All of the proposed goals and objectives take into consideration the state of knowledge as of 2025, assuming that all scientific objectives of current missions are achieved in the next 15 years. The DRM asserts the important role humans will play in planetary exploration as well as the need for effective human-robot cooperation.

The basic mission scenario includes sending a crew of six astronauts in three consecutive missions. Taking into account the scientific objectives, each visit would explore a different site. Mission hardware would be sent to Mars before crew departure. Similar to Mars Direct, the DRM proposes producing the ascent propellant from *in-situ* resources, which would significantly decrease the mass and size of the landing modules. A nuclear power source would enable the propellant production process as well as provide the energy for crew surface systems. This scenario calls for a long-duration mission that enables up to 500 days of surface activity by the astronauts. An essential component of this mission architecture is autonomous payload deployment and operational robotic infrastructure. Crew launch depends on the functionality of pre-landed systems.

The DRM enables long-distance and long-duration missions by using a pressurized mobile home for the astronauts, called the Commuter. In addition, the Telecommuter, which is a teleoperated mobile robotic device, enables exploration to be conducted from a local environment, increasing both the area that can be covered and total exploration time, as well as reducing the risk to astronauts for more dangerous Extra-Vehicular Activities (EVA). The second part of the mission is the launch, assembly, and testing of the Mars Transfer Vehicle (MTV), an interplanetary crew support vehicle for the return trip. The time on the surface would be spent performing scientific exploration and research. After each mission period, some surface systems would be put in stand-by mode for potential re-use by future crews, and autonomous surface experiments would continue after crew departure.

Finally, the report addresses the key challenges for such a mission. There are many challenges, but the most important are human health and performance, landing large payloads on Mars, heavy lift capabilities, use of local resources, advanced propulsion systems and robust surface power sources, and hardware reliability and supportability.

2.4 Economic and Political Aspects of Mars Exploration

The important political and economic factors related to future space explorations generally, and to Mars missions in particular, are macroeconomic and mission-related. The macroeconomic aspect analyzes how much of the national (or in the case of the EU, community) assets are designated for space exploration. Because of certain developments and priorities, the available funding for space agencies and exploration missions vary over time, and is the primary indicator of the political and societal will. Funding choices are further validated through the economic ability of the country. The available funding and the national capacity to increase these available assets are two of the main factors determining whether a mission can be carried out by either a sole nation or a consortium of nations. Another possibility for evaluating the budgetary constraints affecting human and robotic cooperation for future space exploration is to compare the mission objectives and tasks of a purely robotic mission with the additional costs and benefits of introducing the human presence. This approach would result in a baseline of cost drivers for a purely robotic mission. In addition to these robot related costs, further expenses due to human presence will arise as a result of the increased mission complexity.

2.4.1 Macroeconomics

National Budgets and Spending on Space

The worldwide government space budget in 2010 reached USD 87.12 billion, increasing approximately by 0.3 percent since 2009. These space budgets account for civil and defense-related activities. A yearly budget breakdown by country is detailed in Table 2-1, where the main players are the United States, the European Union, Japan, Russia, China, and India. The recent global trend in space investment shows a slow increase; however, there is a high variability at a national level in terms of countries that have significantly increased their financial contribution to the space sector. An example is India, whose 2010 space budget increased by 16.78 percent since 2009. At the other end of the spectrum, other countries have restricted their space related budgets. Germany, Japan, and Canada are among the countries that have made cuts by reducing their national budgets by percentages of 3.1, 1.7 and 3.8 percent respectively, and Germany is increasing its ESA participation (see Table 2-2) (Walter-Range et al., 2011).

Table 2-1: Global Space Activity Revenues (Walter-Range et al., 2011)

Global Space Activity Revenues

Billion US Dollars reported in its yearly value

Country/Administration		2007	2008	2009	2010	2010-2009 Growth
US	DoD Space	22.42	25.95	26.53	26.66	0%
	NRO	10.00	10.00	15.00	15.00	0%
	NGA	3.00	3.00	2.00	2.00	0%
	NASA	16.25	17.40	18.78	18.72	0%
	NOAA	0.80	0.96	1.25	1.40	12%
	DoE	0.03	0.03	0.04	0.04	5%
	FAA	0.01	0.01	0.01	0.02	50%
	NSF	0.33	0.63	0.80	0.64	-20%
	FCC	-	-	-	0.01	N/A
	USGS	-	-	-	0.15	N/A
Non-US	ESA	4.02	4.27	5.16	4.6	-11%
	EU	-	-	1.56	1.63	5%
	Brazil	-	0.13	0.19	0.18	-3%
	Canada*	0.34	0.27	0.30	0.29	-5%
	China	1.50	1.70	1.79	2.24	25%
	France*	0.95	0.97	1.06	0.92	-13%
	Germany*	0.39	0.60	0.77	0.64	-17%
	India	0.66	0.82	1.06	1.25	18%
	Israel	-	0.01	0.01	0.01	0%
	Italy*	0.65	0.44	0.47	0.44	-5%
	Japan	2.21	3.50	3.72	3.83	3%
	Russia	-	1.50	2.90	3.04	5%
	South Korea	1.32	0.23	0.23	0.21	-6%
	Spain*	-	-	0.06	0.05	-17%
	UK*	0.12	0.09	0.10	0.10	4%
	Non US military space	1.77	1.95	2.18	2.30	10%
	Emerging Countries	-	-	0.17	0.74	-
TOTAL		**66.77**	**74.46**	**86.14**	**87.11**	

**Excludes ESA contribution*

Table 2-2: International Space Budget Growth (Walter-Range et al., 2011)

International Space Budget Growth

Currency reported in its yearly value

Country	Currency	2008	2009	2010	2010 - 2009 Growth
ESA*	Euro	3.030	3.590	3.740	4.3%
Brazil*	BRL	0.294	0.298	0.330	10.8%
Canada*†	CAD	0.317	0.315	0.3030	-3.8%
France†	Euro	0.691	0.738	0.749	1.5%
Germany*†	Euro	0.426	0.537	0.521	-3.1%
India*	Rupee	40.700	49.600	57.900	16.8%
Italy*†	Euro	0.310	0.330	0.360	9.7%
Japan	Yen	314.00	344.800	339.000	-1.7%
Russia*	Ruble	45.020	87.900	94.900	8.0%
South Korea*	KRW	287.000	267.900	262.000	-2.2%
UK*†	Pound	0.060	0.060	0.070	9.7%
USA	USD	57.980	64.420	64.630	0.3%

** Civil space budget only.*

† National budget only. Excluding ESA contribution.

The total global civilian space budget for 2010 has been reported to be USD 41.15 billion. This accounts for approximately half of the total space budget, where the average national investment of the main players is approximately 0.045 percent of the country's Gross Domestic Product (GDP) at current prices, excluding the USA and Russia, where the investment to GDP ratio is significantly higher (Walter-Range et al., 2011). This ratio has slightly increased from the 0.040 percent in 2008 to the current value (see Table 2-3), (Walter-Range et al., 2011), (International Monetary Fund, 2011) and (Federal Reserve, 2011).

Table 2-3: Space Spending as a Percentage of GDP at Current Prices

Space Spending as a Percentage of GDP at Current Prices

Currency reported in its yearly value

Country	Currency	GDP 2007	Civil Space Budget 2008	%	GDP 2008	Civil Space Budget 2009	%	GDP 2009	Civil Space Budget 2010	%
USA	USD	14061.8	17.40	0.124%	14369	18.78	0.131%	14199	18.72	0.132%
Russia	Ruble	33248	45.02	0.135%	41429	87.90	0.212%	39101	94.90	0.243%
France	Euro	1896	1.25	0.066%	1947	1.50	0.077%	1907	1.43	0.075%
Canada	CAD	1530	0.35	0.023%	1600	0.35	0.022%	1527	0.34	0.022%
Germany	Euro	2432	0.96	0.039%	2481	1.19	0.048%	2397	1.20	0.050%
India	Rupee	47633	40.70	0.085%	54873	49.60	0.090%	59520	57.91	0.097%
Italy	Euro	1546	0.65	0.042%	1568	0.70	0.045%	1521	0.73	0.048%
Japan	Yen	515520	314.00	0.061%	505113	344.80	0.068%	474297	339.00	0.071%
South Korea	KRW	975013	287.00	0.029%	1026452	267.90	0.026%	1063059	262.00	0.025%
Brazil	BRL	2661	0.29	0.011%	3005	0.30	0.010%	3143	0.33	0.010%
Spain	Euro	1054	0.15	0.015%	1088	0.23	0.021%	1054	0.26	0.025%
UK	Pound	1405	0.27	0.019%	1446	0.30	0.021%	1393	0.31	0.022%
China	Yuan	26581	11.81	0.044%	31405	12.23	0.039%	34405	15.48	0.045%
			Average*	0.040%		Average*	0.042%		Average*	0.045%

**Excluding US and Russia*

The United States' budget is a large component of this figure, especially the NASA budget allocation, with a total of USD 18.72 billion (accounting for 45 percent of the international reported budget). This budget is expected to remain stable until 2014, providing about USD 15 billion per year to space sciences, technology, exploration and operations. More details are presented in Table 2-4. The USA is followed by ESA, which accounts for a total USD 4.6 billion, from which USD 2.2 billion is devoted to launchers, science, human spaceflight, exploration, technology, and microgravity research. The ESA budget breakdown is presented in Table 2-5 (Walter-Range et al., 2011).

Table 2-4: NASA Fiscal Year Budget Request (Walter-Range et al., 2011)

NASA Fiscal Year Budget Request

Billion US Dollars

Budget Authority	Fiscal Year 2010	Fiscal Year 2011	Fiscal Year 2012	Fiscal Year 2013	Fiscal Year 2014
Science	4,497.6	4,469.0	5,016.8	5,016.8	5,016.8
Earth Science	1,439.3	-	1,797.4	1,821.7	1,818.5
Planetary Science	1,364.4	-	1,540.7	1,429.3	1,394.7
Astrophysics	647.3	-	682.7	758.1	775.5
JWSP	438.7	-	373.7	375.0	375.0
Heliophysics	608.0	-	622.3	632.7	653.0
Aeronautics	497.0	501.0	569.4	569.4	569.4
Space Technology	275.2	327.2	1,024.2	1,024.2	1,024.2
Exploration	3,625.8	3,594.3	3,948.7	3,948.7	3,948.7
Human Exploration	3,287.5	-	2,810.2	2,810.2	2,810.2
Commercial Spaceflight	39.1	-	850.0	850.0	850.0
Exploration R&D	299.2	-	288.5	288.5	288.5
Space Operations	6,141.8	6,146.8	4,346.9	4,346.9	4,346.9
Space Shuttle	3,101.4	-	664.9	79.7	0.8
ISS	2,312.7	-	2,841.5	2,960.4	3,005.4
Space and Flight Support	727.7	-	840.6	1,306.8	1,340.7
Education	180.1	182.5	138.4	138.4	138.4
Cross-Agency Support	3,017.6	3,018.8	3,192.0	3,192.0	3,192.0
Construction and Environmental Compliance and Restoration	452.8	448.3	450.4	450.4	450.4
Inspector General	36.4	36.4	37.5	37.5	37.5

Table 2-5: ESA Budget by Program, 2010 (Walter-Range et al., 2011)

ESA Budget by Program - 2010

Program	Funding 2010
Navigation	€714.0 M
Earth Observation	€708.4 M
Launchers	€566.6 M
Science	€409.5 M
Human Spaceflight	€330.4 M
Telecommunications	€325.4 M
General Budget	€211.4 M
Associated to General Budget	€196.7 M
Exploration	€102.0 M
Technology	€84.8 M
Microgravity	€79.9 M
Space Situational Awareness	€9.9 M
European Cooperating States Agreement	€5.2 M

A mission available budget is directly linked to the space budget and, thus, to the percentage of federal/national budget assigned to it. This federal/national budget is dependent on the current political climate and the country's GDP. An increase on the space budget / GDP budget ratio may be required to accomplish an ambitious space program, affecting other sectors as they may see their available budgets reduced. This economic effort entails social, political, and financial issues, and is an important factor to take into account when considering a mission, either on a national level or internationally. The USA commitment to space during the Apollo era is a clear example where the space budget / GDP ratio increased, having a peak value of 0.8 percent of GDP. The value has not exceeded 0.3% since the 1970s (Augustine et al., 2009).

Return on Investment from Space

Governmental investment in space follows diverse rationales, whose importance differs from country to country and through time. The original rationales were to increase national security, national prestige, international leadership, and scientific knowledge. As space has gradually become a more mature sector, additional rationales have appeared. These new rationales include enhancing military capabilities, creating a basis for space commercialization, providing tangible benefits to society, and assisting in social and economic development (Logsdon, 2011). Consequently, one of the aims for space activity is having a tangible return on the invested money. This return is not necessarily direct, and includes motivations to create and meet space-specific demands: to stimulate innovation, research and development (R&D), to improve the competitive advantage of domestic industries, and to develop human infrastructure and capabilities. Space activities aim to increase the commercialization of spin-off and spin-in technologies, increase the space market entries of new businesses, and stimulate national and international commerce (Simpson, 2011).

From a purely financial point of view, there are different means to estimate the financial return of space investments using a macroeconomic approach. The most common is the diffusion-based model that measures the effect of space activity according to four different factors: technology, commercial, organization and methods, and work related. The technology factors include developing new and diverse products as well as improving their quality. Commercial factors take into account the improvement in international cooperation and new sales networks. The organization and methods factors measure the improvement in quality control, project management, and production techniques. Finally, the work related factors focus on the development of a critical mass of specialists and the development of production techniques. By evaluating the influence of these factors, the Bureau d'Économie Théorique et Appliquée (BETA) has estimated a financial return on investment from space activities in different ESA programs of approximately 3:1, a ratio having strong variations, depending on the subsector analyzed (Peeters, 2011), (Cohendet, 1997).

Successful human-robot cooperation in space exploration is extremely influential on, and supportive of, research and development of robotic technologies on Earth. New space technologies are needed to address current problems, such as harmful effects on the crew from functioning in microgravity and exposure to radiation. The cost associated with developing such technologies can be extremely high. Robotic solutions could take the form of humanoid robots to perform tasks in hazardous environments or robotic elements to aid in crew training in microgravity and crew operations. Although very expensive, these solutions would lead to spin-off technologies and application on Earth that can be used to further justify their costly development.

2.4.2 Mars Mission Cost Drivers for Robot and Human Payloads

From a general economic standpoint, the cost of a mission to Mars is significantly influenced by the total mass that has to be launched into Low Earth Orbit (LEO), transported to the Martian orbit and/or surface, and returned back to Earth. This section highlights the major cost drivers and explains to what extent the introduction of humans in the mission will affect the technologies to be developed, the systems to be designed and the eventual mass to be launched, thereby driving the cost of the overall mission.

Robotic missions cost elements

Table 2-6 reports high-level cost data of recent robotic missions to Mars, based on the available figures in open literature. These mission costs refer to the entire cost of the program, including the cost to design, build, test, launch, and operate the spacecraft.

Table 2-6: Mission costs of recent missions to Mars (Walter-Range et al., 2011)

Mission Costs of Recent Missions to Mars

Mission (launch year)	Organization	Mission components	Cost
Mars Pathfinder (1996)	NASA	Lander + Rover	US$265 million [1]
Mars Global Surveyor (1996)	NASA	Orbiter	US$219 million + US $20 million/yr (operations) [2]
Mars Exploration Rovers (2003)	NASA	Two rovers	US$820 million (price tag of the original mission) [3]
Mars Express (2003)	ESA	Orbiter	€150 million (excl. orbiter instruments and Beagle 2 lander) [4]
Mars Reconnaissance Orbiter (2005)	NASA	Orbiter	US$720 million [5]
Mars Science Laboratory (to be launched in 2011)	NASA	Rover	~US$2 billion [6]

1 http://mpfwww.jpl.nasa.gov/missions/past/pathfinder.html

2 http://mars.jpl.nasa.gov/mgs/faqs/faq_general.html#G1

3 http://www.msnbc.msn.com/id/21327647/

4 http://www.esa.int/SPECIALS/Mars_Express

5 http://planetary.org/explore/topics/mars_reconnaissance_orbiter/facts.html

6 http://www.lpi.usra.edu/pss/jan92009/presentations/mslBudgetStatusMcCuistion.pdf

According to (Beaty et al., 2008), the current consensus for the end-to-end mission costs of the Mars Sample Return (MSR) mission that will collect rock and dust samples from Mars and to return them to Earth for analysis, ranges from USD 3 to 8 billion, depending on the final requirements and international cooperative structure.

Consequently, the current costs for robotic Mars missions are in the range of several hundred million to several billion USD. The most important cost drivers can be attributed to the development of space infrastructure required for the mission (such as the launch system, orbiter and/or lander, rover, scientific instruments, etc.), and mission operation costs. For example, approximately 65 percent of NASA's MRO program cost is attributed to the spacecraft design, manufacturing and test, 25 percent to the operations (which are still ongoing) and slightly more than 10 percent to the launch. Overall costs are subject to increase, consistent with increases in the mass and the complexity of the mission.

Additional Cost Drivers with Human Crewed Missions

The inclusion of humans in space directly affects the cost of a mission. In addition to the added costs of returning humans safely to Earth, additional cost factors associated with crewed missions are the need for Environment Control and Life Support Systems (ECLSS).

The ECLSS has to sustain the health and the performance of the crew. These systems allow a human being to survive during a space mission, which include supplying water, air, and food to astronauts while managing waste (Clement, 2011). A variety of technologies exist or can be adapted for use in the ECLSS in the context of a long-duration mission to Mars with astronauts onboard. The associated technological readiness level however, is still quite low for long-duration enabling ECLSS technologies. The currently deployed ECLSS on board the ISS is based on technologies selected and designed in the 1990s, which most probably are not optimal for future long-duration missions and should be extensively redesigned to reduce mass and improve reliability. Closed-loop, also called self- sustained Life Support Systems (LSS), which are used to recycle non-useful waste products and renew resources, will be essential. In particular, recycling and *in-situ* utilization of Mars' water resources will be critical capabilities for human missions to Mars to reduce the mass of launched materials to lower the overall cost (Rapp, 2006).

The number of astronauts in the crew, the total mission duration, and the selected readiness level of technologies for life support will drive the mass, and hence, the cost of the ECLSS. Some studies indicate that the mass and launch cost can be reduced by up to one half by substituting current ISS devices by more advanced and optimized technologies (Jones et al., 2009) . As a result, significant research, development, and design effort in the field of ECLSS should accompany the design of the future long-duration human missions to Mars. Exploration by humans on the surface of Mars, in cooperation with robots, will further increase the costs by necessitating specific space suits and a surface habitat. The development of new space suit technologies and long-term surface habitats will be mandatory to allow astronauts to operate as desired on the Martian surface. Long-duration space missions, with particular attention to surface activities, will also necessitate the use of ambulatory health care via medical packs or kits (as included on the ISS).

An important engineering cost driver is the need for a highly reliable spacecraft infrastructure incorporating built-in redundancies to ensure an acceptable level of safety for crew, robotics, and equipment. These considerations will further increase the mass of the spacecraft, thereby increasing the total cost of the mission scenario. In addition to the usual tools of sample collection and analysis (e.g., robotic arms, drilling systems, spectrometers), effective human-robot interaction on Mars will also require specific research facilities, such as roving vehicles.

Launch Cost Aspects

When designing a mission to Mars, the required mass during the different phases (transfer from Earth to Mars orbit, landing-on and lifting-off from the surface of Mars, and the return to Earth) can be translated into an equivalent mass required into LEO to derive the launch requirements and finally estimate the total launch costs. The estimated ratio of the initial mass launched to LEO to the transferred payload mass is given in (Rapp, 2006), and has been used to derive scaling factors for transferred payload mass in a mission relative to the required mass in LEO (Table 2-7). This conversion can be achieved through a simple Delta-V calculation using the rocket equation and accounts for the propellant mass needed to transfer the payload mass when considering only classical chemical propulsion systems.

Table 2-7: Scaling factor linking the initial mass into LEO to the payload mass

Scaling Factors for Mars Mission

Ratio of the initial mass into LEO to —	Scaling Factor
The transferred payload mass to Mars orbit	3
The transferred payload mass to Mars surface	7
The return mass from Mars to Earth	8

The table should be read as follows:

- To insert 1 kg payload into Mars orbit requires launching an equivalent mass of 3 kg into LEO (of which 2 kg will be used solely to propel the payload to the Martian orbit)

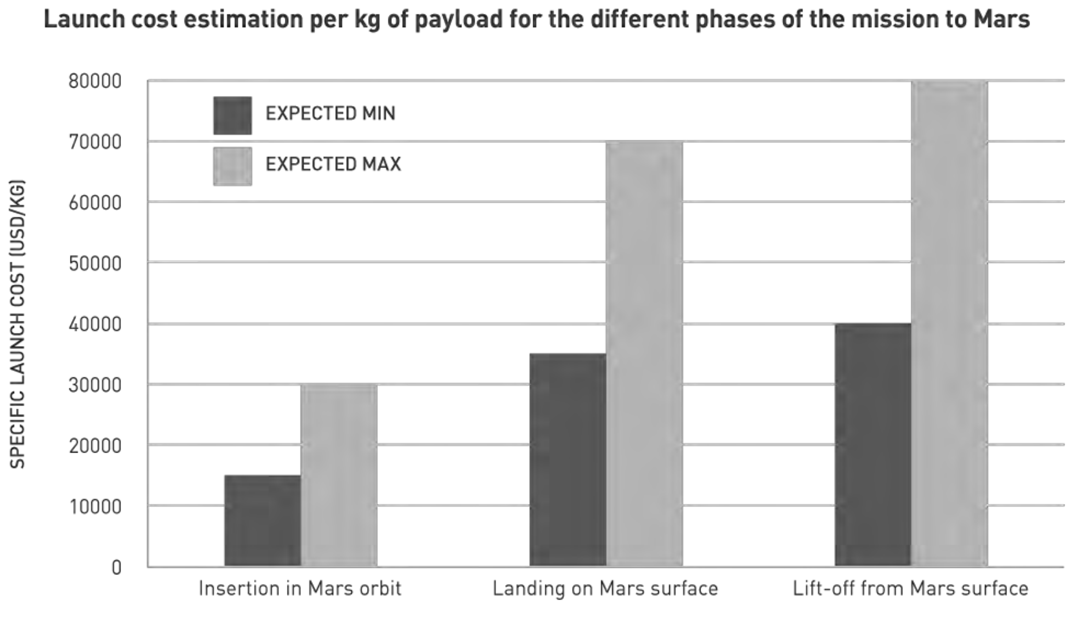
- To land 1 kg payload onto the surface of Mars requires launching an equivalent mass of 7 kg into LEO (of which 6 kg will be used solely to propel the payload to the Martian surface)
- To return 1 kg payload from Mars orbit to Earth requires launching an equivalent mass of 8 kg into LEO (of which 7 kg will be used solely to propel the payload to Mars and then back to Earth)

Depending on the mass required to be transferred at a given phase of a Mars mission, the total initial mass to be launched from LEO can be significantly impacted; hence, the overall mission cost, which is strongly dependent on the launch cost to LEO, is similarly impacted.

Considering the current heavy-lift launch vehicles, the specific launch cost into LEO typically spans from USD 5,000 to 10,000 per kilogram (Guest, 2011). Future use of the commercial Falcon Heavy launcher from SpaceX may reduce this cost to between USD 1,500 to 2,500 per kg; however, this was not considered in this analysis. Using the previously mentioned mass ratios and launch costs, an approximate scaling for the costs to launch one kg in a given phase of the mission was determined and is shown below (Figure 2-2).

- For a (human/robotic) payload to be inserted in Mars orbit: between USD 15,000 and 30,000 per kg
- For a (human/robotic) payload to land on the surface of Mars: between USD 35,000 and 70,000 per kg
- For a (human/robotic) payload to reach Mars and to return back to Earth: between USD 40,000 and 80,000 per kg

Figure 2-2: Launch cost estimation per kilogram of payload for the different mission phases



It should be noted that the scaling factors above include significant uncertainties; nevertheless, this process illustrates the dramatic impact on the launch cost of any additional mass that has to be landed on the surface of Mars and brought back to Earth.

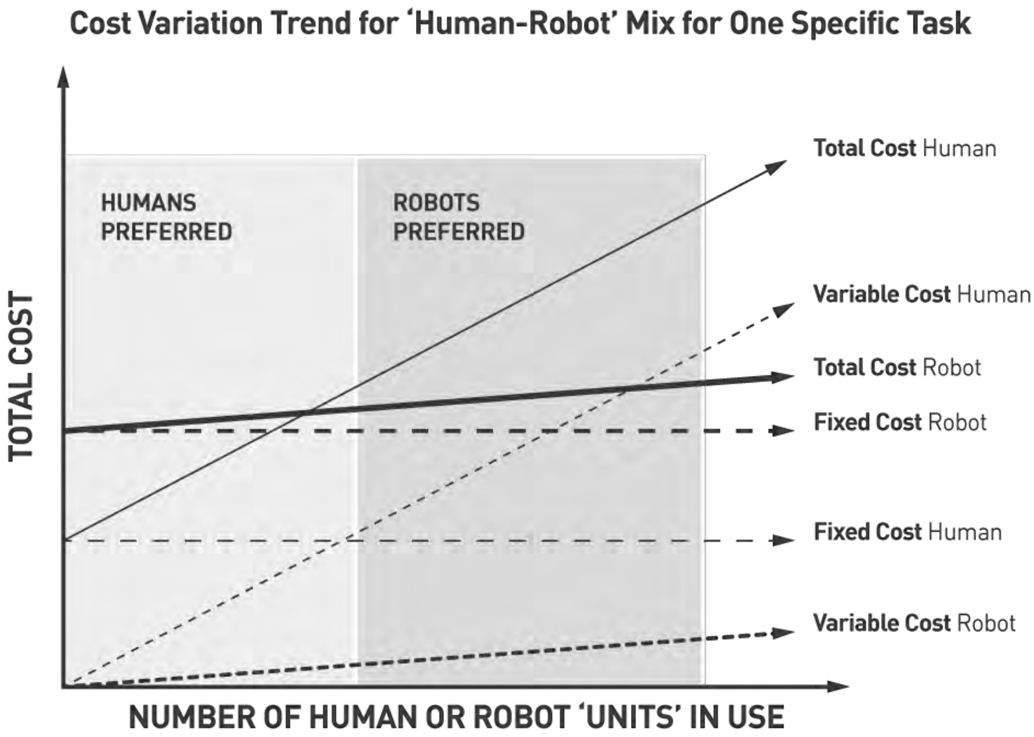
The Ideal Mix of Human-Robot Cooperation from a Financial Point of View

The key financial aspect with regard to human-robot cooperation is to provide an estimate of how the mission costs might vary as a function of the degree to which automation and robotics are used. The CHARM team has proposed a novel way of discussing this very sensitive topic in a generic way. The total cost of any service or operation is made up of fixed costs and variable costs. The fixed costs, like development or implementation, are independent of how often the service or the application is used. Variable costs fluctuate as a function of the number of units in use. A simplified trend analysis generated by the CHARM team will discuss the fixed and variable costs for both the human and robot components for space missions below.

The fixed cost for both for human and robotic space exploration are very high due to the unique space environment. The development cost for the autonomous solution involving robots, however, may be higher than the fixed costs associated with maintaining life support for humans in outer space. This fact results from the need to have extensive pre-mission research and development, as well as the requirement that the mission robots have to incorporate a very high degree of autonomy and sophisticated control systems in the field.

The variable costs are dependent on the number of unites (people, robots) employed in a certain scenario. For human spaceflight, generally a slightly reduced proportional increase can be assumed, in that doubling the number of astronauts leads to slightly less than double the costs. However, the variable cost for potentially mass produced robots or parts of the robots may be far lower that their human counterparts due to factors of scaling in mass-production.

Figure 2-3: Cost of human versus robot payloads



As shown in Figure 2-3, the general trend for the costs of humans is displayed in dark gray. The least expensive combination depends on the specific task and the number of units deployed, and generally moves from human to robot as the number of units is increased. Based on the trend that fixed costs might be higher for robots, but the variable costs might be higher for human participants, there are points where the least expensive options are with the use of humans, of robots, or from a mix of the two. For example, a task requiring a large number of repetitive tasks can be handled by robots much more economically than by humans.

The above described variations in cost as a function of the utilization of robots has to be applied for all tasks encountered during the mission. Certain tasks like remote sensing can be carried out by robots far more cheaply than by humans, while humans are cheaper and more successful in handling complex, and, especially unforeseen circumstances. This detailed mission task analysis will then result in an optimal human/robot mix from the standpoint of economics, and has been incorporated into the CHARM model.

Concluding Remarks on Mars Mission Cost Drivers

The additional mission costs (including upstream research, development, design, manufacturing, training and testing procedures, and launch costs) associated with sending a human mission will be addressed when the robotic and human missions are compared in Chapter 5. The risk for cost overruns must also be considered, as many necessary technologies (such as a closed-loop ECLSS) still are at low technology readiness levels, and the cost of the required development effort remains uncertain. Human spaceflight still remains a very costly endeavor, with cost being "[the] primary issue in formulating a human spaceflight plan" (Augustine et al., 2009). Within this context, the mission cost turns out to be one of the most important driving factors that need to be accounted for in the trade-off and decision-making process. Consequently, a cost analysis will have to be undertaken, to establish whether the benefits of including a human “payload” can outbalance the cost factor and what the best use of robotics and automation is when considering the financial aspects of space missions.

2.5 Societal Aspects of Mars Exploration

Space Robotics and Social Awareness

A mission to Mars can create a large amount of international awareness about space exploration, or it can go largely unnoticed by the general public. Regardless, the knowledge gained by such an endeavor benefits humankind as a whole. The amount of global attention given to certain Mars missions could ultimately factor into the implementation of that mission. How the public would react to a mission to Mars can be gauged by examining two of the ongoing Mars projects; the Mars500 analog experiment and the MER program.

Mars500 is a cooperative project by ESA and the Russian Institute for Biomedical Problems (IBMP) to improve and gain knowledge to prepare humans for Mars exploration. The experiment is to take six members as the crew of a simulated flight to Mars and seal them in an isolation chamber with personal contact only among the crew and a simulated 20 minute communication delay to ground control. This project is both cooperative and international in nature. ESA and IBMP selected crew which came from four different countries: China, France, Italy and Russia. Mars500 has also gained international recognition from the BBC, CBC, RIA Novosti, CNET, National Geographic and The Discovery Channel. It has also gained attention through online social networks such as Twitter, Facebook and YouTube. Although only a test simulation, Mars500 has gained worldwide recognition and illustrates how a future mission to Mars may be viewed by the public (ESA, 2010).

On the opposite spectrum, the MERs, Spirit and Opportunity, were two of NASA's more recent robotic rovers to explore the surface of Mars and its geology. Spirit and Opportunity both landed on Mars in January 2004, and have exceeded original mission duration expectations by over thirty times. The mission has been extended several times and still continues today with discoveries being continuously made. The exceptional results of the MER program have gained international recognition and have been featured on the Discovery Channel, the BBC and many websites, captivating the public`s attention and illustrating how a purely robotic mission can inspire and captivate the world (NASA, 2011f).

In terms of international cooperation and human-robot cooperation, the Mars500 analog experiment and the MERs are at the opposite end of the spectrum. It is important to note that both have important scientific results and both have gained international recognition, demonstrating that public support is present for Mars missions. Through examining and comparing examples like Mars500 and the MER project, it appear that a future Mars mission scenario, whether robotic or including humans, would incur a wide amount of public support. The question remains what the difference in support would be between an all robotic mission and an all human mission, and how a balance between the two extremes can be met.

2.6 Conclusions

Throughout the history of Mars exploration, there have been a series of missions that have largely focused on understanding the basic physical properties of the planet, investigating the possibility of past or present life, and testing preliminary steps required for future human exploration.

Multiple landers, rovers, and orbiters have mapped, explored, and examined Mars and its moons. These successful missions have provided invaluable experience and a variety of data for future missions to Mars. They have paved the way for future human missions to Mars by conveying important precursor information about the planet as well as providing insight into the necessary technical infrastructure.

Organizations and agencies have planned hypothetical missions for future human exploration, and gradually it has become clear that the costs, dangers, and challenges of exploring Mars may be too great for any one nation to undertake alone. Nations and space agencies have thus formed collaborative bodies to pool skills, knowledge, and resources to aid in the future exploration of the Red Planet. The migration towards a global space framework is the key to achieving a successful human Mars exploration. This migration also makes financial sense, by dispersing the financial burden and risk among multiple parties, thereby reinforcing the stability of such missions.

Based on sociopolitical, governmental, and financial considerations, the CHARM team believes that a human mission to Mars is achievable. With this in mind, the team proposes a model to assist in effectively selecting the degree of human-robot cooperation on different Mars scenarios. The following chapter will look at human and robotic interactions and the major considerations of robotics to accomplish a comprehensive mission.

3 HUMAN-ROBOT COOPERATION

Humans have intellectual capabilities such as intuition, creativity and complex decision-making skills that robots cannot yet demonstrate. Despite this, robotic aids and helpers are still necessary in the human exploration of space, to help mitigate some of the risks to crew health and wellbeing. The physiological fragility of a human and the complexity of life support systems make a purely human mission unrealistic.

Well known effects of the microgravity environment, solar and galactic radiation, high accelerations during launch and landing, an enclosed atmosphere and psychological factors are all important issues that must be addressed. Viable solutions must be developed before a human mission to Mars can take place. Robots would have the responsibility of undertaking tasks that would be deemed too dangerous or physically demanding for a human, and help maximize the efficiency of the mission. With an appropriate balance of human and robot participation, it is likely that political will and public support will drive support for a human mission.

This chapter provides a detailed assessment of the ways in which current cutting edge technology is used to support humans in exploring the solar system. The discussion considers the ways in which humans interact with robots and robotic systems, and the ways in which such technologies are used in cooperation with humans to aid in meeting the requirements of mission objectives.

3.1 Human - Robot Interactions

3.1.1 Robotic Aids to Human Health

Some of the health risks and challenges associated with long-duration missions and the ways in which robotics technology can aid humans include:

Solar and Galactic Radiation — A Mars mission would take astronauts out of the Earth's magnetosphere and expose them to higher levels of solar and galactic radiation than that experienced by astronauts currently in LEO. The chronic exposure to such higher radiation levels can increase the probability of developing cancer. The pressurized capsules used to house a crew can provide some level of protection against certain radiation types, but any external work or maintenance will lead to increased exposure. In this case, robotic helpers situated outside of a surface base or orbital habitation will reduce the demand on EVA excursions.

Life Support Control and Monitoring — To support humans on a mission to Mars, a reliable life support system needs to be onboard. The longer the mission, the greater chance of failure (Jones et al., 2010). The life support systems onboard a spacecraft or in a habitat must include the control of a variety of components. These components are atmospheric control, water and waste management, and food supply (Jones et al., 2010). Each of these systems has a major impact on the efficiency and success of a long-duration mission in outer space. Using multiple degrees of automation in monitoring the life support system will liberate astronauts' time and energy to focus on assignments that need complex decision-making skills.

Musculoskeletal and Cardiovascular Conditioning — On the Earth's surface, gravity significantly affects most of our motoric behavior such as the coordination of limbs. It has been estimated that about 60 percent of our musculature is devoted to opposing gravity, and healthy bone remodeling is highly dependent on loading conditions emerging from gravitational reaction forces during movement (Clement, 2003).

Psychological Issues — Another important health risk considered for long-term spaceflight are psychological issues. High or low work load, performance pressures, and lack of privacy can affect the mental state of crew members (Drysdale et al., 2003).

3.1.2 Benefits of Human-Robot Cooperation

The way we interact with machines influences our perceptions of technology. Additionally, the more intuitive a technology is, the more efficiently and effectively a person can interact with it. This section investigates the most effective ways of interacting with robots for a given Mars mission, and how this interaction will be received by the public. Human-robot interaction is an interdisciplinary field linking social factors, interface design, human cognitive science, and the academic field of communications (Hirata and Kosuge, 2004). When discussing human-robot interaction, it is important to recognize whether this interaction is between robots and an operator (i.e., via a flight-crew or from mission control), or with the general public. From the operator point of view, the robot has to perform certain tasks successfully, as trained or commanded. When considering how someone from the general public might perceive a robot, different aspects of human-robot interaction become relevant.

Humans and robots working together create many benefits, including more efficient and productive data collection. Robots do not suffer from the effects of fatigue or illness and can work around the clock on tasks to aid the crew. Robots can also provide more precise results than their human counterparts, although human presence is still crucial for on-site supervision of mission exploration. Another benefit is that robots are not only essential for assistance in performing tasks more efficiently and accurately, but they are a source of additional labor for repetitive or tiring work that requires minimal supervision (such as drilling).

Perhaps in the not-so-distant-future, as our expectations grow and robots become more autonomous in their capabilities, they will be equipped with enough intelligence to be capable of learning and evolving. As a result, it is feasible to consider a scenario where robotic assistants question or challenge commands. Humans should not be intimidated by the robot intelligence; instead, they should expect to work together with robots in a respectful and equal environment (Furse, 1999).

3.1.3 Human Perception of Robots

An important issue to consider in the analysis of HRI is the view of society about robots, especially the implementation of robots in space exploration. Data exists about the general public's opinion about robots and automation. A survey conducted in seven countries, consisting of 467 participants, came to some interesting conclusions about the differences in opinion between countries regarding the way the public perceives robots (Bartneck et al., 2007). Factors like the level of exposure to robotics through the media or through personal experience were the main issues related to the difference between the countries studied. The part of the population that was most exposed to the world of robotics might not necessarily be as open and receptive to it. This was because knowledge and exposure to robotics brought an understanding of their possible drawbacks. Consequently, a more critical view might exist among people with significant background exposure to automation and robotics.

Numerous studies have been conducted to measure influence on the public perception of the physical aspects of robots. The more anthropomorphic a robot is (i.e. the more the robot resembles a human), the more humans tend to accept it. This acceptance drops in what has come to be known as the "uncanny valley", where robots similar but unfamiliar to humans tend to alienate people (DiSalvo et al., 2002). Public perception is generally favorable regarding the use of robots for space exploration. Contemporary pop culture has been very productive in generating images and promoting the development of robots. The contemporary understanding is that while society largely supports robotic exploration of the solar system, human spaceflight is not as universally supported (Bell, 2007).

3.1.4 Interacting with Machines

Our Relationship with Machines

"Just as emotions are critical to human behavior, they are equally critical for intelligent machines, especially autonomous machines of the future that will help people in their daily activities." (Norman, 2003) Emotional aspects of HRI are often underrated in comparison with functional and technical considerations. From pop culture novels and movies to research labs, it is evident that humans are inclined to establish a human way of interacting with robots. Robots in movies are seen as friends to humans (Moon, 2009), saviors (Wall-E, 2008), co-workers (Bicentennial Man, 1999), and antagonists (Terminator, 1984). In practice, we have developed robotic technologies that often imitate our being, and in some cases go beyond our abilities. Whether they are manufactured machines that dance with us (Partner Ballroom Dance Robot developed in Japan (Yasuhisa, 2006)) or serve us in extreme scenarios (Mars rovers), they all seem to have something in common: it is not unusual for humans to connect with them at an emotional level. Even the very simple robots that operate in rescue operations have an element of safety and survival system in them (Norman, 2003).

A robot has to refrain from wearing down its components. Does this mean that robots should have emotions (such as fatigue or fear) to be able to survive or communicate with us? Or, is the notion of intelligence more suitable to address robotic reasoning and judgment capabilities? Like any other tool, our emotional relationship with machines can be defined by how deeply we are willing to engage with them. If a robot is perceived as too complicated to operate or communicate with, it is less likely that people will understand its functionality; therefore, intuitive robot interactions should be highly valued. There are findings from other fields where machines and tools have a close relationship with humans. For example, our relationship with mobile phones has evolved from a functional-based interaction, to a deeper reliance on them as we depend on them not only to communicate, but capture and watch pictures, videos, and be entertained.

Recent advances in technology have transformed machines from passive tools into interactive platforms that engage users in a direct way. All these examples show that, as a society, humanity is evolving to be more receptive and accepting of robots as the human-robot interface becomes more fluid.

Levels of Interaction

The way we interact with robots is largely determined by our level of engagement with them. For example, virtual reality has been shown to be a very efficient way of robotic interaction. Two levels of interaction in the context of space activities are discussed here: teleoperation (direct user controlled) and side-by-side cooperation (full or semi-autonomous robots).

- Teleoperation is where a human remotely operates a robot and directly controls every motion of the robot. This technique is used with robots such as the Canadarm2 on the International Space Station (ISS). One key benefit of teleoperation is to keep humans from exposure to harsh environments such as space.
- Autonomy allows side-by-side cooperation between humans and robots without direct control. For example, when an astronaut is performing an EVA, an autonomous robot can respond to its environment without relying on direct commands from a human operator.

Means of Interacting with Machines

Speech recognition systems allow direct command of a robot without physical control, such as a joystick or keyboard. Allowing a user to provide instructions to a computer or robot vocally presents a more intuitive method of interaction (Rogalla, 2002). Although there are challenges with the accuracy of these systems, they help users to interact with machines in complicated situations. Intention recognition provides endless possibilities to make the human-robot interaction field more anthropic (Georgia Tech College of Computing, 2000). Research in this field has investigated the use of human brainwaves, muscular electric signals, and small movements of muscles. Variations in brainwaves as they are increasingly altered under stress are not easy to detect or control. Facial or ocular muscular movements are easier to detect, but more difficult to distinguish in situations where fine control tolerances are necessary. Knowledge gained from these fields of research could be applied to augment the level of interaction between robotic components and humans in a space exploration mission.

Augmented reality is the science of enhancing presentation of a distant reality using visual and audio interfaces, and "refers to the enhancement of the actual perceived environment with information that has been obtained by other means" (Georgia Tech College of Computing, 2000). Wearable technologies and how people can interact with these aspects are also areas that have been pushing robotics forward. Both methods of representing information offer a more intuitive way of communicating with machines. Throughout the history of augmented reality, a number of tools have been developed to increase user perception about a distant reality. As an extension of our hands, gloves were one of the first tools developed for this purpose. Most research in gloves has been limited to virtual reality or gesture recognition. Applying wearable technology and augmented reality in situations where robots have to be operated remotely is used in some research for space applications (Carr et al., 2001), (Wang et al., 2009), however, there are vast opportunities for further adoption of the technology.

Real-time interaction between mission operators, humans or robots, and the public can cultivate people's relationship with space activities. Previous robotic missions to Mars (like the NASA rovers Spirit and Opportunity) involved sending rovers to the surface of Mars with a goal to find past evidence of water. A live video stream or artist renderings of Spirit and Opportunity could find their way into pop culture or daily life through social platforms. Both rovers were equipped with cameras and scientific measurement instruments to send data back to Earth, making it a feasible feat. Interactive platforms (such as public spaces, or urban interactive displays) could stream video from the next lander on Mars, or show a short animation of mission achievements. If audience scale is the measure of how successful a mission has been in getting public attention, agencies have to find more outreach outlets to convey their achievements. Nevertheless, the Mars rovers and their activities were well received by the public at large.

3.2 Robot Considerations

The success of a Mars exploration mission relies on understanding the current technological and scientific infrastructure capabilities for such an endeavor. However, it also relies on recognizing the existing gaps in these complex areas, and identifying feasible solutions to fill in these gaps. This section provides a background to the engineering considerations for a Mars mission including surface mobility, terrain assessment, multi-agent interaction, manipulation and high level autonomy, and their relation to human-robot cooperation and robot-robot cooperation.

3.2.1 Robotic Systems

Robotic Manipulators

The use of robots for manipulation tasks in controlled environments, such as factories, has historically been very successful. These sophisticated manipulation tasks are, however, executed within tightly controlled environments. Human manipulation of robots outside of these areas raises numerous challenges, specifically in situations that include unknown and vast open areas (e.g., Mars) or with humans present (e.g., on a space station). Unknown or irregular surroundings significantly decrease the ability of a robot to predict or plan future movements or maneuvers. There is a need for robots to have the abilities of perception, active learning, and cooperation with humans. Additionally, robots must be capable of executing dexterous tasks, such as repairing a space station by EVA (Kemp et al., 2007).

Robot manipulation tasks are comprised of force and motion actions, combining the ability to move in any desired direction and to exert a force, normally referred to as the "dexterity" of a given robot manipulator. A mission may depend on a robot having sufficient dexterity to manipulate objects and tools, an important ability for assembly, inspection, maintenance, and planetary surface exploration tasks. Teleoperated robotic arms, "Canadarm1" and "Canadarm2", are integrated parts of the Shuttle and International Space Station, respectively. Both arms have been used extensively in the construction and maintenance of the ISS. The Shuttle Canadarm1 was also used to capture other satellites for maintenance purposes, most notably as part of the Hubble Space Telescope servicing missions.

Bimanual robots are those equipped with two arms for improved dexterous ability. Examples include the University of Massachusetts's "Dexter", the Massachusetts Institute of Technology's (MIT's) "Domo", NASA's "Robonaut" and the German Space Agency's (DLR's) "Justin" (Katz et al., 2006), (Borst et al., 2009). Dexter consists of two seven degree-of-freedom (DOF) arms and three-fingered, four-DOF hands. Domo provides a manipulation system for inherently safe interactions with objects in the environment by employing a series of elastic actuators in the arms (Katz et al., 2006).

Examples for space exploration include Robonaut 1 (R1), designed around the base of a humanoid torso, to assist or replace astronauts during EVA. R1 closely imitates the mechanics of human arms and hands (Ambrose et al., 2000). The R1 arm consists of a shoulder, upper arm, forearm, wrist, and hands with five fingers. R1 has seven-DOF arms of similar size to those of a human, with similar strength and reach but with a greater range of motion. The hand and fingers have a total of 12-DOF. It is capable of fine motion, includes redundancy and safety features, and can endure the thermal conditions of an eight-hour EVA (Ambrose et al., 2000). The two small color cameras on the R1 head deliver stereoscopic vision to the operator's virtual reality display, providing depth perception. On the basis of R1, NASA and General Motors (GM) developed Robonaut 2 (R2), the first humanoid robot deployed in space and the first USA-built robot on the ISS. R2 is more dexterous than R1 and has a deeper and wider range of sensing. It is capable of completing tasks faster than R1 (Diftler et al., 2011).

Justin is a novel humanoid robot, developed by DLR and equipped with two arms and two hands built around an articulated torso with three active DOF and one passive DOF. It also includes a "head" containing various sensors, which gives Justin a total of 24-DOF, 18 for the hands, four for the torso and two for the head (Borst et al., 2009).

The NASA Mars rovers, Spirit and Opportunity (currently on Mars) and the Mars Science Laboratory, Curiosity (due to be launched in November 2011), are designed to carry out tasks that include digging, grasping, and precise positioning through the use of a robotic manipulator. However, the constraints of mass, power, and volume on such missions have a direct implication on the capabilities of such manipulation systems. These include minimal degrees of freedom, low mass, compact storage, relative high payload requirements and the need for a maximized workspace (Volpe et al., 1997).

Today, space exploration robots include both robotic rovers and human assistants. The example systems discussed above have sophisticated manipulation abilities allowing for accurate remote operation, such as the Canadarms aboard the ISS and Shuttle, or autonomous operation, such as the MER rovers on Mars. Despite this level of sophistication, even the most advanced systems are still dependent on a human "in the loop" to direct the execution of commanded tasks.

Mobility

Robotic mobility in space exploration missions has focused on mechanically simple and highly characterized mobility system responses. The first mobile robots, or rovers, used in space exploration were developed in the Soviet Lunokhod program. These were two large, teleoperated rovers both with masses greater than 800 kg. They were landed on the lunar surface by the Soviet Union between 1970 and 1973. The direct but decoupled control of these rovers by their operators on Earth allowed a level of exploration much greater than that achieved by the early Apollo missions. Lunokhod 1 traversed a total of 10.5 km, more than three times the cumulative distance covered by both the Apollo 11 and 12 missions prior to this. (Heiken et al., 1991). The final three Apollo missions, 15, 16, and 17, differed from the previous mission by including a Lunar Roving Vehicle (LRV), a 210 kg, manually driven rover capable of carrying two astronauts over significant distances. The LRV used in the Apollo 17 mission, launched a year prior to Lunokhod 2, traversed a total of 36 km, just a few kilometers short of the distance covered by the Soviet rover. However, the direct human operation of the LRV allowed the vehicle to cover this distance in the course of a little over three days, in contrast to the 145 day duration of the Lunokhod 2 mission.

Once the lunar space race came to a close, the focus switched to Mars and the exploration of its surface. The increased challenge resulted in two outcomes. First, extensive design work was carried out for many surface exploration systems (Muirhead, 2004), (Zakrajsek et al., 2005), although few were ever built or flown. Second, the lack of political desire to continue with expensive human spaceflight missions beyond LEO led to a reliance on robotic explorers, which were inherently limited by the technology available in the early days of the electronics era. Indeed, the only example of an exploration rover flown to Mars before the 1990s was the Soviet Mars Mini Rover (PRoP-M) on the Mars 2 and Mars 3 lander missions, both of which failed (Seeni et al., 2010).

It was not until the NASA Mars Pathfinder mission in 1997 that a mobile robot, "Sojourner", was included as part of a Mars exploration mission. This initiated a new era of exploration using mobile robots. Advances in electronic and power generation technology allowed the rover design engineers to develop an 11kg micro-rover capable of autonomous navigation and operation with no direct human interaction (Matijevic and Shirley, 1997). This system demonstrates an example of robot-robot cooperation in exploring the Martian terrain directly surrounding the lander location. The rover provided a highly mobility platform, based on the novel "rocker-bogie" passive suspension system, on which to mount the scientific instruments necessary to carry out the mission. Navigation of the rover was achieved using imagery of the immediate surroundings, taken by a panoramic camera (pancam), mounted on the lander platform to provide a comprehensive navigation system that allowed the rover to maneuver around the landing site with a high level of autonomy (Mishkin et al., 1998).

The "Sojourner"-like method of navigation and improved mobility proved to be so successful that is has been implemented on the two subsequent generations of NASA Mars rovers (Harrington and Voorhees, 2004), (Prakash et al., 2008). The MERs are also equipped with pancams and their mobility systems used identical rocker-bogie suspension arrangements as the Sojourner rover. The Mars Exploration Laboratory, the most advanced Mars rover built by NASA, is nearly nine times as massive as "Sojourner" and also uses an identical mobility and navigation system design principle. (Volpe and Peters, 2003).

Although alternative, robust, and high performance mobility systems exist terrestrially, the limited number of planetary surface exploration missions has resulted in a narrow approach to mobility system design. The constraint has broadly arisen due to the inability (in all cases except for Apollo) to service the robots *in-situ*. The development of these mobility systems has focused on the use of simple, reliable mechanical systems. This approach has enabled the highest feasible level of confidence in rover performance but has severely limited their overall tractive ability, particularly in challenging terrain, such as in areas of dense rock distribution, or moderate, sandy slopes. Both the Moon and Mars exhibit such dry, loose, sandy terrains and are strewn with obstacles ranging from small rocks and boulders, to craters, dunes, hills, and canyons. Planning for the traversal of unknown and unmapped environments such as these requires significant prior preparation, to determine how the surface material and obstacle distribution will affect vehicle mobility.

Despite the limitations in the distances humans can travel, the inherent adaptability of mobility and the ability to make quick, on-the-fly decisions provides a strong argument for a human presence when performing exploration missions involving traversals away from a base location. Once terrains are well understood, specialized robotic systems, such as cliff climbing, can be selected to perform maneuvers and tasks much more efficiently than a human counterpart. Exploration missions would benefit highly from such cooperative efforts between humans and robots during surface operations. Moreover, human presence in areas of operation where rovers are used increases operator confidence. This allows higher risk maneuvers to be commanded without radio latency and with the fallback that humans in the locale can rectify unexpected issues, such as mechanical failure or changes in the terrain. Conversely, such robots can significantly improve the ability for astronauts to explore their locale within a given mission operation window. Therefore, the mutual benefits in the use of both humans and robots for exploration provide a strong argument in favor of their future cooperative use.

Autonomy

It is often necessary for a robotic system to make decisions without direct human interaction when executing a commanded task. This may be due to the complexity of operating a high-DOF robotic system manually, or other operational constraints. For space-based robotic tasks, these constraints are often due to latency issues, for example, direct communication between Earth and the Martian surface suffers from latencies between 8 and 42 minutes, or longer if a relay through an orbital platform is required (Bajracharya et al., 2008).

To mitigate this issue, robots can be designed to allow autonomous operation based on generic objectives commanded by the operator. Onboard computers make operational decisions based on sensor information and feedback from both the surrounding environment and the current robot state. The computer computes and executes the specific actions necessary to complete the task. The result is an appropriately autonomous system allows robots to operate more efficiently and more safely than when directly operated by a human. Applications of autonomous systems are widespread throughout terrestrial industry and academia. In space exploration, an area that makes wide use of robotic autonomy is rover navigation and mobility.

The mission objectives of ground based robotic platforms commonly make the use of manipulators, such as the MER Instrument Deployment Device (IDD) and Phoenix Lander Robotic Arm (RA). The IDD is capable of autonomous placement of an instrument on a science target (Biesiadecki et al., 2007). The Phoenix RA can autonomously detect fault modes and either adjust the digging trajectory or re-execute the digging command (Bonitz et al., 2008). One of the most sophisticated autonomous systems in use on NASA exploration rovers lies in the navigation and mobility planning software. The unprecedented success and extension of the Mars Exploration Rover (MER) mission, from 90 days to over 2700 days, has provided a long-term platform on which to test advances in autonomous navigation algorithms *in-situ*, in a real-time mission setting.

Autonomous systems are used in all aspects of navigation, path planning, mapping and localization. This technology was initially demonstrated in the Sojourner rover operations. Obstacle detection and avoidance routines allowed diversions to the planned route to be executed, without direct human interaction, during commanded traversals to target locations (Mishkin et al., 1998). The MERs software, based on the Pathfinder flight software, is capable of determining the relative rover location and obstacles between its current position and the target position. Maneuvers to avoid dangerous obstacles between these locations are autonomously planned and executed (Biesiadecki and Maimone, 2006), (Goldberg et al., 2002). Commanded maneuvers are, however, highly susceptibility to large errors due to wheel slip. Other errors can be introduced through dead-reckoning odometry and cumulative errors in sensors such as Inertial Measurement Units (IMUs). This requires autonomous rovers to perform many computer intensive and time consuming processing stages when navigating autonomously. Local human operators can aid in reducing this through either supervised autonomy without significant communication latencies or by direct teleoperation for particularly challenging terrains or obstacles. During normal operations, however, rover navigation autonomy has been shown to be capable of carrying out complicated (but time-consuming) maneuvers with little human aid.

An emerging area of robotic autonomy in space is in the construction of large-scale structures either on-orbit or on other planetary surfaces. Large space structures must be constructed on-orbit (or *in-situ* for future planetary examples), due to payload mass or dimension limitations of contemporary launch vehicles. Many satellite systems currently use mechanical systems to automatically deploy antennae or solar panels as a result of these restrictions (ESA, 2006), (NASA, 2008), (JAXA, 2008). The most obvious example of on-orbit construction in existence today is the ISS. The majority of the ISS construction was carried out manually either by astronauts and cosmonauts on EVA excursions, or by use of the ISS and Shuttle robotic arms (Watson et al., 2002), (King, 2001). However, through its two successful Automated Transfer Vehicle (ATV) missions, ESA has demonstrated a reliable and advanced autonomous docking system (Pinard, 2007). Future applications could include the autonomous construction of a multi-module system based on such technologies with no need for human on-orbit assembly activities.

3.2.2 Automated Systems for Scientific Experiments

A long-duration space exploration mission provides a valuable opportunity to perform scientific investigations in a quest to further our understanding of other celestial bodies, cosmological phenomena, and our own planet. The knowledge gained from such endeavors has been translated to valuable technological advances used to benefit the quality of life of people around the world. This chapter summarizes some of the most important scientific aspects that should be considered for a long-duration space mission based on current capabilities and examples. The scientific endeavors considered include remote sensing of celestial bodies, sample retrieval and processing, and scientific experimentation under various gravitational environments. The current degree of autonomy of robotic missions is also briefly discussed.

Systems for Remote Sensing

The use of emitted or reflected electromagnetic radiation to probe matter at a distance is currently one of the most efficient ways to collect large scale data on Earth and Mars. Active (laser, radio), and passive (multi- or hyperspectral imaging) measurements allow detailed terrain modeling and provide clues on atmospheric and soil compositions, erosion patterns, and even gravitational anomalies. Examples of current technologies using hyperspectral imaging are the Cross-track Infrared Sounder (CrIS) instrument of the National Polar-orbiting Operational Environmental Satellite System Preparatory Project (NPP) to be launched October 25, 2011. CrIS will produce high-resolution, three-dimensional temperature, pressure, and moisture profiles of the Earth's atmosphere (Brill and Schwer., 2011).

In contrast, the active "Shallow Subsurface Radar" (SHARAD) on the MRO was designed to probe the internal structure of the Martian polar ice crust and gather information about subsurface layers of ice or liquid water (Greicius and Dunbar, 2011). Using high frequency radio waves, SHARAD has the capacity to resolve single layers as thin as 7 m down to a maximum depth of 1 km, providing a horizontal resolution of 0.3 to 3 km (Greicius and Dunbar, 2011).

The ChemCam scientific payload on the Mars Science Laboratory (MSL) rover offers an intriguing mix between remote sensing and sample processing and will be launched around December 18, 2011 (NASA JPL, 2011). The laser induced breakdown spectroscopy (LIBS) system targets rock samples, vaporizes a tiny amount, and uses remote-sensing spectroscopy to analyze the sample composition (NASA JPL, 2011). These types of systems can play a valuable role in investigating the surface of Mars and gaining valuable information during precursor missions or during a potential ongoing mission. These examples show that there is a tested and established infrastructure capable of operating with a high degree of autonomy for remote sensing of the Martian surface.

Systems for Sample Retrieval and Processing

Remote sensing provides a wealth of information about scientific targets; however, it is often necessary to take samples *in-situ* for closer investigation. This process encompasses three steps: sample acquisition, manipulation, and analysis. Among the top rationales for using robots for these purposes is the difficulty in accessing the desired samples, considering the risks to human wellbeing. An example of such robotic sample processing systems is the Sample Analysis at Mars (SAM) instrument. The purpose of the SAM instrument is to "search for organic compounds of biotic and prebiotic importance" (Davis et al., 2011). Another example of sample retrieval and analysis is the Rosetta mission using the Philae lander, programmed to investigate the 67P/Churyumov-Gerasimenko comet completely autonomously via both remote sensing and sample analysis, and the Phobos-Grunt mission to return a regolith sample from Phobos. The ESA ExoMars mission also consists of an orbiter to investigate trace gases and a rover capable of acquiring and analyzing samples from a depth of up to two meters using a drill. For these missions, although the degree of autonomy varies, a human operator will still have to exercise control for obstacle avoidance, selection of specific samples, and sample analysis. In cases where this is not feasible (e.g., during Rosetta's deployment of Philae), pre-programmed routines will be used to deal with decision processes, which could enhance the risk of mission failure.

For a distant space mission such as Mars exploration, the driving factor behind deciding the level of autonomy is the access to effective means of communication with the robotic system. The lack of appropriate cognitive algorithms or appropriate level of autonomy as a function of difficulty in communicating with the sample retrieval and analysis system can endanger mission success.

Systems for Scientific Experiments

A long-duration space mission, such as a mission to Mars, offers a valuable opportunity for conducting a complex range of scientific experiments as a secondary objective. However, the size restrictions for scientific payloads and safety concerns for a long-duration mission to the Mars system would impose serious limitations in terms of what types of experimental payloads can be considered. The scientific payloads integrated in specialized science racks on the ISS qualify as precursors for potential research that could be conducted in orbit or in transit to Mars. Some of the most noteworthy areas of research specialize in studying the effects of microgravity on combustion, fluid properties, crystal formation, human cardiovascular and musculoskeletal system, and biological systems. These experiments and conducted in standard payload racks that organize, monitor, and conduct the pertinent experiments with varying levels of human intervention. The racks can be operated manually, remotely from a ground station, or in autonomous mode.

Relevant examples of scientific experiments performed on the ISS include the ESA Biolab (Hartwick, 2011) and the Cell Biology Experiment Facility (CBEF) (JAXA, 2011b). These modules are designed to include scientific payloads for the investigation of the effects of microgravity on biological systems and are a great example of precursors for a scientific rack that could analyze samples from the Martian surface for biological tracers. Another example of relevant scientific modules is the Cardiolab subsystem of the European Physiology Module (EPM), which has been commissioned to investigate the effects of microgravity on the cardiovascular system and countermeasures for maintaining crew general health during long-duration missions (CNES, 2010). These systems could provide a useful insight into the health status of the crew, and due to lack of effective ground control support, should be designed to be user-friendly and compact. Another good example of a scientific payload that could be considered for a mission to Mars is a system for measuring environmental cosmic radiation, such as the Passive Dosimeter for Life Science Experiments in Space (PADLES), (JAXA, 2007). This type of monitoring system should be included as a scientific payload to empirically map the levels of radiation in transit to or in orbit around Mars. This information can be used to design better radiation shielding countermeasures.

These established scientific payloads are an excellent opportunity to investigate an effective level of human-robot cooperation applicable to a Mars exploration mission. Most of the systems are designed with the consideration of minimal human intervention to reduce the safety concerns and simplify the numerous tasks that humans have to undertake. It is recommended that the same approach be used for experiments that would be conducted on a Mars exploration mission.

3.3 Conclusions

The challenges of a long-duration space mission to Mars presents the need to develop highly capable robotic systems to compliment the skills and abilities of a human crew. Human interactions with robotic systems today are somewhat unwieldy, requiring highly trained and skilled operators, particularly in the most sophisticated examples. New technologies in the ways humans interact with robotic and computer systems, such as virtual reality devices and wearable computers, will increase the accessibility of cutting edge technology and ease the training demands on the crew.

Direct interactive methods provide the means for crew to control robots remotely and reduce the risk to human life. Current technology in decision-making processes, critical thinking and reacting to unplanned situations is not sufficient for robotic systems to operate alone, with even the most autonomous of devices requiring a human "in the loop", to varying degrees. Traditional robotic strengths are desirable on human missions, however, particularly in tasks which include dangerous or repetitive settings or actions. The benefits to potential exploration missions provided by robotic helpers in this respect are clear, affording a mission a greater quality and quantity of science objectives.

Therefore, the optimal mix of human and robotic cooperation for a manned Mars mission would likely include significant input from human crew members, aided by robotic assistants. The technologies available today which enable human and robotic interaction and cooperation provide a basis for those which would be included in such a mission. Today, some examples are at greater levels of development than others, however, within time frame suggested by this report the level of sophistication of today's technologies would present a significant list of advanced options for a human Mars mission.

4 MODEL ARCHITECTURE DEVELOPMENT

This chapter outlines the development of the CHARM model. The model is intended to help mission designers select an appropriate degree of human-robot cooperation for a space mission. A review of relevant literature is included to provide an overview of models specific to human-robot cooperation and the general decision-making methods used in engineering disciplines. The literature review provides a baseline for the development of the model architecture. 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.

4.1 Review of Existing Models

4.1.1 Models for Optimizing Human-Robot Cooperation

A number of authors have proposed frameworks for creating optimized human-robot systems for planetary surface exploration missions. Lamamy et al. (2005) developed a six-stage framework and applied it to a Mars exploration case study. In the first stage, a baseline human mission is defined in which automation can be used. In stage two, the mission is broken down into a number of basic tasks such as "find rock," "select rock," and "pick up rock." For the third stage, the potential agents that can carry out each task are identified such as robots, humans, or a combination of the two. In stage four, performance and resource usage models are defined for each possible combination. In stage five, commonalities across tasks are identified (for instance, a common robot platform may achieve more than one task). The sixth and final step is a search for the optimal architecture. A distinctive feature of this framework is that the allocation of automation is based on the value it adds to the overall mission, compared to a model which creates optimal allocation for individual tasks in an isolated way.

Rodriguez and Weisbin (2003) have proposed a method of evaluating the performance of different possible combinations of humans and robots carrying out a particular mission. As with the Lamamy framework, the mission is broken down into a set of tasks, potential agents to carry out each task are identified and performance and resource requirements for each combination of task and agent are computed. This research made extensive use of base-2 logarithms, which allow metrics to be defined in terms of information-theory bits. The research also defined a two-dimensional planar representation of results where one axis represents resource requirements and the other performance, providing an interesting visualization tool.

Although they are potentially very useful, both of these models are problematic in the context of this project. Both models require an extremely in-depth mission analysis to define the functional discrete actions and calculate the necessary metrics. This extensive mission analysis framework is not within the scope of this project. In addition, the extremely large number of possible agent / task combinations would require the development of computer software, which the CHARM team deemed unreasonable for the scope of this project. Finally, and perhaps most importantly, it is not clear how one could use these models to compare radically different missions such as "boots-on-the-ground" versus teleoperation from orbit, or how to capture and trade-off such intangibles as political support and public engagement. For these reasons, the CHARM team has decided not to base the development of our model on this approach.

4.1.2 Decision-Making Methods and Models

The intent of the CHARM model is to aid mission designers deciding the appropriate degree of human-robot cooperation. To achieve this goal, the CHARM team consulted the more general decision-making literature as well as the more specialized examples discussed above.

The Vroom-Jago Method

In the decision-making process, the Vroom-Jago decision model considers the role of the group leader and the members of the group, and determines who makes a decision. The decision-making process occurs on a scale that ranges from purely leader-made decisions, to purely group-made decisions. To determine how to make a decision, the Vroom-Jago model uses a series of seven questions asked in order (McDermott, 2011).

The model classifies decisions into several types, ranging from a decision made by a sole individual without detailed research to a decision made entirely by a group with a great deal of background research performed. These types are described in detail below (McDermott, 2011):

> Autocratic I (A1): One person makes the decisions using the information currently available.
>
> Autocratic II (A2): One person asks others for specific pieces of information but makes the decisions once this information in acquired.
>
> Consultative I (C1): One person acquires information from others and informs them of the final decision but the group is not brought together.
>
> Consultative II (C2): One person is responsible for making the decisions, however, a group is brought together to discuss the situation, hear various perspectives and solicit suggestions from others.
>
> Group (G2): The group makes the decisions together and it is the role of one person to be the facilitator of the discussion (McDermott, 2011).

The Vroom-Jago model is very flexible and claims to be an objective method for determining who should make a decision in a group setting. For example, a decision-making matrix where decision makers' rate criteria can be masked or scaled according to how much influence one or more of the decisions makers should have according to the Vroom-Jago model. However, this method becomes cumbersome if there is a large group of people involved in the decision-making process. A decision may also be too difficult to interpret to answer the seven questions properly, which may render the method irrelevant. It is also important to remember that the model simply provides guidance as to who should make a decision but not the technical detail of how the decision should be made. It may therefore form a useful part of the CHARM model but will need to be complemented by a more detailed decision-making method.

Multi-Criteria Decision-Making Methods

The Multi-Criteria Decision-Making (MCDM) method is a rational approach to decision-making with respect to multiple criteria that need to be fulfilled. In general MCDM is classified into two main types, which arise from the nature of the underlying problem and its solutions. The first type is Multi Objective Decision-Making which assumes continuous solutions to be possible, while the second type is based on discrete solutions, which represents the majority of problems, and is known as Multi Attribute Decision-Making but is sometimes also referred to as MCDM (Xu and Yang, 2001). According to Triantaphyllou (2010), different methods are used depending on whether the underlying data is deterministic, stochastic or fuzzy.

Models used to solve discrete problems are not designed to find the "optimal" solution but rather for ranking optimally with respect to imposed criteria. A solution is called "dominated" if at least one other alternative can be found which performs better. The best solutions are accordingly those which are not dominated, also called "non-dominated solutions". Another category is "satisfactory solutions". These refer to a subset of feasible solutions, which might not be necessarily non-dominated, but exceed the baseline requirements for all listed criteria. The term "satisfactory" in this context is dependent on the level of expectation for each criterion. A "preferred solution" refers to a non-dominated solution which at the same time satisfies the expectations of the decision maker (Xu and Yang, 2001).

Within MCDM there are various different methods and schools of thought which provide different procedures to find solutions. These include the Analytical Hierarchy Process (AHP), the Fuzzy-Set Theory, the VIKOR method and the Fuzzy VIKOR method, which are discussed below.

The Kepner-Tregoe Method

Developed by Charles H. Kepner and Benjamin B. Tregoe, the Kepner-Tregoe decision-making model attempts to collect all the different alternatives that could appear in a mission design, and evaluates them quantitatively, assigning priority to a decision maker's requirements. The Kepner-Tregoe model divides the decision-making process into four steps. The first step is the "situation appraisal"; when the decision-makers analyze the mission objectives to determine the adequate evaluation criteria, and then choose alternative approaches which feasibly achieve those objectives. The "problem analysis" step is based on the determined mission objectives and alternative approaches, and requires the decision makers to evaluate the benefits and drawbacks of each alternative. The "decision analysis" step makes use of a decision-making tool, such as a decision-making matrix to assign a ranking of each criterion within each alternative. The "potential problem analysis" step is based on the rankings of each criteria, and considers the potential problems to the mission that each may cause. Based on this last step, the best alternative to complete the mission objectives is chosen (McDermott, 2011b).

Within the decision-making process, Kepner and Tregoe also proposed a decision analysis method for choosing between alternatives. A decision statement, including what is desired and how to get it, is created. Three parameters should be defined:

- Strategic Parameters — what you need to have
- Operational Objectives — what you desire to have
- Restraints — what the constraints and limitations of the mission are

It is necessary to weigh the operational objectives based on the decision makers' criteria. For each of the alternatives that have been considered, their operational objectives must be rated. Following this, decision makers must choose the top three alternatives and consider the potential problems of these alternatives and the probability that these problems will occur. Finally, decision makers can evaluate the best alternative in a table and choose which alternative poses less risk to mission success (McDermott, 2011b).

Astra Approach: Customized SWOT and SMART Analysis

The Astra team project of the 2010 ISU Space Studies Program used a three-phase interdisciplinary study proposing a technology roadmap for an asteroid mining mission scenario (SSP 2010 Team A, 2010). The first phase consisted of a SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) to compare human and robotic missions. The SWOT method is a qualitative analysis which is simple, robust, transparent, and provides a clear understanding of the problem. The SWOT method is however ill-suited for complicated decisions with multiple evaluation criteria, constraints, and alternative solutions. The second and third phases consisted of a customized Simple Multi-Attribute Rating Technique (SMART) trade-off analysis. The basic steps involved in the SMART analysis are as follows:

1. Determine the objectives of the mission
2. Identify the mission designer(s)
3. Identify the different scenarios which involve various levels of human-robot cooperation
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 scorings to determine the main driving factors influencing the selected scenario

The analyses Astra created were used to study the preferred mission architectures for mining both small and large asteroids in the second phase, and short and long-term missions in the third phase. Attributes were selected according to their use of technologies with high Technology Readiness Levels (TRL) and which avoided dependence on critical technologies. Weights were assigned to attributes with values between zero and one. The weighting reflected the profitability, cost effectiveness, and technical feasibility of asteroid mining. This quantitative method had a suitable level of detail for mission selection, and led the Astra Team to their overall mission design. The ideas from this report have been considered in the development of the proposed CHARM model.

Analytic Hierarchy Process

The aim of the Analytic Hierarchy Process (AHP) decision-making tool is to choose between different alternatives to achieve a common goal. Each of these alternatives is evaluated depending upon different criteria. Each individual criterion is assigned a level of importance through weighting factors (Saaty, 1980). The evaluation criteria have different units of measurement (e.g., mass, cost, reliability, etc.) as well as different weights. Comparing outputs qualitatively is therefore necessary. The Analytic Hierarchy Process (AHP) model uses a relative scaling system to evaluate each of the individual criteria. For example, an individual criterion might be evaluated on a scale of one to ten, and each resulting alternative would therefore get a ranking on a scale of one to ten. This method allows for a system of ranking different criteria in a relative rather than in an absolute manner. Each criterion's importance ranking is determined in a similar fashion. This means that importance weighting for each criterion is not determined by its absolute importance, but more on a relative importance as compared with the other criteria.

The VIKOR method

The VIKOR method considers multiple inputs from multiple decision makers, and provides one compromise output solution. It can be used for multi-criteria decision-making to solve complex space exploration problems. Tavana and Sodenkamp (2009) have effectively used this method to evaluate a set of alternative mission architectures for the human exploration of Mars. This model was expanded to include fuzzy data and proposed a fuzzy decision-making model for technology assessment.

The Fuzzy Method

This method assumes that human decision-makers do not always have a clear idea of all the variables available in a decision-making process. Instead, human intuition, judgment, reasoning, and preference come into the decision-making process, and all of these are difficult to measure quantitatively. Typically, decision-making models do not account for the uncertainty in human knowledge and for the fact that decisions are made based on faulty or incomplete knowledge sets (Dubois and Prade, 1985). Various studies have been performed on the efficacy of this fuzzy method to assist in decision-making when faced with uncertainty (Hardy, 1994). Such situations often occur in engineering applications, especially in cases where a statistical database does not exist for intended criteria, or where the criteria are qualitative in nature.

The Fuzzy-VIKOR Method

This method is a combination of the fuzzy and VIKOR methods and involves three steps (Wang et al., 2006). The first step to take the qualitative inputs from the various decision makers and converting these inputs into a series of aggregate fuzzy numbers. The inputs for a decision process are the assessment criteria (cost, risk, time, etc.,) the relative weighting of importance of each assessment criterion, the list of feasible alternatives and the evaluation of the ratings of each of the alternatives under each criteria category. The output of this first step is a fuzzy decision matrix incorporating the weight of each of the criteria and the ratings from each of the decision makers. The second step is to compare the fuzzy numbers for each criterion and determine a set of reference fuzzy numbers, known as separation measures. These will provide a quantitative description of how well the criteria rank relative to the best alternative for a given criterion. The third step involves converting these separation measures from a set of fuzzy numbers back into a quantitative value through a process colloquially termed "defuzzification". Methods for "defuzzifying" a number are given in several publications (Chen, 1985). Once the separation measure is "defuzzified", the relative rankings for the alternatives are compared to determine the compromise solution, as well as the ranking of each of the alternatives.

4.2 Model Architecture Description

The literature review on decision-making models and human-robot cooperation provide a useful baseline for constructing the CHARM model. This chapter provides an overview of the model development. Please refer to the List of Definitions report section for explanation of the key terms used throughout this section.

The CHARM model was based on the Vroom-Jago, the SMART and the AHP models to evaluate different mission scenarios involving various levels of human and robot cooperation. The Vroom-Jago method simply allows for an objective decision-making approach by following a progression of questions as detailed further on. The SMART method is a means by which different scenarios are evaluated against each other by selecting common attributes and assigning a performance score for each scenario. The attributes must be selected so as to be relevant to comparing the scenarios and must be independent from one another. The SMART model allows attributes to be grouped into global categories to allow a better understanding of the problem (Dennis and Componation., 2004). Using the method described in the AHP technique, weightings are assigned to the attributes to reflect their relative importance. Essentially, they are ranked by their relative importance to the scenarios (Triantaphyllou and Mann, 1995). The attributes are then scored according to their performance for each of the scenarios, 1 being worst and 10 being best. The numbers between 1 and 10 correspond to a linear interpolation between the worst and best scenarios. Mathematical terms used in the model are explained in Table 4-1.

Table 4-1: Mathematical terms used in the model

Mathematical Terms

Term	Description
C	*Category*
A	*Attribute*
W	*Weight*
T	*Total*
S	*Scenario*
P	*Performance*
$i = 1 \ldots n$	*Enumerations of attributes*
$j = 1 \ldots m$	*Enumerations of scenarios*

STEP 1

The first step of the CHARM model involves deciding on the different mission objectives. In other words, the goals and desires must be determined from the proposed Mars missions before using the model. This can range from a sample return mission, to a mission to look for life on other planets, or a mission to find liquid water. This is the step in which the CHARM model can be tailored to any mission and invoking any degree of human and robotic cooperation as desired by the mission designer(s).

STEP 2

The second step in the processes is to determine the mission designer(s). To do this, the Vroom-Jago method is applied. This method considers the role of the group leader and the members of the group, and determines who makes decisions.

STEP 3

The third step of the CHARM model is to determine different scenarios, or means by which the objectives, as stated in the first step, can be accomplished. The stated scenarios will involve the use of different degrees of human and robot cooperation. Each of the scenarios in this step will be evaluated by the CHARM model to determine which one best uses human and robot cooperation to complete the stated objectives. An example of a scenario could be humans in orbit teleoperating robots on the surface of a planet, or a mission entirely performed by humans. It is the responsibility of the mission designer(s) to determine the number of scenarios.

STEP 4

In the fourth step, the mission designer(s) determine the attributes required to evaluate the scenarios, as well as the attribute weightings. These attributes are sorted into predetermined categories for example Scientific & Life Sciences, Technological, Economic, and Societal & Political. The attributes are sorted by category to allow for two levels of weightings: "category weightings" determine the importance of the respective category in achieving the mission objective; the "attribute weightings" determine the importance of the respective attribute within its category. This can be illustrated in the matrix as shown in Table 4-2. The AHP decision-making tool previously described can be used to facilitate the weighting process. Once the weighting process is completed, a total weight for each attribute is computed by multiplying the respective "category weighting" by the associated "attribute weightings."

Table 4-2: CHARM Model category (global) and attribute (high-level) weightings matrix

Global and High-level 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

In the fifth step, the mission designer(s) determine(s) the scoring of the attributes for each scenario. The scores range from 1 to 10, evaluating the relative performance of the selected scenarios with regard to the defined attributes. Thereby, the value 10 is assigned to the scenario performing best with respect to a certain attribute, and the value 1 is given to the scenario performing worst. Values in between are mapped relative to the extreme scenarios. This will represent how important an attribute is for each scenario. The scoring of each attribute is put into a decision matrix along with the total weights as determined in step four. This process is illustrated in Table 4-3.

Table 4-3: 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 sixth step is simply combining weightings and scores to give an overall scenario performance estimate. At this step the mission designer(s) can evaluate and compare the scenario performance to determine which scenario best uses human and robot cooperation to complete the stated mission objectives. This value is calculated based on the sum of the products of total weights and scoring for each attribute. This is shown in (Figure 4-1), where n is the number attributes and m is the number of scenarios.

Figure 4-1: Scenario performance estimate equation

$$SP_j = \sum_{i=1}^{n} TW_i \cdot S_{j,i}$$

where

$$i = 1 \ldots n$$
$$j = 1 \ldots m$$

A sensitivity analysis can then be performed on the CHARM model to determine the extent to which certain attributes are dominating the score. The sensitivity analysis is very important in determining the major factors that are limiting in various scenario aspects, such as human exploration of distant locations, and how they can be changed in the future to enable a preferred scenario.

The output of the CHARM model will provide a mission designer with a scenario containing a mission design skeleton that best uses human and robot abilities to accomplish the stated mission objectives. It should be noted, however, that the output of the CHARM model is a suggestion, and not a binding result. Ultimately, the mission designer(s) has/have the responsibility to determine how to interpret the results and how to apply them. A benefit of the CHARM model is that it is possible to modify the weighting and scoring of the attributes to determine the major driving factors that would enable more favorable futures. This will be discussed in greater detail in Chapter 6. This model can be applied to multiple objectives and can consider as many scenarios as the mission designer(s) can envision. Also, changes in political, technological, scientific, cultural or economic structures can be easily reflected in the weightings and scorings of attributes. Thus, the CHARM model is extremely adaptable.

4.3 Model Attributes

In this section we describe the identification and weighting of appropriate attributes to objectively evaluate mission scenarios. Attributes are grouped into categories to provide a global understanding of the functioning of the model. To enhance the objectivity of the model further, the weighting process incorporates experts from the CHARM team, selected via the Vroom-Jago method.

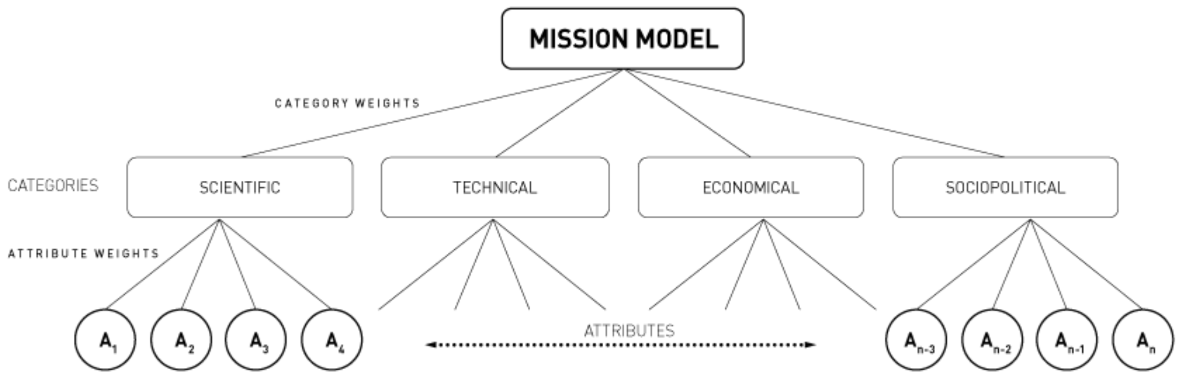
4.3.1 The Weighting Process

The generation of all weighting factors in this section was performed using two methods. First, recommendations were made by six project participants with specialized backgrounds incorporating gathered knowledge from literature reviews. Second, based on pair-comparison and geometric averaging of attributes, and applying the Analytical Hierarchy Process (AHP) (Saaty, 1980), all aspects were prioritized and the results were accordingly compared to the initial estimates. Since both methods produced similar outcomes, and AHP is a proven tool for decision-making in many fields (ISAHP, 2011), the AHP results have been used.

4.3.2 Categories

As a result of the literature review, the following categories have been identified for a Mars exploration mission: Scientific, Technical, Economic, and Sociopolitical. Figure 4-2 illustrates the hierarchical organization of categories and their respective attributes.

Figure 4-2: Scenario evaluation attribute hierarchy



The "category weighting" factors derived from the AHP method denote the relative importance of the respective fields for a successful mission. Their values have been determined to be:

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

4.3.3 The Attributes

The following breakdown structure of individual categories describes the model attributes, which 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 their respective category. The "category weighting" factor describes the importance of a category to the final mission. The influence of an attribute in the model is determined by multiplying "attribute weighting" with its corresponding "category weighting." This is called the "total weight," as described in previously.

The attributes to be used in the model were selected by an international and interdisciplinary group of 41 ISU SSP participants from 16 different countries, but can be adapted to reflect the values and views of any agency or constituency. These attributes are considered to be independent of one another and cover all of the important areas of each category.

The breakdown of each category is as follows:

Scientific

1. Scientific Relevance (Weight: 29%): 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 sample return mission, for example, this would reflect the diversity of samples that can be returned, or the diversity of experiments that can be performed on Mars.
2. Quality of Data (Weight: 17%): The quality of the data returned from a mission will vary depending on what scenario is being considered. In the above example, the CHARM team considered the collector's ability to acquire, as well as the amount of time it takes to select a high quality sample in the vicinity of the scientific target area, to be the most important factors for this attribute.
3. Quantity of Data (Weight: 12%): The quantity of data a mission can provide is another important factor that can influence the final design of a mission and in this case reflects how much sample mass can be returned for analysis.
4. Human Performance (Weight: 19%): The astronauts' ability to perform after landing on the surface of Mars is of major importance to the successful completion of the mission. Short term environmental effects on the astronauts' physiology are considered in this attribute.
5. Long-term Consequences of Spaceflight (Weight: 19%): The implications of radiation, human physiological adaptations to long-duration spaceflight and the implications to quality of life after astronauts' return to Earth is an important aspect to consider. The commitment to astronaut health during and after the mission is a critical aspect in guaranteeing the success of the intended mission. Since neither the immediate death of an astronaut during the mission, nor a high mortality rate due to long-term consequences of spaceflight are acceptable from the medical point of view, both weights are similarly high.
6. Planetary Protection (Weight: 4%): The possible contamination of the Martian surface due to probes or human presence, as well as the contamination of Earth through returned samples are also issues that need to be addressed. This attribute expresses the likelihood of cross-contamination occurring.

Technical

1. Maintainability (Weight: 15%): This is 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. The following factors should be considered in the maintenance of a system:
   - Monitoring the health of a system to predict when the system is going to need maintenance.
   - Capability to repair the system when it is damaged and preventing potential failures of the system.
   - Ease of repairs and maintenance
2. Reliability (Weight: 30%): This is defined as the ability of the technology to perform the necessary functions established for the mission in a hostile environment. Considered in this attribute are the ability of the systems to adapt to multiple environments and the design lifetime.
3. Level of Autonomy (Weight: 25%): This is defined as the capability of the technology or crew (humans and/or robots) 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 or human-robot.

4. Technology Readiness Level (Weight: 30%): This is defined as the level of maturation of evolving technologies that are needed to accomplish the mission.

Economic

1. Mission Cost (Weight: 80%): This attribute includes the required investment, with the cost for system development, launch and operations related to a mission to Mars. Within this definition, the mission cost refers to the whole life cycle cost of the mission, from its initial development, to its execution and its end-of-life costs. According to Augustine et al. (2009) "a primary issue in formulating a human spaceflight plan is its affordability." The end-to-end mission cost has become a strong driving factor when it comes to deciding for a space exploration mission. This has become increasingly clear within the current world economic situation. Consequently, a high weighting was applied to this attribute. Because of the high costs of exploration missions, it is expected that any mission to Mars in the next two decades will be publicly funded through international cooperation. This would help reduce the impact on national budgets, and maintain the level of governmental activity in other economic sectors.
2. The Mission Cost attribute is heavily weighted for two main reasons. First, governments specifically allocate funds for space programs and there is a high accountability associated with public expenditure; therefore, there is a limited degree of freedom in what agencies can achieve based on financial constraints. This perspective was generally supported by the international views of the CHARM team members during informal interviews. Second, the selected AHP method used for determining the weightings mathematically tends to amplify the relative gaps between each attribute within the same category. If this model were from the perspective of a private company, the economic attribute weightings would reflect an emphasis on return on investment.
3. Return on Investment (Weight: 10%): This attribute refers to the economic benefits of executing the mission. These include areas such as job creation, improvement of technologies, competitive advantage of national companies, and spin-off technologies. Historically, the rationale for economic benefit of space missions was less influential when compared with the original political and social rationales such as international leadership, national security, and national prestige. Based on this rationale, this attribute has been given a lower weighting.
4. Risk of Cost Overruns (Weight: 10%): This attribute refers to the risk of having the mission cost significantly increased during the development and/or mission operation phases. The uncertainty associated with the mission cost evaluation can be used to estimate this attribute. The uncertainty level can be related to the technology readiness level of the selected technologies, as well as to the complexity of the mission. For example, the use of already developed and flight-proven technologies should allow the mission cost prediction to minimize the risk of cost overruns. However, the risk of cost overrun does not seem to be a critical influential factor for the initial mission selection. Rather, it plays a major role in the reduction of the scope of the mission objectives, and can even lead to mission cancellation to control the overrun. An example is the announcement by the Bush administration in February 2001 that "it would cancel or defer some ISS hardware to stay within the cap and control space station costs" (Behrens, 2009).

Sociopolitical

1. Public Awareness (Weight: 26%): Societal and cultural growth is affected by the perception and awareness of the public (Hilgartner and Bosk, 1988). Six factors must be considered in defining the effects on public awareness. These are e-media exposure, public involvement, education and outreach, robotic design and aesthetics, public involvement through human-robot interaction advancements, and known societal gain.
2. Long-Term Political Will (Weight 74%): Historically, human space exploration missions

have required a strong policy directive (Hoffman and Kaplan, 1997). NASA's Mars Reference Mission (Hoffman and Kaplan, 1997) document states that "The decades-long time-frame for human exploration of Mars cannot be supported until the role of the space program is well integrated into the national space agenda and the exploration of space is no longer considered a subsidy of the aerospace industry. To accomplish this, the space program must show concern for national and international needs (visible contributions to technology, science, environmental studies, education, inspiration of youth, etc.,) while maintaining a thoughtful and challenging agenda of human exploration of space in which the public can feel a partnership." It is not easy to rationalize the risks and costs of government programs to send humans into space. The rationales considered as factors to influence long-term political will are national prestige and international leadership, public support of policy and strength of international relations. A majority of the political and policy debate surrounding space programs is associated with human spaceflight (Logsdon, 2011) and has a high weighting.

A summary of the weightings of each attribute and category are shown in Table 4-4.

Table 4-4: The weightings of the attributes used in the current scenario 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 Flight	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 %

4.3.4 Interrelations between Attributes

Strong correlations between attributes of different fields can influence the decision process in a detrimental way, as transparency with regards to the weightings is lost. Also no useful information is gained by introducing mutually dependent attributes. In practice, it is not always easy to identify such correlations. In the current model, interrelated attributes have been identified and overlaps were classified as follows:

- Technical and Economic: Technology Readiness Level - Risk of Cost Overruns. In absence of proper cost overrun estimates, often correlations between the risk of cost overrun and technology readiness level are introduced.
- Technical and Economic: Technology Readiness Level - Return on investment: As the amount of new technology is used as an indicator for the possible return of investment of missions, interrelations between those two attributes are produced.
- Sociopolitical: Public Support of Policy – Public Involvement. As public involvement is increased, so is public perception. This has the potential to generate public support for different types of Mars missions, and, consequently, influence the political leaders in their decisions on space policy.

- Political and Economic: Long-Term Political Will – Impact on National Budget. Considering that the mission costs were covered via national budgets in the past, the impact on the national economy is a key factor. Consequently, public support for the space program and the long-term political will indirectly depend on mission cost.
- Technical and Life Sciences: Human Performance - Technological Reliability. The technology of Life Support Systems is the dominating factor concerning the crew's survivability and performance. A high level of human performance implies a high level of technological reliability in Life Support Systems, and therefore in the overall mission design.

4.3.5 Discussion

The Social and Political category has the highest weight as it was found to be the most influential. The most heavily weighted attributes are Long-Term Political Will and Mission Cost. There is a significant gap between the weight of these attributes and the others, which reflects the findings for the current trends in scenario decision-making. The capacity to meet mission objectives is driven by the technical feasibility. The funding obstacles for a mission to Mars are the first limiting factors in the design of such a mission. From the review on the space industry and as discussed in the previous section of the report, the affordability of an exploration mission has clearly become a necessity. As shown by past missions, a strong political will has to be the catalyst for making any substantial space endeavor feasible. The scientific, life sciences and the social-related attributes have been rated with lower weightings since these attributes have not been seen to significantly steer the decision for the mission to Mars, compared with the economic, political and technical attributes. It is worth highlighting that the wide selection of attributes reflects the interdisciplinary approach of the CHARM team. Once combined into the four global categories (science, technical, sociopolitical and financial), the overall weights per category are of the same order of magnitude (approximately one quarter), which considers the ISU disciplines evenly

4.4 Conclusions

In this chapter, the CHARM team has described the development of the proposed model for human-robot cooperation. Users of the model define mission objectives, together with a set of scenarios for achieving these objectives, each of which differs in the degree and form of human-robot cooperation. The competing scenarios are rated using the Simple Multi-Attribute Rating Technique, and a preferred scenario can then be identified. Throughout the model process, responsibility for making decisions related to model inputs is determined according to the Vroom-Jago model. The effectiveness of the process depends on the selection of appropriate attributes and weights for these attributes. On the basis of the research presented in Chapters 2 and 3 we have identified a set of 15 appropriate attributes and have weighted them using the Analytical Hierarchy Process. In Chapter 5 we develop four scenarios for Mars exploration and apply our model to these scenarios to investigate the functionality of the proposed model.

5 APPLICATION OF THE MODEL AND RESULTS

The CHARM model has been developed to evaluate a range of proposed scenarios which all aim to achieve the same mission objective. In this chapter, four mission scenarios are generated to serve as input for the CHARM model. These share the same objective, but exhibit different degrees of human-robot cooperation. Each scenario is evaluated using the CHARM model and is assigned a score relative to the other scenarios based on the weighted attributes chosen. The scenario ranking highest is considered to be the best choice in achieving the mission objective. In a next step, the model is applied with regard to extreme futures, where the category weights are altered to produce scientifically, economically and sociopolitically dominated environments.

5.1 Model Inputs - Mars Mission Scenario Development

Four mission scenarios were developed around different degrees of human-robot cooperation. All scenarios share the same objective. The first step is to state the mission global objectives and the lower level objectives.

5.1.1 Potential Objectives for a Mars Mission

According to the Mars Exploration Program Analysis Group study (MEPAG, 2010), two main categories of mission objectives were considered for developing the specific mission scenarios: to look for evidence of life on Mars and to prepare for human exploration.

For each of these categories, we considered the following objectives:

1. Look for life on Mars
    - Search for any evidence of water presence on Mars
    - Analyze the Martian environment by means of sample return
2. Prepare for human exploration
    - Search for *in-situ* resources that can be utilized for human missions

5.1.2 Mission Objective Selection

The MEPAG outlined 55 fundamental future science investigations associated with the exploration of Mars (MEPAG, 2010). The MEPAG concluded that around half of the investigations "could be addressed to one degree or another by Mars Sample Return," making MSR "the single mission that would make the most progress towards the entire list" of investigations. In addition, the report stated that a high number of the investigations could not be significantly advanced without a sample return (Beaty et al., 2008). The benefit to investigating samples from Mars in laboratories on Earth is the range of scientific analysis that can be conducted when compared with *in-situ* Mars experiments. Additionally, Louis Friedman, former Executive Director of The Planetary Society, called a Mars Sample Return "the 'holy grail' of robotic space missions" due to its significant scientific return on investment (Friedman, 2008). On this basis, the CHARM team has selected a Mars sample return as the mission objective.

5.1.3 Scenario 1 - Robotic Mars Sample Return

Outline

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 (MAV) to lift the sample material into Low Mars Orbit (LMO). There the MAV will then dock with the orbiter and the sample is returned to Earth. The robotic sample return scenario does not involve human spaceflight elements.

Scenario Description

The robotic Mars sample return scenario is based on the iMARS (International Mars

Architecture for Return of Samples) mission concept (Beaty et al., 2008). This scenario calls for two robotic spacecraft: an orbiter composite and a lander composite to be sent to Mars on separate launch opportunities. The term composite is used because each spacecraft is composed of more than one smaller spacecraft. The lander composite arrives at Mars first and deploys a lander to the surface, carrying with it a sample collection rover and a MAV. The rover will be used to collect around 500g of samples up to a distance of 2.5km from the landing site and transfer them to the MAV which will carry them into LMO. By that time, the orbiter composite will have reached Mars orbit. It will rendezvous with the MAV and the sample canister will be transferred to the orbiter. The orbiter will then bring the sample back to Earth orbit, at which point a small reentry vehicle carrying the sample will be deployed and carry the sample to a safe landing back on Earth.

Given the small total sample mass requirement, this mission is designed to maximize scientific value by acquiring multiple small sets of samples which are deemed more useful for characterizing a site than a single large sample. Examples of such samples are regolith blends, dust, and atmospheric probes. The sample collection rover is equipped with a range of scientific instruments to provide *in-situ* feedback to allow ground control to make informed decisions as to which samples to select, and to provide geological context. The rover is also equipped with a mini-corer, allowing sampling up to a depth of 5cm. The rover mobility system is capable of return travel up to 2.5km from the landing site, which allows for geological variety in the samples (Beaty et al., 2008).

The mission is technically complex, and a number of key components are at a low technology readiness level. Of particular concern are: the ability to perform autonomous precision landing with hazard avoidance, the ability to perform autonomous rendezvous and capture in Mars orbit, developing propellants for the MAV that can be stored for long periods of time on the surface of Mars, and the technical requirements imposed by planetary protection considerations. The sample collection rover itself does not require a high degree of automation beyond what has already been demonstrated for Mars. This means that selecting and gathering samples will be a slow process because decisions will be made on Earth and sent to the rover.

In this mission, humans stay on Earth and so no hazards are posed to astronauts. Additionally, because the mission is small in size as compared with an all-human mission the sterilization requirements for forward-contamination under planetary protection guidelines are more easily met. While very interesting from a scientific point of view, a robotic Mars Sample Return is rather expensive for a robotic mission and lacks the public glamour of human exploration. It is questionable, therefore, how much political support this endeavor will have. In addition, there have already been four successful robotic Mars missions; therefore it is likely that interest in a further mission will be diminished. On the other hand, the proposed mission is international; therefore political support is likely to be more stable, meaning that the risk of cancellation is minimal once the project has begun. Also, returning a sample from Mars is perhaps more exciting in the public eye than previous missions that have performed exclusively *in-situ* science.

The financial aspects are also key drivers for accomplishing the mission. The cost estimate for this mission is between USD 3 and 8 billion. The proposed mission is deemed expensive by comparison with an estimated cost of USD 2.5 billion for the most recent robotic Mars mission, the Mars Science Laboratory (Moskowitz, 2011).

5.1.4 Scenario 2 - Mars Orbital Outpost

Outline

The Mars Orbital Outpost scenario is a mission concept where robots on the surface of Mars are operated by humans in Low Mars Orbit. The mission is envisioned for the 2020 time frame. The key advantage to this approach is that the communication delay is significantly reduced in comparison to controlling robotic systems from Earth, allowing for a more effective interaction and use of robots.

Scenario Description

This scenario is derived from the Russian MARPOST mission concept (Harvey, 2007) and sized using the NASA Design Reference Mission 5.0 (Drake et al., 2010). It incorporates the idea of using two so-called "hoppers", which are robotic probes capable of moving between 10-15km on the Martian surface by applying controlled rocket burst locomotion (Yu et al., 2010). The outpost is envisioned as a space station in Low Mars Orbit with robotic control mechanisms used to encounter and capture the probe ascent system containing the samples. The outpost system encompasses life support systems for a crew of five — consisting of a mission commander, pilot, flight engineer, medical specialist and a scientist. The total duration would be fourteen months, with an on-orbit stay of one month.

Heavy lift launchers, such as the Ares V Class, are necessary for this scenario to minimize the number of launches required to lift all the mission critical equipment into the Earth orbit - thus reducing the complexity of assembling the habitat in orbit. Two launches are planned in the initial phase to pre-deploy cargo landers on the Martian surface and the outpost in Mars orbit. Three more cargo launches would be required for propellant systems and crew transit habitat modules, and one launch to deliver the crew to the transit habitat. A total of six launches are required.

Nuclear Thermal Rocket (NTR) propulsion is suggested for this mission scenario considering its merits with respect to mass and reduced travel time. As stated by Drank (2009); "The NTR is a leading propulsion system option for human Mars mission because of its high thrust (10's of klbf) and high specific impulse (ISP 875 – 950 s) capability, which is twice that of today's liquid oxygen (LOX)/liquid hydrogen (LH2) chemical rocket engines." (Drake et al., 2010) This technology has a high technology readiness level as proven during the Rover/NERVA programs (Robbins and Finger, 2011).

Martian samples collected by the hoppers would be brought back to the outpost by ascent stages and then back to Earth in a return module. The primary scientific value of the samples lies in the fact that they provide better and deeper understanding of the Martian surface, which is essential for future human settlements on Mars. These samples can be examined by scientists on Earth to carry out extensive scientific investigations using advanced instruments, a task that cannot be accomplished *in-situ*. The use of hoppers is advantageous in gathering samples from widely different areas on the surface of Mars; however this means of locomotion imposes severe mass limitations. This scenario assumes hoppers can be modified to carry the ascent stages proposed in Scenario 1, allowing for a total sample mass of 1kg.

A deep space exploration mission involving humans would require complex life support systems as well as significant advancements in implementing countermeasures for the effects of radiation and microgravity. For an orbital outpost scenario, the risk and complexity is reduced as compared with a surface landing mission, as there is no danger of the crew being incapacitated by the transition from microgravity to Mars gravity. Human space exploration of Mars, even though not a surface mission, would elevate national prestige and encourage public support for this scenario. However, in most likelihood this scenario will generate less support than a mission including humans on the surface of Mars. The difference in public support and reaction would be analogous to the difference between reactions to Apollo 8 and Apollo 11, where the former was an orbital mission and the latter a lunar landing.

The main economic benefits of deep space exploration would be experienced by enterprises pioneering the research that can eventually take humanity from the information age into the space age. Other potential benefits include the creation of new fields of employment, creating business opportunities for venture capitalists, investors, scientists and other professionals (Berry, 2010). Specific for this scenario would be advances in life support system technologies, propulsion techniques and robotic teleoperation. As we were unable to find a plausible cost estimate for a mission of this type, we can estimate that the cost would be much higher than a purely robotic mission. Yet, having no need for crew landing and ascent equipment, the total mass budget for Scenario 2 is most probably smaller than a mission featuring humans on the surface of Mars. Consequently, the cost is lower than in Scenarios 3 and 4.

5.1.5 Scenario 3 - Human Short-Stay on Mars

Outline

The proposed aim of the short-stay mission scenario is to collect 60kg of Mars samples from the Jezero Crater and return them to Earth. The total mission time is 661 days, of which forty days will be allocated for Mars surface activities. Two out of a total of four crew members will land on the surface of Mars and collect both surface and subsurface samples using rovers and other robotic equipment. At the end of mission, an ascent stage will launch from the surface of Mars to a transit habitat in Mars orbit which will then return to Earth. This scenario has been largely based on the Mars Design Reference Architecture 5.0 (Drake et al., 2010).

Scenario Description

On Mars, the Jezero Crater (18.2°N-77.6°E) situated in the region of Nili Fossae, has a very high potential for the scientific community, because it can answer many questions posed in the MEPAG 2010 report (MEPAG, 2010) concerning life on Mars and the geological history of this region. This site covers the majority of the geological periods on Mars (Noachian, Hesperian and Amazonian), and, as it is situated near the ISIDIS basin floor, it provides the opportunity to investigate the existence of water and whether this basin was ever hospitable to life.

To carry out this short-duration mission, a heavy launch vehicle, such as the Ares V class rocket, will be used to lift the payload into LEO and send it to Mars one year ahead of the crew. The four crew members will be launched in an Orion class capsule using Ares-1 class launchers. The launch time for the cargo will be December 2028, according to the minimum energy launching window. The Mars Transit Vehicle (MTV) and the crew capsule will be launched separately and assembled in LEO. One year after the payload has been sent on its way to Mars, MTV will follow. After entering Mars orbit, the Mars transit habitat will stay in orbit hosting two crew members, whereas the other two astronauts will land on Mars together with a lander/ascent stage which will serve as a backup surface habitat. This minimum energy approach is similar to Apollo missions (Drake et al., 2010).

The astronauts will use a pressurized rover similar to NASA's Surface Exploration Vehicle (NASA ESMD, 2008) as a main habitat and transportation vehicle, allowing for expeditions of approximately two weeks without the need to resupply. The use of exoskeleton suits (Kwa et al., 2009) can mitigate the impact of physiological issues such as muscle and bone loss on the astronauts EVA performance. During 40 days the two crew members could accomplish about 28 EVAs and collect an important variety of samples. The concepts of Mars transit habitat, Mars Lander and Mars surface habitat were derived from the Human Exploration of Mars Design Reference Architecture 5.0 (Drake et al., 2010).

To be able to study the subsurface composition of the Martian soil the crew members will use a drilling system. The Mars Astrobiology Research and Technology Experiment (MARTE) drill system, for instance, can drill to a depth of 8.3m and retrieve samples with a diameter of 27mm. (Winterholler et al., 2005). Due to the limited time frame, no deep drilling will be possible. The samples will be stored in the crew ascent vehicle, and transported back to Earth together with the crew. The arrival at Earth is planned for December 2031. After the return to Earth orbit, only the crew capsule will re-enter and land on Earth; the remaining spacecraft parts will be discarded.

Once the mission is under way, the public reaction will most likely be positive as the scenario features the first human touching ground on another planet. Due to the overall duration of the mission, the interest from the public concerning the mission will not decrease. Attention to the mission would be given during the development, flight, landing and return phases of the mission. As such, the political benefits in terms of national prestige for the contributing countries is likely to be high as it will remind people of Apollo 11 successes. Furthermore, the international cooperation between the different participating countries would be strengthened by the success of this mission.

The cost of landing a human on the surface of Mars is extremely high, thus the financial collaboration of multiple countries will be necessary. However, the return on investment for such a mission is high, largely due to the resulting spin-off technologies and advancements in life sciences and propulsion technology.

5.1.6 Scenario 4 - Human Long-Stay on Mars

Outline

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 Mars and 6 months in transit to and from Mars, for a total mission duration of 30 months. The mission is scheduled to take place between 2030 and 2035 (Drake et al., 2010).

Scenario Description

The scenario is based on the NASA Design Reference Mission 5.0 (Drake et al., 2010). Since the stated mission objective is to provide a sample return, the human presence and the long-stay scenario offers the possibility of choosing the best quality of samples to bring back. The samples will include atmospheric samples, rocks, soil and ice. The samples will be analyzed on Earth or on-site to determine constituents or detect traces of radio-isotopes. During a long-stay human mission, the crew would be able explore further away from their base to carry out much of the research, thus avoiding forward contamination of samples. Thus, robotic equipment capabilities will help to perform more in-depth exploration. Exploratory vehicles will allow humans to cover large areas and drilling equipment will be capable to reach samples in depths of 100m to 1000m below the surface. Due to continuous human presence throughout the sample selection process, we can limit the sample quantity to 100kg of high quality and highly diverse material. The choice of site is one of the key parameters. The Fifth MSL Landing Site Workshop (NASA, 2011) has identified 4 different landing sites on the Martian surface, with latitudes ranging from 26°S to 24°N. In particular, the Holden crater area (26°S-325°E) has been considered the most interesting for sample return mission, because it provides the opportunity to apply a geomorphic systems approach to evaluating and preserving evidence for a sustained, habitable environment (Grant and Golombek, 2011).

The mission requires complex and advanced technologies, which, based on current estimates, will be available in the next 20 years. The split type mission implies the payload is launched, deployed and tested before crew launch. The mission also foresees a high mobility requirement that can be achieved using two small pressurized rovers, one robotic rover, one unpressurized rover and a teleoperated hopper. These systems must have a high level of reliability and ease of maintenance by direct human intervention. Multiple surface operations will be possible with the wide range of robotic capabilities. The first one foresees the use of the robot to survey slopes, rock properties, and environment conditions as reconnaissance support to access difficult or dangerous sites. Cooperative work between human and robot counterparts will help to overcome the limited agility imposed by cumbersome spacesuits.

The mission concept is based on the ability to use heavy-lift launch vehicles and transfer vehicles with nuclear thermal rocket propulsion. These are the main technological challenges to be overcome. In this scenario, *in-situ* resource utilization (ISRU) can help to reduce the total mission mass (Rapp et al., 2005). The purpose of ISRU is to harness and use space resources to create products and services which enable and significantly reduce the mass, cost, and risk of near-term and long-term space exploration (Sanders et al., 2005).

The long-stay scenario requires advancements in countermeasures to mitigate the effects of reduced gravity and radiation on the human body during the transit, in orbit and on the surface. This area is considered one of the greater challenges of a long-duration mission such as this. Regarding the political and societal aspects, the mission requires a very high level of international cooperation and political awareness largely because of the costs and the technological advancements needed. However, the potential prestige and impact on society for such a scenario would likely be greater than any of the other scenarios proposed.

The research and development of necessary technologies up to the mission's launch will require substantial and long-term investments. The last raw estimate of potential cost foresees a total of around USD 500 billion, or perhaps more, to put humans on Mars and return them safely to the Earth (Taylor, 2010). The financial impact on the nations involved will be very strong but the benefits will be also great in terms of national technological advancement prior to the mission, national prestige during the mission and spin-off technologies after the mission. The spin-off potential is probably greater than for the short-duration mission due to the necessity to develop ISRU capabilities.

5.2 Model Application - Scoring

Evaluating the relative performance of the four scenarios with regard to the attributes defined in Chapter 4 is referred to as scoring. Thereby, following the model development framework, the value of 10 is assigned to the scenario performing best with respect to a certain attribute, while the value 1 is given to the scenario performing worst. Values in between are mapped relative to the extreme scenarios. The results of the scoring process are shown in Table 5-1. The scores are explained in further detail.

Table 5-1: The CHARM model scoring matrix used in the current scenario analysis

Current Scenario Analysis Scoring Matrix

Categories	Attribute	Total weight	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Science & Life Science	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 Flight	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

Scoring of Science and Life Science Attributes

1) Scientific Relevance

In our model, the score (ranked from 1 to 10) for scientific relevance is chosen with respect to the scenario's capability to gather samples from widely different Martian sites. Scenario 1 scored 1, because the planned rover range of 2.5km in the iMARS mission concept (Beaty et al., 2008) is the lowest compared to all other scenarios. Therefore, the scenario's capability to collect samples from different, scientifically valuable areas is very restricted. In comparison, the maximum score of 10 is granted to Scenario 2, since so-called 'hoppers' could be used and controlled from orbit. Preliminary design analysis show possible ranges between 10-15km for a hopper (Yu et al., 2010), but these could be extended considerably using compressed Martian atmosphere (Williams et al., 2011). By landing two hoppers on different Martian sites, the mission would be able to recover samples from a wide area around the initial landing site, including descents into deep valleys. Scenario 3 scored 5 as the range of a manned mission using pressurized rovers would be approximately 50km taking two weeks of travel time into account (Drake et al., 2010). In Scenario 4, the possibility to resupply expeditions boosts the score to 8 as the sample collection range may exceed 100km (Drake et al., 2010). The drawback of this scenario is that exploration is still confined to a radial pattern centered at the landing site.

2) Quality of Data

Even using robotic probes on Mars, the decisions on which samples to collect will be taken by humans in the control center. Therefore the amount of time available to choose the sample as well as additional *in-situ* data on the sample are the decisive factors for this attribute. The scoring is performed by comparing the available time for decision-making relative to the overall mission time, including e.g. Mars-Earth signal delay.

3) Quantity of Data

Scores for the quantity of Martian samples returned to Earth have been calculated assuming the following amounts of sample material being returned to Earth:

Scenario 1: 500g (Beaty et al., 2008)

Scenario 2: 2 x 500g as there are two ground vehicles (hoppers)

Scenario 3: 60kg, the median amount of lunar material collected during Apollo missions

Scenario 4: 100kg

The amounts of sample material have been mapped to a scale ranging from one to ten, directly proportional with the amount of samples to be collected.

4) Human performance

This attribute relates to the health effects of space travel and particularly on the likely impact on crew performance. Scenario 1 rates highest since the robots are operated from Earth and therefore no astronauts are involved in the mission. Some of the most serious impacts of adaptations to long-duration spaceflight such as bone loss, cardiovascular deconditioning and muscle mass loss (Clement, 2005) are only felt on return to an environment with increased gravity. The seriousness of these effects will depend on the time available for (re)adaptation and the availability of appropriate medical care. Assuming no artificial gravity in place, Scenario 2 scores highly because adaptation only occurs once the crew returns to Earth, where appropriate medical care and support is available. This situation is largely within our present experience of long-duration spaceflight on Mir and the International Space Station. On the other hand, Scenarios 3 and 4 score poorly because the crew will land on Mars and experience partial gravity in a potentially very debilitated state where no external assistance is available. We consider the impact to be less severe in Scenario 4 because the crew will have a longer amount of time to adapt to the Martian gravity.

5) Long-term consequences of spaceflight

Once again, Scenario 1 has the highest score as no humans are exposed to the risks of spaceflight. For the other scenarios, mission duration is considered to be the most important factor and therefore the long-term mission (Scenario 4) has the lowest score. Scenarios 2 and 3 have similar durations, however the long-term consequences of Scenario 3 are considered to be more severe due to the stresses imposed by a short-duration surface stay where the crew will move quickly from microgravity to Mars gravity and back to microgravity with little time for adaptation.

6) Planetary protection

Planetary protection involves the protection against forward contamination of Mars by biological material from Earth (NASA, 2010c) and back contamination of Earth by biological material from Mars. Precautions to avoid back-contamination are expected to be similar for all of the scenarios. Prevention of forward contamination requires sterilization of any equipment that will be in direct contact with the surface of Mars or any samples gathered (NASA, 2010b). It is believed that this is intrinsically harder to do for a manned mission since the crew is effectively a source of biological contamination. Therefore, Scenario 1 has the highest score for this attribute. This is followed by Scenario 2, because contact with the surface is restricted to robots, but samples returned to the spacecraft, if not properly isolated, could come into contact with the human crew. Scenario 4 has a lower score than Scenario 3 because the larger the surface element of the mission, the more difficult it will be to maintain the required degree of sterilization.

Scoring of Technical Attributes

1) Maintainability

The maintainability attribute is mainly driven by the setup's ability to function without external intervention in terms of resupplying resources or repairing and modifying the equipment during the mission. All missions are assumed to be planned including sufficient resources. Therefore, the evaluation criterion is focused on the possibility to repair and modify equipment during the mission. Scenario 2 scored a value of 3 because astronauts would be able to perform maintenance on the orbiting ship, whereas in Scenario 1, no *in-situ* repairs can be performed. If the feasibility of mission extensions were to be measured with this attribute, a reevaluation of the scoring would be required, as the human missions would need proportionally more additional provisions compared to a single rover, which is basically able to work on solar power alone.

2) Reliability

The reliability aspect evaluates the capability of the mission scenario to achieve given objectives. The complexity of operations and equipment involved in human missions could be more prone to component failures. Human ingenuity and resourcefulness can prove to be vital when unforeseen events change on-site situations. Examples range from cleaning solar panels covered by Martian sand to unlocking rover wheels that are stuck in Martian soil. Such events pose severe problems in purely robotic missions (NASA JPL, 2011c). Consequently Scenario 1 scored poorly, whereas *in-situ* human presence is favored. The difference in scoring Scenario 3 and Scenario 4 arises from the fact, that it can take some time to elaborate possible contingencies to unforeseen mishaps, e.g., the relative impact of a manned rover being stuck for three days on the mission objectives, is dependent on the overall mission duration.

3) Level of Autonomy

The scoring for this attribute focuses on the scenario's ability to allow for on-site surface activity, e.g., sample selection and recovery without the involvement of off-site control-stations. The rover in Scenario 1 would have autonomous obstacle avoidance, but as far as sample selection is concerned, it is entirely dependent on instructions from Earth. In contrast, Scenario 4 will allow human experts to be on-site most of the time, permitting largely independent sample gathering operations. In Scenario 2, experts are close (on orbit) and can select samples in real time, but the robots would still need to be teleoperated reducing the degree of *in-situ* autonomy. Scenario 3 shares most of the benefits of Scenario 4, but the time constraints may not allow humans to be present on-site for all sample selection events.

4) Technology Readiness Level

The scoring for the technology readiness levels of the proposed scenarios were developed using results from the literature review such as Drake et al. (2009) and Beaty et al. (2008) including the current state of life support systems necessary for the different scenarios involving manned missions to Mars.

Scoring of Economic Attributes

1) End-to-End Mission Cost

The most significant cost driver is the involvement of humans, since safe return strategies for astronauts have to be implemented. A robotic Mars Sample Return mission has been estimated to cost between USD 3 and 8 billion (Beaty et al., 2008), whereas a manned surface mission has been estimated to cost in the region of USD 500 billion (Taylor, 2010). Among the manned missions, Scenario 2 is expected to have the lowest overall cost since it is not necessary to develop landers, ascent vehicles and surface infrastructure suitable for a human presence on the surface. Out of Scenarios 3 and 4, it is expected that Scenario 4 will be the most expensive due to the longer duration and larger crew.

2) Return on Investment

It is assumed that the return on investment is largely driven by the amount of new technology that needs to be developed. This increases with the technical scope of the mission. Since Scenario 1 can be considered a progression from past robotic missions, it has the lowest score. Scenarios 3 and 4 require the largest amount of new technology. Scenario 4 scores the highest because the long-duration implies more complex surface infrastructure, particularly with regard to life support.

3) Risk of Cost Overruns

As noted in Chapter 4.3.4, in the absence of a detailed mission-analysis a correlation between this attribute and the technology readiness level is introduced. For this reason the scores assigned for this attribute are the same as those for the technology readiness level attribute.

Scoring of Public Awareness Attribute

Purely robotic missions are currently operating on the surface of Mars, therefore the impact on public awareness of sending another robotic probe to Mars is assumed to be small when comparing Scenario 1 to the other scenarios since they all involve the novelty of human presence in the Martian vicinity. Scenario 4 scores highest, due to the longer mission duration and the consequent, longer media exposure. The high cost probably also fosters public involvement.

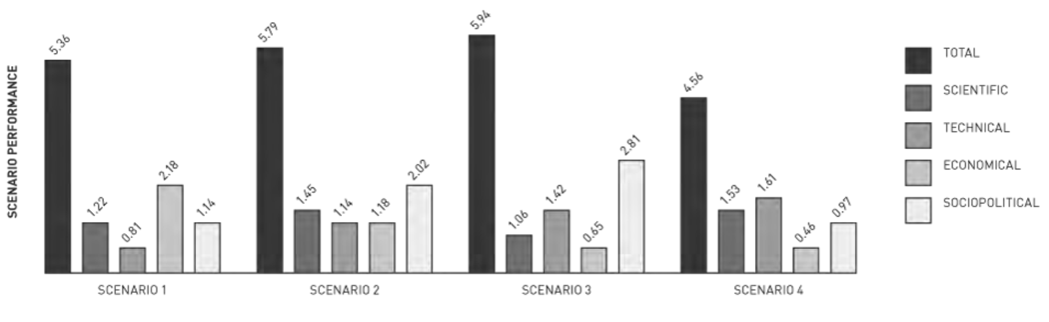
Scoring of Long-Term Political Will Attribute

This attribute is arguably the most influential and it has the highest associated weight. Despite the fact that, at least in the USA, there is no clear trend in public opinion on whether to send astronauts to Mars (CBS News, 2009), (Rasmussen Reports, 2009), a large amount of national prestige and visibility can be gained from such a venture. For the scoring, two main points were considered. First, heeding the example of Apollo 11, the political support would be largest for Scenario 3, a so-called boots-on-Mars approach. In contrast, a long-term commitment of supporting people on Mars, having even greater financial implications, might not be considered as politically enticing and therefore Scenario 4 scores lowest. The ongoing approval of funding for purely robotic missions is reflected in a score of 5 for Scenario 1. The amount of political support for Scenario 2 was estimated by comparing the public impact of the actual landing on Moon to the first lunar orbit of Apollo 8.

5.3 Model Results

Using the scoring and total weightings for each of the attributes, the Scenario Performance of each of the scenario was determined and is shown graphically in Figure 5-1.

Figure 5-1: Scenario Performance scoring including the social and political aspects

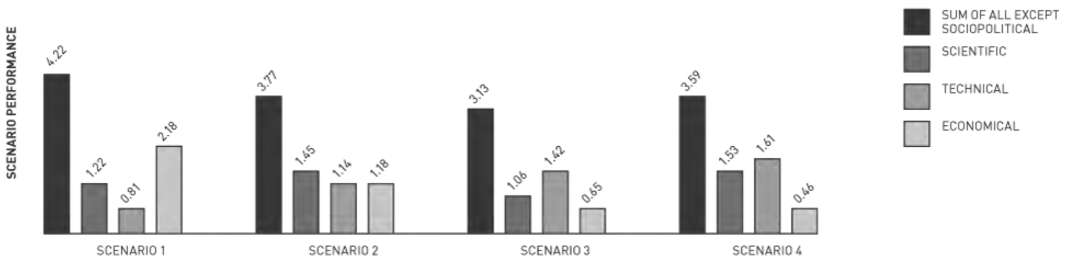


Based on the evaluation of all the attributes, the best scenario incorporating human and robotic cooperation for a Mars sample return is a short-stay mission, see Figure 5-1. A detailed analysis of human-robot interactions of this scenario can be found in the Appendix. To focus on the key impacts of the selected scenario, it has been divided into three main aspects: Scientific and

Technical, Public and Political, and Financial Impact.

The largest driving factors leading towards the selection of the short stay on Mars are the social and political attributes. A mission that puts a human on the surface of Mars would undoubtedly provoke a much more positive societal support than any other mission. Compared to the long-stay variant, political support is far more likely for a short-duration mission, as no vast financial long-term commitment to Mars is required. Interestingly enough, the short-stay human mission to Mars scenario ranks poorly in all the other categories with the exception of social and political categories. This is better illustrated in Figure 5-2 which shows how the scenarios compare if the Sociopolitical category was to be omitted.

Figure 5-2: Scenario Performance excluding the social and political attributes



As it can be seen, when the social and political attributes are excluded, the scenario featuring a short-stay of humans on Mars ranks the poorest among all the examined scenarios. Furthermore, it also shows that Scenario 1, the all robotic mission scenario, ranks the highest. This is largely due to lower cost and high technology readiness level. In addition, the differences in scientific merit from the four scenarios are relatively small. Hence, the choice of mission, in the case where the social and political category is neglected, would be primarily governed by economics. This result appears reasonable, because it shows the fully robotic scenario as being preferred if no strong political drivers are involved - a precise reflection of the current space exploration climate.

5.4 Conclusion

In this chapter, four competing mission scenarios have been generated and used as inputs to the CHARM model defined in the previous chapter. They include Scenario 1 - a fully robotic mission; Scenario 2 - a Mars orbital outpost mission with human crew in orbit and controlling rovers on the ground; Scenario 3 - a short-stay human mission on the surface of Mars and Scenario 4 - a long-stay human mission on surface of Mars. These aim to serve the same mission objective - to collect and return samples from Mars – while featuring different degrees and forms of human-robot cooperation. The scenarios have been evaluated by applying the CHARM model. As a result, the scenario ranking highest, and thus recommended by the CHARM team for a Mars sample return, is Scenario 3, a so-called "boots-on-Mars" approach. The performance of this scenario is mainly driven by the sociopolitical impact of a human presence on the surface of Mars, especially so for a short duration mission involving no political long-term commitment. Eliminating societal and political influences as the main drivers for scenario selection, the model reflects the current Mars exploration trend of sending robotic probes as the preferred method. Areas affected as a result of the selected mission scenario are addressed. Scientific and technical, public and political, and financial impacts are further investigated in the Appendix B. In the next chapter, we will conduct a sensitivity analysis investigating the dependency of the chosen scenario on various changes in attribute weightings and scorings, as a check on the robustness of the CHARM model results.

6 VALIDATION OF THE MODEL

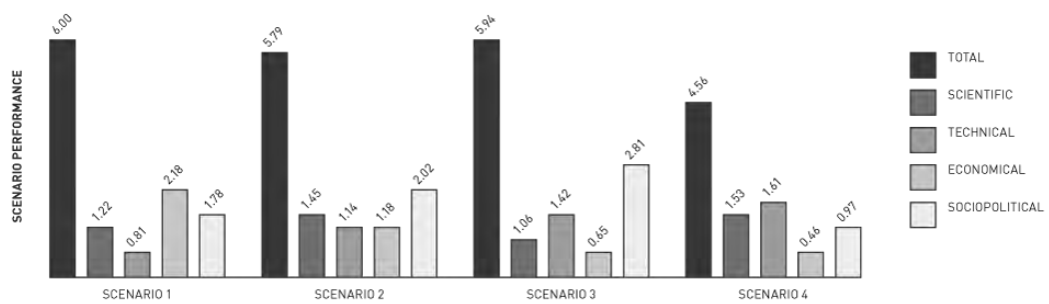
The CHARM team has developed and applied a model that determines the dominant mission scenario based on attributes related to human-robot cooperation and relative scores between scenarios. In this chapter, the stability and validity of the model is discussed. First, a sensitivity analysis investigates the dependency of the scenario selection process on variations in attribute weighting and scoring. Then, two different approaches to validating the model are discussed. Such studies are essential when selecting a scenario in practice, because they enable mission designers to have a critical view and reflect on the relevance and correctness of choices that were made.

6.1 Sensitivity Analysis

This study shows the stability of the results with variations in both the scoring and the total weighting of the attributes and considers score variations associated with future advances in technology. Of the four categories, the Social and Political category has the highest weight at 29%. Of the attributes, two significantly stand out; the Long-Term Political will with a total weighting of 21.3% and the Mission Cost at 19.2%. The third highest scored attribute is Public Awareness with a total weighting of 7.6%. Particular focus will be on these as they are most influential. The two three situations considered variations on the scoring; the last one is a study on category weighting.

As described in Chapter 5, the major contributing attribute to the scenario selection is the Long-Term Political Will. By varying the scoring of this attribute for each scenario it can be determined how dependent the preferred scenario is on the level of political support for the mission. For instance, if the level of political support for the robotic scenario was raised from 5 to 8, leaving all other attributes the same, it would result in the preferred mission being the robotic scenario, as shown in Figure 6-1.

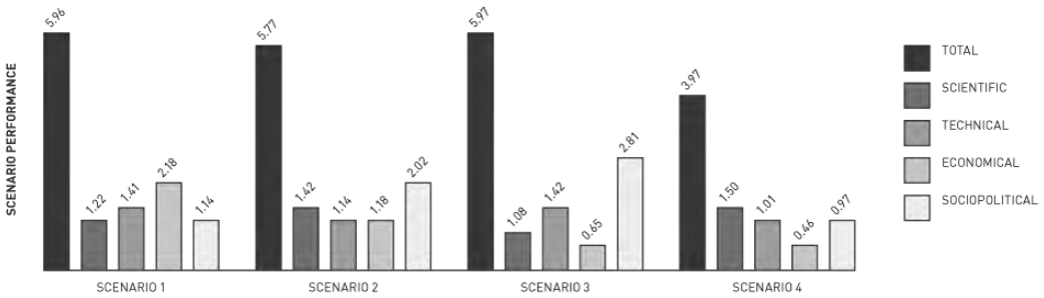
Figure 6-1: Effect of Long-Term Political Will on Scenario 1 performance



Since the scores are relative to the scenarios that are considered, it is difficult to establish what a "Long-Term Political Will" score of 8 specifically refers to. However, it helps illustrate the importance of governmental support and the impact it can have on a space project. It also illustrates how dependent the CHARM model is on certain scoring values such as Political Will. Hence, a means of accurately quantifying the attributes is critical in determining the best degree of human and robotic cooperation. For example, political will could be better quantified by determining the percentage of the public support of one scenario over another. However, the means to do this is ultimately up to the decision maker.

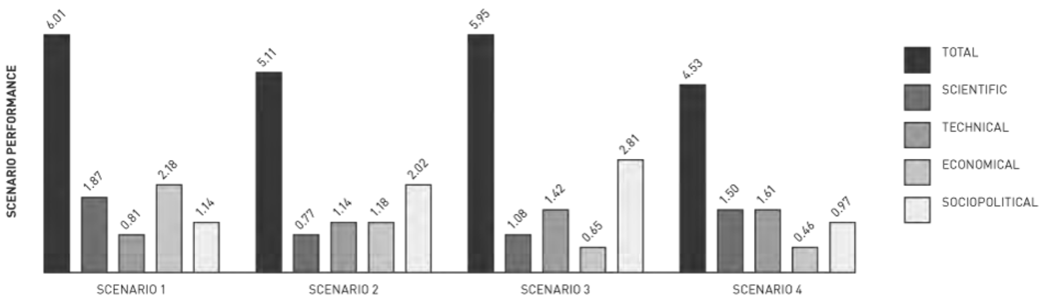
Keeping all other attributes the same, the sensitivity analysis can also be used to determine how dependent the CHARM model is on accurate knowledge of current and future technological capability. In the CHARM project, the major technical driving factor is the level of Reliability, which is dependent on the technological expectations of the present and future. This refers to the ability of the technology to perform the necessary functions established for the mission in a hostile environment and is part of the technical attributes used in the CHARM model. In the CHARM study, it was assumed that the level of reliability will be lowest for an all-robotic mission and highest for a long-duration human mission. If this case is reversed and robotic technologies advance such that robotics become extremely reliable and life-support technologies for humans do not advance in the same manner, the scoring trend would be as shown in Figure 6-2. The preferable scenario effectively becomes a tie between the robotic and the human short stay on Mars scenarios. If this is the case, a more detailed analysis is necessary to choose between these scenarios.

Figure 6-2: Effect of Reliability on scenario performance



In the Scientific & Life Sciences category, the heaviest weighting is on the Scientific Relevance attribute. If hopper robots or several robots traveling to various locations were used, a very large surface area could be explored rapidly. This would significantly increase the diversity of the samples collected, which would increase the rating of the Scientific Relevance attribute. If this were the case, the scoring would be reversed such that the robotic scenario would score the highest and the short-stay scenario would score lowest, as is presented in Figure 6-3.

Figure 6-3: Effect of Scientific Relevance on scenario performance



The case studied in Figure 6-3 shows that with advances in the range and speed of robots, the preferable scenario is the robotic mission, despite its lower scoring in the social and political categories when compared to the short-stay mission. Since the scoring of both robotic and human short stay missions are close, the decision maker(s) using the CHARM model must predict to the best of their ability how future technology will affect the scoring of the attributes.

The sensitivity of the CHARM model to changes in economics can be shown by varying the economic category weighting instead of varying the individual attribute weights. This is because it is unlikely that a significant change in technology would cause a large reduction in the cost of human missions relative to purely robotic missions. The economics category weighting could vary according to changes in federal budgets allocated to space agencies. If the category weighting of economics increases from 24% to 30%, the results will differ, as shown in Figure 6-4.

Figure 6-4: Effect of Economics category weighting on scenario performance

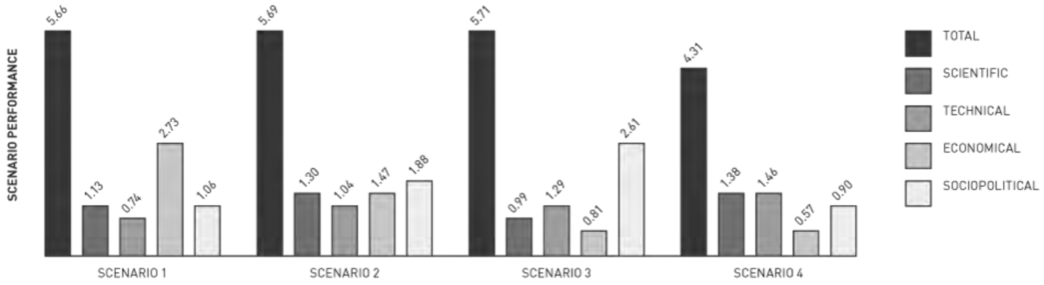


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Figure 6-4 shows that with a small increase in the weighting of the economic category, the first three scenarios rank very closely, with a slight preference in the short human stay scenario. It is thus crucial to understand the global space economy and try to predict future trends as accurately as possible.

All of the above analyses show that although the CHARM model can be a valuable tool for assisting in determining an optimal mix of human and robotics among a set of scenarios, mission designers should not use it blindly. Rather, they must keep in mind that scoring uncertainties can affect the outcome. These arise from lack of detailed mission scenario knowledge. The relevance of performing a sensitivity analysis is to understand how the output varies according to changes in the scoring of the most heavily weighted categories as well as the weighting of the attributes themselves.

As illustrated in the CHARM model, the two most influential attributes are the Long-Term Political Will and the Mission Cost. This is similar to the driving factors that govern past and present space exploration missions. When using the CHARM model, a mission designer must be able to justify the weighting and the scoring of all of the attributes. The mission designer must also keep in mind that a modification in the weighting or the scoring of the most influential attributes can affect the outcome of the preferred scenario.

6.2 Validation Considerations

The CHARM model is a rational approach that evaluates alternate scenarios with respect to attributes, and scores their performance relative to one another. The attributes are given weights to reflect their importance and the highest scoring scenario is the preferred one. The model was developed by a multidisciplinary team of 2011 ISU SSP students. The scenarios were developed through researching important exploration objectives to Mars. From the research phase of this study, the attributes were selected according to essential aspects of mission scenario design, and weighted according to their importance. Chapter 4 contains a detailed discussion of this process. The CHARM model is therefore unique and represents the team's approach to scenario selection. Scenario selection is a complex process and validating the results is not straightforward. Two approaches can be taken to strengthen the choice of preferred scenario: validation of the sub-sections within the model, and validation of the model with another model. These are discussed in the section below.

The first approach is to obtain external expert opinions on the choice of attributes, the weightings and the scorings. The attributes could be reviewed by mission design experts to ensure that they cover the essentials of scenario selection without being redundant. The attribute weightings reflect the interest of the people using the model, and therefore one would expect them to be different for different space agencies and thus not directly comparable to those presented here. However, the use of a rational weighting selection method such as the AHP gives credibility to the weightings selected in the CHARM model. The scoring of the scenarios with respect to attributes is the last element within the model that can be validated. The higher the level of detail a scenario contains, the easier it will be to score objectively. When scoring future technologies, there is an inherent uncertainty in the scores. The scoring in the CHARM model was based on available information and is justified in Chapter 5. After having studied each component of the CHARM model, to validate the outcome of the model, a different decision-making method could be used to evaluate the same scenarios. Alternate decision-making methods have been reviewed in Chapter 4.

6.3 Attribute Extremes Analysis

The model can be further analyzed to determine the robustness of the scenario selections. Using the attribute categories to imagine "extreme" futures focused around each of them, the resulting preferred scenario should, in theory, reflect the potential state of global affairs. To test this theory, the attribute weights were artificially adjusted to strongly favor each category respectively. An identical scoring scheme resulted in the following preferred scenarios in each case:

- Economic: Scenario 1
- Sociopolitical: Scenario 3
- Science and Life Science: Scenario 4
- Technology: Scenario 4

In a future where global events are focused primarily on economic factors, the CHARM model selects a preferred scenario favoring robotic explorers alone. Many events may lead to such an outcome, such as geopolitical shifts, an energy crisis, or another global banking crisis. The argument for a comparatively cheap mission is clear, human exploration of space is extremely expensive. Today's robotic missions to Mars are based on international collaboration, a fact that has put the continuation of the ESA ExoMars rover project in jeopardy. The large scale economies associated with space exploration in addition to the typically slow responses in the industry to new technologies will produce a compounded effect on the development of new exploration methods. As such, space exploration will most likely remain "business as usual" for the near and mid-term future.

Turning the focus to a future directed by social and political drivers, the preferred mission in this case would likely include a short term, manned mission to the Martian surface. Although this mission would still require significant international collaboration, the primary drivers will likely relate to matters of national prestige. It also represents the "easier" option in the "boots on Mars" case. Unlike a long-duration alternative, this scenario would be born from the lack of competition to drive innovative solutions at an accelerated pace. As a result, like the Apollo missions, the trip to Mars would be a discrete event, with no thought for future infrastructure. Equipment flown would be abandoned upon completion of the mission and, as in the 20th century, it is unlikely to lead to a future of sustainable space exploration programs.

It is unsurprising that in both the scientific and technology focused futures, both drive the model to indicate a long-term, manned surface mission to Mars as the preferred option. A future producing a global society so strongly focused on scientific objectives would need to be driven by a strong influence, for example, the confirmation of past or present life on Mars. The science will drive the technology advances necessary to provide the infrastructure for a Mars mission lasting two or three years (or more). The ultimate outcome could manifest itself in one of several ways. For example, current international cooperative agreements would likely be reinforced as existing agencies strive to achieve the objectives on the path to a manned exploration of Mars. Additionally, states currently operating independently and uninterested in cooperative efforts (or manned spaceflight) would still provide the competitive basis to drive the acceleration in technology development.

The CHARM model in each of the attribute categories above suggests viable future scenarios in all four cases. This is the result that would be expected based on past and current sociopolitical, economic, technological and scientific events in the space sector. The result is, the model appears robust in the attributes which drive it and presents a strong basis for use in future mission design tasks.

6.4 Conclusion

As seen in this chapter, variations in weighting and scoring can have a significant influence on the outcome of the model, especially with the most heavily weighted attributes, which are Long-Term Political Will and Mission Cost. Although the attributes were chosen and weighted using rational approaches, they were applied to scenarios to be executed in the near future, and therefore there is an associated amount of uncertainty involved. The outcome of the model should not be used blindly. Rather, it is intended to be seen as a learning process for better understanding all of the individual decisions to be made when selecting a scenario.

Furthermore, two approaches were presented which could be used to confirm the specific scenario selected by applying the CHARM model. These include revising the attributes, weightings and scorings of the model with other mission designers, and following an alternative decision-making process for validation. Although interesting, these methods were not explored further because they exceed the scope of the CHARM project.

When using a trade-off method, it is advisable to analyze the scoring and generate a new scenario from the attributes that scored best. Variations on this new scenario can incorporate new ideas that originated through the first iteration. The best scenario from the first iteration can be used as a baseline and a second iteration can compare the performance of the newly generated scenario and the new ideas. Using this convergence-divergence method, a very efficient scenario can be reached within several iterations. This next step in mission design would be more relevant for complex scenarios than for those considered by the CHARM model.

7 CONCLUSIONS

CHARM's primary objective was to propose a model for effective human-robot cooperation and apply it to Mars exploration scenarios for the time-frame between 2015 and 2035. To do so, the team studied past, present, and future Mars exploration missions, extracted the objectives, and built a database of mission information. From this, an objective was chosen for further investigation in this study. Human-robot cooperation was investigated to determine different ways one would go about accomplishing the objective. Four scenarios were developed, each containing different levels of human-robot interaction. A variety of mission development and mission ranking and selection models were reviewed in order to propose the CHARM model. Attributes pertaining to the development of this model were analyzed. These were then grouped into categories and weighted according to their importance. The scenarios were scored and a proposed scenario was presented. Using the model, an analysis of extreme futures was performed. A sensitivity analysis was conducted on the results and the validity of the model was discussed. The selected scenario was then analyzed in detail according to the following: technical, societal, political, financial, mission risk and futures studies.

To date, Mars exploration has focused on understanding the basic physical properties of the planet, investigating the possibility of past or present life and the preliminary steps required for future human exploration. Landers, rovers and orbiters have mapped, explored, and examined the Martian system. More importantly, they have paved the way for future human missions by conveying important information and insight into the technical infrastructure necessary to achieve this. Through the planning of hypothetical missions of human exploration of Mars, it has become clear that the costs, dangers, and challenges may be too great for any one nation to undertake alone. The migration towards a global space framework is the key to achieving successful human exploration of Mars. The need for international, intercultural, and interdisciplinary approaches to space exploration is of importance. Based on the sociopolitical, governmental, and financial considerations, the CHARM team believes that a human mission to Mars is achievable.

Challenges involved with long-duration space missions to Mars invoke the need to develop sophisticated robotic systems to reduce the risk to human life and commonalities in these systems to reduce development costs. The hazards to humans on a mission are extensive and often difficult to overcome. However, current robotic technologies do not allow for the same range of creative tasks that a human can perform. Simple cognitive tasks involving critical thinking such as selecting an optimum sample to collect, or reacting in an unplanned situation is not yet practical by robotic means. There are certain tasks that are particularly dangerous or repetitive that may be better performed by an autonomous or remotely controlled robot. Therefore, the optimal mix of human and robotic cooperation for a manned Mars mission is found in the complimentary tasks robots are capable of performing to aid human coworkers.

The key output of this project is the CHARM model for human-robot cooperation. This model combines a number of established methods for rational decision-making to aid mission designers in making objective comparisons between scenarios with differing degrees of human-robot cooperation. Fundamental to the effectiveness of the model is the identification of an appropriate set of attributes by which each scenario may be evaluated. The CHARM team proposes a set of 15 such attributes which were developed following a thorough interdisciplinary literature review and which draw on the varied experiences and expertise of team members. By following a formal and objective Analytical Hierarchy Process to set the weightings assigned to each attribute, a client organization is able to customize the model to reflect the priorities and realities it faces. An important strength of the model is its broad scope which captures the scientific, technical, economic and sociopolitical influences on the decision-making process.

The CHARM model covers a broad scope of attributes as previously mentioned. Four competing mission scenarios have been developed for the time frame between 2015 and 2035 and serve as input for the CHARM model. These are (1) a fully robotic mission; (2) a Mars orbital outpost mission with the human crew staying in orbit and controlling rovers on the ground; (3) a short-stay manned mission on the surface of Mars; and (4) a long-stay manned mission on surface of Mars. All these scenarios aim at collecting and returning soil samples from Mars. Many aspects of a long-duration human Mars mission are still unknown. There are still milestones in technology that need to be reached to complete a successful human mission to Mars. Some very important topics that need to be addressed when considering human spaceflight are the physiological and psychological effects from long-duration flight, the development of life support systems, and effective countermeasures. Each scenario is scored relative to the others. A justification of the scoring is a rational approach to the application of the model.

The scenario ranking highest, and thus recommended by the CHARM team, is the so-called "boots-on-Mars" approach. Its performance is mainly driven by the sociopolitical impact of a human presence on the surface of Mars, especially so for a short duration mission, that does not involve long-term political commitment. Eliminating the influence of societal and political influences as the main driver for scenario selection, the model reproduces current Mars exploration policy via robotic probes as the preferred method. The results of the model were analyzed considering economically, sociopolitically, scientifically, and technically driven extreme futures. This analysis highlighted different scenarios as being preferable depending on the future considered: an unmanned robotic mission for the economic-centered future, a long-stay scenario for the scientific and technology-centered future, and the short-duration mission considering a highly politically dominated future.

Variations in the weighting and scoring can have a significant influence on the outcome of the model, especially with the most heavily weighted attributes (Long-Term Political Will and Mission Cost). Although the attributes were chosen and weighted using rational approaches, they were applied to scenarios to be executed in the near future, and therefore there is an associated amount of uncertainty involved. The outcome of the model should not be used blindly. Rather, it is intended to be seen as a learning process for better understanding all of the individual decisions to be made when selecting a scenario. Furthermore, two approaches were discussed which could be used to confirm the specific scenario selected by applying the CHARM model. These include revising the attributes, weights, and scoring of the model with other mission designers, as well as following an alternative decision-making process.

Other than the development of the scenario model to establish the optimal level of human-robot cooperation on a Mars mission, the CHARM team also conducted a literature review pertaining to the development of this model. Critical gaps in the research were identified throughout the research process. Suggestions are made by the CHARM team on how to address the gaps in the research and answer the questions that need to be addressed to successfully complete a human mission to Mars with robotic cooperation. It is clear in the context of the research carried out that it is not feasible for a single nation to attempt to carry out a mission to Mars. From a technological and financial perspective it makes more sense for nations to collaborate for a successful mission to Mars. This suggestion has already been made by many research projects before CHARM such as MAP (2010) but it is the purpose of this report to reiterate the importance of international cooperation. The political drive that enabled the Apollo program is non-existent today so cooperation between nations is essential if a Mars mission is to succeed between 2015 and 2035. CHARM proposes that our model incorporates all of the key attributes that will lead to a mission involving an international collaboration of technology and research. This is reflected in the interdisciplinary attributes and the weighting associated to them. It is also important to consider other aspects of research that need to be addressed before a mission can be selected. To successfully complete a human mission to Mars, it is essential that a sustainable life support system be established. This could mean the development of a bio-regenerative life support system. Also required is research into effective countermeasures, which may include the development of more efficient countermeasures.

To conclude, the CHARM team has proposed a feasible model for selecting a successful scenario for space exploration, and applied it to a selected Mars exploration objective. The robustness and reliability of the model has been tested to show that the model performs well under a various range of inputs. 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.

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8 APPENDIX - FURTHER ANALYSIS OF PROPOSED MISSION

In this Appendix, the CHARM team examines some of the problems which arise due to the selected mission scenario and proposes methods to resolve or avoid them.

8.1 Scientific and Technical

8.1.1 Preparing for Mars

To prevent diseases, mental disorders, and other problems that can jeopardize the mission, an Astronaut Selection Board will be established. The goal of this board will be to select four healthy and highly qualified individuals as crew for the mission. These astronauts will be from different disciplines in the fields of engineering, life sciences, physical sciences, and mathematics; they will also be evaluated based on their education, training, and experience as well as unique qualifications and skills for astronaut training (NASA, 2003). A primary goal of the selection will be to ensure high levels of physical and mental health throughout the astronaut training, the mission preparation processes, and for the duration of the mission. The CHARM Team will analyze crew preparation for such long-duration human spaceflight focusing on the aspects of human-robot interaction that can be used during this stage of the mission.

Operational Training

Pre-flight ground and LEO training of astronauts with the robotic systems that they will use during the mission is crucial for the overall success of the mission. The long-duration nature of the mission requires that crew members dedicate a significant proportion of their careers to this human-robot cooperation training.

The training for a human mission to Mars requires improving mission operation simulations incorporating humans and robots on Earth. These training areas should include: teleoperation of rovers to simulate operation from orbit and surface exploration techniques to maximize the human-robot partnership on the surface.

The first astronaut-rover interaction was studied in 1999 at Silver Lake in California's Mojave Desert (Cabrol, 2007). The experiment included a rover, a support rover team, an EVA suited test subject, and an EVA support team. The goal of the experiment was to simulate operational procedures using different kinds of human-robot cooperation. In one test, the rover was a scout, sent to pre-examine an un-known area. In a second test, the rover was used as a video coverage assistant to assist the human. A third test used a rover as the human's field science assistant.

This research showed that rovers can be used as human assistants, independent scouts, and collaborators by using high levels of autonomy. The different levels of human-robot cooperation modes mentioned above required specific training, including situational awareness of the crew and robot during different surface activities.

Another useful training tool is the use of Virtual Reality (VR) (McGhan et al., 2007) to help simulate mission operations between humans and robots, whether that be on the surface or through teleoperation. In fact, VR programs can log each user's response times and choices, enabling assessment of overall performance.

In addition, the astronaut can interact with an active simulation that changes in real time according to the input. The VR can be used for flight simulation, for preparing the crew for the worst-case scenarios and for adapting the training to individual needs. For example, VR was used for the training of astronauts for the Hubble servicing missions in 1994.

VR can also simulate operational conditions on the Martian surface. The VR system includes mission scenarios that allow the user to visualize and operate in complex large scale simulations for the Martian surface human – robot exploration activities. The VR simulators will be able to reproduce Martian environment, including gravity, geology, and weather in the future.

A very important part of the preparations include actual ground base Earth simulations similar to NASA's D-RATS field testing, conducted in the Arizona desert (NASA, 2011e). NASA's D-RATS experiments aim to evaluate several aspects for the future human exploration missions, including Mars' moons and surface.

At NASA's D-RATS, it is possible to simulate mission elements including geology exploration and operational activities in combination with rovers, habitats and other elements of Martian exploration architecture. For example, astronauts can perform specific tasks to determine different levels of robotic automation.

Because there is a limited number of crew, the long-duration mission training should include a high level of cross-training, due to the limited number of crew, so that the mission failure is minimized in the event a crew member becomes incapacitated.

8.1.2 Transit Flight to Mars

The next phase of the mission is the flight from Earth to Mars. From the human-robot interaction point of view, the mission can be divided in several phases: rendezvous and docking, the transit flight to Mars, and the return flight.

Rendezvous and Docking

Rendezvous and docking are undertaken both for the cargo mission and for the human flight. This process should be completed autonomously for the payload and both transit vehicles and with a human assistance approach for the crew capsule. For the manned rendezvous and docking the crew would monitor the processes, using spacecraft video screens. The crew can interrupt the spacecraft approach in case of a failure scenario (ESA, 2011e).

NASA has performed several rendezvous and docking missions that have been piloted by astronauts who have been aided by cameras to determine the spacecraft's attitude (NASA, 2006). The active cooperation module performs the complete process through three main stages: signal processing, pattern recognition, and active trajectory generation. All of the orbital robotics display various human-robot types of cooperation, differing in the amount of automation, and robotic involvement.

8.1.3 In-flight Operations

Due to the great diversity of robotic and autonomous systems that might be used in this phase of the mission, the analysis of the human-robot interaction during the trip from Earth's LEO to Mars' orbit is separated into several categories according to the type of work to be done. These categories are: EVAs, function support, health risks, and countermeasures.

EVA - In case of spacecraft subsystem failure in flight phase, an EVA might be required to repair or exchange the damaged part. To overcome health risks related to human EVA in deep space, a dexterous robot will be a part of the crew. The present dexterous robot aboard the ISS is Robonaut 2 (NASA, 2011c), which is currently programmed to work inside a spacecraft. Future upgrades of this system will provide us with a robot capable of sustaining work in an extravehicular environment. These human-robot cooperative tasks will provide a useful work terrain and give astronauts an invaluable help for these difficult and dangerous spacewalks. This interaction would include both robotic automation concepts, as well as teleoperation methods. Another type of robotic machine, called the Autonomous Walking Inspection and Maintenance Robot (NASA JPL, 2011b), is a robot that can be used for the adjustment and repair of solar panels. The robot is a good solution for the maintenance of more fragile spacecraft components thanks to its ability to distribute the weight force on a larger panel-surface.

Function Support - On the long journey to Mars, some routine work will occupy a large amount of the crew members' time. The same dexterous robot prepared to perform EVA, can help the crew with their duties such as bio-experiments or data monitoring.

Health Risks - Another aspect to consider while analyzing the application of robotics during long-duration spaceflight is its use in health risks countermeasures of bone and muscle loss. Exoskeleton systems can be designed so as to provide resistance to astronaut's in-flight movements (Bar-Cohen and Breazean 2003). This application provides a greater usage of muscles and, thus, a more efficient physical training to maintain as much as possible the natural muscle tone and mass. As the human moves, the robot-suit exerts resistance to the movements, aiding the human in their physical training.

In addition, surgical robots should be included to help the astronauts with repetitive high precision medical tasks in the emergency situations. For deep space missions, a mixture of teleoperation, telementoring and telemedicine consultancy is advised (Haidegger and Benyo, 2008).

8.1.4 Operations on Mars

Proposed Architecture for the Exploration of the Martian Surface

Two crew members will land on the Martian Surface with a lander/ascent stage which will serve as a backup surface habitat. The astronauts will use a small pressurized rover, a main habitat, and transportation vehicle.

The CHARM team proposes two different exploration areas for the mission (Figure 8-1). The first one, close to the landing site, can be explored by unpressurized rovers. The second area is explored by two crew members in a pressurized rover to improve the efficiency of mobility and the size of the explored area. The robotic exploration area is studied using unpressurized rovers, controlled remotely by the crew in orbit. The mission management foresees the possibility of cooperation between the unpressurized rover and the crew members on the surface, when they are not performing excursions with the pressurized rover.

The mission is contingent upon successful landing and deployment of cargo on the Martian surface before crew arrival. This cargo lander is used to store consumables and fuel for the pressurized rover. In addition, an *in-situ* fuel generation system will produce the fuel for the surface activities and ascent vehicle and oxygen for the crew. Due to the unproven nature of ISRU, a backup consumables reserve for a short–stay will be sent to the surface.

Figure 8-1: Mars rover operations

Human and Robots Cooperative Exploration

Exploration around the landing site can be carried out through the cooperation between astronauts and two unpressurized rovers. These rovers can be a version of NASA´s humanoid robot, Robonaut, attached to a chassis similar to NASA's Centaur that can carry tools, take pictures and videos or collect samples. On Mars, humans in a spacesuit have limited mobility, dexterity, field of view, tactile sensitivity, and range of motion to accomplish the required tasks. The exposure to a different gravity field can also make physical performance more difficult for the astronauts. Additionally, the astronauts will experience bone loss and muscle atrophy during more than six months of flight. To remedy this problem it is necessary to carry out a process of re-adaptation that can be performed with exoskeletons. This technology could facilitate the process of lifting heavy loads and could also be used to increase the loads the astronauts have to lift on Mars. The astronaut can use a teleoperated robot to perform tasks which would be too difficult to accomplish due to the thickness and low flexibility of the spacesuit. In this case, the gestures performed by the robot would be similar to the gestures an astronaut is able to perform without the constraints of a spacesuit. This offers a large range of very precise movements allowing the carrying out of the most difficult tasks (Burridge et al., 2009). An additional benefit of this method is that the robot does not require the pressurized environment an astronaut requires. These robots will be able to collect samples in the thin Martian atmosphere. This permits an optimal analysis of these samples (Neal, 2000).

One demonstration of human and robot cooperation is the EVA Robotic Assistant (ERA) project developed jointly between NASA and academia (Burridge et al., 2009). The ERA is equipped with different kinds of sensors that can be used to track and follow the human subject such as stereo cameras, laser rangefinders, or differential GPS. The laser provides the human's relative position to the robot in such a way that it can maintain the desired distance from the human. The human tracking data is also used to generate a map of the explored area that can be used to calculate the current distance between the astronaut and the habitat. Furthermore, robots can help astronauts to carry out his experiments, optimizing the very restricted time available during their EVA. The robots can find paths to explore the planetary surface, tracking, mapping, and deploy science instruments.

These robots, working at different automation levels, will collect samples in an area near the landing site and will select them, with the help of astronauts, to cover the different geological units around the Jezero crater. Before the crew landing, the unpressurized rovers can be controlled from Earth to start the exploration of the area close to the human landing site to guarantee a safe landing of the crew and to deploy the payload, such as the ISRU module and communication system. In particular, the rovers could be used to deploy the ground based array of receiver and GPS pseudolites to guarantee centimeter-level localization (LeMaster and Rock, 2001). During the stay on Mars, the astronauts can use robots in manual mode to collect samples in areas difficult to access or perform tasks requiring a high precision. While astronauts on the surface are at rest, the robots can operate in semi-automatic mode or be operated from orbit by the crew members in the Mars orbiter since the round trip communications delay between a Mars geostationary orbit and the surface is only about one-eighth of a second (Podnar et al., 2007). During this semi-automated study phase, the robots will have access to well-known land areas to limit mission risks.

These robots can also help astronauts in the assembly and maintenance of tools needed in their experiments. For example, the deep drill system is rather complex and requires a large dexterity to be able to put in place in good conditions (Lin et al., 2008). A robot similar to Robonaut will be a very useful helper to carry out these tasks. Once the science units are set up, the robots can intervene if problems arise. Preventing contamination of the sample is paramount to mission success. Once the deep drilling ends, the robots must be able to collect samples and place them under vacuum for further analysis. Concerning the deep drill system, it could be interesting to apply it on the depositional fans to study the variation of the composition of the soils upstream the Jezero crater.

A pressurized rover will explore the area far from the landing site. The farthest distance of exploration is estimated at 50 km, so that in case of malfunctions it would be possible to bring the crew back to the habitat in 8 hours (maximum time for the current space suit). To this end, a mobility chassis is included in the mission equipment.

The pressurized rover offers the possibility of 14-day sortie durations for the astronauts, taking advantage of the unique human perception, judgment and dexterity. The ability to rapidly ingress and egress from the pressurized rover allows the astronauts to dynamically choose the most effective work environment for performing a given task. The use of the pressurized rover offers the possibility to perform laboratory analysis with equipment on-site. This allows reduction in return mass because only the highest value samples are transported back to the base. The pressurized rover offers different advantages regarding the life support system. The first advantage is radiation protection when significant solar particle events (SPEs) occur. The pressurized rover is able to bring the crew back autonomously in the case of an extended SPE (NASA, 2010d). In addition, the pressurized rover provides medical capabilities based on the duration of the expedition and the distance. The rover offers the possibility to perform physical exercises during the travel from site to site. It also reduces the astronaut's decompression stress as it allows a quick switch from a short sleeve to a space suit environment (Johnson et al., 2010).

Sample Pre-analysis on the Surface of Mars

From a scientific point of view, it is necessary to identify the appropriate samples to be collected *in-situ* for further analysis. Cooperation between humans and robots could be a possible solution not only for choosing proper samples but for ensuring the quality of the data that will be extracted. Sample manipulation, *in-situ* pre-analysis and sample transportation will be carried out according to certain standard procedures such as sample containment or sample contamination avoidance (DeVincenzi et al., 1998). These precautions are needed to ensure the quality of data. A possible approach to analyzing the interaction between humans and robots could be achieved through a two-stage task. First, the two crew members observe and identify potential adequate samples followed by robotic sample verification. This verification varies depending on the scientific objectives of the mission. An example, according to (Mahaffy, 2008) can be to "search for organic compounds, chemical state of light elements or isotropic tracers of planetary change".

Other aspects of human-robot cooperation emerge when the samples are transported from the extraction point to the Mars Ascent Vehicle. During the journey, the human-robot crew may have to avoid geological obstacles on the surface of Mars. In that case, human and robot capabilities can be synergized to overcome such problems.

8.1.5 Back to Earth

Once on Earth, the conditions do not require the same degree of cooperation between humans and robots as they required in the hostile environment of space. However, there are still some tasks that can be performed with the help of robots. Essentially, these tasks include the re-adaptation to gravity and the treatment of the samples returned from Mars to avoid contamination.

Analysis of samples back on Earth

To prevent contamination of samples coming from Mars, a very careful process must be followed. Otherwise, the inappropriate preservation of samples could, for instance, produce a false positive response when searching for traces of life on the Martian samples. Apart from the protection of the samples from Earth's environment, some measures have to be taken to prevent back-contamination, which refers to the contamination of Earth that could occur if surviving organisms from Mars started to spread on Earth (Neal, 2000). To achieve these isolation requirements, it is possible to cooperate with robots that are able to manipulate these samples following the orders given by humans. The robots will also relieve humans from repetitive tasks.

The required process for the analysis depends on the type of samples that are being examined and on the experiment's hypothesis. However, the benefits of using robot assistance are present in all the analysis. The first step is to provide a complete isolation of the sample, so that the working environment is safe. It allows working in a sealed container that prevents contamination in both directions. Robot manipulation will also provide more accuracy, ease of repeatability and efficiency. Some standard analysis can be automated; in the case of Mars samples it would be necessary to define the objectives of the analysis to perform it in the most efficient way.

Nevertheless, there are also some disadvantages that include the difficulties of automating some steps. When automation is not possible, the alternative is teleoperation of robots. The movements of a human have to be translated to signals that can be interpreted by the robot, so there has to be a mathematical process in between. If this is the case, it is of crucial importance to convert efficiently human movements into robot movements taking into account the difference between the capabilities of movement of humans and robots. There has to be also a precise monitoring of all the variables affecting the sample to prevent some possible damage on it. For instance, it is necessary to have control over the force applied over the sample to make sure its integrity is preserved. The monitoring system has to make use of haptics (technology related to the sense of touch) so that astronauts have real-time feedback about the force applied to the sample (Osinski et al., 2011).

In conclusion, the capabilities of teleoperated robots are useful for all the phases and requirements related to analysis and for the collecting of samples on Mars, the preservation of them during the flight and its treatment once on Earth.

An innovative solution for re-adaptation to Earth: Exoskeletons

Many physiological problems arise when a long-term exposure to microgravity characterizes the mission. Decrease in bone mineral density, disuse muscle atrophy or desensitization of the vestibular system to tilt signals are examples of the problems that our four crew members will face when landing on Mars or when landing back on Earth (Hecht et al., 2002). During the phase of re-adaptation to Earth's gravitational conditions, the cooperation between humans and robots can be relevant. In particular, it is possible to use exoskeletons to contribute to the force an astronaut has to possess to keep the upright standing position.

An exoskeleton is basically an external skeleton that can support and protect the body. The principle of this equipment is to capture the low bioelectric signals the brain sends to the muscles to make them move. These signals are read through sensors attached in the user's skin and are called intention signals (Cyberdyne, 2011). These signals are analyzed and interpreted to induce movement in the exoskeleton. Stimulating these connections, it allows the user to work more efficiently and thus progress faster during its re-adaptation. It is also possible to operate the exoskeletons based on orders saved and programmed in its memory.

Until the present days, the main applications of exoskeletons have been focused on military and defense purposes. New applications are appearing related to medical and industrial purposes, mainly for treatments for paraplegic people. This application could also include the treatment of astronauts due to the similarity of the symptoms. One of the exoskeletons that has already been built and tested is the Berkeley Lower Extremity Exoskeleton designed by the Defense Advanced Research Projects Agency (DARPA) (Kazerooni et al., 2006). Its main purpose is to help the workers carry heavy loads and give protection to soldiers.

8.2 Public and Political

8.2.1 *Societal impact through Social Media*

A way to increase public awareness and support is through the use of social media. Twitter is one of the many avenues being used. Updates and interactions with crews and robots will also increase public awareness. There are already three NASA robots with Twitter feeds. Robonaut2 (@AstroRobonaut) has 50,000 followers, Mars Phoenix Rover (@MarsPhoenix) has 150,000, and MER rovers Spirit and Opportunity (@MarsRovers) with 140,000 as of August 2011. Any robot used by the CHARM team, should have a Twitter feed to complement astronaut Twitter feeds for informing and interacting with the public. This method could also be used to demonstrate cooperation between astronauts and robots if they ‘talk’ to each other through social media.

8.2.2 *Political support increases mission stability*

A successful Mars mission not only needs public support but also requires political support. International cooperation is a valuable asset to nations; as it boosts its political sustainability. Within the United States, a program reduces its risk of cancellation if international agreements are present. For example, the US Congress only approved the ISS by one vote the year before Russia joined the partnership (Broniatowski et al., 2006). The political will to support a Mars mission could be increased or decreased based on the desire of a particular country to cooperate on an international level. Because many countries and agencies are involved, no one country can decide to stop the project. The CHARM team proposes a collaborative program to create a stable and cost effective method of sharing commitments and expenditures.

8.2.3 *Public-Private Partnerships*

Not only can countries and agencies collaborate, but there is an opportunity for the private sector to enter partnerships and collaborations. In addition to governmental funding of space agencies, the private sector could be a solution for additional support. A successful example of this is the relationship between NASA and General Motors for the development of Robonaut 1 and Robonaut 2.

8.2.4 *Societal impact of crew training*

Effective astronaut training takes into account all technical and scientific aspects of the mission. But these aspects are not separated from the societal and political implications. In order for the mission to have a social influence, we will need to promote all of the mission activities, including training activities of the astronauts. One way NASA is currently engaging the public is through the “Participatory Exploration” program. Participatory exploration is simply involving the public directly in NASA's mission, and it is being applied to many programs across the spectrum (NASA, 2010). Even crew training can be an interesting aspect of the mission to share with the public. For example, the public can participate in the training through interactive astronaut presentations (similar to NASA Speaker's Bureau), or students can suggest experiments to be performed on analog missions. For our mission we suggest that all space visitor centers from participating countries build interactive, low-fidelity robots, similar to the ones used in our mission, where visitors and children can operate. This could increase public awareness through active participation.

8.2.5 Human-robot cooperation for launch

Launching stage is a quite short period of time and compared with other stages of the mission, it is a much more routine assignment. Launching from Earth is usually teleoperated by the ground station and much of the procedure is automatic and predesigned onboard via the computer control systems. In other words, the human-robot cooperation consists of humans contributing via ground control while the onboard control is robotics.

Launching from Mars should be more automated; considering the latency from the ground station command, humans should play an important role to configure the system and make the decision under conditions which require intelligence. It means that human does the important tasks and robot focuses on the pre-programmed jobs. This kind of distribution can take advantage of both humans and robots in a mission. The launch, one of the most exciting moments of any mission, should be enjoyed by all via live broadcasts in all participating countries. Considering the large number of viewers of the launch phase for most missions, it is an incredible opportunity to educate, advertise, and showcase the cooperation of humanity.

8.2.6 Human-robot cooperation during Flight to and from Mars

The more positive sociopolitical response favors a human-centered approach during the voyage to and from Mars. However, since a long-duration human spaceflight to another planet has never occurred, two relevant examples of a similar experience from the past missions can be examined instead: the Apollo missions and the effect on crew onboard the ISS.

Furthermore, a key aspect that should be explored is the cultural differences which will impact the human-robot interaction as well as the sociopolitical perception. Certain interfaces such as instruction and operational languages should be established. In addition, public's reaction should be considered regarding if it is required to comply with interface standards of another nation. For example, how will the politicians react if an American astronaut needs to works with a Chinese robot while the two nations are prohibited from collaboration with one another? The sociopolitical impact is hard to determine, but it needs to be considered during interplanetary travel due to the conflict that may arise as a result of such issues.

Moreover, the specific details of the human-robot interaction in flight conveyed to the general public would be controlled by the media, who most likely would only report on controversial issues. The amount of media exposure would then affect the public and political perception. Since the voyage to and from Mars requires long periods of isolation and confinement, humans could start to develop communication relationships with different robot interfaces. The reaction of how society will react to the idea of humans having conversations with machines is an issue that should be considered in the human-robot interaction design.

8.2.7 Human-robot cooperation for Landing on Mars and Earth

An important consideration for the sociopolitical reaction of the human-robot cooperation during EDL on Mars and Earth is the level of automation needed for crew survival. The prolonged periods of microgravity experienced by the astronauts severely limits their capabilities once they are introduced back into high gravitational forces. Therefore, the level of automation of the EDL systems requires high redundancy and comprehensive levels of automation; this is because the sociopolitical community would otherwise not react well to any mission related accidents.

8.2.8 Human-robot cooperation for Operations on Mars: Sample return

From a societal perspective, the general public relates to astronauts more than to their robotic counterparts. This is mainly because astronauts are ambassadors of people's dreams of space exploration and travel. For this reason, significant discoveries should be associated with human involvement, rather than robotic operations. The effect that a sample return Mars mission has on education is evident from past space exploration. Examples of this include the unprecedented USA spending on education and research during the space race in the twentieth century. It is also predicted that an increase in science fiction, literature, and films would accompany Mars exploration accomplishments. This assumption is based upon a similar increase that happened during the space race to the Moon. For this reason, it is preferable to have an effective level of human-robot cooperation to perform decision-making tasks throughout the exploration phase of the surface of Mars mission. Thus, human intuition and intelligence is used and supported with robotic capabilities. It is important to distinguish between the human ability for decision-making and the robotic capabilities for mundane or dangerous tasks when considering effective human-robot cooperation. Problems arising preventing smooth mission operation could cause society to cease to support future space missions.

From a political viewpoint, human exploration of the surface of Mars would be accompanied with significant national prestige, since it would be the first human mission to another planet. The large scope of the mission means that several nations will be collaborating. Politicians would be interested in a human Mars exploration mission, rather than robotic exploration, happening during their time in office, because of the association of historical contribution to space exploration. Because of international aspect of the project, there is a level of political risk involved. In the event of an unsuccessful mission, popularity and support could drop. This type of political risk is something that would be taken in to account when a nation is considering supporting a mission. Another risk associated with national collaboration is the possible breakdown of political relationships. Potential conflicts between nations could arise from possible mission schedule adjustments or discrepancies between mission objectives.

8.3 Financial Impact

This financial impact analysis studies the effects the chosen scenario has on the economy. The section presents the macroeconomic impact of the mission on the national budget considering effects such as public funding requirements, spin-off technologies and other indirect benefits. The mission cost implications are then presented, where cost estimation for a Human Mars landing mission is given for the participating nations.

8.3.1 Macroeconomic Impact

The described and selected short duration mission to Mars requires a high degree of development in robotics and human-robot cooperation and interaction. Several macroeconomic factors have to be secured. A long-term massive increase in space budget of the participating nations has to be guaranteed, together with the political will to spend the majority of that space budget on an international Mars mission. This section analyzes the mission impact from a purely financial point of view.

According to (Taylor, 2010), the cost of a long-duration mission to Mars in an international frame can cost up to half a trillion USD, or even more. This estimation is going to be assumed as an initial estimation for the selected short duration mission that takes into account the possible drawbacks and cost overruns, keeping in mind that it may have a lower cost compared to the long-duration mission proposed in (Taylor, 2010).

The short duration mission selected is proposed to be launched in 2028 and the mission would end with the astronauts' safe return on Earth in 2031. Assuming that the political decision of supporting the mission is secured in 2012, the first budget allocation for the Mars mission would start in 2013. The mission economic support, then, would have to be extended during 18 years until the end of the mission, with an average yearly investment of USD 27.78 billion. Two possible approaches to finance such a mission appear: national enterprise of a space leading nation (e.g. USA) or an international approach (e.g. ISS-like organization). By performing a deeper analysis on the macroeconomic implications of the mission, the stand alone national approach reveals to be far from the current national economic possibilities.

The USA civil space budget accounted for almost one half of the worldwide civil space spending in 2010 (Walter-Range et al., 2011). Thus, if a national approach to a mission to Mars is to be done, the USA may be the most probable nation to do it. In 2010, the NASA budget was USD 18.78 billion (Walter-Range et al., 2011). Assuming that the required yearly investment is added to the current budget (no budget relocation is done), that total NASA yearly budget would have to increase by USD 27.78 billion, an increase of a 148.4% with respect to the 2010 budget. The 2010 NASA budget represents a 0.131% of the 2009 USA GDP at current prices. The budget increase would represent a 0.196% of the 2009 USA GDP at current prices. The new NASA budget would require, then, a 0.328% of the 2009 USA GDP. NASA's budget has not been over the 0.3% of the GDP since the 1960s with the Apollo Program during the Space Race (when a peak of 0.8% was reached) (Augustine et al., 2009). According to the presented values and considering the stabilized tendency in percentage of the GDP invested in civil space budget, it is reasonable to assume that the selected short duration mission would have to be an international enterprise.

A Mars exploration mission would need a huge investment, so it would be better to have international cooperation. The ISS is a good example of a multi-national cooperation in space activity. The main parties to invest in the ISS are Russia, the United States, the European Union, Japan, and Canada. The percentage of investment is USA - 76.6%, Japan - 12.8%, Europe - 8.3%, and Canada - 2.3% respectively (Logsdon, 2011b). Russia is responsible for some operational costs. For a potential Mars mission, the investment scale of the above mentioned parties could be estimated to be the same as the ISS case; however, Russian data is not include the cost estimation in the ISS case. Considering past USA and Russian missions to Mars and the difference between the GDP of Russia and the USA, a ratio of about 8:1 can be estimated between USA and Russian expenditures. It is shown that the cost for each nation is much lower should all ISS nations contribute to the investment instead of a single nation. However it is still a high financial burden for each nation, such that new parties including China, India, Korea, and Brazil should be considered in sharing the costs.

The BETA (Bureau d'Économie Théoriqueet Appliquée) method, presented in Chapter 2, offers approximately a 3:1 financial return on the investment (Cohendet, 1997). Then, when considering a Mars exploration mission with a USD 500 billion investment, the total indirect economic return can be estimated to be about USD 1500 billion.

8.3.2 Mission cost implications

As stated previously, a mission to Mars with humans landing on the surface, even during a short duration, is undoubtedly very expensive. The last NASA estimation of the potential cost to put humans on Mars and return them safely to the Earth is approximately USD 500 billion, or even more. Actually, a great uncertainty remains with regard to this cost, but it can be considered as a first relevant order of magnitude for the mission scenario proposed by the CHARM Team. This section addresses some specific financial aspects related to the selected mission.

Human Payload Economic Factors

As emphasized in the state-of-the-art review section in Chapter 2, the inclusion of humans in a mission to Mars directly affects the cost of a mission. To explore some of the human impact costs, the article (Rapp, 2006) proposes a way to estimate the total mass of the required ECLSS System for a mission to Mars, from which a launch cost can be evaluated:

For a long-duration mission, a rough economic evaluation has been attempted for a Mars Surface Habitat Lander using state-of-the-art ECLSS technologies (without *in-situ* water utilization). Starting from tabulated daily human requirements for water, foods, oxygen consumption and waste disposal, the paper derives the total mass budget by taking into account the number of crew and the mission duration. The estimation leads to a total of 33.9 metric tons for a crew of six and a mission duration of 600 days on the Martian surface.

By comparison, for a crew of two astronauts staying 40 days on the Martian surface, the total ECLSS mass becomes 0.75 tons. In addition to that, we have to add the ECLSS needs for the crew of the two astronauts staying in orbit: 0.59 tons. This required mass can then be translated into a launch cost of USD 35 to 70 million using the scaling factors derived in Chapter 2.

Considering now a crew of five astronauts staying on the Martian surface during 18 months (alternative long-duration scenario), the required ECLSS mass becomes 25.4 tons, which can be translated to a LEO initial mass of 178 metric tons, hence a total launch cost of USD 0.8 to 1.9 billion (this would require at least 8 launches with a heavy-lift launcher solely to provide ECLSS needs during Mars operations).

The short-duration scenario, compared to the long-duration scenario, provides an interesting cost saving just in terms of baseline ECLSS needs. These cost savings remain an order of magnitude less than the total potential mission cost. But the real cost differences between the short duration mission and the long-duration mission might come from the required number and robustness of robots and rovers, advanced scientific research facilities, surface habitat, etc. More than the launch costs, the design, development, and building costs may drive the cost differences.

Besides, no significant mass savings can be expected for the short duration mission on the Martian surface by using indigenous water on Mars. Such a technology should be developed for the preparation of future long-duration missions as it would be a condition to make such missions more affordable but does not seem to be worth (accounting for the sophisticated machinery required to enable *in-situ* water utilization and associated development costs) including it for the first manned mission.

The numbers provided above are subject to significant uncertainties. In particular, they are research-based rather than engineering systems-based, and thus optimistic as they do not consider allocations for margins, redundancy or spares.

Robotic Payload Economic Factors

This section addresses the cost-benefit analysis of a multiple rover/robot system that would be implemented in the selected mission scenario, reflecting a variable degree of automation. Using the quantitative data derived in Chapter 2, the launch cost of a Martian rover characterized by a mass of 1000 kg (which is similar to the mass of the NASA Mars Science Laboratory) would be comprised between roughly USD 35 to 70 million. Undoubtedly, this cost corresponds only to a marginal part of the total mission cost (less than 0.01%). It can be anticipated that, for the selected scenario, the design, development and building costs will anyway dominate the launch costs.

The launch of several similar rovers/robots, i.e., with the same overall design features, may significantly increase the range of the exploration area on Mars, particularly in the framework of a short duration mission, while not significantly impacting the overall end-to-end mission cost. Consequently, a good way to maximize the scientific benefits with a minimum additional cost (and thus maximizing the return on investment) with humans and robots on Mars would be to maximize the commonalities of the multiple robots. This approach minimizes the additional development costs (which are the same for each unit) and provides some redundancies. It has been successfully used in NASA's Mars Exploration Rover mission involving two rovers, Spirit and Opportunity, with the same design. Otherwise, increasing the number of robots or rovers that have a specific design for meeting specific tasks might significantly impact the development cost, thereby affecting strongly the overall mission costs. From a cost-benefit perspective, a mission including multiple rovers/robots in cooperation with humans is beneficial when the design of these robots has many commonalities, reducing research and development costs.

8.3.3 Conclusions of Financial Impact

Significant uncertainties still remain regarding the potential cost of the selected scenario. Because the mission includes humans landing on the surface of Mars, the mission will undoubtedly require a large investment that is well above the current space budgets of any one nation. Considering the selected scenario, international cooperation is an efficient way to disperse cost and risk. This scenario also calls for extending international cooperation to non-traditional parties. At a smaller scale, a cost benefit can be achieved by designing robots/rovers with many commonalities. The cost savings attained by a short duration mission compared to that of a long-duration mission at a micro level is quite significant due to the lower requirements of the life support system.

8.4 Conclusion

To summarize, there is a vast number of risks involved in preparation for a mission, and many aspects are impacted as a result. However, CHARM team's proposed mission scenario avoids most of the risks imposed and hence is the appropriate solution.