“To conduct a study for increasing crew safety during lunar surface exploration through task allocation between astronauts and robots.”

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ALERTS
Analysis of Lunar Exploratory Robotic Tasks for Safety

Final Report

International Space University
Masters Program 2008
The 2007/2008 Master Team Project of the International Space University (ISU) was conducted at the ISU Central Campus in Strasbourg, France.

The cover depicts a view of the Earth from a lunar orbit. The logo represents the interpretation of a common hazard sign highlighting the symbiotic relationship between astronauts and robots for improving crew safety.

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ABSTRACT

Throughout history, humans have been enthralled by exploration and are once again venturing into outer space – beyond Low Earth Orbit (LEO), considered the final frontier. Space agencies around the globe have declared their intention to return humans to the Moon with a sustained human presence within the next couple of decades. Extended surface stays will require the performance of a wide variety of tasks, and it will be paramount that the crew performing these tasks are safe. Consequently, the question must be posed “how can lunar surface exploration be made safer for astronauts?”

A list of 65 common tasks was generated as a result of discussion with industry experts and a thorough survey of literature on lunar base designs and grouped in ten different categories. Each task was evaluated to create an extensive list of all identified risks to astronaut safety. The impact of each risk was quantified by scoring the probability of occurrence (likelihood) and the magnitude of its effect (severity) using a classification table and risk matrix developed from a number of sources, including the European Space Agency’s (ESA) HUMEX study and the National Aeronautics and Space Administration’s (NASA) Bioastronautics Roadmap. A decision tree was created and applied to each task to determine what type of robotic platform would be most beneficial, and the enabling technologies for that type of robot are proposed.

This report makes recommendations to increase crew safety primarily through the use of robotic technology; however, using an interdisciplinary approach towards the subject matter, crew systems, policy and law, and management recommendations are also suggested. The foundation of an International Space Exploration Safety Board, a decision tree for robotic platform solutions to safety risks, and a novel integration scheme for risk criteria are proposed as a result of this project.
“The sea is our approach and bulwark; it has been the scene of our greatest triumphs and dangers…” So said R L Stevenson in Virginibus Puerisque, 1881. Well before 1800s, the seas have tested the courage and determination of a civilization’s bravest men, the political will behind their adventures and the hope of prosperity that their discoveries would bring.

Earlier voyages at sea were more like battles with the forces of nature. Soon humans learned to use tools to find their way, stay healthy at sea and to be more informed about the winds, with bigger ships and better sails. One such tool was the Astrolabe, the origins of which lie in Ancient Greece (ca. 225 BC), and which made possible the conquests of Alexander the Great throughout the Mediterranean. The Astrolabe was known to scholars from then on, and was used as a slide rule of the Heavens. When Prince Henry the Navigator established his seafaring fleet, he began using the Astrolabe to navigate ships. For many years, this gave the Portuguese the exclusive ability to navigate open waters, which other countries could not do. The ability for them to learn to use the right tools to prepare for what dangers lay ahead made them the most successful seafarers.

Today, we stand at harbor preparing for another historic voyage. The sea that lies ahead promises the same risks, same dangers and demands just as much determination. Our ships are being designed and so are our tools. The need now is to understand how to use these tools and prepare to face the risk. This is what 22 dedicated team members embarked on at ISU with the ALERTS Team Project. The knowledge that they have accumulated in 10 weeks of full time work will prepare the global space community for sustained exploration for the next destinations – Moon, Mars and beyond. It was a pleasure to see the team develop a thoughtful methodology and engage in a timely analysis that has been already welcomed by space agencies and space community members around the globe – much like the praise that wise seafarers rightly earned. We wish them all the best in their endeavors that lie ahead!

Isabelle F. Scholl & Bijal ‘Bee’ Thakore
AUTHOR PREFACE

The Analysis of Lunar Exploratory Robotic Tasks for Safety (ALERTS) project was developed by an interdisciplinary group of 22 students from 18 different nationalities with very diverse educational and cultural backgrounds. Our project began in the fall of 2007 with a literature review that allowed us to identify gaps in the literature regarding the design, establishment, operation, and evolution of a lunar base. Gaps that have been identified included lunar dust mitigation strategies, lunar base evacuation strategies and procedures, and radiation protection.

The team had a challenging time finding a topic that was both interesting and focused enough to the point where we felt we could offer a significant contribution to the space community. Through the literature review, references were found pertaining to human-robot interaction and the utilization of robotics for lunar tasks. However, we recognized that the literature was scarce as to how robotics could potentially be implemented in order to increase crew safety.

Through many meetings, discussions, idea posting sessions, external communications, and voting, the team managed to narrow down the topics, and finally focused on one of the gaps resulting from the literature review: the use of robotic technology to increase crew safety during lunar surface exploration. With our field of research identified, a mission statement was defined, and an intensive and focused study was initiated in March 2008.

The team compiled a set of tasks and performed a risk analysis, which led to our main deliverables: the comparison of different risk criteria and the aggregation of one proposed system for the purpose of assessing safety risks to astronauts, the creation of a decision tree summarizing the key robotic results of the report, the proposal to establish an International Space Exploration Safety Board, and the development of an interactive software, which has a user-friendly interface and is a standalone tool to help the reader follow the processes that we used, and highlights the robotics recommendations that our team proposed.

One of the most challenging aspects of this project for our team was applying ISU’s 3I philosophy: Interdisciplinary, International, and Intercultural. The subject matter lent itself easily to technical, legal, and policy aspects, but proved more difficult in the application of business and finance aspects. However, as the project progressed, we ultimately realized that losing a crewmember on the surface of the Moon because of an accident would be catastrophic for any national space agency in today’s risk adverse society.

Throughout our research, we approached more than 500 industry professionals and experts through personal communication and surveys, and in the process made many useful contacts that provided helpful suggestions and guidance. Hence, we would like to thank all the individuals who contributed to this project, and to our personal development as future members of the space community. We hope that this work can be used as an important accompaniment for the establishment of a lunar base, and that our recommendations will be implemented and provide a foundation to be improved upon in the future.

Sincerely,

The ALERTS Team
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<tr>
<td>ACROBOT</td>
<td>Active Constraint Robot</td>
</tr>
<tr>
<td>AESOP</td>
<td>Automatic Endoscopic System for Optimal Positioning</td>
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<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
</tr>
<tr>
<td>ASAT</td>
<td>Anti-Satellite</td>
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<tr>
<td>AURORA</td>
<td>Auxiliary Climbing Robot for Underwear Ship Hull Cleaning of the Sea Adherence and Surveying</td>
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### B

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<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>BEAR</td>
<td>Battlefield Extraction-Assist Robot</td>
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<td>BSLSS</td>
<td>Buddy Secondary Life Support System</td>
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### C

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<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>C&amp;D</td>
<td>Control and Display</td>
</tr>
<tr>
<td>CASPAR</td>
<td>Computer Assisted Surgical Planning And Robotics</td>
</tr>
<tr>
<td>CEV</td>
<td>Crew Exploration Vehicle</td>
</tr>
<tr>
<td>CISM</td>
<td>Critical Incident Stress Management</td>
</tr>
<tr>
<td>CMAS</td>
<td>Canadian Center for Minimal Access Surgery</td>
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<tr>
<td>CNES</td>
<td>Centre National d'Etudes Spatiales (French Space Agency)</td>
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<tr>
<td>COSPAR</td>
<td>Committee on Space Research</td>
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<td>CPM</td>
<td>Critical Path Method</td>
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<td>CSA</td>
<td>Canadian Space Agency</td>
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<tr>
<td>CSTS</td>
<td>Crew Space Transportation System</td>
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### D

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<th>Definition</th>
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<tr>
<td>DARPA</td>
<td>Defense Advanced Research Projects Agency</td>
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<tr>
<td>DLR</td>
<td>Deutsch Zentrum für Luft-und Raumfahrt (German Space Agency)</td>
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<tr>
<td>DNA</td>
<td>Deoxyribonucleic acid</td>
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### E

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<th>Definition</th>
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<tbody>
<tr>
<td>ECSS</td>
<td>European Cooperation for Space Standardization</td>
</tr>
<tr>
<td>ECLSS</td>
<td>Environmental Control and Life Support System</td>
</tr>
<tr>
<td>EMU</td>
<td>Extravehicular Mobility Unity</td>
</tr>
<tr>
<td>EPIRIB</td>
<td>Emergency Position Indicating Radio Beacons</td>
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<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ERA</td>
<td>European Robotic Arm</td>
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<tr>
<td>EU-O_SHA</td>
<td>European Agency for Health and Safety at Work</td>
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<tr>
<td>EURON</td>
<td>European Robotics Research Network</td>
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<tr>
<td>EVA</td>
<td>Extra-Vehicular Activity</td>
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### F

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<th>Acronym</th>
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<tbody>
<tr>
<td>FMEA</td>
<td>Failure Mode and Effects Analysis</td>
</tr>
<tr>
<td>FMECA</td>
<td>Failure Mode, Effects and Criticality Analysis</td>
</tr>
<tr>
<td>FO</td>
<td>Fan Out</td>
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### List of Acronyms

#### G
- **GDP**: Gross Domestic Product
- **GLOBE**: Global Learning and Observations to Benefit the Environment
- **GPS**: Global Positioning System

#### H
- **HBI**: Human Based Intelligence
- **HRI**: Human-Robot Interaction
- **hTERT**: Telomerase Reverse Transcriptase

#### I
- **IAASS**: International Association for the Advancement of Space Safety
- **ICJ**: International Court of Justice
- **IE**: Interaction Effort
- **IGA**: Inter-Governmental Agreement
- **IOSH**: Institution of Occupational Safety and Health
- **IR**: Infrared
- **ISESB**: International Space Exploration Safety Board
- **ISO**: International Organization for Standardization
- **ISRO**: Indian Space Agency
- **ISRU**: In-situ Resources Utilization
- **ISS**: International Space Station
- **ITAR**: International Traffic in Arms Regulation
- **IVA**: Intravehicular Activity

#### J
- **JAXA**: Japanese Aerospace Exploration Agency
- **JEM**: Japanese Exploration Module

#### L
- **LCG**: Liquid Cooling Garment
- **LEO**: Low Earth Orbit
- **LEV**: Lunar Exploration Vehicle
- **LLO**: Low Lunar Orbit
- **LOI**: Lunar Orbit Insertion
- **LM**: Lunar Module
- **LRV**: Lunar Roving Vehicle
- **LSS**: Life Support System
- **LTO**: Lunar Transfer Orbit

#### M
- **MCP**: Mechanical Counter Pressure
- **MIT**: Massachusetts Institute of Technology
- **MSS**: Mobile Servicing System
- **MVL**: Man Vehicle Laboratory
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<tr>
<td>NGR</td>
<td>Next Generation Robot</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<tr>
<td>NOTES</td>
<td>Natural Orifice Translumenal Endoscopy</td>
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<tr>
<td>NT</td>
<td>Neglect Tolerance</td>
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<tr>
<td>OSHA</td>
<td>Occupational Health and Safety Administration</td>
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<td>OSMA</td>
<td>Office of Safety and Mission Assurance</td>
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<tr>
<td>P2P-HRI</td>
<td>Peer-to-Peer Human-Robotic Interaction</td>
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<tr>
<td>PERT</td>
<td>Program Evaluation and Review Technique</td>
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<tr>
<td>PLB</td>
<td>Personal Locater Beacons</td>
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<td>PLSS</td>
<td>Portable Life Support System</td>
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<td>PMSS</td>
<td>Project Management Space Systems</td>
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<td>PEVA</td>
<td>Pedestrian Surface Excursion Activity</td>
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<td>RAD</td>
<td>Robot Attention Demand</td>
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<td>REVA</td>
<td>Rover Extra Vehicular Activity</td>
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<tr>
<td>RMS</td>
<td>Remote Manipulator System</td>
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<tr>
<td>ROSKOSMOS</td>
<td>Russian Federal Space Agency</td>
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<tr>
<td>SAR</td>
<td>Search And Rescue</td>
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<tr>
<td>SI</td>
<td>Safety Intelligence</td>
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<tr>
<td>SPDM</td>
<td>Special Purpose Dexterous Manipulator</td>
</tr>
<tr>
<td>SRP</td>
<td>Standardized Robotic Port</td>
</tr>
<tr>
<td>SRM&amp;QA</td>
<td>Safety, Reliability, Maintainability, and Quality Assurance</td>
</tr>
<tr>
<td>TCT</td>
<td>Task Completion Time</td>
</tr>
<tr>
<td>TE</td>
<td>Task Effectiveness</td>
</tr>
<tr>
<td>TMG</td>
<td>Thermal Meteoroid Garment</td>
</tr>
<tr>
<td>TRL</td>
<td>Technology Readiness Level</td>
</tr>
<tr>
<td>UNESCO</td>
<td>United Nations Educational, Scientific and Cultural Organization</td>
</tr>
<tr>
<td>USA</td>
<td>United States of America</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>VGTV</td>
<td>Variable Geometry Tracked Vehicle</td>
</tr>
<tr>
<td>WCE</td>
<td>Wireless Capsule Endoscopy</td>
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</tbody>
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1 INTRODUCTION

“We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard…” (Kennedy, 1962). The space race was the call to arms by the United Stated of America’s (USA) President John F. Kennedy to put a man on the Moon. This was a long and difficult development that claimed the lives of both American astronauts and Soviet cosmonauts. President Kennedy challenged the USA to put a human on the Moon in the middle of the Cold War, but while the program’s impetus was originally national prestige, there was much more to be gained. Unforeseen technologies would be developed, and tens of thousands of people would be employed in many new companies. After the USA political agenda – to be the first to land a man on the surface of the Moon – was achieved, the focus of lunar exploration shifted towards science. Over the course of the Apollo program more than 380 kg of lunar samples were collected and brought back to the Earth for analysis. Seismological and other scientific experiments were performed. Measurements of lunar gravity, heat flow, and charged particle environments were taken. This ultimately resulted in a better understanding of Earth’s closest neighbor, which in turn has led to more knowledgeable theories on the formation of the Earth (Taylor, 1994).

A review of the agendas of the world’s various space agencies shows that there are plans to return to the Moon for some of the same reasons that existed during the Apollo era; however, the global environment has greatly changed since the 1960s. The Cold War is over, and international cooperation now plays a crucial role in the next generation of human space exploration. At the same time, technology has experienced numerous advancements, making robots invaluable tools for planetary exploration. On the one hand, there are scientists and citizens that challenge the benefit of putting humans back on the Moon, arguing that it is less expensive and safer to send unmanned missions. On the other hand, there are many others who do not share this sentiment. The safest place for astronauts is on the Earth’s surface, but this is not why we have astronauts, nor why we engage in human exploration.

The Apollo era witnessed something beyond the knowledge gained and technical challenges overcome during the six missions that landed men on the surface of the Moon. The imaginations of people around the world were caught by the exploration of the Moon’s new and exciting environment, allowing them to dream about new frontiers and extending civilization to other celestial bodies. This was a type of exploration that the world had not experienced since Columbus and Magellan sailed the seas; since Lewis and Clark explored the Pacific Northwest of the United States; and since the first Antarctic explorations were undertaken by Roald Amundson, Sir Ernest Shackleton, Admiral Byrd, and Robert Scott.

Unfortunately, these endeavors were not without risk. When looking back in history, Magellan’s voyage, for example, was considered a great success despite the crew’s heavy casualties. Of the five ships and 270 crewmembers that started the voyage, only one ship with 18 crewmembers returned (The Mariners’ Museum, 2004). Society’s perception of risk, however, has changed dramatically over time, with the result that the world is far more risk averse than ever before. Today, crew loss is regarded as completely unacceptable. Ensuring the safety and wellbeing of a crew venturing into the harsh environment of space is necessary to gain public and thus government support.
Exploration is innately risky, and limiting the risk to human life is of vital importance. Just as technology was developed to make the original Moon landings possible, there are current and developing technologies that can make future lunar landings safer for humans. Robotic technology is already making a terrestrial impact on human safety. Robots such as the Battlefield Extraction Assist Robot (BEAR) (Vecna Robotics, 2006a) can be sent into hazardous environments to aid and retrieve injured soldiers. It is easy to recognize how this valuable technology could be adapted to human planetary exploration where an astronaut may be injured while performing an Extra-Vehicular Activity (EVA). But this is only one example of how astronaut safety can be increased through the use of robotics.

This chapter begins by discussing the reasons for reestablishing a human presence on the Moon, since a discussion of crew safety cannot occur without human involvement. This is followed by a discussion on our perception of risk and how it has changed with time. The chapter will conclude by setting the stage for further discussion on robotics and how it can increase crew safety.

1.1 Man on the Moon

Thirty-six years after the last man walked on the Moon, humans are ready to go back. Several unmanned missions have been sent recently (e.g., Kaguya, SMART-1, and Chang'e-1) and additional ones are planned for the near future, mainly to explore our natural satellite. So far, only the Apollo missions allowed men to walk on its surface. In the 20 years since the establishment of the Space Exploration Initiative in 1989 the dream of building a permanent lunar base has made its way into the programs of space agencies worldwide (Spudis, 1992). The American presidential directive in 2004 established clear long-term plans to return to the Moon (ESTEC, 2006). While space agencies are ready to send humans back to the Moon, criticism toward manned exploration missions has not vanished. The most often cited counter-argument asks why more money is put into space when allegedly there are too few resources already to address more critical problems on Earth (Spudis, 1992). If space has an important role to play in answering the challenges Earth is facing today, what is the contribution of manned missions? With technology having evolved to the point that Martian robots can be operated from Earth, the benefit of returning humans to the Moon again is questionable.

The first argument for a human presence on the Moon is a technical one. Robots are able to assist humans or accomplish complex tasks; however, no individual robot could completely replace the capabilities of a person. Humans are unique, and robots are not yet able to reach the same level of analysis and synthesis (Space Studies Board, 1997). The orange soil found during the Apollo 17 mission by astronauts Harrison Schmidt and Eugene Cernan would not have been discovered using robot systems available at the time. Robots programmed to look for typical lunar samples would certainly have ignored that strange sample that has generated so much interest (Hill, 2007).

One of the greatest benefits of manned missions is the ability of astronauts to adapt to unanticipated contingencies. It has been noted that during the Apollo 17 mission, a technical problem led to lunar dust spraying up over the rover. The electronics started to overheat, but the astronauts managed to improvise and replace the fender using lunar maps and tape. Without the intervention of the astronauts, the mission would have been ended much earlier. Despite the progress made in robotic technologies, human abilities are still necessary for numerous tasks.
Another argument in favor of sending people back to the Moon is simply discovery. Humans are driven by their curiosity and their wish to discover more about their environment and the unknown. Jacques Arnould once said, “A society with no imagination, and thus with no ambitions of discovery and exploration, is a dead society” (ISU, 2005). Exploration is a primary objective of any space mission and a global aim for humankind. Understanding the solar system and the universe starts with exploration. Humanity has always searched to go beyond its limits, through exploration of the deepest seas, desert areas, and outer space.

Beyond exploration, human space programs have been motivated by other concerns. The human space program initially began as a political maneuver, and astronauts were the ones who could bring pride and prestige to their country (Mendell, 2004). While the political context of the Cold War is over, another dimension of national prestige exists. Budgets and government support rely heavily on public opinion.

### 1.2 Risky Endeavors

History has demonstrated that exploration is a risky endeavor that has equal or more potential to end in disaster than in success. Even with this in mind, the great explorers of the past embarked on their great journeys. This was captured accurately by Robert Falcon Scott who, after losing the race to the South Pole, noted down in his final journal entry: “We took risks, we knew that we took them. Things came out against us, and therefore, we have no cause for complaint.” Shortly after, Scott and his crew perished only thirteen kilometers from safe haven (Stuster, 2005).

Whether for the purpose of migration, economic gain, political or religious agenda, or simply for challenge and adventure, exploration has played an essential role in humanity's progress. During the early part of human civilization, nations relied on exploration to maintain their economic and political strength against both their enemies and allies. As such, it was common practice to send large numbers of people on risky missions to ensure the security of the nation’s interests.

Loss of life was considered an acceptable risk, and to be expected during exploration. This was clearly demonstrated in the 15th century when Prince Henry the Navigator deployed fifteen expeditions to Cape Bojador before one successfully made it back to Portugal (Sandrone and Wagner, 2007; HistoryWorld, 2008a). Vasco da Gama, following in Henry's footsteps, set on a quest to conquer additional territories for Portugal, which claimed the lives of many sailors. However, both Henry and da Gama received praises for their great achievements (HistoryWorld, 2008b). In addition, efforts made to improve exploration technology, such as ships and navigation tools, were mainly driven by mission success and not by crew safety, although they did contribute indirectly to improving crew safety (Sandrone and Wagner, 2007; and HistoryWorld, 2008a).

More emphasis on crew safety began during the polar expeditions of Fridtjof Nansen, Roland Amundsen, and Ernest Shackleton in the late 19th and early 20th centuries. All three explorers strongly believed in ensuring the safety and comfort of their crew through the provision of a proper diet, well tested and reliable equipment, careful crewmember selection to promote positive crew dynamics, and expedition simulations that are similar to today's space mission.
simulations. Nansen was especially noted for his ingenious ship design that mitigated hull failure from ice floe pressure. Incidentally, Nanson suffered cost overruns, due to the increased crew safety margins and cargo capacity, but this did not deter him in his efforts. Shackleton's attentiveness for his crew's safety made him well known for having never lost a crewmember during his expeditions. He risked his own life to save one of his crewmembers from nearly drowning in the frigid waters of Antarctica, and was relentless on his rescue campaign to retrieve his men who were stranded off the coast of Antarctica on Elephant Island (Stuster, 2005).

As time progressed in the twentieth century, the perception of acceptable risk and the value of human life have become more stringent, and thus crew safety and risk mitigation strategies have come to play a more important role in exploration. In the mid-twentieth century, when political agenda was the main driver for space exploration, human safety was of the utmost importance. President John F. Kennedy clearly stated this in his address to congress when he said: “First, I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the earth” (Kennedy, 1961). As a result, new technologies were developed and tested under an enormous time pressure to maximize the safety of the men who bravely ventured into the unknown. Therefore, vast amounts of resources and ingenuity were employed to anticipate and minimize risks through fast paced technology development and risk mitigation techniques.

These techniques were integrated on different levels into the space mission architectures, and the general motto of “Failure is not an option” (Kranz, 2000) was adopted, which from the standpoint of the goal set by Kennedy also included the safety of the crew. From a systems engineering perspective, “every effort was made to simplify space system design” (Lovell, 2004). Redundancy systems were installed to provide a safety margin in case of an onboard system failure. This was accompanied by intense training of both the astronaut and flight control teams. From a mission design perspective, crew safety was maximized by integrating a “Free Return” trajectory, enabling the spacecraft to automatically return to the Earth after circumnavigating the Moon once, in the case of an engine failure. Even after the termination of the Apollo program, as humanity retreated back to LEO, safety requirements have continued to grow more stringent. Especially with growing interest to establish a permanent human presence in space, a number of nations have been working to develop knowledge and expertise necessary to mitigate the potential hazards of long-term exposure to space environment.

The Space Shuttle, Skylab, Mir, and the International Space Station (ISS) are examples of how humans have acquired the knowledge and experience to develop systems able to sustain human life for safe longer-duration exploration missions. Currently, the ISS represents the largest international endeavor in human space exploration. It integrates the experience gained and technology developed by different countries in their manned and unmanned space programs to achieve a common goal. However, as mentioned in the “Final Report of the International Space Station Independent Safety Task Force”, the ISS is not exempt from risks and vulnerabilities, “that could lead to its destruction, compromise the health of its crew, or necessitate its premature abandonment” (NASA, 2007a). Other concerns to the safety of the crew are the high-risk activities associated with a mission, such as launch, return to earth, EVAs, or the inherent risks of the space environment.

Any accident or event that threatens the health of a crewmember can have enormous consequences on public opinion of current and future human space missions. The loss of the
space shuttle Columbia during re-entry was a tragic reminder of the effect of human loss during space exploration on the mission, economy, and public opinion (Kauffman, 2005). A return to the Moon will hold the attention of the public, and for this reason the experience and lessons learned from the shuttle, Skylab, MIR, and ISS, regarding crew safety are vital to the success of lunar missions. Furthermore, national prestige, economic gain, and the desire to explore are only justifiable causes to return man to the Moon if there is minimal risk to human life. Especially now that robots have been successfully implemented for the Shuttle, ISS and planetary missions, human involvement in space exploration is considered necessary only for applications where robots cannot replace the unique abilities of humans. In addition, robots may be used to assist astronauts to foster increased crew safety during the establishment and operation of a lunar base.

1.3 Robots and Safety

Robotic technology is used to assist in the performance of tasks in terrestrial and space applications. Its extensive use aboard the Space Shuttle and the ISS show its potential for future lunar missions.

1.3.1 History and Definitions

The word “robot” was invented in 1920 by the painter/writer Josef Capek, and originates from the Czech term “robota”, which means "compulsory labor" (Hubbard, 2005; Zunt 2004).

In 1942, Isaac Asimov first used the word “robotics”, which describes the study of robots, and introduced the “Three Laws of Robotics” in his short story called “Runaround” (see Section 4.5). Less than 15 years later, in 1956, the world's first robot company, Unimation Inc., was established by Joseph Engelberger and George Devol. Later, in 1961, Devol developed and installed the first industrial robot at a General Motors plant (Hubbard, 2005; McKerrow, 1991).

There is no single definition for the word “robot”. In the present study, “robot” is defined as a machine that is directly controlled or pre-programmed in order to perform a variety of tasks. Because of its characteristics, a computer program could technically be called a “robot.” However, within the scope of this report it is referred solely to physical machines.

For a space robot, the definition can be narrowed down to “a machine that is designed ultimately to reproduce human capabilities, particularly for strenuous or dull tasks in potential harmful environments” (Ellery, 2000). The space robot is designed to assist humans for tasks that have to be performed in dangerous environments.

In 2003, NASA proposed the separation of space robots into two opposing classifications, in-space versus surface environments, or autonomous versus human-assistance applications. Therefore, the final categorization of a space robot is one of the following: 1) In-space autonomous capabilities considering assembly, inspection and maintenance; 2) In-space astronaut-assistance for orbital EVA; 3) Surface exploration considering autonomy for mobility, instrument deployment, sample operations and science investigations; or 4) Surface human assistance for surface EVA (Pedersen et al., 2003).

This report will focus on two of the four categories of robots as defined above by NASA:
surface exploration, and surface human assistance for surface EVA.

The term “autonomy” is important for this study. It defines the capacity of any artificial system to operate without any form of external control (human control) in the real-world environment for a certain time (Beckey, 2005). There are usually 3 different levels of autonomy depending on the level of human intervention and the range of tasks that such a system can perform: non-autonomous, semi-autonomous, and fully-autonomous systems. The first category refers to teleoperation. The second category refers to situations when portions of a task are performed autonomously by machines but can otherwise be controlled by humans at any moment. Finally, fully-autonomous systems refer to systems capable of performing entire tasks independent of human interaction.

The notion of “multifunctional robot” is also important. In the present study, this refers to the situation when different instruments with varying capabilities are mounted on a single robotic platform, not so much to the ability of a robot to perform several tasks simultaneously. The objective is to have a single machine that would be used for different tasks, which would have to be performed on the Moon. Consequently, this has a direct economic impact on the feasibility of a lunar mission because the number of robots required on the Moon can be substantially reduced.

1.3.2 Use of Robots for Human Safety

The concept of human-robot coexistence was conceived in the early 1900s. Although once regarded as fiction, it is slowly advancing towards reality. Not only are robots used as assistants in industrial capacities, but they can also function in other, more complex roles, such as acting as a bedside nurse in a hospital setting. Moreover, some believe that Next Generation Robots (NGRs) will be an integral part of the average household, by running errands or performing housework (METI, 2004). The terrestrial application of robots has been transferred into space exploration, such as the use of the Canadian Robotic Arm by ISS astronauts to assist EVA activities.

The underlying factor propelling the use of robots, besides increased efficiency, is the increased safety of human beings. Humans are gradually assigning robots to perform highly dangerous tasks in order to protect human life (Weng et al., 2007). For example, the development of teleoperated robots to manipulate radioactive materials can overcome safety problems that exist in the nuclear industry (McKerrow, 1991). The significance of robotics for lunar exploration stems from the harsh environment of the Moon from which astronauts need to be protected. The introduction of robots and the development of precise robotic architectures will increase crew safety on the Moon by reducing the need for humans to perform certain risky tasks.

On the other hand, the potential exists for robots to cause injury to astronauts while working together. There have been incidents on Earth in which an industrial robot's malfunction has caused severe injuries to workers. The first recorded fatal accident involving a human and a robot occurred in Japan in 1981 (The Economist, 2006). A factory worker at a Kawasaki manufacturing plant entered a restricted safety zone to perform maintenance on a robot, and after failing to completely deactivate the robot, the robot's powerful hydraulic arm pushed the engineer into adjacent machinery. It is in this regard that the report strives to examine all facets of human-robot interaction in the context of a lunar base, and improve crew safety through the use of robotics.
1.4 Scope and Reader's Guide

Safety is a primary concern in all human spaceflight programs, both ethically and politically. In addition, the development of a lunar base will open new opportunities for human-robotic interaction and the evolution of new robotic systems. This report focuses on the reduction of risks arising from working on the lunar surface, and the improvement of astronaut safety through the application of robotic systems. By examining the potential utility of current and developing robotic technologies for terrestrial and space applications, a guide for allocating tasks and describing interfaces between astronauts and robots during the early stages of a lunar base has been developed that takes into account ethical considerations and current legal frameworks.

The wide range of activities involved in the construction, development, and operation of a lunar base requires the establishment of clear definitions and the adoption of assumptions to restrict the scope of this report, and allow for thorough and in-depth analysis:

- The terms "safety" and "risk" are used throughout this report. Crew safety is defined as the freedom from injury, danger, or loss of an astronaut's health and physical well-being. In this case, risk refers to the probability of a direct negative impact on an astronaut's safety, not the probability of mission compromise.

- Robotics is a general term that has been used to describe a wide variety of mechanical systems. Within the scope of the report, robotics includes those systems that reproduce the capabilities of humans to perform repetitive or physically difficult tasks in a dangerous environment. This definition encompasses fully or partially automated, and teleoperated, robotic systems such as arms, manipulators, and rovers.

- There are a number of long-term crew health and safety risks inherent to being in a lunar environment, such as radiation exposure and psychological stress. The currently available literature, however, discusses these concerns and their mitigation strategies in depth. This report, therefore, focuses only on crew safety risks associated with astronaut tasks that can be assisted with robotics, such as compensation for musculoskeletal degeneration or perceptual and motor deficits.

- The early lifetime of a lunar base has been divided into three distinct phases (see Section 2.2) of which only the first two will be investigated. Risk uncertainty resulting from a newly established base infrastructure and a novel environment highlights the importance of astronaut safety during these early phases.

- Tasks are highly dependent on the goals and objectives of the base. To maximize the report's applicability, only generic categories of tasks regardless of long-term base objectives, such as construction and maintenance, have been taken into consideration.

The connection between robotics and crew safety is progressively and logically revealed throughout the report as it narrows from a historical discussion of safety during manned lunar missions, progresses through an analysis of risks associated with tasks performed on a lunar base, and culminates to a set of recommendations for the integration of astronauts and robotics. To achieve this goal, the report is divided into the following six chapters:
Chapter 1: Introduction. This chapter discusses the reasons and necessity of establishing a permanent human presence on the Moon, as well as potential objectives of a lunar base. In addition, the role that risk to human safety has played in past and present exploratory missions is examined, along with the potential of robotics to reduce the safety risks faced by future lunar astronauts. Finally, the scope of the report is established in parallel with the required definitions and assumptions.

Chapter 2: Development of a Human Presence on the Moon. Here the current plans and timelines for future manned lunar missions are summarized. Lunar base development is divided into three phases based on the integration of current agencies’ plans and discussions with experts involved in lunar base architecture and design. This is followed by a listing and explanation of all the tasks associated with early phases of lunar base development.

Chapter 3: Risk Analysis. A safety risk analysis, identifying, analyzing, and prioritizing all identified tasks, is presented. To conclude, current and proposed human mitigation strategies for the risks associated with high priority tasks is summarized.

Chapter 4: Robotic Aspects. This chapter investigates robotic technologies that could reduce astronaut risks that are currently being employed on Earth or in space, and developing technologies that show substantial promise. This includes discussion of Technology Readiness Levels (TRL), current technological trends, and expert opinions. Furthermore, the impact of human-robotic interaction and synergy on crew safety is examined.

Chapter 5: International Safety Board. An international organization concerned with crew safety is proposed here, in parallel with a legal framework regulating artificial intelligence (AI), robotic safety standards, and human-robot interaction as robots become more advanced. Financing relationships between governments, private industries, and international outreach programs are also examined.

Chapter 6: Recommendations and Conclusions. This final chapter presents recommendations for the allocation of robotic and astronaut tasks to increase crew safety. In addition, directions for future investigation are suggested. This is based on the integration of all relevant issues and aspects of crew safety and robotics discussed throughout the report into clear and concise arguments.
Sending humankind back to the Moon is an heavily involved process that requires careful planning and a large investment of resources by governments and space agencies. After mission objectives are established, architectures can then be developed, and the tasks required for the establishment and operation of lunar outposts and bases can be identified. This chapter begins by reviewing current robotic and manned lunar mission architectures proposed by the world’s space agencies. General phases of lunar base development are subsequently defined, and the various aspects of base operations and management are explained in greater detail. 66 generic tasks are identified and grouped into one of ten broad categories based on the lunar base phase in which they begin.

2.1 Current Agency Lunar Objectives and Mission Architectures

Space agencies in USA, Russia, China, Japan, Europe, and India are currently unveiling their plans for lunar missions. Nevertheless, just a few have fully incorporated a complete lunar base architecture. The only detailed plans of lunar base missions in the near future have been published by NASA and ESA.

2.1.1 NASA

NASA’s global exploration strategy and lunar mission architecture is open, extensible, affordable, and flexible. A flexible architecture has the ability to react to changes in exploration priorities and methods applied to the early stages of exploration. Programmatic flexibility of the lunar architecture is necessary to ensure adaptability to political and budgetary changes. This flexibility enables resilience against changes in the sphere of cooperating entities and their priorities. The success of the lunar mission architecture will depend on assembling the best activities that work efficiently toward achieving its specified objectives. (Dale et al., 2006).

NASA’s lunar exploration program is divided into two phases. Starting in the year 2020, initial missions will be performed by four astronauts for short periods of time until the base is developed enough to accommodate the continual presence of rotating crews by the year 2024. The number of astronauts will highly depend on the overall interest of other participating countries within the lunar missions. (Dale et al., 2006)

For an extended and sustained human presence on the Moon, the size of the outpost and its location will be determined based on data that will be obtained from the Lunar Reconnaissance Orbiter and Lunar Robotic Lander. Temperatures are much more moderate in the polar areas, and also allow for the continual use of solar power. Specific areas of the Shackleton crater are almost permanently lit by the Sun and are adjacent to permanently dark areas with the potential for the presence of volatiles. Thus, a polar location is also preferred from an In-situ Resource Utilization (ISRU) perspective. (Dale et al., 2006)

The initial outpost layout will depend on the type of lander that will provide the components necessary for assembling the first outpost. There are five architectural options under evaluation by the NASA lunar architecture program:
NASA is planning a very open strategy in terms of international cooperation, and intends to perform initial technology demonstrations to support subsequent development of lunar base elements by other countries. NASA itself is planning to develop lunar surface transportation capabilities and infrastructure such as an EVA system, Crew Exploration Vehicle (CEV) for initial surface capability, and surface suits for long duration EVA missions. Concerning mobility on the lunar surface, NASA is working on a basic rover, pressurized rover, and techniques and instruments for moving regolith and unloading module. Initial navigation and communication systems are also components of the NASA architecture. Utilization of robotics is considered a broad and primary component of the lunar mission architecture, and includes descent and landing system, small satellites, robotic rovers, instrumentation for material identification and characterization, and ISRU demonstration and utilization. NASA also wants to develop a number of specific capabilities such as drilling, scooping, and sample return and handling (Cooke et al., 2007).

One of the most important aspects of the planned lunar missions is the possibility to use the lunar environment as a unique laboratory, which could serve as a test-bed for future human and robotic missions to Mars and other celestial bodies, as well as to generate technological spin-offs. Robotic missions would be performed to test technical capabilities and to characterize critical environmental parameters and lunar resources. Other drivers of the NASA lunar architecture include specific metrics and management techniques for dealing with relative risks, crew time on the Moon, overall time available for exploration and incidental early returns from missions (Cooke et al., 2007).

2.1.2 Roskosmos

In December 2007, Roskosmos unveiled its Luna-Globe program for lunar exploration, which consists of three stages. The first stage begins in 2011-2012 with robotic missions to search for water and mineral deposits in the lunar polar regions, and to determine the composition of the lunar core (Shevchenko, 2008; TheSpaceReview, 2007). In addition, Roskosmos is planning the launch of a new orbital manned space station complex, which would ensure transportation for both Moon and Mars missions (Novosti, 2007a). When mineral deposits have been located, a new generation heavy rover would be launched to the lunar surface as a part of the robotic missions. These robotic missions will be performed in cooperation with the ISRO that, according to a signed agreement, will provide launch services, instrumentation, a transfer rocket, and the rover itself (Shevchenko, 2008). During the second stage, Roskosmos intends to send astronauts to the Moon by the year 2025 and establish a permanent lunar base between the years 2027 and 2032. The third stage of the Russian lunar plans centers on ISRU and industrial development related to Helium-3 mining for commercial purposes. A Helium plant is planned to be built up over the following 50 years (Novosti, 2007b). Russia is also working on a feasibility study of lunar tourism, beginning with tourist trips to the ISS for one week, followed by flybys around the Moon (Koelle et al., 2005). Roskosmos is also pursuing cooperation with the Chinese space agency, who also plan to initiate lunar surface robotic missions between 2010 and 2012 (MoonDaily, 2007a).
2.1.3 JAXA

The Japanese Aerospace Exploration Agency (JAXA) unveiled a new lunar exploration plan in 2007. Their strategy includes robotic exploration space missions performed by Selene-2 and Hayabusa-2, as well as long-term manned lunar missions. The general objectives of JAXA are the expansion of human activities in space, development of international collaboration, contribution to sustainable development, and the promotion of science. Furthermore, JAXA is pursuing the goal to enrich society through scientific and technological developments that stimulate space spin-offs, and by bringing the foundations of a new culture based on knowledge of the space environment. (Kawaguchi, 2007)

The Japanese lunar mission architecture is currently in the preliminary development phase and is largely dependent on the results of lunar robotic missions that will be performed by 2010. Their lunar mission objectives include the development of an autonomous space exploration system, the possible utilization of lunar resources and the scientific research concerned with understanding of origin and evolution of the Moon and Earth. (Kawaguchi, 2007)

The Kaguya mission is the first phase of lunar robotic orbital exploration, which will then be followed by the Selene-2 lander and rover, and the Selene-X advanced and highly autonomous robotic lander which will have the capability of performing construction assembly, sample analysis, moonquake observations and demonstration of ISRU. Robotic missions are preferred over those requiring the involvement of astronauts when monotonous or dangerous astronaut tasks are concerned. Human exploratory missions with participation in an international lunar outpost program will be within JAXA’s final phase. (Kawaguchi, 2007)

2.1.4 ESA

The European Space Agency’s (ESA) general objectives are to support international space exploration, to serve humanity, to increase knowledge, and to address and to learn how to deal with the global European challenges of the future. Furthermore, ESA wants to foster European values and to create a knowledge-based society. ESA’s Human Space Flight Vision Group plans are to operate a permanent outpost on the Moon with an astronaut presence by the year 2025. (Hovland, 2005)

ESA’s Concurrent Design Facility has provided a Lunar Exploration Study that outlines the objectives for various future lunar mission architectures, to demonstrate and test technologies and operations for human missions to Mars. The primary objectives are to perform and demonstrate long term habitation possibilities, while secondary objectives are focused on the development and demonstration of closed-loop technologies, as well as gaining experience in module assembly procedures in LEO (Hovland, 2005). A second component of ESA’s lunar mission architecture deals with construction of the lunar base itself and establishing the capability of sustainable lunar exploration on the Moon.

The major objectives of this mission architecture are to perform multiple landings in different locations and to maximize EVA time on the lunar surface. An important component of this mission architecture is placing a habitable hub in Low Lunar Orbit (LLO) with the transportation capability of several lunar landers. The habitable space and operations of the module will be determined based on the type of module used (inflatable or conventional modules). Excursion missions to the lunar surface would be performed by a Crew Transfer Vehicle (CTV) with docking support provided by two Lunar Excursion Vehicles (LEV) attached to the hub (see Figure 2-1). The LEV (see Figure 2-2) is composed of three modules: a Lunar
2.1.5 Supply Chain Management

The supply chain is a fundamental part of any lunar architecture design. There are five launch strategy options in the ESA lunar architecture: 1) utilizing the ISS as a spaceport for exploration; 2) direct transfer to LLO via LEO; 3) direct transfer to the lunar surface via LEO. Options 4) and 5) are proposals for dedicated orbit logistics vehicles for efficiency and flexibility issues. All transportation strategies include on-orbit assembly infrastructure, in-space cryogenic fuel storage, and a lunar surface mobility or gantry system supporting robotic missions. (Hovland, 2005)

The transportation systems are defined in three options (Hovland, 2005)

- Lunar Cargo Transportation System
  - Transfer of cargo to Lunar Hub (LLO)
  - Transfer of cargo to lunar surface base (Pole)
  - Baseline launcher Ariane 5 (20+ tons to LEO)

- 10 ton cargo class transfer
  - 2x Ariane 5 to Lunar Transfer Orbit (LTO)
  - Rendezvous & docking in LLO
  - Descent to surface

- Crew transfer
  - 3x Ariane 5 to LEO (if no person rated Ariane 5 than 1x Soyuz launch to LEO)
  - Rendezvous, assembly, and docking in LEO
  - Cryo Lunar Orbit Insertion (LOI), storable ascent and return to Earth – direct re-entry

Under NASA's plan, the Earth to Moon supply chain is accommodated by the Constellation program. The transportation system infrastructure is designed as an end-to-end system. The major factors considered are the lander design and the ascent vehicle of the transportation chain design. Redundancy and critical path capabilities are important in the implementation of transportation system management (e.g., international cooperation with Russian and European
The NASA lunar supply chain system has logistic re-supply capability provided by the lunar lander for both human missions and cargo missions. (Dale et al., 2006)

The lunar supply chain is based on two launchers: Ares V, which launches mission cargo or a lunar lander to LEO; and Ares I, which carries the Orion crew vehicle. The crew vehicle has to meet the lander in LEO and, after connecting, will perform a translunar injection burn for Earth departure. After arrival in LLO, the astronauts enter the lunar lander's ascent stage crew module. The lander will then perform the descent, braking, and landing burns (see Figure 2-3) (Bienhoff et al., 2008).

![Figure 2-3: NASA transportation architecture (Cooke et al., 2007)](image)

### 2.2 Lunar Base Management

Establishment of a lunar base is a costly and risky long-term program. Therefore, a sound management mechanism is required to provide continuity, consistency, and sustainability of the mission, while taking into account budget constraints and other challenges. For a project of this scale to be a success, tools such as the Program Evaluation and Review Technique (PERT), Critical Path Method (CPM), and Project Management Space Systems (PMSS) must be applied (Eckart, 1999). Methodologies such as the Failure Mode and Effects Analysis (FMEA) and the Failure Modes, Effects and Criticality Analysis (FMECA) will play an important role in identifying potential failure points, and assessing their risk (Reliasoft, 2004).

Risk management of the planning and designing processes, flight operations, productivity, delivery of resources, and costs and debt servicing of the lunar base are required to eliminate or mitigate the effects of identifiable risks to astronaut safety. However, the high complexity of management and operation may increase costs and the risk of failure (Schmitt, 2006). The most effective means of risk management begins by establishing the purpose and constraints of the system (or mission) followed by creating a complexity simulating model to correctly address the possible risks (Reid and Romero, 2003). In general, the occurrence of risk can be mitigated by two strategies, the elimination of risky procedures or activities; and the use of strategies that reduce the probability of occurrence to acceptable levels (NASA, 2005).
Space missions involve highly complex procedures and operations. Major mission planning is based on a clearly defined timeline of all procedures, processes, and tasks to ensure safety and efficiency. The duration of missions and the implication of tasks performed in later phases is an important factor of the timeline. Poor mission and task planning can significantly increase the risk in long-term missions. The distance from the Earth has a significant impact on telecommunication, especially when delays in communication can be a contributing factor in selecting a strategy for task management decisions. (NASA, 2005)

Through the analysis of current space agency plans, three specific phases have been identified that provide a common and easily understandable context throughout the report. These phases were designed to reflect the objectives of leading space agencies (e.g., NASA).

**Phase 1 (Lunar Outpost):** A solid structure similar to a lunar lander will be established to house 3 to 4 astronauts for mission durations of less than one week. This will be a temporary outpost that will be used for reconnaissance to locate an appropriate site for a base, as well as for conducting some scientific experiments. The limited number of tasks being performed will only require basic and proven robotic architectures to be used. Additionally, only open loop life support systems will be necessary. This phase is expected to last approximately 3 to 5 years.

**Phase 2 (Lunar Base):** Once an appropriate base location has been identified, structures, possibly inflatable, will be deployed to the surface of the Moon to establish a lunar base capable of housing a maximum of 15 astronauts for durations of up to 180 days. This phase's main focus will be to carry out more complex experiments and test advanced technologies in life support and ISRU such as bioregenerative closed loop Environmental Control and Life Support System (ECLSS) and Helium-3 extraction. In addition, robotic architectures extending from terrestrial based applications will begin to be implemented to facilitate maintenance, construction and ISRU operations. Phase 2 is expected to last an additional 10 to 15 years.

**Phase 3 (Lunar Base):** Phase 3 is a continuation of Phase 2 with the addition of a hybrid closed loop ECLSS (e.g., physico-chemical and bioregenerative) with a minimum closure of 75% of the water, oxygen and food loops. ISRU will commence to enhance the self-sustainability of the base. Advanced robotic systems that incorporate changes to previously tested systems will be implemented. The duration of this phase is not defined, as it is not within the scope of this project to look beyond Phase 3.

**2.2.2 Lunar Surface Operations**

A lunar surface mission begins when a lunar lander touches down on the lunar surface and ends when the lunar lander ascent stage takes off. Lunar surface operations include lunar base and infrastructure buildup (e.g., robotic teleoperation of structure assembly, regolith manipulation), landing pad buildup (e.g., remote operations of rover regolith microwave sintering), prospecting robotic operations, oxygen production and other ISRU operations. To perform astronaut lunar surface operations, the habitat and supporting systems must be operational (Smith et al., 2008). The lunar mission architecture specifies the rules that govern lunar surface operations. These operation rules define parameters such as maximum and nominal operation times for EVA, and logistical capabilities and relative positioning systems between operational zones (Bienhoff et al., 2008).
2.2.3 Lunar Base Re-entry Strategy

Pressurized facilities and habitats will need to be designed according to the selected lunar dust mitigation strategy. Air locks should fully comply with this mitigation strategy and should also function as dust locks. This ensures that any intake of lunar dust can be safely contained and removed. The interior needs to be easy to maintain and keep clean, or should be designed to automatically accumulate and eliminate any dust that escapes from air/dust lock. The air/dust lock will also be used as an astronaut changing and space suit maintenance area after EVA activities. Therefore, these procedures must also comply with the selected lunar dust mitigation strategy. (Schmitt, 1988)

2.2.4 ECLSS

One of the primary requirements for a lunar base is to sustain human life in a hostile environment. The ECLSS is responsible for this function and can be broken down into five categories: atmosphere management, water management, waste management, food production and storage, and crew safety. Autonomous or robotic operations should be the major system processes of life support operations, excluding an astronaut from these processes as much as possible. Regenerative systems should be applied to mitigate re-supply operations and to lower the complexity of the automated maintenance system. (Schmitt, 1988)

2.2.5 Habitation and Integrated Operations

The complexity of the human habitation process requires precise timing and specific task management, while maintaining a high level of flexibility. The mitigation of operational astronaut safety risks in the habitation process will be based on harmonization of defined lunar mission goals and overall wellbeing of astronauts. Here, robotics may support human “work” activity to reserve valuable operational time of an astronaut for the other, more important activities (Eckart, 1999). The prioritization of operations should be based on crew safety, crew efficiency and mission contingency requirements. In general, lunar base maintenance operations should always take precedence over science, exploratory, or ISRU operations. During initial human missions, astronauts will work without extended breaks until completion of the missions. However, recreation, personal time, personal hygiene, food preparation and eating, and sleep periods are habitation tasks that must be performed by the astronauts. Other operations, such as maintenance, housekeeping, system checks and inspections, would be performed according to the habitat design and mission architecture safety design and time requirements (Bienhoff et al., 2008).

2.2.6 Energy Production Management

The lunar base will need significant amounts of energy, especially in the advanced phases. The options for power production on the lunar surface include solar energy, nuclear fission, or a combination of lunar-mined hydrogen and oxygen fuel cells (Schmitt, 2006). If fuel cells are used, re-supply from Earth has to support energy demands that are not covered by in-situ oxygen and hydrogen production. Safety margins need to include at least one missed re-supply mission in the event of delayed transport. (Schmitt, 1988)

2.2.7 Resources Production Management

Any production on the lunar surface would minimize the re-supply needs for a lunar base. This may significantly reduce the costs of future lunar missions. Propellant and construction
materials production on the Moon are theoretically possible. For example, in-situ resources could be used for the production of thin solar cell film. Silicon extraction can also be carried out through carbothermal reduction (Malla and Maji, 2004). Resource production can involve repetitive tasks in a hostile environment like the lunar surface where robotic solutions can effectively be employed. The resource production also depends on the capabilities of the transportation system, resource allocation, deposit size and the limitations of transporting lunar material to Earth. Therefore, resource production depends highly on future prospecting missions that will establish the possibility of ISRU.

2.2.8 **Lunar Base Crew Organization**

Analogous environments and digital simulations have been demonstrated to play an important role in the mitigation of operational risks for human missions in space. These simulations test medical and behavioral facts using tests such as saturation diving, centrifuge, mock vehicle expeditions, polar expeditions, or submarine environment experience. Polar expeditions and submarine experience are especially useful analogues for long-duration space missions.

Crew interaction, cohesiveness and leadership are important factors for ensuring the success of potential lunar missions and missions in analog environments (NASA, 2005). The specific roles and specializations of astronauts must be clearly defined and planned within the mission architecture, as well as operational simulations, training and synergy of astronauts with robotic assistance for activities on the lunar surface (Jolliff, 2007). As mentioned earlier, this important quality necessitates the presence of an astronaut on the Moon, as current robots are incapable of acting unless “every detail is resolved definitively” (Reid and Romero, 2003).

2.2.9 **Lunar Base Safety Funding**

Most lunar missions have been planned for a long-term vision, which requires a large budget financing to develop the technology, reach a sustainable safety level, and operate on the Moon. Cost is a major issue for a long mission exceeding 10 years. Although many space faring nations have dedicated a budget for their lunar missions and are looking at international cooperation (See Section 5.1), given the scope of the project, it would be worthwhile discussing some fundraising options which are suggested below.

The space financing options vary from government funding, venture capitalists, public-private-partnership (PPP) among others. Each of the mentioned options has their advantages and disadvantages depending on the different purposes and sources.

Generally, PPP is interesting for the private entities that need large amount of money to cover an overall risk whereas the government funding is looking for attractive investments on the technological development and scientific research. However, the mutual interests from both parties are required as the primary funding options. Venture capitalists on the other hand are professionals specialized in investment in new growing market (Peeters and Gurtuna, 2007). They are however very selective in their investments and require high return interests.

Another innovative funding approach that is suggested in this report is the idea of issuing some kind of bonds referred as “lunar bonds” (Appendix D). Bonds are for the debt security, issued by authorized organization that owes the holders a debt and is obliged to repay the principal and interest, called the coupon, at a later date, termed maturity (AllBusiness, 2008). The participants of such market are mainly institutional investors, governments, traders, as well as individuals.
The lunar bond option, however, needs collateral guaranteed which is not apparent for a lunar base mission due to the fact that profitability about the Moon is unknown. Regarding other financing options, a return on investment is required but the lunar base is not predicted to generate a profit based on the uncertainties involved. It is difficult to predict any spin-offs, and other sources of revenue because currently planned lunar missions are scheduled to occur at least 10 years into the future. Therefore, these funding possibilities and, particularly, the lunar bonds are potential strategies developed by the emergence of the lunar base.

Apart from availability of natural resources on the Moon, a market for such resources must also exist. He-3, for example, is one resource present in abundance on the Moon; fusion with deuterium could produce a new source of energy that could be sold back on Earth (Crabb and Jacobs, 1992). The commercialization of lunar resources and the potential are hard to define due to the legal issues involved within: lunar natural resources exploitation, the state of benefits from the Moon, and the impact of the ‘common heritage of mankind’ principle under the 1979 Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (herein referred as the ‘Moon Agreement’) (Moon Agreement, 1979). These are some possible examples of potential economic benefit stemming from a lunar base.

2.3 Lunar Tasks

Irrespective of lunar base mission architecture, most base designs have a number of tasks in common throughout their establishment, development, and operation. For this report, a list of common tasks was generated and compiled as a result of discussion with industry experts and a thorough survey of literature on lunar base designs, including space agency and independent designer sources. Some tasks in particular were taken from Gies (1996), a study on different lunar base construction techniques and equipment. The list excluded any tasks to be performed off-surface such as cargo transport from the Earth to the Moon and spacecraft landings or takeoffs. A total of 66 tasks were identified and grouped into one of ten classifications:

1. **Base Construction**: All tasks associated with the preparation and construction of a lunar habitat including all infrastructure (see Table 2-1)
2. **Base Operation and Maintenance**: Those tasks necessary for normal mission operations on the lunar surface and for regular upkeep of base systems (see Table 2-2).
3. **ISRU**: Tasks related to the extraction, processing and transport of lunar resources (see Table 2-3).
4. **EVA Support**: Tasks necessary before and after EVAs in order to maintain optimum performance and safety (see Table 2-4).
5. **Safety Emergencies**: Those tasks performed in the event of an emergency while on the lunar surface (see Table 2-5).
6. **Personal Astronaut Activities**: Tasks required to maintain the physical and psychological well-being of crewmembers (see Table 2-6).
7. **Lunar Exploration**: Any activity required during exploration activities of the lunar surface outside of the lunar base perimeter (see Table 2-6).
8. **Lunar Science**: Comprises of all tasks to be performed related to lunar science experiments (biological, material, geological and life science) both inside and exterior to the lunar habitat (see Table 2-8).
9. **Robot Operation and Maintenance**: Consists of tasks specifically related to the operation, control, and maintenance of any robotic system (see Table 2-9).
10. **Public Relations**: Activities in support of terrestrial mass media and events (see Table 2-10).
Based on the lunar base phases defined in Section 2.2, each task was subsequently correlated with applicable base phases. Tasks that would begin in earlier phases of development were assumed to continue to some extent into subsequent phases, though the frequency of the task and the way in which it is performed could vary. As an example, the task of waste management will begin in Phase 1 of base development. Waste management must obviously be performed in Phases 2 and 3, but depending on the number of base occupants, base operations, and mission objectives, the frequency of the task may increase. Tables 2-1 to 2-10 show the complete task list, the phase of base development corresponding to when the task is expected to begin, and whether the task is performed inside or outside the lunar habitat, or both.

**Table 2-1: Base Construction**

<table>
<thead>
<tr>
<th>TASKS</th>
<th>DESCRIPTION</th>
<th>(O)UTSIDE/ (I)NSIDE</th>
<th>PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handtool tasks</td>
<td>Use of handtools for tasks that are complex or require substantial dexterity, or in support of other tasks.</td>
<td>O/I</td>
<td>1</td>
</tr>
<tr>
<td>Surveying</td>
<td>Initial surveying for semi-permanent or permanent structures.</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>Power system installation</td>
<td>Installation of solar arrays, RTGs, fuel cells or combustion generators, and all associated components.</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>Laying of electrical cables</td>
<td>Any tasks related to unrolling and laying of electric cable between habitat modules and power sources.</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>Lifting/stabilizing</td>
<td>Lifting, placing, and stabilizing of structural members/modules.</td>
<td>O</td>
<td>2</td>
</tr>
<tr>
<td>Connecting/disconnecting service lines</td>
<td>Service connections for hydraulic, pneumatic, water, and electrical lines.</td>
<td>O/I</td>
<td>2</td>
</tr>
<tr>
<td>Joining</td>
<td>Welding, riveting, or other methods of fastening structural members.</td>
<td>O</td>
<td>2</td>
</tr>
<tr>
<td>Connecting modules</td>
<td>Connecting of individual habitat modules in multi-module designs.</td>
<td>O</td>
<td>2</td>
</tr>
<tr>
<td>Excavation/Minning</td>
<td>Includes scooping, scraping, dozing, and ripping using heavy machinery similar to terrestrial designs. Use of explosives may also be considered.</td>
<td>O</td>
<td>3</td>
</tr>
<tr>
<td>Hauling</td>
<td>Includes loading, transport, and unloading of large quantities of construction material and lunar soil using heavy machinery.</td>
<td>O</td>
<td>3</td>
</tr>
<tr>
<td>Placing</td>
<td>Includes spreading, piling, compacting, and shaping of lunar soil using heavy machinery.</td>
<td>O</td>
<td>3</td>
</tr>
<tr>
<td>Transportation</td>
<td>Transportation of cargo, equipment, and personnel using lunar vehicles for the purpose of base construction.</td>
<td>O</td>
<td>3</td>
</tr>
</tbody>
</table>
## Table 2-2: Base Operation & Maintenance

<table>
<thead>
<tr>
<th>TASKS</th>
<th>DESCRIPTION</th>
<th>(O)UTSIDE/ (I)NINSIDE</th>
<th>PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housekeeping</td>
<td>Cleaning of habitat surfaces (interior and external) and scientific payloads; replacement of filters, bulbs, etc.</td>
<td>O/I 1</td>
<td></td>
</tr>
<tr>
<td>Waste management</td>
<td>Management of rubbish, human waste, and biological waste.</td>
<td>I 1</td>
<td></td>
</tr>
<tr>
<td>Climbing structures</td>
<td>Climbing in and out of habitat for EVA; climbing of base structures for maintenance purposes.</td>
<td>O 1</td>
<td></td>
</tr>
<tr>
<td>ECLSS/Life support maintenance</td>
<td>Monitoring and maintenance of ECLSS.</td>
<td>O/I 1</td>
<td></td>
</tr>
<tr>
<td>Fuelling operations</td>
<td>Fuelling, defueling, changing of fuel tanks.</td>
<td>O 2</td>
<td></td>
</tr>
<tr>
<td>Unloading/stowage of resupply cargo</td>
<td>Removing cargo from resupply craft and transporting</td>
<td>O 2</td>
<td></td>
</tr>
<tr>
<td>Harvesting</td>
<td>Cultivation and processing of on-site food sources such as grains, vegetables, etc.</td>
<td>I 2</td>
<td></td>
</tr>
<tr>
<td>Food processing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irrigation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crew rover maintenance</td>
<td>Changing of batteries, repair to damaged components, cleaning away dust, etc.</td>
<td>O 2</td>
<td></td>
</tr>
<tr>
<td>Power system maintenance</td>
<td>Periodic cleaning, adjustment, or replacement/repair of power system components.</td>
<td>O 2</td>
<td></td>
</tr>
</tbody>
</table>

## Table 2-3: ISRU

<table>
<thead>
<tr>
<th>TASKS</th>
<th>DESCRIPTION</th>
<th>(O)UTSIDE/ (I)NINSIDE</th>
<th>PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining</td>
<td>Location and extraction of lunar resources.</td>
<td>O 3</td>
<td></td>
</tr>
<tr>
<td>Processing</td>
<td>Processing of lunar resources into refined or more usable products.</td>
<td>O/I 3</td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td>Transportation of raw lunar resources from extraction site to processing site.</td>
<td>O 3</td>
<td></td>
</tr>
<tr>
<td>Refined material production</td>
<td>Production of any refined product using lunar resources (e.g. concrete, fuel, etc.)</td>
<td>O/I 3</td>
<td></td>
</tr>
</tbody>
</table>

## Table 2-4: EVA Support

<table>
<thead>
<tr>
<th>TASKS</th>
<th>DESCRIPTION</th>
<th>(O)UTSIDE/ (I)NINSIDE</th>
<th>PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Donning/doffing of EVA suits</td>
<td>Any tasks related to putting on or taking off EVA suits.</td>
<td>I 1</td>
<td></td>
</tr>
<tr>
<td>EVA suit maintenance/repair</td>
<td>All tasks necessary in the upkeep of EVA suits</td>
<td>I 1</td>
<td></td>
</tr>
<tr>
<td>Pre-breathe</td>
<td>Pre-breathing by astronauts prior to EVA</td>
<td>I 1</td>
<td></td>
</tr>
</tbody>
</table>
## Table 2-5: Safety Emergencies

<table>
<thead>
<tr>
<th>TASKS</th>
<th>DESCRIPTION</th>
<th>(O)UTSIDE/ (I)NSIDE</th>
<th>PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transporting injured</td>
<td>Transportation of injured crewmembers on EVA back to lunar habitat.</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>Minor surgery/telesurgery</td>
<td>Surgery restricted to the management of minor problems and injuries; surgical procedures of relatively slight extent and not in themselves hazardous to life.</td>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>First Aid/CPR/trauma treatment</td>
<td>Response to situations or conditions having a high probability of disabling or immediately life-threatening consequences or requiring first aid or other immediate intervention (including surgical and non-surgical procedures like CPR).</td>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>Treatment of psychiatric emergencies</td>
<td>Dealing with crew who suffer from acute psychiatric conditions.</td>
<td>O/I</td>
<td>1</td>
</tr>
<tr>
<td>Evacuation</td>
<td>Removal of crewmembers from lunar base to evacuation spacecraft.</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>Retrieval of stranded</td>
<td>Search and recovery of lost or stranded crewmembers during lunar excursions.</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>Fire fighting</td>
<td>Suppression of fires within lunar habitat.</td>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>Death management</td>
<td>Care, removal, and/or stowage of body(ies).</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>Quarantine</td>
<td>Isolation of crew, animals, or samples that have been exposed to infection material or have recently arrived from Earth.</td>
<td>I</td>
<td>2</td>
</tr>
<tr>
<td>Emergency dentistry</td>
<td>Treatment of dental problems requiring immediate intervention.</td>
<td>I</td>
<td>3</td>
</tr>
<tr>
<td>Major surgery/telesurgery</td>
<td>Major operative procedures on organs, regions, or tissues in the treatment of diseases, including use of lasers. Operations may be carried out for the correction of deformities and defects, repair of injuries, and diagnosis and cure of certain diseases.</td>
<td>I</td>
<td>3</td>
</tr>
</tbody>
</table>

## Table 2-6: Personal Astronaut Activities

<table>
<thead>
<tr>
<th>TASKS</th>
<th>DESCRIPTION</th>
<th>(O)UTSIDE/ (I)NSIDE</th>
<th>PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hygiene</td>
<td>Includes bathing, dental/oral hygiene, and toilet-related tasks.</td>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>Eating-Nutrition</td>
<td>Includes the preparation and consumption of meals.</td>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>Sleeping</td>
<td>Daily rest periods.</td>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>Communication</td>
<td>Communication between crewmembers, crew with ground control, and personal communications.</td>
<td>O/I</td>
<td>1</td>
</tr>
<tr>
<td>Recreation</td>
<td>Leisure activities.</td>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>Psychological monitoring</td>
<td>Monitoring of crewmembers’ state of mind throughout a mission.</td>
<td>O/I</td>
<td>1</td>
</tr>
<tr>
<td>Medical countermeasures</td>
<td>Carrying out required physiological and psychological countermeasures.</td>
<td>I</td>
<td>1</td>
</tr>
</tbody>
</table>
### Table 2-7: Lunar Exploration

<table>
<thead>
<tr>
<th>TASKS</th>
<th>DESCRIPTION</th>
<th>(O)UTSIDE/INSIDE</th>
<th>PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travelling</td>
<td>Travelling to lunar sites of interest for exploratory, geological, surveying or ISRU purposes.</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>Sample collection</td>
<td>Physical sampling of lunar geology.</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>Navigating</td>
<td>Navigating between lunar base and points of interest.</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>Repelling/Climbing</td>
<td>Descent/ascent of high inclination slopes requiring special equipment.</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>Transporting scientific instruments</td>
<td>Transportation of any instrumentation necessary for exploration activities.</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>Communication</td>
<td>Communication between crewmembers during excursions.</td>
<td>O</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 2-8: Lunar Science

<table>
<thead>
<tr>
<th>TASKS</th>
<th>DESCRIPTION</th>
<th>(O)UTSIDE/INSIDE</th>
<th>PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample analysis</td>
<td>Analysis of lunar, biological, material, and human samples within lunar habitat.</td>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>Sample preparation</td>
<td>Preparation of lunar, material, biological, and human samples.</td>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>Measurement taking</td>
<td>Taking of various scientific measurements exterior to the lunar habitat.</td>
<td>O</td>
<td>1</td>
</tr>
<tr>
<td>Experiment setup</td>
<td>Setup of various scientific experiments.</td>
<td>O/I</td>
<td>1</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Maintenance of software/hardware, calibration of instruments.</td>
<td>O/I</td>
<td>1</td>
</tr>
<tr>
<td>Data processing</td>
<td>Processing of any raw data collected during experiments, including the transmission of data back to Earth for further analysis and processing.</td>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>Life science BDC</td>
<td>Baseline data collection of human physiological and biochemical parameters.</td>
<td>I</td>
<td>1</td>
</tr>
<tr>
<td>Control of experiments</td>
<td>Monitoring and control of experiment conditions and procedures.</td>
<td>O/I</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 2-9: Robot Operation and Maintenance

<table>
<thead>
<tr>
<th>TASKS</th>
<th>DESCRIPTION</th>
<th>(O)UTSIDE/INSIDE</th>
<th>PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remote control of robots</td>
<td>Remote operation of robotic systems.</td>
<td>O/I</td>
<td>1</td>
</tr>
<tr>
<td>Maintenance of robots</td>
<td>Maintenance of robotic systems.</td>
<td>O/I</td>
<td>1</td>
</tr>
<tr>
<td>Integration of robots</td>
<td>Integration of individual robotic components as transported to the lunar base</td>
<td>O/I</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 2-10: Public Relations

<table>
<thead>
<tr>
<th>TASKS</th>
<th>DESCRIPTION</th>
<th>(O)UTSIDE/INSIDE</th>
<th>PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interviews</td>
<td>Providing media coverage for Earth programming.</td>
<td>O/I</td>
<td>1</td>
</tr>
</tbody>
</table>
As mentioned earlier in Section 1.4, the focus of this report is on the early development stages of a lunar base. For this reason, all tasks to begin in Phase 3 were omitted from further analysis. A full listing of all tasks associated with Phases 1 and 2 can be found in Appendix A. Following the filtering of Phase 3 tasks, the level of required participation by astronauts in each remaining task was next identified.

According to Salleberger (1999), tasks for humans to perform should require high mechanical dexterity, such as required when assembling complex parts. Both repair operations as well as the operation of experimental equipment are attributed with an unpredictable level of complexity, and therefore should be carried-out by astronauts. Even some predictable tasks can be accomplished by astronauts should it be difficult to program a robot. Geological surveying and in-field analysis is another example of tasks to be undertaken by astronauts due to the requirement of identifying unpredictable patterns, motions, color, intensity, and time. Tasks for robotic execution should involve integrating many similar and predictable sub-tasks, such as routine operations in an experiment. Tasks requiring extreme physical labor should also be carried-out by robots (e.g., rapid, precise, stable motions, or high-force operations). (Salleberger, 1999)

In light of the above mentioned criteria, tasks were classified as A(stronaut), S(hared), or R(obotics). A(stronaut) tasks will only be performed by astronauts, while S(hared) tasks might have robotic assistance, but will require some degree of astronaut participation. R(obotics) tasks will likely be performed by autonomous robots. Classifications were made based on results from a literature survey of terrestrial analogs and current space applications. For the purpose of this report, only tasks which require some level of astronaut participation but may be assisted by robotics (‘S’ ranking) in Phases 1 or 2, were considered for further analysis. Table 2-11 shows the remaining tasks, categorized by phase, which were considered in a subsequent risk analysis.
Table 2-11: Shared tasks for early lunar base development

<table>
<thead>
<tr>
<th>CLASSIFICATION</th>
<th>TASKS</th>
<th>PHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td><strong>Base Construction</strong></td>
<td>Lifting/stabilizing</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Connecting/disconnecting service lines</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Joining</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Hand tool tasks</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Surveying</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Connecting modules</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Power system installation</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Laying of electrical cables</td>
<td>A</td>
</tr>
<tr>
<td><strong>Base Operation &amp; Maintenance</strong></td>
<td>Fuelling operations</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Unloading/stowage of resupply cargo</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Harvesting</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Food processing</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Irrigation</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Climbing structures</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Crew rover maintenance</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Power system maintenance</td>
<td>A</td>
</tr>
<tr>
<td><strong>Safety Emergencies</strong></td>
<td>Transporting injured</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Minor surgery/telesurgery</td>
<td>S</td>
</tr>
<tr>
<td><strong>Lunar Exploration</strong></td>
<td>Sample collection</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>Rappelling/Climbing</td>
<td>A</td>
</tr>
<tr>
<td><strong>Lunar Science</strong></td>
<td>Transporting scientific instruments</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Sample preparation</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Measurement taking</td>
<td>S</td>
</tr>
<tr>
<td><strong>Robot Operation and Maintenance</strong></td>
<td>Integration of robots</td>
<td>S</td>
</tr>
</tbody>
</table>

International Space University, Masters 2008
3 RISK ANALYSIS

Crew safety has been, and will always be, a priority for manned space flights. It is important to consider all potential risks that threaten the integrity and health of the astronauts living and working on a lunar base, in order to provide safe conditions for human activity. There are different kinds of hazards when considering human safety on a lunar base, such as those risks inherent to the Moon’s environment, risks related with living in a distant and confined place, and the risks associated with daily work activities.

The space and lunar environments are different from that of the Earth, and therefore constitute potential inherent risks to human permanence on the Moon. Some of the principal differences on the Moon include a reduced gravity, only one sixth of the Earth's, cosmic ionizing radiation, solar ultraviolet radiation, the absence of significant atmosphere or water, extremes in temperature, and lunar surface dust (Horneck, 1996). In addition to the inherent risks of the environment, there are some conditions related with living on a lunar base that constitute potential risks to the physical and psychological areas of the crew such as isolation, confined space, food restricted in quality and diversity, lack of privacy, high noise, altered day-night cycle, constrained social interaction, distant and remote communications with family, and stressful workloads (Brady, 2005). Finally, the human body can suffer spontaneous pathologic events that range from partially defined symptoms to systemic diseases, or accidental traumatic injuries (MEDES-CNES, 1992).

Space agencies have done comprehensive work and research by identifying risks and requirements to provide safe conditions to astronauts on ISS, lunar, and Mars missions. NASA’s Bioastronautics Roadmap is a tool used to identify, assess, and reduce risks for the crew. It considers a lunar mission of 30-days with four astronauts and focuses on health and medical risks, as well as engineering and system performance risks (NASA, 2005). ESA evaluated the human response limits for a lunar mission of 180-days with crew size of four through the “Study on the Survivability and Adaptation of Humans to Long-Duration Exploratory Missions”, also known as the HUMEX study (Horneck et al., 2003). One of the objectives of this study was to assess factors related with human health, well-being and performance.

Although all of the above mentioned risks, and the physical, chemical, or biological hazards of a lunar base, constitute important threats to crew safety, this report will consider only the potential risks associated with tasks that astronauts would perform on a lunar base in the first or second phases of its development, as defined in Section 2.2. The risks evaluated in NASA’s Bioastronautics Roadmap and the results of the HUMEX study were used as guides in the process of identifying and assessing these risks.
3.1 Criteria, Methodology, and Results

The following sections describe the framework and procedure for the risk assessment, as they were defined and carried out for this project.

3.1.1 Risk Definition

There is currently no universally accepted definition of risk; instead, many space agencies seem to adopt their own definition entirely. For NASA, “risk is characterized by the combination of the probability that a program or project will experience an undesired event... and the consequences, impact, or severity of the undesired event, were it to occur” (NASA, 2007b). ESA defines risk as, “an undesirable situation or circumstance that has both likelihood of occurring and a potential negative consequence on a project” (European Cooperation for Space Standardization, 2007; Reid and Romero, 2003). These definitions are used by space agencies for projects or missions, and can be applied to analyze cost, schedule, safety, or environmental impact. However, when considering the aspect of crew safety, a suitable definition for risk is provided by the Institution of Occupational Safety and Health (IOSH). According to the IOSH, and supported by the European Agency for Safety and Health at Work (EU-OSHA), a risk can be defined as a "combination of likelihood and consequences of a specified hazardous event." These organizations also define accident as an unplanned event leading to damage, injury/illness, death or loss, and incident as an event causing damage, injury/illness, death or loss, or that has the potential to do so (IOSH, 2002).

3.1.2 Identification of Risks per Task

Once a definition of risk has been established, each task presented in the previous section was evaluated for the possibility of risks to astronauts if they were to perform the task. Specific risks that are common to all EVA activities were combined within a generic EVA risk category, resulting in three so-called generic tasks: EVA, Pedestrian EVA (PEVA), and Rover EVA (REVA). An extensive list of risks for all the tasks was created and summarized in Appendix B. Given the time constraints and limited resources of this project, it was impossible to consider all the risks associated with each task listed; therefore, only the tasks that had the greatest impact on an astronaut's wellbeing were considered.

The impact of each risk was evaluated by scoring the probability of occurrence (likelihood) and the magnitude of its effect (severity) (Preyssl et al., 1999). Likelihood and severity of each risk were compared to determine which risks had the greatest impact on crew safety. Determining likelihood and severity is a difficult process, and it involves many uncertainties and many assumptions influenced by the perception and level of acceptance of risk among different populations and organizations. Different classifications of likelihood and severity from various sources are shown in Table 3-1 and Table 3-2, respectively. The differences in estimating and assessing risks generate a variation when scoring risks (Department of Health and Aging-Australian Government, 2007); therefore, a standardization of classification and criteria is required to effectively score the different risks encountered.

Most of the classifications presented were established to assess projects or missions, and not for assessing crew safety. For this reason classifications for emergencies and health risks outside of the space sector were considered.
<table>
<thead>
<tr>
<th>AUSTRALIAN GOVERNMENT</th>
<th>ESA</th>
<th>NASA BIOASTRONAUTICS</th>
<th>NASA - GUIDELINES RISK MANAGEMENT</th>
<th>UK GOVT</th>
<th>NASA NPR 8000.46</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marginal: there is minimal or no negative impact</td>
<td>Negligible risk items with a potential of increase or being triggered by other risk</td>
<td>No impact to crew</td>
<td>Discomfort or nuisance</td>
<td>Insignificant number of injuries or impact on health</td>
<td>Negligible: a condition that could cause the need for minor first aid treatment but would not adversely affect personal safety or health;</td>
</tr>
<tr>
<td>Minor: there is some negative impact</td>
<td>Small injury</td>
<td>Short-term minor injury, illness, incapacitation on impairment to crewmember</td>
<td>First aid event per Occupational Health and Safety Administration (OSHA) criteria</td>
<td>Small number of people affected, no fatalities, and small number of minor injuries</td>
<td>Moderate: a condition that may cause minor injury or occupational illness</td>
</tr>
<tr>
<td>Immediate: the negative impact is substantial</td>
<td>Significant injury</td>
<td>Serious injury, illness, incapacitation or impairment, but not long term</td>
<td>No lost time injury or illness per OSHA criteria</td>
<td>Moderate number of fatalities with some casualties requiring hospitalization and medical treatment</td>
<td>Critical: a condition that may cause severe injury or occupational illness</td>
</tr>
<tr>
<td>Major: the negative impact is severe</td>
<td>Severe injury</td>
<td>Significant impairment, not permanent</td>
<td>No lost time injury or illness per OSHA criteria</td>
<td>Significant number of people with multiple fatalities, multiple serious or extensive injuries</td>
<td>Catastrophic: death or permanently disabling injury</td>
</tr>
<tr>
<td></td>
<td>Lethal injury</td>
<td>Irreversible, catastrophic impairment or death</td>
<td>Loss of life</td>
<td>Very large numbers of people impacted, significant numbers of fatalities, serious injuries with longer-term effects</td>
<td></td>
</tr>
</tbody>
</table>

2. Schroeter, 2007
3. NASA, 2003a
4. NASA, 2008a
5. UK Resilience – Cabinet Office, 2008
6. NASA, 2007b
### Table 3.2: Comparison of classifications for likelihood

<table>
<thead>
<tr>
<th>SCORE</th>
<th>AUSTRA-LIAN GOVT&lt;sup&gt;1&lt;/sup&gt;</th>
<th>ESA&lt;sup&gt;2&lt;/sup&gt;</th>
<th>NASA BIOASTRONAUTICS&lt;sup&gt;3&lt;/sup&gt;</th>
<th>NASA - GUIDELINES RISK MANAGEMENT&lt;sup&gt;4&lt;/sup&gt;</th>
<th>ESA&lt;sup&gt;5&lt;/sup&gt;</th>
<th>UKGOVERNMENT&lt;sup&gt;6&lt;/sup&gt;</th>
<th>NASA NPR 8000.4&lt;sup&gt;7&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/ A</td>
<td>Highly unlikely</td>
<td>Remote</td>
<td>Very low</td>
<td>Not likely</td>
<td>&lt;20%</td>
<td>&lt;0.1% (&lt;1:1000)</td>
<td>Negligible</td>
</tr>
<tr>
<td>2/ B</td>
<td>Unlikely</td>
<td>Unlikely</td>
<td>Low</td>
<td>Low likelihood</td>
<td>20 – 40%</td>
<td>0.1 – 1% (1:100 – 1:1000)</td>
<td>Rate</td>
</tr>
<tr>
<td>3/ C</td>
<td>Likely</td>
<td>Likely</td>
<td>Moderate</td>
<td>Likely</td>
<td>40 – 60%</td>
<td>1 – 10% (1:10 – 1:100)</td>
<td>Unlikely</td>
</tr>
<tr>
<td>4/ D</td>
<td>Highly likely</td>
<td>Highly likely</td>
<td>High</td>
<td>Highly likely</td>
<td>60 – 80%</td>
<td>10 – 100% (1:1 – 1:10)</td>
<td>Possible</td>
</tr>
<tr>
<td>5/ E</td>
<td>Near certainty</td>
<td>Very high</td>
<td>Near certainty</td>
<td>&gt;80%</td>
<td>Max.</td>
<td>100% (1:1)</td>
<td>Probable</td>
</tr>
</tbody>
</table>

2. Schroeter, 2001
3. NASA, 2003a
4. NASA, 2008a
5. Preyssl et al., 1999
7. NASA, 2007b
3.1.3 Likelihood

Currently, there is no common standard how to rate the likelihood of health and safety risks to astronauts with regard to incidents, accidents, or emergencies that could potentially occur while astronauts are performing tasks on the lunar surface.

Submarine and Antarctic missions are analogous to exploratory missions on the Moon, and could provide information about the possible occurrence of hazardous events. For example, the occurrence of certain types of illnesses during extended submarine missions are similar to the rate of occurrence encountered during space flights (Ball and Evans, 2001). The occurrence of health concerns among crewmembers aboard 136 submarine patrols between 1997 and 1998 were analyzed and their occurrences were estimated. This study estimated the occurrence of illness to be 119.8/100,000 person-days, and the occurrence of accidents to be 37.2/100,000 person-days within a population in an isolated environment. The occurrence of injuries was found to be 48.8/100,000 person-days, where open wounds were 21.0 /100,000 person-days (Thomas et al., 2000; Thomas et al., 2003; Ball and Evans, 2001). In analogous environments the annual occurrence of surgical diseases requiring evacuation or invasive intervention is approximately 1/10,000 person-days; this means that for a crew of six, the probability will be approximately once in four years (Cermack, 2000). The HUMEX study analyzed the probability of diseases, injuries, and death on lunar missions. This study evaluated health statistics from the general population, and from professions exposed to hazards on a more regular basis; professions such as, fighter pilots, helicopter pilots, and astronauts (Horneck and Comet, 2006). The estimated occurrence of injuries for a lunar mission with duration of 180 days, and a crew size of four astronauts are presented in Table 3-3 using the HUMEX study.

Table 3-3: Estimated incidences of injuries per mission of 180 days, 4 crewmembers in a lunar base according to HUMEX. (Horneck and Comet, 2006)

<table>
<thead>
<tr>
<th>TYPE OF INJURY</th>
<th>INCIDENCE PER MAN-YEAR</th>
<th>INCIDENCE PER MISSION ON SURFACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head injury</td>
<td>0.002</td>
<td>0.004</td>
</tr>
<tr>
<td>Internal injury</td>
<td>0.0005</td>
<td>0.0010</td>
</tr>
<tr>
<td>Open wounds</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Contusions</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>Crushing injury</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Burns</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Radiation short term (standard limits respected)</td>
<td>0.0001</td>
<td>0.0002</td>
</tr>
<tr>
<td>Radiation long-term (standard limits respected)</td>
<td>0.0008</td>
<td>0.0016</td>
</tr>
<tr>
<td>Dislocations</td>
<td>0.005</td>
<td>0.001</td>
</tr>
<tr>
<td>Sprains / Strains</td>
<td>0.07</td>
<td>0.14</td>
</tr>
<tr>
<td>Fracture of upper limb</td>
<td>0.006</td>
<td>0.012</td>
</tr>
<tr>
<td>Fracture of lower limb</td>
<td>0.003</td>
<td>0.006</td>
</tr>
<tr>
<td>Mortality by injury (excluding spacecraft failure)</td>
<td>0.0004</td>
<td>0.0008</td>
</tr>
<tr>
<td>Mortality by illness or injury (excluding spacecraft failure)</td>
<td>0.0024</td>
<td>0.0048</td>
</tr>
</tbody>
</table>
Based on the previous statistics, it is possible to conclude that the classification of likelihood used by the Bioastronautics Roadmap is not appropriate to assess risks with the tasks listed previously, because the percentages of each level might not be applicable to the probabilities of incidents or accidents on a lunar base. In addition, the acceptable level of risk in this classification would not be adequate for some of the potential risks of each task. For example, according to the Bioastronautics Roadmap, an estimated probability of 1 percent in mortality would be classified as acceptable, but would be very high for the safety targets identified in the HUMEX study. This issue is also evident in the NASA Risk Management Guidelines (NASA, 2008a) where the classification cannot be compared with the statistics presented previously. ESA’s criteria for likelihood (Schroeter, 2001), has different categories of likelihood that can involve a large range of probabilities, which allows for a difference in interpretation due to lack of reliable numerical data; for instance, an event could be likely for one member of the team but unlikely for the other according to their subjective interpretation and division of the categories of likelihood.

The scoring of likelihood involves subjectivity and uncertainties, but numerical classifications for the different levels allows a common scoring system between different people making the assessment. A classification with numerical categories applied by ESA (Preyssl et al, 1999) could be a tool to compare probabilities in HUMEX. However, that classification is proposed for missions and projects, it does not consider health and safety, and it is not clear if manned space missions were included as part of its original intent. Finally, the classification of likelihood in the Emergency Preparedness Guidelines in the United Kingdom (UK Resilience – Cabinet Office, 2008) provides a better definition of the levels to be applied to the safety objectives in the HUMEX study than any other classification, while also being designed to assess emergencies. Although it was not designed for lunar exploration, it seems to be the best classification to estimate the probability of risks for human and robotic tasks on the lunar surface with regards to crew safety. The scoring scale used to evaluate likelihood is presented in Table 3-4.

3.1.4 Severity

Although the criteria of the Emergency Preparedness Guidelines in the United Kingdom (UK Resilience – Cabinet Office, 2008) can be applicable to score likelihood, it cannot be applied to score severity on a lunar base. Its classification divides severity according to the impact of the emergency on populations. For example, a moderate number of fatalities can be accepted as a moderate risk. Agencies on the other hand have developed classifications to score severity relating to cost, schedule, performance, mission, safety or science. The NASA Risk Management Guidelines (NASA, 2008a) use the criteria of OSHA to score the impact on crew safety. However, there is no difference between some of its categories of severity, and it only mentions injuries or loss of time as impact. ESA’s categories for crew health (Schroeter, 2007) only take into consideration levels of injury. The classification proposed by NASA Bioastronautics Strategy (NASA, 2003a) covers not only injuries, but also impairment and long term consequences. All consequences of the astronaut’s health and safety such as, injury, illness, impairment, and long term effects are important when determining the impact and severity of an effect on the crew. The scoring scale used to evaluate severity is presented in Table 3-4.
### Table 3-4: ALERTS classification of severity and likelihood. (Adapted from: Schroeter, 2001; Schroeter, 2007; NASA, 2003b; UK Resilience - Cabinet Office, 2008)

<table>
<thead>
<tr>
<th>SEVERITY</th>
<th>LIKELIHOOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCORE</td>
<td>CLASSIFICATION</td>
</tr>
<tr>
<td>5</td>
<td>Lethal injury. Irreversible or catastrophic impairment</td>
</tr>
<tr>
<td>4</td>
<td>Severe injury and long-term impairment, but not permanent</td>
</tr>
<tr>
<td>3</td>
<td>Significant injury, illness, incapacitation or impairment, but not long term</td>
</tr>
<tr>
<td>2</td>
<td>Small injury or minor, illness, incapacitation, or impairment to crewmember</td>
</tr>
<tr>
<td>1</td>
<td>Negligible risk items with a potential of increase or being triggered negatively by other risk items</td>
</tr>
</tbody>
</table>

#### Table 3-5: 5x5 risk matrix (Adapted from: Schroeter, 2007; NASA, 2008a; personal communication, Walter Peeters, 6 May 2008)

The 5x5 risk matrix is used to prioritize risks based on their severity and likelihood. Each cell in the matrix has a risk score ranging from 1 (lowest risk) to 25 (highest risk). The matrix helps in identifying which risks are acceptable, which require mitigation, and which are unacceptable and require mandatory mitigation.

#### 3.1.5 Risk Scoring Results and Task Prioritization

After completing the risk assessment process with the score of likelihood and severity for each risk, a predetermined numerical value was given to the final combination of likelihood and severity for each risk. These values represent the risk priority score for each cell of the 5x5 risk matrix and they are assigned from one (lowest risk or A1) to 25 (maximum risk or E5) in the matrix.
risk matrix. See Table 3-5. NASA and ESA have different prioritization of cells on the risk matrix; however, ESA's prioritization of cells of the risk matrix was used for this report (Schroeter, 2001; Schroeter, 2007, NASA, 2008).

Finally, the scores of all the risks for each task were combined to obtain the total score of the risks per task allowing comparison between tasks, and subsequently yielded the prioritization of tasks. The results of the risk analysis, including the numerical scores of each risk and total numerical score of each task, are presented in Appendix B. Table 3-6 shows the list of tasks organized by total risk score or priority. It should be noticed that all tasks involving EVA have higher scores due to the risks associated with EVA in addition to the risks of each task.

<table>
<thead>
<tr>
<th>No.</th>
<th>TASK</th>
<th>No.</th>
<th>TASK</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Retrieval of stranded</td>
<td>16</td>
<td>Climbing structures</td>
</tr>
<tr>
<td>2</td>
<td>Transporting of injured</td>
<td>17</td>
<td>Joining (welding, fastening)</td>
</tr>
<tr>
<td>3</td>
<td>Solar panel maintenance</td>
<td>18</td>
<td>Laying of electrical cables</td>
</tr>
<tr>
<td>4</td>
<td>Rappelling/Climbing</td>
<td>19</td>
<td>Handtool tasks  (exterior)</td>
</tr>
<tr>
<td>5</td>
<td>Unloading/stowage of resupply cargo</td>
<td>20</td>
<td>Surveying</td>
</tr>
<tr>
<td>6</td>
<td>Power system installation</td>
<td>21</td>
<td>Connecting/Disconnecting service lines (interior)</td>
</tr>
<tr>
<td>7</td>
<td>Connecting/Disconnecting service lines (exterior)</td>
<td>22</td>
<td>Integration of robots (interior)</td>
</tr>
<tr>
<td>8</td>
<td>Fuel operations</td>
<td>23</td>
<td>Minor surgery/telesurgery</td>
</tr>
<tr>
<td>9</td>
<td>Connecting modules</td>
<td>24</td>
<td>Sample collection</td>
</tr>
<tr>
<td>10</td>
<td>Experiment setup (exterior)</td>
<td>25</td>
<td>Handtool tasks  (interior)</td>
</tr>
<tr>
<td>11</td>
<td>Integration of robots (exterior)</td>
<td>26</td>
<td>Experiment setup (interior)</td>
</tr>
<tr>
<td>12</td>
<td>Crew rover maintenance</td>
<td>27</td>
<td>Sample Preparation</td>
</tr>
<tr>
<td>13</td>
<td>Transporting scientific equipment</td>
<td>28</td>
<td>Irrigation</td>
</tr>
<tr>
<td>14</td>
<td>Measurement taking</td>
<td>29</td>
<td>Harvesting</td>
</tr>
<tr>
<td>15</td>
<td>Lifting/stabilizing</td>
<td>30</td>
<td>Food processing</td>
</tr>
</tbody>
</table>

### 3.2 Current and Proposed Countermeasures

By combining the tasks selected for further evaluation in Section 2.3 with the risk assessment performed in Section 3.1, a number of high priority risks associated with those tasks were identified. Table 3-7 presents the thirty risks associated with these tasks after the low probability risks (score <7) were eliminated. A number of risks are common across the tasks, therefore, current and proposed human spaceflight mitigation strategies will be discussed by risk as opposed to by task.
Table 3-7: Thirty selected high priority risks

<table>
<thead>
<tr>
<th>RISK LEVEL</th>
<th>SCORE</th>
<th>RISK</th>
<th>TASK</th>
</tr>
</thead>
<tbody>
<tr>
<td>A5</td>
<td>10</td>
<td>Radiation exposure (acute) - lethal</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>19</td>
<td>Radiation exposure (chronic)</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>10</td>
<td>Micrometeorite impact</td>
<td></td>
</tr>
<tr>
<td>B4</td>
<td>14</td>
<td>Suit tear</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>10</td>
<td>Failure of life support</td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>13</td>
<td>Finger injury</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>11</td>
<td>Poor visibility</td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>16</td>
<td>Lunar dust infiltration</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>12</td>
<td>Psychological stress (performance impairing)</td>
<td>EVA</td>
</tr>
<tr>
<td>D1</td>
<td>7</td>
<td>Psychological stress (normal activity-related stress)</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>10</td>
<td>Sun-blindness</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>10</td>
<td>Broken visor</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>11</td>
<td>Overexertion</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>7</td>
<td>Fatigue</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>8</td>
<td>Roll-rover</td>
<td></td>
</tr>
<tr>
<td>B4</td>
<td>14</td>
<td>Falling</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>8</td>
<td>Electrocution/shock - major</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>10</td>
<td>Electrocution/shock - lethal</td>
<td></td>
</tr>
<tr>
<td>B4</td>
<td>14</td>
<td>Stranding of rescuer</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>8</td>
<td>Stranding</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>10</td>
<td>Pinching - lethal</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>10</td>
<td>Battery explosion</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>8</td>
<td>Additional injury resulting from movement</td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>19</td>
<td>Delay/insufficient time</td>
<td></td>
</tr>
<tr>
<td>B5</td>
<td>17</td>
<td>Insufficient rescue time</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>8</td>
<td>Locating difficulties</td>
<td></td>
</tr>
<tr>
<td>B5</td>
<td>17</td>
<td>Insufficient equipment</td>
<td></td>
</tr>
<tr>
<td>B3</td>
<td>12</td>
<td>Contamination of wound</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>8</td>
<td>Unpredictable complications</td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>7</td>
<td>Contamination of environment</td>
<td></td>
</tr>
</tbody>
</table>

3.2.1 Radiation Exposure (Acute) – Lethal

Solar events produce extreme levels of radiation, and present a serious health risk to astronauts. High doses of radiation can result in acute radiation syndrome, which includes marrow syndrome, gastrointestinal syndrome, cardiovascular syndrome and central nervous system syndrome (Epelman and Hamilton; 2006).
According to Epelman and Hamilton, two mitigation strategies to prevent radiation exposure are early warning and more effective shielding. These strategies provide opportune information to move astronauts inside a heavily shielded safe-haven module (Epelman and Hamilton, 2006). Monitoring systems, dosimeters, and biological markers are also required to determine the absorbed dose. Drugs such as amifostine can also be used as cytoprotective agents before radiation exposure. The habitat should have facilities to make the clinical diagnosis. Therapeutic capabilities should be included to manage fluid loss, antiemetics and electrolytes control. Growth factors to stimulate bone marrow or stored stem cells could be used in case of immunosuppression. Antimicrobial therapy for infections or sepsis associated with damage of the mucosa in the gastrointestinal syndrome is mandatory. Laparoscopic and ultrasound-guided drainage capabilities could be important in case of abscess or peritonitis. The cardiovascular/central nervous system syndrome includes nervousness, a burning sensation of the skin, profuse watery diarrhea, altered blood pressure, cerebral edema, seizures and coma. The irradiated crewmember could also develop vasculitis, pericarditis, and meningitis leading to death within 2 to 7 days. In this case palliative therapy with sedation and pain control is the best therapy (Epelman and Hamilton; 2006).

3.2.2 Radiation Exposure (Chronic)

Depending on sex and age when the astronaut was first exposed to radiation, the 10-year career limit of radiation exposure for astronauts range from 0.4 to 3.0 Sv, (Townsend and Fry, 2002). Radiation can cause Deoxyribonucleic Acid (DNA) damage and cell death, mutations and chromosomal aberrations that can be associated with carcinogenesis (Ohnishi, 2004).

One mitigation strategy is primary prevention with selection of astronaut that could be less sensitive to the effects of radiation. (Epelman and Hamilton; 2006). It is also important to provide passive radiation shielding of habitats and suits, and space weather forecasting. It is possible to use antioxidants to reduce the effects of free radicals, which are produced as consequence of radiation exposure. Monitoring of radiation exposure can be done by dosimeters for the astronauts. It is also necessary to use biodosimeters to determine the biological effect of radiation using blood samples and analyzing chromosomal aberrations in lymphocytes (Buckey, 2006). Different strategies of antitumor gene therapy exist such as inducing expression of proapoptotic genes, controlling assembly of oncolytic virus, and activating prodrugs in tumor cells. Many of these therapies have shifted their target towards the expression of Telomerase Reverse Transcriptase (hTERT) gene (Olausson et al., 2006; ISU, 2005). Finally, immunotherapy has been proposed as an option to treat tumors. It is also possible to use antitumoral vaccination since tumors express antigens that can be used as targets. Cytotoxic T lymphocytes can recognize peptides derived from those antigens destroying the tumoral cells in early stages. In this case, the catalytic subunit of telomerase hTERT is also a promising candidate as a human tumour-associated-antigen. The telomerase immunotherapy can induce clinical responses without major treatment-related side effects. (Olausson et al, 2006; ISU, 2005)

3.2.3 Micrometeorite Impact of Astronaut

The probability of an astronaut being struck by a micrometeorite over the course of one year on the surface of the Moon is $10^{-8}$ to $10^{-6}$ (Heiken et al. in ISU, 2008). Although this is a very low probability, a particle as small as 1 mm in diameter can have sufficient kinetic energy to damage the spacesuit and place the astronaut’s health at risk (Ware et al. in Harris, 2001; and Larson &
Pranke in Waldie, 2005).

Currently, USA and Russian EMUs for the ISS, similar to Apollo suits, employ a Thermal Meteoroid Garment (TMG) over the pressure bladder layers to protect against damage of the pressure bladder from micrometeorite impact. The TMG is a multilayer garment capable of dissipating the kinetic energy of micrometeorite particles. However, current TMG assemblies are typically designed to stop 1 mm diameter particles traveling at a speed of 17 km/s (Harris, 2001; and Waldie, 2005). The Russian Orlan series spacesuits, in addition to a TMG assembly, employ a redundant pressure bladder that will activate if the primary bladder fails (Abramov and Skoog, 2003). Although the Russian suits provide better protection than the USA EMU, a secondary bladder adds complexity to the suit and in turn introduces more potential sources of failure, as well as making suit maintenance and repair operations more difficult. Furthermore, both the USA and Russian EMUs employ a HUT, which provides more robust protection to the upper torso area.

The Apollo helmets were constructed from a hard composite shell and covered with TMG for added protection. The visor assembly consists of an outer shell, which in combination with the transparent polycarbonate pressure dome protects against micrometeorite impact damage or any other damage that may result from falls and collisions. Next generation suits for lunar exploration intend to employ the above features for protection against micrometeorite impacts and other hazards that may puncture or tear the suit (Pelton and Marshall, 2006). However, due to the differing design philosophies between USA and Russian spacesuits, it is not clear whether or not all lunar spacesuits will implement a redundant pressure bladder (Abramov and Skoog, 2003; and Thomas and McMann, 2006). Additionally, there is work in progress in the USA at ILC Dover to develop a gas pressurized suit with self healing capabilities against punctures not exceeding 2 mm diameter. If the puncture exceeds 2 mm, the suit sensors will alert the astronaut and other personnel, as well as identify the location of the puncture (Shiga, 2006). In parallel with ILC Dover, the Man-Vehicle Laboratory (MVL) at the Massachusetts Institute of Technology (MIT) is working to develop a Mechanical Counter Pressure (MCP) suit. MCP spacesuits, unlike gas pressurized suits, will not undergo depressurization if the pressure garment is punctured or torn (Waldie, 2005). Instead, the astronaut would only suffer injury in the localized area where the suit was punctured or torn. Additionally, unlike gas pressurized spacesuits, punctures and tears on MCPs can be repaired “on the fly” during EVA using “patching” or “stitching” techniques (Waldie, 2005; personal communication, Waldie, 17 March 2008). However, the TRL of MCP suits is still quite low and it is not certain if they will be available by Phase 2 of a lunar base.

3.2.4 Suit Tear

General suit tear or puncture due to dust abrasion or contact with sharp edges, although very low in probability, was always a concern for the Apollo astronauts. For this reason, it has recently been recommended that NASA should continue to pursue development work on self-healing spacesuits (NASA JSC, 2007). In addition, the mitigation strategies listed for micrometeoroid impact risks are directly transferable to general suit tear or puncture. Increased wear resistance of the outer garment, advanced dust mitigation methods and more dust resistant materials also need to be developed in order to mitigate suit abrasion (NASA Glenn Research Center, 2005; Yamagata, 19 March 2008). Finally, regular maintenance, cleaning and thorough inspections before and after EVAs will ensure maximum suit integrity.
3.2.5 Failure of Portable Life Support System

Assuming that the fundamental architecture of the Portable Life Support System (PLSS) for future lunar mission remains similar to Apollo and ISS EMUs, the failure of the following four main systems can compromise the safety of the astronaut:

Thermal Control System: The Apollo and ISS Extravehicular Mobility Units (EMUs) use a Liquid Cooling Garment (LCG) to maintain the astronauts’ body at comfortable temperatures when operating under direct sunlight. However, due to the colder EVA conditions for the ISS, a passive heating system referred to as the LCVG Bypass has been incorporated into the USA EMU. The LCVG Bypass keeps the crew comfortably warm when performing EVAs in the shadow by intentionally retaining body and electronic component heat by forcing the cooling water to bypass the spacesuit. Therefore, since the crew on the lunar surface will be required to work in shadowed regions from time to time, a system similar to the LCVG Bypass will be required. A system similar to the Apollo Buddy Secondary Life Support System (BSLSS) (Figure 3-1) will also be required to allow the sharing of a single liquid cooling system if one crewmember experiences a cooling system failure (Thomas and McMann, 2006; NASA, 1971).

Oxygen Supply: The primary oxygen supply system of the Apollo and ISS spacesuits is capable of providing oxygen supply for eight hours. If the primary system fails or becomes depleted, an emergency oxygen supply system activates to provide life support for 30 minutes. The Apollo emergency oxygen system was also capable of providing 90 minutes of oxygen supply if the BSLSS is used for additional cooling (NASA, 1971; Jones, 2006). However, since the duration and intensity of the EVAs during the establishment and operation of a lunar base is likely to be greater than the Apollo missions, it will be necessary to have a backup system that provides oxygen supply for longer than ninety minutes. Furthermore, since the BSLSS did not permit oxygen sharing, it will be advantageous to design next generation suits to permit oxygen sharing between crewmembers. Yamagata supports this and adds that future lunar and Mars spacesuits should be designed to permit oxygen sharing between crewmembers similar to the extra mouthpiece for SCUBA (personal communication, Yamagata, 19 March 2008).

Carbon Dioxide Scrubber: If the CO₂ removal system fails during EVA, the EMU will gradually become saturated with CO₂ and suffocate the astronaut. Therefore, it is important to have a
reliable CO₂ removal system. Even with a highly reliable system, it is important to have a mitigation strategy for unexpected increases in CO₂ concentration. The USSR KRECHET-94 lunar suit developed in the 1960s, compensated for such situations with a system that automatically activated an injector to provide ventilation to the helmet at a rate of 40 L/min with an oxygen flow of 3 L/min to decrease the carbon dioxide concentration to a safe level.

The USA EMU for the ISS currently uses a regenerative CO₂ scrubber called METOX. In addition, an infrared (IR) CO₂ sensor is installed to monitor the levels of oxygen within the suit (Thomas and McMann, 2006). It is expected that a regenerative system will be used for lunar missions, however given the intensity level of the missions, a closed loop CO₂ recovery system will be needed for long duration missions (Charles, 2008).

Power: If the PLSS battery fails, the LCG, communication system, and other pumps and fans required for fluid flow will cease to function. A simple mitigation strategy for future spacesuits will be to have a backup battery capable of providing power to allow the crewmember to return to the base or a pressurized rover.

Finally, it will significantly add to the safety of the crew if an emergency Life Support System (LSS) is mounted onboard non-pressurized Lunar Roving Vehicles (LRVs). In the event of any PLSS failure, astronauts can easily connect to the onboard LSS and drive back to base.

3.2.6 Hand Fatigue and Injury from Spacesuit Gloves

Due to the stiffness of the pressurized gloves, poor fit and poor hand-to-glove interaction have resulted in repeated cases of finger injuries such as fingernail delamination and swelling and pain over the finger knuckles. Apollo astronauts also reported that continuous gripping was the most fatiguing part of EVA tasks (Scheuring and Jones, 2007; NASA JSC, 2007; and NASA JSC, 2003). Maintaining maximum dexterity and injury free hands is important since most tasks performed by the astronauts heavily rely on the use of their hands. Any limitations placed on the use of their hands can result in sub-par or unsafe task execution. Recent studies have also shown that a hand injury can lead to a number of other injuries which can significantly reduce crew safety and performance (Johnson et al., 2004; NASA JSC 2003).

Current mitigation strategy for fatigue related to repetitive gripping includes special physical conditioning exercises, while fingernail delamination is minimized by providing the best fitting gloves possible. However, these strategies have proven to be inadequate and the following recommendations have been provided by astronauts and researchers (Scheuring and Jones, 2007; NASA JSC, 2007; Johnson et al., 2004; and NASA JSC, 2003):

- Reduce glove stiffness by reducing suit operating pressure
- Provide custom designed gloves for each crewmember for optimum fit
- Integrate mechanical closure for gripping
- Designers should consider a wrist seal and depressurized glove
- Robotic power-assisted gloves should be used for repetitive tasks
- Develop special inner bladder surfaces
- Develop special liners that can be worn inside the gloves to prevent skin erosion and swelling
In addition to the above recommendations, the MIT MCP suit (Bio-Suit) shows some promise in alleviating hand fatigue and injury problem.

The Bio-Suit is intended act as a “second skin” to augment human skin by actively reacting to physiological and environmental changes to provide a constant pressure to the body at all times. In addition, it will use shape memory alloys and electro-active polymers which will function as artificial muscles to enhance the physical abilities of the astronaut. Furthermore, as illustrated in Figure 3-2, the suit can be “sprayed” directly to the skin to provide constant contact and pressure, and thus eliminating the problem of skin erosion and swelling (Space.com, 2005; and Newman et al., 2004). However, as discussed earlier, it is not certain if the Bio-Suit will be ready for Phase 1 or 2 of the lunar base.

![Figure 3-2: Artist’s impression of an astronaut applying a polymer spray as a second skin to provide MCP (Brensinger, 2008)](source)

### 3.2.7 Poor Visibility During EVA

Poor visibility could result from helmet fogging, upheaval of lunar dust, vomiting episode, working in the shade, scratched visor and poor peripheral vision due to bulky suit design (NASA JSC, 2007; Charles, 2008; NASA Glenn Research Center, 2005; and Hoffman, personal communication, 30 November 2007). Poor visibility can lead to a situation where the astronaut becomes disoriented and could accidentally walk or drive into a crater or off a ledge which could lead to a serious injury and even death.

To minimize fogging, anti-fogging solutions should be used to wipe the polycarbonate surface. However, according to Apollo astronauts, using anti-fogging agents was not always effective to prevent fogging. Instead a more effective system needs to be developed to prevent fogging in all operating conditions (NASA JSC, 2007).

Space motion sickness affects crewmembers on the initial 2 or 3 days of the mission. Countermeasures to prevent vomiting and adverse consequences during this period include avoidance of activities that could increase symptoms, delay of tasks demanding high performance and pharmacological treatment (Jennings, 1998). EVA would be limited during the first days while astronauts adapt to the new environment and the risk of vomiting is reduced. In addition, astronauts should not be permitted to participate in EVA if they are not in good health. However, a system needs to be developed to allow rapid recovery from a vomiting episode (Charles, 2008).

When performing EVAs in shadow regions, astronauts should work at least in pairs and should use sufficient illumination. Also, all measures should be taken to minimize dust upheaval in order to maintain maximum visibility. However, if there is significant dust upheaval, the EVA crew should wait until the dust subsides, which should be almost immediate due to the vacuum environment (NASA Glen Research Center, 2005).
To minimize scratching of the helmet and visor, all measures should be taken to prevent dust build-up on them. If dust build-up is unavoidable, the crew should refrain from wiping the dust off as it can scratch the surface. Care should also be taken to minimize visor and helmet contact with the regolith, boulders, and other abrasive objects (NASA Glenn Research Center, 2005).

Finally, Apollo suits as well as ISS EMU are very bulky in design with a fixed helmet that greatly hampers the peripheral vision of the astronaut. For this reason, Apollo astronauts have recommended the redesign of the helmet with a swiveling neck so that the astronaut can view their surroundings more easily. Organizations such as ILC Dover and MIT MVL are also working to develop more streamlined spacesuits that offer minimal suit volume and greater peripheral view (NASA JSC, 2007; Newman et al., 2004; Thomas and McMann, 2006).

3.2.8 Lunar Dust Infiltration

During Apollo, the crew had a great deal of difficulty with lunar dust infiltrating the EMU seals and zippers, as well as contaminating the inside of the suit. This resulted in significant wear and difficult operation of the zippers and seals due to the abrasive nature of the dust. On a few occasions small leaks developed in the suits, which caused concern among the astronauts (NASA JSC, 2007; NASA Glenn Research Center, 2005). Contamination inside the spacesuits also resulted in skin irritation, and exposure to the fine dust in the Lunar Module (LM) during microgravity flight resulted in eye and cardiovascular irritation. This effect was not noticed when the LM was on the lunar surface because the astronauts generally wore their suits at all times, which will not be practical for long duration missions. Therefore, dust build up inside the habitat must be prevented since prolonged exposure could lead to detrimental impact on the crew’s health (Khan-Mayberry, 2007).

With this in mind, astronauts will need to be vigilant to minimize dust upheaval and dust build up on EVA suits and equipment. Before entering the habitat, effective dust removal systems will need to be put into place so that the interior of the habitat and spacesuits are not contaminated. Finally, increased wear resistance of the outer garment, advanced dust mitigation methods and more dust resistant materials also need to be developed in order to mitigate suit abrasion and dust buildup (NASA Glean Research Center, 2005).

3.2.9 Psychological Stress (Performance Impairing)

A traumatic event can generate stress disorders in people involved. In addition to the victim, a traumatic event can generate stress disorders in people involved. In addition to the victim, rescuers and professionals of emergency services can develop acute and post-traumatic stress disorder (Fullerton et al., 2004; Smith and Roberts, 2003); therefore, trained astronauts could develop similar symptoms in emergency situations. Some factors that could play a role in the development of these disorders include early experiences of violence, previous traumatic events and severity of the trauma (Jonsson et al., 2003). Witnessing the injury or death of a crewmember could have emotional effects on the rescuers, which can threaten performance and psychological conditions during and after rescue operations. Additional psychological effects can be induced if the safety of the rescuer is also compromised while executing the rescue. Crew selection according to the risk factors, emergency training and ground support are important for reducing risk associated psychological stress. Critical Incident Stress Management (CISM) and psychological debriefing have been used as countermeasures; however, their effectiveness has been questioned (Regel, 2007). Psychotherapy and medications can also treat the syndrome.
3.2.10 **Psychological Stress (Normal Activity-Related Stress)**

Spaceflight and long duration exploration missions induce a great deal of stress on astronauts. Living and working conditions of a lunar base will likely involve heavy workloads, lack of sleep, monotony, environmental factors and conflict with crewmembers or ground control which can lead to physical, psychological and interpersonal stress. If not managed appropriately, stress can be detrimental to the safety of the crew due to reduced alertness, attention, speed, accuracy and working memory in the primary task. For complex tasks, stress is associated with increased mental effort, sympathetic activation, subjective fatigue, neglect of subsidiary activities, and reduced use of working memory (Kanas and Manzey, 2003). Select-out and select-in crew selection processes, and training are essential countermeasures. Analogous environments can be used to improve the personal and interpersonal skills of the astronauts. In addition to improvements in habitability and communication, training in counseling and psychotherapy as well as ground support are necessary. Medications to control sleep disorders can help but would require continuous monitoring for adverse effects that can threaten performance during EVA tasks. Other possible tools could be remote monitoring systems for cognitive performance, human errors, fatigue, and sleep patterns. Voice analysis for frequency, amplitude and speech rate can provide information about the conditions of the astronaut (Buckey, 2006). On board monitoring systems are useful for monitoring of the physical and psychological condition of the astronauts. For example, systems like the Spaceflight Cognitive Assessment Tool for Windows could help to detect changes in the neurocognitive status of the person (Kane et al., 2005). Finally, optical computer recognition of facial expressions has been tested to measure the presence of stress induced by workload performance demands (Dinges et al., 2005).

3.2.11 **Sun-blindness**

An intense amount of energy is emitted from the Sun which can cause blindness if the appropriate precautions are not taken. This is especially important for operations in outer space or on the Moon where there is no atmosphere to provide some shielding against harmful radiation (Kitchin, 2002). Also, sun glare from the surface of the Moon and other reflective surfaces can hamper the vision of the astronaut, which can create hazardous working conditions. For this reason the Apollo spacesuits were equipped with a visor assembly that consisted of a gold plated outer visor, an Ultraviolet (UV) stabilized second protective visor and three manually adjustable eye shades (NASA JSC, 1987). The outer visor filtered a significant amount of visible, UV and IR radiation, while the second visor filtered UV radiation and rejected IR radiation. The three eye shades were used to prevent glare from the lunar surface and other reflective surfaces. For added safety, only the outer visor could be adjusted in the full up or down position. The second protective visor was not adjustable, providing sun protection at all times (NASA JSC, 1987). However, even with all sun protective gear in place, astronauts are instructed to never look directly at the Sun.

3.2.12 **Broken Spacesuit Transparent Dome (Helmet)**

If the pressure dome suffers significant damage, there is little that can be done to provide sufficient pressurization to the helmet. However, the KRECHET-94 lunar suit, developed by the USSR in the 1960s, was equipped with a safety feature to automatically provide oxygen supply at a rate of 24.5 L/min for emergency depressurization such as a helmet leak. Since the PLSS was designed for a maximum operating time of 10 hours with oxygen flow rate of 1.5 L/min, the maximum operating time in emergency mode was expected to be 36 minutes.
Therefore, a similar system should be implemented on future surface exploration suits to minimize the chances of catastrophic depressurization due to helmet damage.

### 3.2.13 Overexertion/Fatigue

A major source of astronaut overexertion and fatigue is poor mobility and dexterity of the spacesuit. For this reason, both Russia and the USA have been developing and testing planetary exploration spacesuits with a large focus on improved mobility and dexterity (ISU, 2008; Abramov and Skoog, 2003; Thomas and McMann, 2006). Custom fit spacesuits also improve mobility and dexterity, and reduce required effort to perform a task.

The University of Maryland Space Systems Laboratory is currently working to develop a gas pressurized spacesuit, referred to as the morphing upper torso (MUT), that dynamically adjusts to each user’s body shape to provide the closest fit possible (Jacobs et al., 2006). In addition, MIT’s Bio-Suit will be designed to fit as a “second skin” to provide an ideal fit and superior mobility and dexterity over gas pressurized suits. The effectiveness of a MCP suit in minimizing overexertion and fatigue was demonstrated in the 1960s through a series of tests performed by Webb Associates. The tests showed increased mobility and dexterity, reduced metabolic cost due to movement, and excellent heat dissipation from evaporation of sweat over a gas pressurized suit (Webb in Thomas and McMann, 2006). Additionally, MIT MVL team suggests the use of smart materials to act as artificial muscles to enhance the physical abilities of the astronauts (Space.com, 2005; Newman et al., 2004).

The availability of spacesuits capable of augmenting physical ability is especially attractive for long duration lunar missions where astronauts will likely experience muscle and bone atrophy. Working in a gravity environment with reduced muscle and bone strength will make the astronauts more susceptible to muscle strains, bone breaks, and ligament tears. Even with the stringent exercise routines the crew will be expected to maintain, it is not certain if they will be able to maintain their original physical strength and endurance. Therefore, EVA suits capable of enhancing the physical abilities will enable crewmembers to live and work on the Moon more efficiently, effectively, and safely. However, as mentioned earlier, it is not certain if spacesuit technology such as the Bio-Suit will be ready for Phase 2 of the lunar base.

In addition to enhancing spacesuit technology to achieve optimum performance, Carr et al. (2003) and Hodgson et al. (2003) recommend the incorporation of advanced information interface systems that require minimal physical interaction to minimize movement inside the suit. Finally, EVA durations, physical loading, nutrition and regular exercise regimes should be optimized to foster a living and working environment that is not overly demanding on the crew.

### 3.2.14 Rover Roll-Over

Since a rover roll-over, especially in an un-pressurized rover, has a high probability of causing major or lethal injury, it is critical to establish and follow safe rover driving practices. For instance, the LRV for the Apollo 15 to 17 missions was designed for maximum slope inclination of 45 degrees and the astronauts were required to adhere to this limitation. In addition, the LRV should be designed with wide wheelbase, low center of mass and independent drive motors for each wheel for maximum stability, traction and power transmission; all of which will be essential for negotiating more hazardous terrain (Morea, 1992).
3.2.15 Falling

Falling on the lunar surface can result in exposure to a number of other risks, including suit tears from the sharp edges of lunar rocks, lunar dust infiltration, psychological stress, a broken spacesuit transparent dome, as well as contributing to overexertion and fatigue. There are two classifications of fall: 1) falling from standing and 2) falling from a height.

In the past, falling from standing in reduced gravity has only been an issue during the Apollo missions. The reduced flexibility of the EVA suit and altered center of gravity resulting from the added weight of the life support system caused several astronauts to fall during the Apollo 15 and 17 missions, however, none sustained any serious injury. To facilitate recovery after a fall, the Soviet lunar spacesuits included a semi-circular hoop that allowed an astronaut to roll over and pick himself or herself up (personal communication, Shane Jacobs, 20 March 2008). In addition, reduced peripheral vision made it difficult to identify tripping hazards like the lunar lander's ladder rungs (Jones, 1995).

The most significant risk during the Apollo 11 surface EVA was falling from a height during entry and exit of the lunar lander (personal communication, Buzz Aldrin, 25 April 2008). Lunar base tasks that include climbing structures or crater walls would present a significant source of risk for falling from a height. In this case, the only applicable analogue can be found in terrestrial activities such as mountain climbing, or construction based tasks. The most important technique used to ensure safety while climbing is tethering, and a number of safety devices are used and have been patented (e.g., Farnsworth, 1968; Fountain, 1970; Hillier, 1980; Casebold, 1993; Swager, 1993). Rock climbers also reported that training and specialized skills are essential to improving safety (Attarian, 2002). Proper equipment such as appropriate non-slip EVA soles (Chang et al., 2005) and adequate climbing training in a controlled buoyancy reduced gravity analogue would contribute to reducing the probability and effect of this risk.

3.2.16 Electrocution/Shock - Major and Lethal

The risk of electrocution and shock represents a major hazard for astronauts performing EVAs. Death or severe incapacitation can occur from serious tissue damage and heart arrhythmias resulting from an electrical shock hazard generating voltage greater than 32 V (Stewart, 2007). Currently, the most effective countermeasure for avoiding electrocution is prevention. During the STS-120 solar panel repair EVA, there was a high risk of electrical shock. To prevent exposure to live current, ISS EVA protocol identified all electrical shock hazards and outlined safety distance margins at each step of the EVA. In addition, the astronauts worked with Kaplon tape covered tools to provide insulation while working around potential electrical shock hazards (NASA, 2007c). The EVA suit also represents a potential source of electrical hazard, as exposed metallic contact points on the surface of the suit, particularly around the neck, could facilitate electrical arcing through vulnerable parts of the body (Kramer et al., 2006).

3.2.17 Stranding or Entrapment of EVA Personnel

One of the inherent risks of exploration is the possibility of EVA crew becoming stranded or entrapped. Based on early polar exploration missions, stranding or entrapment generally occurs due to equipment failure, lack of proper tools and human error (Stuster, 2005). In light of this, the best mitigation strategy is to develop equipment that has sufficient redundancies to prevent single point failures and secondary failures are independent of the first failure and will not result
in a catastrophic failure (Harris, 2001; personal communication, Paul Graham, 01 May 2008). Furthermore, sufficient equipment, training and expertise should be provided on each EVA to overcome in-field challenges. EVA support team at the lunar base should also be prepared for rapid deployment in case a rescue EVA will be required (personal communication, Paul Graham, 1 May 2008). Best practices in traverse planning and maintaining constant communication with the lunar base, mission control will significantly reduce possibilities of the crew navigating off course or into unsafe regions. EVA crewmembers should never work alone and should maintain radio and visual communication to minimize possibilities of emergency situations which could result in immobilizing the crew (Harris, 2001; personal communication, Buzz Aldrin, 25 April 2008). Pre- and post-EVA systems operations checks and regular maintenance are crucial in order to prevent potential failures during EVAs.

In addition to the risk of the primary EVA crew becoming stranded or entrapped, precautions must be taken to prevent the rescue EVA crew from also becoming stranded or entrapped. If the rescuer also becomes stranded or trapped, more time, effort and resources will be required for the rescue operation. Therefore, the rescue crew will be required to be aware of the operating conditions the source of the emergency (e.g., rover roll-over due to steep terrain) so that the rescuer does not repeat the same mistakes as the stranded crew. It is also imperative that the rescue crew not engage in rescue operations which have a high probability of further endangering the rescuer or the rest of the crew, and should be well equipped to provide proper aid.

### 3.2.18 Pinching – Lethal

Crush injuries sustained during module connection and other construction activities have not previously been a concern in the microgravity environment. However, crush injuries become a potential risk in a reduced gravity environment and the extreme operating conditions on the Moon. The causes and countermeasures are similar to those found in the construction industry on Earth.

There are three identified causes of accidents that can result in a crush injury: 1) unsafe acts; 2) unsafe conditions; and 3) structural failure (Krishnamurthy, 2004). Unsafe acts are preventable through proper training, and proven competence. Failures caused by equipment operators (e.g., crane operators) that resulted in injuries were found to be only three percent (Krishnamurthy, 2004). While caution must be taken when applying terrestrial data to space applications, teleoperation of robots to perform construction activities will not likely contribute significant added risk if proper training is provided.

Unfortunately, unsafe conditions are unavoidable while working on the lunar surface. However, they can be mitigated by the proper establishment of working protocols, and in-depth analysis and identification of immediate environmental hazards (Murie, 2002).

Given the occurrence of injuries on Earth, the most likely cause of crush injuries on the lunar surface will occur from structural failures (Krishnamurthy, 2004). Human space flight, in general, demands strict adherence to predetermined regulations that define the integrity of all objects sent into space. Long-term exposure to radiation, micrometeorites, and lunar dust on the lunar surface is a unique environment for space materials. Constant monitoring and testing will ensure the stability of support structures, connections, and materials (Murie, 2002).
3.2.19 Explosion Risks

Depending on the design and materials used, batteries can explode for different reasons. Explosions can result from overheating, excessive internal pressure, or the release of explosive gases from the battery (CCOHS, 1999; Bullis, 2007). Explosion can be avoided through appropriate thermal and pressure control, as well as by adhering to safety guidelines for the proper handling of batteries. The silver-zinc batteries used in the Apollo Lunar Rover Vehicle (LRV) were protected from extreme temperatures via thermal blankets and radiators, while an internal relief valve ensured that over-pressurization did not occur. Both the pressure and temperature were monitored on a Control and Display console (C&D). (Morea, 1992) For more modern lithium-ion batteries, better materials are being developed for electrode separators that can prevent internal overheating (Bullis, 2007). Ensuring that batteries are designed to withstand the extreme lunar environment and are defect free through proper quality assurance during and after manufacture can reduce the probability that an explosion will occur.

3.2.20 Additional Injury Resulting from Movement

Accidents can involve injuries of multiple parts of the body and in some cases require transportation of the injured person. Inadequate and unsafe transportation can generate secondary neurological injuries in case of cervical spine trauma or in circumstances where the mechanism of injury has the potential to cause cervical spine injury (Del Rossi et al., 2004). Between 3-25% of the spinal cord injuries occur after the initial trauma, either during the transit or early in the course of management. To reduce the probability of further injury, cervical and the entire spinal column are normally immobilized at the scene and during transport. To achieve this goal, different devices are used to provide immobilization such as hard backboard, rigid cervical collar, lateral support devices, and tape or straps to secure the patient (Neurosurgery, 2002). Requirement of immobilization and transportation of an injured astronaut during lunar EVA presents a major challenge due to the configuration of the spacesuit.

The helmet and the rest of the space suit provide protection against trauma and it could also limit movement of the neck and body while transporting the astronaut. However, the devices mentioned above may require modifications and improvements for safe transport operations for instance modifications of the stretcher shown in Figure 3-3. Even though the probability of such injuries is low and application of immobilization is difficult, the ability to effectively protect against additional injury during mobilization and transportation will be necessary.

3.2.21 Delay or Insufficient Rescue Time

Readiness of the emergency response and rescue system are important to provide better assistance to the injured, stranded or trapped person. Depending on the circumstances, delays in rescue operations could mean catastrophic results. An astronaut unable to return to the rover or to the habitat by him/herself is a hazard that requires immediate attention and support. The
survival time would be determined by the condition that limits the return of the astronaut and
the time that the space suit can continue providing vital support. EVAs generally last around 7
hours, plus or minus a half hour depending on the use of the air and water available from the
backpack, which also has a 30-minute emergency air supply (Federation of Galaxy Explorers,
2008). According to the Constellation Space Suit System the spacesuit for a lunar sortie could
maintain astronauts safe up to 120 hours to ensure safe return to Earth (Dutton and Johnson,
2007). In this case, spacesuits used for lunar exploration would contribute to the rescue
activities. Protocols limiting exploration in possible walkback areas reduce the risk of insufficient
time allowing astronauts to return to the habitat or vehicle.

3.2.22 Locating Difficulties

In emergencies in remote areas such as mountains, oceans or poles, identifying the specific
location of a possible strained or injured person constitutes a serious challenge for rescue teams.
For this reason, multiple beacon systems inside ships, airplanes and portable devices have been
designed to help rescuers localize the emergency area faster. The beacons transmit information
via satellites to Search and Rescue (SAR) personnel that help identify the owner. Some of the
beacons incorporate Global Positioning System (GPS), sending navigation signals in order to
provide precise geographical location. Three types of beacons exist: Emergency Position
Indicating Radio Beacons (EPIRBs), Emergency Locator Transmitters (ELTs) and Personal
Locator Beacons (PLBs). EPIRBs are used by ships, ELTs are used in aviation and PLBs are
designed to be used in land-based applications. Some of them are designed to survive and
activate automatically in case of accident. PLBs are portable and must be activated manually.
One additional function is using digital messages to mitigate false alarms (NOAA, 2008; NASA,
2008b). Automatic or manually activated emergency beacon systems could, therefore, also be
used on the Moon to localize a stranded, entrapped or lost astronaut. Personal locators or
transmitters inside the rover, similar to what was developed for the Apollo and USSR lunar
programs (Abramov and Skoog, 2003; Morea, 1992) could be used to transmit bearing and
distance information to the habitat, control center, other rovers and satellites orbiting the Moon
to provide information about the exact position of astronauts in case of emergency.

3.2.23 Insufficient Equipment

Rapid and easy access to tools and emergency equipment will improve safety of the crew by
enabling the crew to deal with system failures, falls, crashes, collisions, explosions or drop of
elements and other in-field emergencies. Physical obstacles or objects may interfere with rescue
and evacuation, thus instruments to remove or overcome obstacles are necessary. It is
impossible to provide all the elements for each event; however, insufficient emergency
equipment or absence of tools to rescue personnel could result in unfavourable conditions that
could lead to injury and even death. Instruments for rescue and extrication need to be easy to
manipulate and transport, and must provide different services for cutting, spreading, pulling or
pushing in order to remove any heavy objects.

3.2.24 Unpredictable Complications

Any surgical procedure involves the risk of complications that are related to the location, type
and complexity of the surgery. They can be divided into intra-operative and-post operative
complications. Intra operative complications include lesions of vessels, nerves, soft tissues,
organs and associated structures, or adverse reactions to anesthetics and medications used for
the procedure. Possible countermeasures are specific for each situation. The health care provider should know the risks of the procedure and be able to overcome the potential circumstances. Practice in simulations and real scenarios, provide the experience required they should be based on current knowledge and best practice and clinical evidence (Clarke, 2007). Bleeding is one of the most frequent complications. Technologies have been developed to reduce this risk and to make a better and faster control of bleeding for open and minimally invasive surgery (e.g., gelfoam, oxidized cellulose, fibrin glue, recombinant human thrombin and cyanopolymer glues) (Untch et al., 2007). Mechanical techniques like hemoclips of titanium and linear stapler cutting devices, or hemostasis using energy such as electrocautery, ultrasonic oscillation, electrothermal bipolar vessel sealers, argon beam energy, and radiofrequency energy (de la Torre et al., 2007) have also been developed.

3.2.25 Wound Contamination

Wound contamination depends on the type of wound, conditions and circumstances in which it was produced. In addition to the wound care, immunological and nutritional conditions of the person play an important role avoiding microorganism proliferation. Common strategies to reduce the risk of infection are exploration and removal of foreign bodies, cleansing with water or antiseptics and debridement (Lee, 2007; Kumar and Leaper, 2008). It is also important to provide aseptic surgical techniques and sterile instruments. Instruments can be contaminated with blood, fluids and microorganisms from manipulation or previous procedures; therefore, use of new instruments during each procedure and/or sterilization of instruments between procedures is required. Techniques for sterilization include high temperature exposure using steam or dry heat, low temperature, and immersion in liquids (Rutala and Weber, 2004). Finally, antibiotic prophylaxis or therapy should be given according to the type of wound.

3.2.26 Contamination of Habitat Environment

Contamination of the habitat or the environment can occur when microorganisms or corporal fluids such as blood, secretions or waste products are dispersed. On earth some of the risks with biological material include transmissible diseases like Hepatitis B; however, astronauts are screened for all infectious diseases to exclude any possibility of disease spread. Biological waste from gastrointestinal diseases with emesis or diarrhea would become a potential source of contamination (Epelman and Hamilton; 2006). This could be a hazard to the other astronauts especially regarding food and water sources. In the case of surgery, this topic becomes more important for procedures that involve cleaning or drainage of contaminated wounds such as an abscess. Special management of waste, surgical residuals, fluids, water and contaminated instruments will be necessary to avoid further contamination.
The development of robotic technology has undergone significant progress and improvements in design and operation in recent years. Robots are designed for a variety of tasks and prove to be beneficial in both terrestrial and space applications. Unmanned scientific exploration missions show the potential of robotic technology in autonomous and teleoperated surface exploration. The construction and operation of the ISS illustrates the benefit of using robots to assist astronauts in their challenging tasks in order to increase both task efficiency and crew safety. Robotic technology is expected to play an important role for future human space missions, including the construction and operation of a lunar base.

This chapter continues the preceding analysis of astronaut tasks and their associated risks. It also presents an overview of the different areas robots are currently and successfully employed to assist humans, the ability of robots to improve task efficiency in both terrestrial and space applications, and the potential of robotic technology to increase crew safety in future missions to explore the lunar landscape. Terrestrial applications of robots are included in this discussion because of their proven heritage, in particular for search and rescue, scientific exploration in harsh environments, and industrial applications.

An in-depth analysis of these applications indicate the potential of robotic technologies for future lunar missions, and the modifications and improvements that still need to be undertaken. In this regard, space agencies and universities alike have a wide range of research projects currently under way, investigating traditional and non-traditional concepts and methodologies. These allow for an insight into the prospects of robotic technology for near- and long-term space exploration and its advantages for crewed lunar missions.

The discussion and evaluation of the various robotic examples in this chapter include an indication of their respective technological readiness. The maturity of a specific technology is identified through a set scale using NASA’s Space TRL scheme. This scale is divided into nine possible levels, 1 being the youngest and least proven technology, and 9 being the most mature with flight heritage (see Figure 4-1). (Johnston, 1995)

While a robotic system has the potential of increasing task efficiency, it is in itself ineffective without proper astronaut-robot synergy being present. Measuring the synergistic relationship between both parties using metrics is thus essential for evaluating the effectiveness of a robotic system. Optimized communication is vital for a functioning relationship between astronauts and robots. These aspects are analyzed by evaluating possible interface methods. The legal and ethical aspects related to astronaut-robot interaction and the use of robots on the lunar surface are also included within this discussion.
The chapter concludes by examining the prioritized tasks listed in Section 3.3, thereafter providing recommendations as a result of applying a decision tree based on how robotic technologies could potentially be used to mitigate the risks associated with these tasks in order to maximize crew safety. Fourteen of the highest priority tasks are discussed in particular detail with respect to specific robotic systems that can be implemented to improve crew safety.

4.1 Robotic Technology in Space Applications

The extraterrestrial environment is probably the most challenging application of robotics. Space application of robotics imposes unique drivers on the technologies implemented. Since the major space agencies are undertaking aggressive exploration missions there is a growing need for an increasing sophistication, intelligence and autonomy (Lai, 2006). In the following section robotic technologies that are currently used in space applications to assist astronauts in their tasks are described. Moreover, a general overview of the technologies that are currently being proposed for implementation in the space environment are also considered.

4.1.1 Robotic Technology Currently In-Service

Robotic technology in space applications can be divided into two broad categories: spaceborne robotic manipulator arms, and surface exploration robots. The examples presented here fall within levels 8 and 9 of NASA's TRL (Johnston, 1995).

Spaceborne advanced manipulators are currently installed aboard the Space Shuttle and the ISS to assist astronauts in performing deployment and repair operations involving a variety of hardware and components. Examples of such robotic manipulator arms include the Remote Manipulator System (RMS) and the Canadian-built Dextre.

RMS is a teleoperated arm that is attached to the Space Shuttle's payload bay. Astronauts use it to handle and manipulate payloads, and to perform repair and retrieval tasks on the Space Shuttle. It consists of "shoulder yaw and pitch joints; an elbow pitch joint; and wrist pitch, yaw, and roll joints," to correspond to the capabilities of a human arm (NASA, 2003c). It also "provide[s] a mobile extension ladder for extra vehicular activity crewmembers for work stations or foot restraints; and [can] be used as an inspection aid to allow flight crewmembers to view the shuttle or payload surfaces through a television screen on the RMS" (NASA, 2003c).

Dextre, or Special Purpose Dexteroius Manipulator (SPDM), is a recent addition to the ISS, and is used by crewmembers to “remove and replace small components on the Station’s exterior that require precise handling” (RASC, 2008). It can therefore significantly "reduce the amount of time that astronauts and cosmonauts spend working outside the ISS in the hostile space environment" (CSA, 2001). Essentially, Dextre is a two-armed teleoperated robot that features among other things hands with specialized grippers, video equipment, built-in socket wrenches and lighting (see Figure 4-2).

Dextre is one of three components of the Canadian Mobile Service System (MSS), a robotic system dedicated to assist astronauts in ISS assembly and maintenance tasks (CSA, 2001). Besides Dextre, the MSS includes a mobile base and the famous 17.6 m long Canadarm2, which currently assists in moving heavy payloads and the docking of the Space Shuttles. One of the important aspects of Canadarm2 is the feature of “self-relocation, so it can be attached to
complementary ports spread throughout the station's exterior surfaces" (MDA, 2006). Such versatility proves how efficiently complex tasks can be accomplished when the appropriate robotic technology is implemented to assist astronauts.

Eurobot is a teleoperated three-armed, multi-jointed robot, developed by ESA to assist astronauts aboard the ISS during EVAs, or sometimes to perform tasks in their place (see Figure 4-3). Eurobot is capable of climbing the exterior structures of the ISS and attaching itself to the handrails used by astronauts (ESA, 2006). For this purpose, its three arms have been designed to resemble a human arm in size and available strength, but to be more efficient in maneuverability and versatility (ESA, 2007). Eurobot helps to stow tools and equipment, and can hold objects while astronauts work. This assistance increases task efficiency and safety (ESA, 2006).

Currently, ESA is also developing the European Robotic Arm (ERA), to be installed on the Russian segment of the ISS. Besides payload manipulation and inspection of the outer surface of the ISS, ERA will be used to transport cosmonauts and astronauts alike to pre-defined locations during EVAs (ESA, 2006). This will make EVAs more efficient, leading to a reduction of total EVA time and risk for astronauts.

Current semi-autonomous surface exploration rover technology continues to be developed in the hope of eliminating the need of astronaut to conduct EVAs for scientific experimentation and exploration.

The two successful wheeled Mars Exploration Rovers, still operational on the Martian surface, illustrate the state-of-the-art of semi-autonomous surface exploration rover technology (see Figure 4-4). They comprise a series of scientific instruments such as microscopic imagers or spectrometers (NASA, 2007d) that could be useful for geological experiments on the Moon. In terms of autonomy, both rovers integrate auto-navigation software that analyze the terrain using stereo-camera pairs that allow production of three-dimensional (3D) terrain maps. Different travel paths are analyzed and the rover automatically chooses the safer and shortest route. Autonomous driving software is also present for obstacle-avoidance purposes (NASA, 2007e).

Several surface exploration rovers are currently in development. Some of them include locomotion systems other than wheels, such as, tracks used on the Nanokhod (developed by ESA), or the hopping capability of Minerva (developed by JAXA). The 1100 g Nanokhod robot can reduce EVA activity of the astronauts on the Moon's surface through its capability of performing measurement tasks large distances from a static landing site (ESA 2006d). The
hopping capability of Minerva might offer great advantages to future lunar robotic systems in terms of mobility, efficiency and speed (Fiorini et al., 1999), and might be of use, for example, in search and rescue missions.

![Figure 4-4: Mars Exploration Rover (NASA, 2007f)](image_url)

4.1.2 Proposed Robotic Technology

A variety of robots with advanced specifications for lunar and interplanetary missions is currently being developed by space agencies, including telerobots, aerobots, rovers, manipulators, free flyers, and climbers. To effectively extract information from celestial bodies, robots must have a high level of flexibility, sensitivity, control and autonomy. For this purpose, NASA, for example, had planned to develop as part of its telerobotics program, component technologies like virtual reality telepresence, advanced display technologies, proximity sensing for perception and robotic flaw detection (Lavery, 1997). Robotic sample acquisition technology is also being developed for the collection and analysis of samples on celestial bodies. The technology uses a combination of two robots where one is stationary and collects and stores samples while the other uses visual/radio frequency goal detection technology to navigate and retrieve samples (NASA, 2008c).

These technologies and the ones presented hereafter fall within levels 2 and 3 of NASA's TRL (Johnston, 1995).
Robonaut is a humanoid robot being developed as a joint project between NASA and the Defense Advanced Research Projects Agency (DARPA) (see Figure 4-5). It is designed to be teleoperated and promises to be a virtual replacement of astronauts on a planetary surface. Robonaut utilizes a suite of sensors and instruments to allow the robot to behave like an astronaut, while allowing its human operator to be virtually-immersed in the external environment. The intent of building such sophisticated and dexterous robots is to potentially have astronauts conducting EVAs replaced with a highly skilled and accurate robotic system.

The Personal Satellite Assistant (PSA) is a project headed by NASA Ames Research Center (Figure 4-6). It was originally being developed for a space station environment to assist astronauts with housekeeping tasks. The main goal of PSA is to “perform failure assessment, operation documentation, maintenance, and fault recovery” (Dorais, 2002). The PSA houses sensors capable of measuring gases, temperature, and air pressure, while being able to perform video conferencing, and maintaining communications with electronic support devices, such as computer servers, avionics systems, and wireless LAN bridges. Primary tasks covered by the PSA include environmental monitoring, communications, remote operations support, and crew worksite support. (Jones, 2003)

The PSA offers a unique type of robotic system that behaves and operates differently from traditional space robotic systems. The purpose of the PSA is to provide passive and active support to the astronauts in day-to-day life, but can also be applied to task-specific astronaut duties. In a passive mode the PSA quietly watches an astronaut's environment ensuring that everything is in order and operating at optimal levels. In active mode the PSA acts as a communications medium relaying necessary information to astronauts in regards to the task they may be performing. The PSA provides services that were not offered in prior robotic systems, and in doing so these services increase the security of an astronaut both passively and actively. Unfortunately, use of the PSA on the ISS was vetoed by the astronauts themselves who were not comfortable with the idea of having a robotic observer in close proximity (personal communication, Walter Peeters, 17 April 2008)
4.2 Robotic Technology in Terrestrial Applications

For nearly 50 years, robots have been implemented in a variety of terrestrial applications, ranging from manufacturing to military applications. They have been used in industry to do routine jobs including assembly line work, lifting heavy machinery, and transporting materials (NASA-Rover ranch, 2003). Technological advances enable robotic systems to execute more sensitive and intricate tasks, such as carrying scientific instruments, taking sample measurements, and performing surgery. Thus, in recent years the use of robots in terrestrial applications emerged and expanded into new areas, such as transportation, construction, mining, forestry, and health care. (Technowatch, 2006). This expansion of robotic applications can largely be attributed to a desire to improve overall safety and efficiency.

This section presents in more detail four terrestrial applications of robots. The technologies presented herein fall within levels 5 and 6 on NASA's TRL scale (Johnston, 1995).

4.2.1 Industrial Application of Robots

Robotic systems are widely used throughout the industrial sector to carry-out sets of tasks as quickly and efficiently as possible. Most of the tasks performed by industrial robots involve rudimentary movements and actions that are highly repetitive, features particularly common to manufacturing industries. Robots are also used to conduct or assist in tasks that may pose a potential threat to the safety of on-site personnel. These duties can involve the handling of dangerous equipment or toxic substances, such as those present in the chemical and nuclear industries.

Activities associated with the construction, maintenance, and operation of a lunar base have numerous analogs to those in the industrial sector where routine tasks, such as inspection and maintenance can be performed remotely via a suitable robotic system. In a similar fashion, implementing robotic systems capable of performing repetitive and menial tasks on a lunar base has the potential of alleviating astronaut schedules for more important responsibilities.

Within the scope of industrial robots, robotic arms used to manipulate heavy and cumbersome payloads represent a large percentage of all the robotic systems employed. Similarly, robotic arms could be used to assist base construction and cargo transportation activities.

In the nuclear industry, the use of mobile service robots for remote inspection and maintenance is becoming more common (Luk et al., 2006). A nuclear power plant requires continuous and scrupulous monitoring, and the design of reactors often restricts the access of service engineers. Furthermore, inspection tasks must often be conducted on unstructured and rough terrain, or even vertical surfaces. Such circumstances make it difficult for human inspectors to be directly involved. Similar environmental constraints are also likely to be found on the lunar surface. The scaling of vertical terrain, or structures or operations in sites that are precariously located, call for the use of robotics.

4.2.2 Search and Rescue (SAR) Robots

Attempts to search for and rescue injured or stranded persons in emergency or disaster situations pose a tremendous risk to human rescuers, for example locating persons trapped under a collapsed building. For similar rescue operations, robotic systems are a welcome
addition to search and rescue teams and allow them to survey potentially dangerous areas remotely. The concept of such search and rescue robots offers real potential for direct translation to lunar applications. Much of the advanced technology used by these robots lies within their locomotion trains and can be used for lunar robotics. The topography of the lunar surface shows similarities with the irregular terrain found in many emergency or disaster situations.

An example for such an SAR robot is the Micro Variable Geometry Tracked Vehicle (micro-VGTV). It has the capability to alter its general shape through low-level polymorphism, achieved by the use of its accordion-like outer chassis (MICRE, 2002). This makes the robot extremely versatile regardless of the type of terrain encountered. The SPAWAR Urbot (Figure 4-7) is a custom military manufactured robot with a platform that is unique in its ability to fully operate in an inverted position. When the platform becomes inverted, the robot detects this condition and adjusts the camera and controls to the new orientation (MICRE, 2002). Such adaptability and versatility could be very beneficial for roving robotic systems on the Moon, especially if the robotic system is delegated mission critical tasks.

Another example of a robotic system designed to assist human rescue operations is the BEAR (Atwood and Klein, 2008). "BEAR is an extremely strong, extremely agile teleoperated robot roughly the size and shape of an adult male human" (Atwood and Klein, 2008). Originally designed by the USA military to carry casualties from the battlefield, BEAR can rescue injured persons from dangerous areas and take them back to safety. It can also be used to "lift heavy objects, carry them for long distances as needed, over obstacles such as stairs or rough terrain, and set them down safely" (Atwood and Klein, 2008).

Unlike most terrestrial SAR operations, where the prime objective is for the robotic system to find a victim and report back with their position, a stranded or injured astronaut would need to be extracted from their location on the lunar surface and to be brought back to the habitation module. In such a challenging situation, the BEAR concept shows potential for being utilized on the lunar surface to extract stranded or injured astronauts. However, proper carrying techniques would need to be developed in order to accommodate any type of injury or fracture encountered on the lunar surface. The robot is robust enough to handle weights upwards of 500 lb (Atwood and Klein, 2008), which is more than sufficient for tasks on the lunar surface. Figure 4-8 illustrates how BEAR would carry a human.
4.2.3 Robots used for Environmental Studies

In the area of Earth sciences and environmental monitoring, robots are being used to reach places that would otherwise be difficult to access, to take samples and measurements which are being relayed back to scientists. Such places include the Arctic and Antarctic regions, volcanic craters, and the deep sea. One robot designed for such a task was Dante II, an eight-legged robot employed to study an active volcano in Alaska (Figure 4-9). “Its mission was to rappel and walk autonomously over rough terrain in a harsh environment, receive instructions from remote operators, demonstrate sophisticated communications and control software, and determine how much carbon dioxide, hydrogen sulfide, and sulfur dioxide exist in the steamy gas emanating from fumaroles in the crater” (NASA Rover ranch, 2003).

Dante II is capable of working autonomously, but can also be teleoperated. Due to the harsh conditions present on the crater floor, it was infeasible for humans to venture within, and thus Dante II was made capable by a control station 120 km away (Bares and Wettergreen, 1999). A robotic system like “Dante II saves volcanologists from having to enter the craters of active volcanoes. It also demonstrates the technology necessary for a robot to explore the surface of the Moon or planets” (Schempf, 2000).

An example like Dante II this illustrates how technology developed for terrestrial applications can be of advantage to lunar tasks. The robots used for environmental studies are primarily intended to study environments that are dangerous for humans to enter into. If key experiments can be carried out by autonomous or teleoperated robots like Dante II, fewer EVAs would have to be conducted, thus reducing the overall level of risks to astronauts.

4.2.4 Medical Telerobotics

Performing remote surgery on an astronaut on the lunar surface by operating a telerobotic surgical system from Earth is an attractive prospect that could reduce the risk of compromising a mission resulting from a forced evacuation, as well as the risk of severe and permanent astronaut injury resulting from delayed access to definitive medical care. Medical telerobotics for space applications is a relatively recent development, but has already shown significant potential for terrestrial applications. Currently, different robotic systems exists as servo-assistants (e.g., AESOP and other assisting arms), assistant-coordinators (e.g., Hermes), semi-autonomous effectors (e.g., Robodoc, CASPAR, ACROBOT, Probot, and PAKI), and remote control or teleoperated (e.g., da Vinci) (Sanchez-Martin et al., 2007). According to the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES), robotic surgery is routinely used in minimally invasive general surgery, pediatric surgery, gynecology, urology, cardiothoracic surgery and otorhinolaryngology (SAGES, 2007).

The potential of medical telerobotics for space applications, however, is less clear due to the
communication delay between the Moon and the Earth. Only a small number of modern remotely operated telesurgical systems have been tested in analogue environments and extreme conditions during NASA’s NEEMO 7, 9, and 12 missions, and zero-gravity flights (SRI International Medical Product Development, 2007; Doarn, et al., 2007; Thirsk, et al., 2006).

The main effect, however, of adding distance between the surgeon and operating site is the latency caused in data transmission. The transfer of control and audio/video data is limited by the speed of light, and at this speed, round-trip communication delay to the Moon approaches three seconds. Surgery is a real-time process, which requires the surgeon to react to unanticipated events and the surgical system to respond promptly to commands. A number of studies have shown that a significant degradation of surgical performance at these latencies renders it impossible to safely complete any kind of remote surgery (Anvari, et al., 2005; Kim, et al., 2005; Rayman, et al., 2006). Figure 4-10 shows how surgeons shift from using normal surgical skills to adopting a less effective and efficient move-and-wait strategy between 300-500 ms of latency.

These challenges limit the use of medical telerobotics to distances where latencies do not exceed 300-500 ms. Remote telerobotic systems could thus be implemented on a lunar-synchronous orbiting spacecraft or space station, between multiple lunar bases, or between a lunar base and mobile habitat or pressurized rover. On the other hand, local medical telerobotics would not suffer the same latency effects as remote medical telerobotics, and could provide the same benefits previously mentioned should immediate surgical intervention be required in the lunar base. However, most of the robotic telesurgical systems used on Earth are used only for elective or non-emergency-type surgeries, thus implying the difficulty in developing the robotic capabilities for handling emergency situations.
4.2.5 Exoskeleton

An exoskeleton is a basic robotic framework which functions around a human in order to increase strength and endurance of the wearer using motors and hydraulics for movement and load-bearing. One of the most advanced exoskeletons on the market is the Japanese HAL-5 from Cyberdyne Inc., an already commercially available full body suit weighing only 23 kg (see Figure 4-11). HAL-5 harmonizes the movement of joints and muscles by picking up the body's own neural signals, and can amplify the wearer's strength by 2 to 10 times. Such exoskeleton systems are currently aimed at assisting first and foremost the physically weak and injured. (Cyberdyne Inc., 2008)

The technology being developed here is the ultimate example of human and robotic synergy. The fusing of the two entities boasts numerous benefits through a complete translation of every body movement to the robotic frame. However, this can in turn pose a large risk should a malfunction of the exoskeleton occur. These exoskeletons could be implemented within spacesuits to alleviate astronaut tasks with the aim of preventing astronaut overexertion; however, as more complexity is added, the likelihood of failure also increases, and thus poses additional risks to the wearer (personal communication, Buzz Aldrin, 25 April 2008). Further research needs to be carried out on the benefits of using such technology on celestial bodies like the Moon, but the possibility does exist and the benefits are evident.

4.3 Future Developments and Concept Studies
Most of the technology and advanced ideologies presented occurs at advanced research facilities or through educational institutions. Most of these advancements are in their infancy, but it is the hope that they could be applied to operations on a lunar base to have a direct or indirect effect on improving crew safety. Technologies presented here fall within levels 2 and 3 of NASA's TRL (Johnston, 1995).

4.3.1 Modular Robotic Technology

Modular robotics offers a unique and beneficial approach to future lunar missions through designs based on reusability and reconfiguration, allowing for standardized parts to be added or removed as needed. For the technology to be effective, the robots must be able to adapt to changing tasks.

This methodology occurs on a high-level where larger-scale parts can be swapped-in and out as required, such as robotic extremities, sensory instruments, and locomotion trains, as opposed to low-level parts like motors and actuators. This approach does have some limitations, such as the production of only a few types of robots, but is advantageous in allowing for the assembly procedure to be greatly simplified (Farritor and Zhang, 2000).

At the heart of each modular robot is the core module, which may or may not include a power and control module depending on the production choices made. Any module that is to be attached to the robot must be attached to the core module through a Standardized Robotic Port (SRP). Every core module of a robot requires a power module and a control module to be attached in order to operate. The power module will provide energy to the robot, and the control module will perform command and communication operations as required by the robotic tasks (Farritor and Zhang, 2000). Figure 4-12 shows the core module with the power and control modules.

The reconfiguration procedure would involve a pre-assembled modular robot dedicated to assembling other modular robots. With the presence of crew on the lunar surface, a crewmember may perform the reconfiguration of the robotic element himself (Farritor and Zhang, 2000). Figure 4-13 shows what a complete modular robot could look like.

The benefits of utilizing a modular approach are abundant. This methodology is highly logical in the sense of utilizing robotic elements for as long as practically possible, while instilling reusability at a higher degree. Every robotic part possesses a singular use, but its usage can play-out in a variety of cases and unforeseen situations, and each element can be utilized whenever called-upon. Another benefit of using such an approach is the redundancy factor. The ability to
swap-in and -out certain modules of a robotic element allows for damaged or malfunctioning components to be inter-changed with new or working parts, assuming failures occur within the modular elements and not the main core module. Such versatility directly results in this being a cheaper approach in general. Instead of having separate robotic elements or different missions being developed, just one mission with slightly more complex robotic elements can be developed to handle the various objectives of several missions.

4.3.2 Self-Replicating Robots

Several current research projects are focused on a particular approach concerning the future of autonomous robots: self-replication. The technology currently in development is based on modular robotics. Self-replication consists of a robot able to construct a replica of itself using passive components (i.e., extra components like additional modules or built with the extraction of raw materials from the surrounding environment) (Chirikjian and Suthakorn, 2002).

This technology is currently being developed at several universities, such as Cornell University. Recent projects in this regard have demonstrated that self-replicating technology is feasible. In 2005, Hod Lipson and his team at Cornell developed molecube technology, an advanced project focused on kinematic self-reproduction. Molecube technology consists of an assembly of modules that forms machines that work as autonomous robots with the ability to reproduce themselves as long as they are fed by extra modules. However, the machines that are proposed here are only a proof of concept, which is to say that they do not include any other useful function.

This type of technology could offer significant advantages during space missions, particularly during planetary exploration and colonization missions such as a lunar base. The integration of self-replicating robots and, more generally, of modular robots would make the mission more robust and flexible (e.g., supplies of spare modules could be sent to a location to allow for autonomous reparation or replication), more economic (e.g., reduction of launch cost), and more versatile (i.e., this type of robot can adapt itself to the surrounding environment). Moreover, such robots could potentially replace humans inside potential dangerous environments thereby increasing crew safety. In the literature surveyed, it appears that some projects have considered using self-replicating technology to build an infrastructure to support a future lunar base (Pfeifer et al., 2003, Freitas et al., 1980).

Although this technology can represent great potential for future exploration missions, its integration inside space agencies plans for missions to Moon beginning 2020 is not conceivable. Self-replicating technology is not expected to be available within the time frame associated with Phases 1 and 2 of lunar base development. Although some proofs of concepts have been produced, it is very difficult to predict how well public opinion will accept this technology given the integration of higher AI, an issue that continues to concern groups of people (Beckey, 2005).

4.3.3 Health Sector Robots

As mentioned previously, there are significant limitations in current medical robotic systems such as size, weight, and technical requirements. Those considerations would become more important when planning transportation and utilization of this technology for a lunar base. Natural orifice surgery using miniature robots as tools for surgeons could provide one solution for the limitations of current technology for diagnosis and treatment reducing injuries to the
patient.

The first option is Wireless Capsule Endoscopy (WCE). In the future, a robotic platform could be available with active mechanisms for locomotion, cutting edge microsensors for diagnosis or therapy, and multipurpose tools for minimally invasive surgery (Moglia et al., 2007); however, such platforms would be limited to the lumen of the gastrointestinal tract. Natural Orifice Transluminal Endoscopy (NOTES) is another option. In this technology, in vivo mobile robots are introduced through natural orifices and then inserted into the abdominal cavity through small incision in the gastric, rectal, vaginal or vesical walls (Swain, 2008). Natural endoscopic transgastric abdominal surgery, as such procedures are known in the medical community, could replace traditional laparoscopy in the future (Rentschler et al., 2007). These robots explore hollow cavities with locomotion systems based on “inch-worm” motion through grippers and extensors, rolling tracks or rolling stents. They use electricity and/or vacuum as sources for locomotion and are provided with cameras or manipulators (Rentschler et al., 2007). Mobile robots are able to move and climb inside the abdominal/pelvic cavity on highly deformable structures without causing visible damage (Lehman, 2007). Other robots used in minimally invasive cardiac interventions, such as HeartLander or the Articulated Robotic Medical (ARM) probe, are teleoperated systems proved in porcine models that are under further development. They provide locomotion on the surface of the heart, visual feedback to the physician, ablation, or therapy through needles or catheters. (Patronik et al., 2005; Patronik et al., 2006; Ota et al., 2006) These robots are shown in Figure 4-14.

The Canadian Center for Minimal Access Surgery (CMAS) and NASA performed training experiments in an abdominal cavity simulator using in vivo robots from the University of Nebraska during NEEMO 9 in 2006 (Rentschler et al., 2008). Mobile in vivo robots could be used even in case of trauma, delivering drugs, clamping an artery or stopping bleeding in remote environments such as a battlefield; however, more development in miniaturization of optical components and batteries is required (Lehman, 2007). This application could provide fast diagnostic and therapeutic capabilities, with low mass requirements for the entire mission. Wireless capability is the next step for this technology. These robots could also be delivered by non-medical personnel (Hawks et al., 2008).

![Figure 4-14: Miniature mobile robots for minimally invasive surgery (Ota et al., 2006a; Lehman et al., 2007; Ota et al., 2006b)](image)

Tumors and cancer associated with exposure to space radiation could be early detected and
treated at cellular level using nanotechnology while astronauts are on the Moon. Nanorobots or nanobots could be introduced into the vascular system or at the end of catheters into vessels or cavities of the body. They could search for tumors, make the diagnosis and treat with ablation by nanomanipulation in early stages of the disease (Jain, 2008). Nanobots are considered to be a real possibility. In fact, the first operating biological nanorobot could appear in the coming five years and more complex diamondoid based nanorobots in ten years (Patel et al., 2006; Jain 2008); therefore, they could be available to protect astronauts against radiation effects for a Phase 2 or 3 lunar mission. Currently, one of the most promising approaches to intravascular robots was created by researchers at the Israeli College of Judea and Samaria in Ariel. Researchers there are developing a miniature robot that travels through the bloodstream with the ability to crawl within the human body's veins and arteries. The Israeli robot's diameter is one millimeter and could be a hub for tiny manipulator arms to be manipulated within a variety of vessels of differing diameters (Grimi, 2007).

Finally, an implantable multifunctional biorobotic system called Visychip has been proposed for human space exploration missions. This device would monitor the interior human body parameters and exterior environment. When sickness or danger is detected, the Visychip would be able to deliver the appropriate dose of a required drug through diffusion via a nanoporous membrane. The Visychip would monitor environmental radiation and its effects in the body. This technology could send information about health and safety conditions to a watch-like device worn by an astronaut or to medical support computers. In addition, the Visychip could be used to locate and assess condition of crewmembers in case of emergency (ISU, 2005). These capabilities would be particularly beneficial for astronauts performing EVA tasks where safety risks are substantially more pronounced.

4.4 Astronaut-Robotic Synergy

As demonstrated in Chapters 2 and 3, most tasks associated with the early phases of establishing an outpost or base on the Moon will require some degree of involvement by astronauts. Robotic systems may be employed to work with and enhance the performance of astronauts, or may be operated remotely by astronauts in order to reduce the safety risks to astronauts. In either case, robotic systems will not be designed with full autonomy, but will be teleoperated or semi-autonomous in nature. Sections 4.1-4.3 have illustrated the various robotic technologies that currently exist or are under development that could potentially assist astronauts perform lunar tasks. However, the ability of astronauts to interact with robots and the quality of that interaction will be a much greater factor in the decision making process of which technologies to use rather than the physical capabilities and level of readiness of the technology. As Fong et al. (2005) suggest, “cost pressures and other mission constraints (e.g. risk minimization) will keep astronaut teams small, [and thus] the effectiveness of Human-Robot Interaction (HRI) will have a major impact on the productivity and performance of future missions” (Fong et al., 2005). Understanding how astronauts and robots will interact in the lunar environment and how that interaction can be evaluated both qualitatively and quantitatively will play an important role in mission planning.

Research in this domain is currently ongoing. For example, the Peer-to-Peer Human-Robot Interaction (P2P-HRI) project at the NASA Ames Research Center was established to develop techniques to enhance synergy between human and robotic coworkers. It thereby focuses on "supporting tasks that are essential for basic mission operations and that are well-defined and
narrow in scope. These include shelter and work hangar construction, piping assembly and inspection, pressure vessel construction, habitat inspection, and in-situ resource collection and transport” (Fong et al., 2005). The entire P2P-HRI system prides itself on increased capability, flexibility, and overall effectiveness. It allows astronaut-robot teamwork to be implemented in a variety of environments and situations (Fong et al., 2005). In order to achieve such demands, the P2P-HRI philosophy emphasizes effective use of bi-directional communication between human and robot, as well as a paradigm shift from the old master-slave relationship to one where humans and robots are considered peers. Two benefits of such a system are

- "it allows humans and robots to communicate and coordinate their actions"
- "it provides interaction support so that humans and robots can quickly respond and help the other (human or robot) resolve issues as they arise" (Fong et al., 2005)

Systems such as P2P-HRI will allow for more effective teamwork between humans and robots. The philosophy can be implemented using a variety of robotic technologies, including teleoperated and semi-autonomous systems, and may thus prove to be very beneficial in future lunar missions as robotic technology evolves.

4.4.1 Teleoperation and Semi-autonomy

Teleoperation involves directly controlling a robotic system from a remote location. The primary advantage for such operation is the increased safety of the operator by keeping them away from the hazardous area. A main constraint in teleoperation is latency, the length of time for the delay of a signal. This is directly related to the distance of operation between the operator and the remotely controlled system. For operators on the Earth the latency is in the order of a few seconds, round-trip; whereas, if the operator were in a lunar base operating a robot outside, latency would not be an issue.

There are various interface methods through which a human operator would be able to interact with a teleoperated robot. Traditionally, the use of a joystick and simple monitors were sufficient; but, with the increasing demand of remote operators for a greater presence in the work environment, other systems must be considered. The immersion of an operator in the working environment such that the operator is provided with the sensory equivalent of being on-site is considered telepresence (Salleberger, 1999). Telepresence achieved through “teleoperation is assumed to include an immersive ‘virtual’ environment, so that the human views the scene from the robot’s point of view” (Landis, 2004).

The use of advanced haptic devices will aid in providing the operator with a greater sense of presence. This experience “will require a high-fidelity, high-bandwidth connection to give the humans a fully detailed virtual presence in the robotic body” (Landis, 2004). Technologies such as ultra-responsive force reflecting hand controllers that allows operators to “feel” the environment, and stereoscopic vision that gives the operator depth perception (Salleberger, 1999) are examples of the type of technology to be employed. Figure 4-15 illustrates what such a system could look like, and how it can be used.
An example of surface exploration using teleoperation is where “samples can be collected by teleoperated robots, and analyzed by humans in the shirt-sleeve environment of a fully equipped on-site laboratory” (Landis, 2004). Once the most interesting sites have been identified, “initial forays by telerobots can be followed by detailed ‘in person’ visit by space-suited humans. The purpose is to save the humans for goal-oriented exploration once [it is] known exactly where and what to look at by telerobotic exploration” (Landis, 2004). The use of teleoperation boasts many advantages, but most importantly allows for limiting the duration and the total number of EVAs conducted by an astronaut, and therefore significantly reduces the occurrence of any risks associated with such an activity.

Semi-autonomous robots are the next step in robotic technology toward full autonomy. This type of robot remains partly controlled by humans via teleoperation but can operate independently the majority of the time, thus enabling astronauts to focus on the tasks instead of robot control and monitoring. Semi-autonomous robots can be reprogrammed at any moment by a remote operator so long as the distance between the operator and robot is small (i.e., non-interplanetary missions). They have yet to be used to any large extent in space, but depending on the complexity of the task, semi-autonomous robots could potentially accomplish the same tasks as an astronaut performing an EVA or assist astronauts. As the level of autonomy increases, more emphasis must be put on developing robot self-awareness (i.e., recognition of physical limits and the need for human assistance) and human-awareness (i.e., recognition and awareness of the operator or crewmember being assisted). This would imply a necessary improvement in communication between robots and astronauts.

Current technology permits human operators to broadcast simple commands to robots; conventional human-robot dialog is limited to ‘master-slave’ commanding and monitoring. As a result, system performance is strictly bound to the operator’s skill and the quality of the user interface. Such human-robot communications can take place on three levels: in a shared space, via line-of-site (e.g., between an astronaut in a habitat to a robot outside on the lunar surface), and over-the-horizon. As the level of interaction increases in the future between robots and astronauts, and tasks become more complex, it is necessary to pay particular attention to how astronauts and robots communicate between each other. Future astronaut-robot communication will likely take advantage of video display, sound, physical gestures and motion, spoken language, gaze direction and facial expression in real time (Alami, 2008).

4.4.2 Metrics for Evaluating Human-Robotic Interaction

When considering the relationship between humans and robots, it is important to understand the roles of each with respect to each other within the entire scope of a mission. Simply stated, robots are subject to their human operators and programmers and are designed to perform
specific tasks and fill particular needs of the mission. There is no clear-cut way of examining how well these needs are fulfilled except by examining how effectively tasks are performed by a human-robot joint team. Measuring human and robotic interaction is very difficult largely due to the fact that it is qualitative rather than quantitative. This does not mean, however, that evaluating HRI is impossible. Table 4-1 shows three different types of high level metrics and how they can be used to measure HRI.

<table>
<thead>
<tr>
<th>METRIC</th>
<th>MEASURED BY</th>
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<tbody>
<tr>
<td>Effectiveness</td>
<td>Task success</td>
</tr>
<tr>
<td>Teamwork efficiency</td>
<td>Analysis of breakdowns, subjective questionnaire data, time measures</td>
</tr>
<tr>
<td>Astronaut workload</td>
<td>NASA Task Load Index (TLX)</td>
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</tbody>
</table>

Additionally, computer scientists specializing in HRI have devised a certain number of metrics for quantifying the effectiveness of interaction between humans and robots. The results of using such metrics can subsequently be used to judge the worth of HRI; the goal being to progressively reduce the level of human interaction required in the relationship without diminishing the overall effectiveness of the task (Olsen and Goodrich, 2003). Metrics that guide the design of HRI include task effectiveness (TE), neglect tolerance (NT), robot attention demand (RAD), interaction effort (IE), and fan out (FO) (Olsen and Goodrich, 2003).

**Task Effectiveness (TE)**

TE is the measure of how well a human-robot team accomplishes a particular task (Olsen and Goodrich, 2003). Within TE there are a number of metrics that can be considered, including: “time-based metrics that attempt to maximize the speed of performance, error-based metrics that attempt to minimize mistakes or damage, and coverage metrics that measure how much of some larger goal is achieved” (Olsen and Goodrich, 2003). The intent of evaluating TE is to ensure that efficiency is maximized, but this is largely governed by the task to be accomplished.

**Neglect Tolerance (NT)**

NT is the measure of autonomy of a robot with respect to a certain task, or in other words, how the robot’s current task effectiveness declines over time when it is neglected (Olsen and Goodrich, 2003). This is characterized by the neglect curve shown in Figure 4-16: Characteristic neglect curve (Olsen and Goodrich, 2003). The curve approximately identifies how a robot’s task effectiveness declines as the duration of user neglect increases; the longer the user does not acknowledge the robot, the greater the decline in overall task effectiveness.
Neglect time is the threshold time at which point anything the robot does goes below the minimum standard of effectiveness required. This determines the maximum time that a robot can be “neglected” without having an unacceptable level of effectiveness (see Figure 4-17: Neglect time (Olsen and Goodrich, 2003)). While both neglect time and overall task effectiveness are related to each other, they are dependent on the task to be carried out, the effort involved, and most importantly, the complexity of the task itself. Figure 4-18 shows the relationship between these three aspects.

“Neglect tolerance is [the] basic mechanism for measuring the autonomy of a robot” (Olsen and Goodrich, 2003). The longer a robot can be left to function autonomously, the longer an astronaut is free to focus on other tasks, including the supervision of other robots. Two ways of measuring NT are to either determine the average neglect time of the robot, or to estimate the progress of the task as a function of the active usage of the robot by a user (Olsen and Goodrich, 2003). There are numerous ways to increase NT, but most would involve a trade-off with task duration. In other words, tasks using robots that have increased NT will typically take longer than those with more frequent astronaut interaction.

Robot Attention Demand (RAD) and Interaction Effort (IE)
RAD is the measure of how much attention a robot requires from the operator. This can otherwise be defined as the fraction of the total task time that the operator must devote to attending to the robot. RAD represents a relationship between NT and interaction effort (IE). IE is best described as the time required to interact with the robot. The relationship between these three measures is shown by: RAD = IE / (IE + NT). Reducing RAD can be accomplished by either increasing NT or decreasing IE; however, increasing NT will not always guarantee a reduction in RAD, due to the fact that NT and IE are not independent. (Olsen and Goodrich, 2003)

Fan-Out (FO)
Another constraint point in FO is directly related to human limitations, and specifically memory, especially when related to controlling multiple robots. (Olsen and Goodrich, 2003)

At a certain point, however, an increase in the number of robotic systems working on a single task no longer increases TE. This point is known as task
saturation. Saturation can occur for two reasons: the task is too simple, or the task space is too crowded for more robots. Task saturation leads to the plateau effect seen in Figure 4-19.

### 4.4.3 The Dichotomy of Robotic Safety

One of the primary objectives for employing robots on the lunar surface is to increase crew safety through the allocation of tasks. Having robots perform certain tasks implies that astronauts can be substituted within a certain degree. Omitting astronaut participation within the protocols of a task immediately results in an increase of overall crew safety by eliminating any risks that can be encountered through the execution of the task. Such autonomy within robotics seems difficult and may not seem feasible given the importance of proper execution of some tasks. This brings forth a degree of synergy that must exist between robotic systems and astronauts. The two must work together in order to carry out many of the tasks on the lunar surface. Having one without the other would yield added risks and offer a lack of efficiency.

Incorporating robotic systems within lunar mission tasks will prove valuable to the improvement of crew safety; however, the same robotic systems can in turn result in new hazards to astronauts. This dichotomy has always existed since the employment of robotic systems within the workplace and none is more apparent than in an industrial setting. Numerous studies have examined the various safety issues involving robotic systems within a workplace where human personnel are present. The hazards of directly working with robotic systems are significant, but with the proper safety standards and procedures employed, hazards can be eliminated.

The main hazards when working with robots occur within the working envelope of the robot (IWD, 1987). Figure 4-20 shows what a working envelope of a robotic manipulator arm would like.

When determining the safety guidelines to be implemented, the different types hazard causes must first be identified. Such causes include:

- "Aberrant behavior of robots caused by control system faults" (IWD, 1987)
- "Jamming of servo-valves" (IWD, 1987)
• "Robot movement cutting its umbilical cord" (IWD, 1987)
• "Fault in data transmission causing a larger than anticipated movement of the robot arm" (IWD, 1987)
• "Programming and other operational errors" (IWD, 1987)
• "Precision deficiency, deterioration" (IWD, 1987)

These causes yield three categories of potential hazards:
• Impact - Classified as being struck by a part of the robot. It can be caused by unexpected motion of a robot, or the robotic system ejecting or dropping a workpiece (IWD, 1987; Olesya, 2006; US Department of Labor).
• Trapping - The movement of a robotic system in close proximity to a fixed object or person causing them to be crushed or trapped (IWD, 1987; Olesya, 2006; US Department of Labor).
• Other - This includes hazards based on the direct application of the robotic system itself. They can include electric shock, burns, fumes, radiation, toxic exposure, etc. (IWD 1987).

The sources of these hazards may arise from:
• Control errors - Faults that occur within the control system that can include software errors, electrical interference, faults in the hydraulic pneumatic or electrical sub-controls (IWD, 1987; US Department of Labor, 2005).
• Mechanical errors - Caused by parts or tools carried or manipulated by a robotic system. A mechanical failure can result in the ejection of workpieces. This can be attributed to overloading, corrosion, fatigue, or a lack of maintenance (IWD, 1987; US Department of Labor, 2005).
• Environmental hazards - The application of the robotic system through operation can cause hazards that may include fumes, flying particles, dust, vapor, or a flammable and explosive environment (IWD, 1987; US Department of Labor, 2005).
• Human errors - Can be caused by incorrect operation or by a lack of familiarity of the robotic system (IWD, 1987; US Department of Labor, 2005).

When employing a robotic system, it is important to survey the possible hazards that may lead to a risk of injury through its operation (IWD, 1987). Once this analysis has been undertaken, guarding procedures must be carried-out in order to eliminate any hazards. The areas of hazard can be broken-down into three levels:

• Level 1 - The perimeter of the work area (IWD, 1987; Olesya, 2006)
• Level 2 - Within the work area (IWD, 1987; Olesya, 2006)
• Level 3 - Adjacent to the robotic system (IWD, 1987; Olesya, 2006)

The level of hazard is directly related to the robotic system used, and the method through which it is operated. Level 1 hazards can usually be avoided through the use of passive measures, such as a physical barrier around the working area. Level 2 hazards requires sensing humans within the working envelope of the robotic system, and can be accomplished by using presence sensing devices. Level 3 hazards require detecting the presence of a person, while allowing operation to terminate upon any contact or obstruction; this can be achieved through trip devices or collision detectors. (IWD, 1987)

The implementation of these various hazard avoidance techniques as determined by the level of the hazardous area is very subjective and differs with each type of robotic system employed. It is
important to note that to guarantee the safety of the crew within a robot’s working area would require additional sensors and equipment, which would greatly increase the cost of the total system (Olesya, 2006).

As a general rule-of-thumb, when robots directly interact with a human and collaborate on tasks, they should be operated at a safely reduced speed not exceeding 2.5 cm/seconds using hand-guiding actuators with an emergency stop located on the end-effector. Furthermore, when working with humans the maximum power and force shall not exceed 80 W and 150 N, respectively. (Olesya, 2006)

Adding robotic systems to the lunar surface has many benefits, but potential hazards do exist, especially when considering interaction with astronauts. A clear and thorough analysis must be conducted in measuring any risks or hazards involved when working with robots.

4.5 Recommendations

As already discussed, the completion of certain tasks on the surface of the Moon implies inherent danger for humans. The use of robots is envisioned in two capacities: replacing and assisting humans. The result is a means to perform tasks while avoiding as much of the possible dangers associated with them. Taking into account the technologies currently available, both on Earth and in space, as well as the future developing technologies, it is possible to propose one or more robotic solutions for precise situations.

An exhaustive list of tasks (66 tasks), classified according to the associated risks and the corresponding phases, has been proposed in Chapter 3. A decision tree dedicated to analyze all of those tasks was developed for this purpose. The objective of the tree is to determine what robotic platform (or concept) should be used for a particular task to improve crew safety. This will allow for a clear distinction between astronaut and robotic tasks. The nine primary tasks were selected according to a prioritization scheme.

4.5.1 Decision Tree

The decision tree (Figure 4-21) provides a quick and easy method to analyze an exhaustive list of tasks by following a flow-chart that asks several simple yes or no questions. The decision tree filters out any tasks that should only be performed by an astronaut. It would technically be possible to employ a robotic system for all tasks, but the feasibility based on the complexity of the task would suggest an astronaut would be best suited to perform some tasks; the tasks classified as “Astronaut tasks” indicate this.

For the tasks that require the use of robots, a series of questions are proposed with the intent of recommending a single robotic classification (see Table 4-2). These classifications identify what type of platform or robotic concept would be best utilized. For each of the classifications, the level of autonomy must also be specified, which would have an effect on the classification result. The autonomy can be broken down into non-autonomous, semi-autonomous and fully autonomous. However, the purpose of specifying the level of autonomy is to gauge the level of astronaut involvement within the task.
Table 4-2: Robotic platform classifications

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>ROBOTIC PLATFORM / CONCEPT</th>
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<tbody>
<tr>
<td>A</td>
<td>Intravehicular Activity (IVA) teleoperated robot</td>
</tr>
<tr>
<td>B</td>
<td>Fully-autonomous robotic arm equipped with locomotion system</td>
</tr>
<tr>
<td>C</td>
<td>Non/Semi-autonomous robotic arm equipped with locomotion system</td>
</tr>
<tr>
<td>D</td>
<td>Fully autonomous fixed robotic arm</td>
</tr>
<tr>
<td>E</td>
<td>Non/Semi-autonomous fixed robotic arm</td>
</tr>
<tr>
<td>F</td>
<td>Fully-autonomous mobile robot working in shadowed conditions</td>
</tr>
<tr>
<td>G</td>
<td>Non/Semi-autonomous mobile robot working in shadowed conditions</td>
</tr>
<tr>
<td>H</td>
<td>Autonomous rover dedicated to transport heavy equipments between predefined locations</td>
</tr>
<tr>
<td>I</td>
<td>Teleoperated rover dedicated to transport humans during unplanned events</td>
</tr>
<tr>
<td>J/J-Prime</td>
<td>Small fully-autonomous rover</td>
</tr>
<tr>
<td>K/K-Prime</td>
<td>Small non/semi-autonomous rover</td>
</tr>
</tbody>
</table>

It is possible for a suggested robotic platform to be used as a solution for a number of tasks, thus leading to those tasks being grouped accordingly. Over the duration of lunar missions, it is evident that a robotic architecture would become increasingly complex if one particular robot is intended for every single task. Thus, multifunctional robots should be considered preferentially (Laufer, 2008). The decision tree was designed to provide the lowest level of robotic platform distinction.

If a task has not been identified as being “astronaut only” the operating environment of the robot is then be determined: IVA or EVA activity. The level of mobility must then be considered, including locomotion. Mobility refers to an advanced degree of freedom, when a robot can move freely, either autonomously or by teleoperation, within an area in all directions or between two locations while avoiding obstacles. However, non-mobile robots like heavy manipulators could also be integrated with locomotion systems.

The next decision level requires evaluating the operation environment in the case of an EVA, which would have an effect on the power system required. Two main scenarios can be envisaged: the performance of the task in night conditions or within a permanently shadowed crater. The first scenario would prove to be the most challenging in regards to a robotic design, especially during search and rescue operations (Laufer, 2008), solely due the low temperatures and the duration of darkness. Operations within a permanently shadowed crater would limit the duration of the activities being conducted. Based on the phase definitions and proposed robotic capabilities, only small robots could be utilized for such a scenario.

Finally, two types of mobile robots operating in sunlight conditions are separated depending on their size:

- Robots dedicated to carry heavy instruments or transport human beings. These objectives require large rovers to be dedicated to transportation. The design of this type of rover would be heavily influenced if a life support system were to be integrated. However, this specification is not a criteria of the decision tree; it is more so a variable that can be taken into consideration for more detailed recommendations.

- Smaller rovers to perform installation, maintenance or scientific tasks. For many
scientific tasks, the physical participation of astronauts may be desirable, thus the duration of the task must also be considered. These requirements define categories J/J-Prime and K/K-Prime. The “Prime” classification is used to indicate an EVA activity in cooperation with a robot. For example, a task that requires a travel duration greater than 8 hours to perform a scientific experiment would only use a teleoperated robot (K category); whereas, if the task can be performed in less than 8 hours, the K-Prime classification is used and refers to the use of the same robotic platform in conjunction with EVA support.

The results are summarized in Figure 4-22. Twenty-nine tasks correspond to astronaut-only tasks and the remaining 31 fall into corresponding robotic solutions. Seventy-two percent of outdoor tasks correspond to two defined categories of robots: C (non-autonomous robotic arms with locomotion means) and K/K-Prime (non-autonomous small rovers). It is important to note that there are six robotic categories that remain unused. From these results it can be concluded that in the context of developing robotic systems to improve crew safety, only a few platforms should receive the majority of industry resources.

The results presented could be called to question in regards to the level of autonomy. A fully-autonomous system leads to a more complex and more expensive solution. Such a system would ideally be used for tasks frequently performed tasks with a strict set of instructions or where teleoperation would not be possible. These types of tasks do not reflect the procedures within Phases 1 and 2 that constitute the scope of this study. Thus the preference of partially autonomous robot would be chosen.

The use of such a decision tree is not limited to the present study, and can certainly be extended to other phases of a lunar base development. Furthermore, it can be expanded to include additional criteria to better define a robotic solution. An easy to use computer program has been developed based on this decision tree. The user answers a series of simple questions that ultimately define an appropriate robotic platform to improve crew safety. The program can be expanded as additional tasks are identified and defined. This product is available on the attached CD-ROM.
4.5.2 Robotic Solutions

The following recommendations, found in Tables 4-3 to 4-11, cover the scope of the top fourteen tasks affecting the overall safety of crew on the lunar surface as identified in Chapter 3. These tasks were further grouped into nine overall tasks, by way of some tasks being combined due to identical actions involved in each of the tasks. For each of the nine tasks presented, a robotic category was assigned which correlates to the classification outlined within the decision tree representing a generic robotic platform. The following descriptions outline how the robotic solutions can or cannot be implemented within a general architecture. The “effects on risk” outline how the safety risks previously identified are mitigated or unchanged should the robotic solution be implemented. In addition, the “general benefits of robotic systems” are identified and will be referred to as needed when discussing the “effects on risk” for each task. The cost identified is an approximate figure based on technology currently being developed or already available that is analogous to the proposed solution. The TRL is based on NASA’s standard for evaluating the maturity of technology (see Figure 4-1). The “Feasibility” of the robotic solution also discusses any changes or modifications that would need to be implemented for the solution to be employed within Phases 1 and 2 of a lunar base.

General benefits of robotic systems: The use of robotic systems will significantly reduce the frequency and the amount of time astronauts will be required to exit the habitat to perform various tasks. This in turn will significantly reduce the likelihood of all risks associated with the general tasks of EVA, PEVA and REVA (refer to Appendix B). In the event that an astronaut is required to exit the habitat (i.e., perform a EVA) to carry out a task, robotic assistance will reduce the amount of physical exertion required by the astronaut, and therefore further reduces fatigue, overexertion and suit trauma (i.e., finger injury from the gloves).

Table 4-3: Retrieval of stranded/Transportation of injured

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TRL</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>• BEAR: $1.1M USD (development of BEAR – FY 2008) (Vecna Robotics, 2006b)</td>
</tr>
</tbody>
</table>

Description: This teleoperated rover would be controlled by an astronaut that is on-site or from a location in the lunar base. The purpose of the robot would be solely to assist or potentially carry an astronaut from one location to another. The destination could be to a crew rover vehicle, or a habitation module.

Effects on Risk: In addition to the general benefits of incorporating robotic systems, the use of a robot aid significantly reduces the chances of a rescuer stranding since the rover is capable of withstanding more hazardous conditions than astronauts (e.g., solar events). Furthermore, since the rover will transport the injured, it will reduce the number of astronauts required to execute the rescue and REVA will not likely be necessary as part of retrieval. Finally, because transporting an injured person can be a physically demanding task, the incorporation of robotic systems will substantially reduce the risk of fatigue and overexertion.

Feasibility: The proof-of-concept of such a robotic system seems viable in a general scheme of the scenario involved. However, this type of robot (i.e., BEAR) has yet to be employed for a terrestrial purpose, and in order to put this system in practice further advancements need to be made to handle the dynamics involved in treating an astronaut as a potential casualty, and the proper protocols involved for operations on a lunar base.
Table 4-4: Solar panel maintenance/Power system installation

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TRL</th>
<th>COST</th>
</tr>
</thead>
</table>
| C        | 6   | • Dextre: $200M USD (FY2008) (CBC, 2008)  
          |      | • Apollo Lunar Roving Vehicle: $100M USD (FY 2008) (converted from 1978) (Williams, 2005; Williamson, 2008) |

Description: A sophisticated manipulator robot with the capability of general maintenance could be proposed for simple day-to-day tasks of general maintenance. However, due to the possibilities of the level of complexity that could arise, this would be best performed by an astronaut with the assistance of such a robotic.

Effects on Risk: In addition to the general benefits of incorporating robotic systems, the use of a large manipulator to lift astronaut or handle structure will reduce the need for the astronaut to climb structures, and in turn reduce the likelihood of falling. The manipulator can also allow better positioning of various components to provide optimum work envelope.

Feasibility: Implementing a complex robotic system capable of handling the various types of situations that can occur during maintenance activities would be very difficult. Therefore, it would be much simpler to propose that this task as be conducted by an astronaut with the assistance of a robotic arm outfitted with a lifting system for the astronaut, or implement a retractable structure that would eliminate the need for climbing.

Table 4-5: Rappelling/Climbing

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TRL</th>
<th>COST</th>
</tr>
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</table>

Description: For the sole purpose of climbing and performing a few minor tasks, a non-autonomous robotic system can be implemented. However, such a system would eliminate any physical astronaut involvement and will not be able to assist the astronaut for such a task. It may not be possible for a robot to directly assist in rappelling and climbing duties, but it is possible to have a robot indirectly assist with the tasks by providing support as a utility robot capable of carrying the necessary tools or samples for the astronaut.

Effects on Risk: In addition to the general benefits of incorporating robotic systems, a teleoperated climber can carry tools and samples for the astronaut. This means that the astronaut will not be encumbered by the tools and samples, and therefore minimizing the risk of falling.

Feasibility: A robotic solution would be possible especially in a location that has a crater, but only a limited amount of tasks could be conducted. This would not be a feasible application of a robotic solution, but an autonomous system could be utilized to assist the astronaut with tasks that require rappelling and climbing. A robotic rover could also be used for the role as a utility robot for an astronaut conducting this task.
### Table 4-6: Connecting/Disconnecting service lines/Fueling operations

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TRL</th>
<th>COST</th>
</tr>
</thead>
</table>
| K/K prime (e.g. Figure 4-5) | 6   | • $3 million USD (FY 2001) (over 3 years) (Bonsor, 2001)  
• $300 million USD (FY 2004) (to put into service) (redOrbit, 2004)  
Average cost from 3 sources: $100 million USD (FY 2008) |

**Description:** This teleoperated robot harnesses the capability to handle a varying degree of tasks that require various levels of precision.

**Effects on Risk:** In addition to the general benefits of incorporating robotic systems, the need for the astronaut to use hand tools will also be minimized, thus reducing hand tool risks, as well as other system related risks such as electrocution. The implementation of a robotic system will alleviate the need for the astronaut to perform repetitive tasks, which in the long run could pose a risk to the crew due human errors resulting from neglect of subsidiary activities and reduced working memory.

**Feasibility:** Such a robotic solution would be designed with the purpose of replacing astronauts on the lunar surface. Its design makes it capable of handling numerous tasks with the precision and dexterity of an astronaut. This robot is currently being rigorously tested and should be operational by the proposed Phase 1 or 2.

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### Table 4-7: Connecting modules

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TRL</th>
<th>COST</th>
</tr>
</thead>
</table>
| C        | 4   | • Dextre: $200M USD (FY 2008) (CBC, 2008)  
• Apollo Lunar Roving Vehicle: $100M USD (FY 2008) (converted from 1978) (Williams, 2005; Williamson, 2008)  
Approximate cost of an integrated system: $250M USD (FY 2008) |

**Description:** In order to connect together habitation modules during Phase 2, a robotic solution such as a crane-like system would need to be directly operated, or teleoperated by an astronaut. This may or may not require the operation supervised by an astronaut on the surface.

**Effects on Risk:** Initial risk analysis assumed the use of a teleoperated manipulator, and therefore the risks associated are not affected.

**Feasibility:** The technology used in cranes, for example, is very basic; in order to be space-worthy the various components and parts of such a crane would need to be outfitted with the appropriate materials and composites suitable for the lunar environment. Such a robotic solution is highly feasible.
Table 4-8: Experiment setup/Measurement taking

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TRL</th>
<th>COST</th>
</tr>
</thead>
</table>
| K/K prime (e.g. Figure 4-5) | 6   | • $3 million USD (FY 2001) (over 3 years) \(\text{Bonsor, 2001}\)  
• $300 million USD (FY 2004) (to put into service) \(\text{redOrbit, 2004}\)  
• $25 million USD (FY 2008) (development over a decade) \(\text{The National Academies Press, 2008}\)  
Average cost from 3 sources: $100 million USD (FY 2008) |

**Description:** This robot harnesses the capability to handle a varying degree of tasks that require various levels of precision. The experiment is required to be considered within a “black-box” approach, where the details of the experimental equipment are ignored. Depending on the complexity of the experiment setup and the taking of measurements, an astronaut may be required onsite.

**Effects on Risk:** In addition to the general benefits of using robotic systems, the need for the astronaut to use hand tools will also be minimized. This, in turn, will reduce hand tool risks.

**Feasibility:** Such a robotic solution would be designed with the purpose of replacing astronauts on the lunar surface. Its design makes it capable of handling numerous tasks with the precision and dexterity of an astronaut. This robot is currently being rigorously tested and should be operational by the proposed Phase 1 or 2.

Table 4-9: Integration of robots

<table>
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<tr>
<th>CATEGORY</th>
<th>TRL</th>
<th>COST</th>
</tr>
</thead>
</table>
| C            | 3   | For K/K-prime category:  
• $3 million USD (FY 2001) (over 3 years) \(\text{Bonsor, 2001}\)  
• $300 million USD (FY 2004) (to put into service) \(\text{redOrbit, 2004}\)  
• $25 million USD (FY 2008) (development over a decade) \(\text{The National Academies Press, 2008}\)  
Average cost from 3 sources: $100 million USD (FY 2008)  
For C category:  
• Dextre: $200M US (FY2008) \(\text{CBC, 2008}\)  
• Apollo Lunar Roving Vehicle: $100M USD (FY 2008) \(\text{converted from 1978}\) \(\text{Williamson, 2005; Williams, 2008}\)  
Approximate cost of an integrated system: $250M USD (FY 2008) |

**Description:** Due to the non-specification of the robots being integrated, two approaches can be taken; when dealing with small rovers, a more dexterous robot can be implemented; when dealing with larger components, a robotic solution such as an arm could be utilized. This task may involve the physical interaction of the robotic system with an astronaut.

**Effects on Risk:** In addition to the general benefits of using robotic systems, the need for the astronaut to use hand tools and physical interaction with the system will also be minimized. This, in turn, will reduce hand tool risks, as well as other system related risks such as electrocution.

**Feasibility:** The technology proposed would be possible to implement for both instances to the extent of integration required. Both a dexterous or a more robust robot can be employed by Phases 1 or 2.
### Table 4-10: Crew rover maintenance

<table>
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<th>CATEGORY</th>
<th>TRL</th>
<th>COST</th>
</tr>
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<tbody>
<tr>
<td>C</td>
<td>5</td>
<td>• Dextre: $200M USD (FY2008) (CBC, 2008)</td>
</tr>
</tbody>
</table>

**Description:** Once the rover is at the maintenance site, the rover might need detailed maintenance requiring access by an astronaut to the undercarriage and therefore a robotic manipulator arm would be employed to hoist the rover. The maintenance tasks would be conducted directly by EVA-suited astronauts.

**Effects on Risk:** In addition to the general benefits of using robotic systems, the need for the astronaut to use hand tools will also be minimized. This, in turn, will reduce hand tool risks.

**Feasibility:** Robotic manipulator arms have been used in a variety of space applications, and should also be easily developed for the purpose of rover maintenance on a lunar base.

### Table 4-11: Unloading/stowage of resupply cargo/Transporting scientific instruments

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>TRL</th>
<th>COST</th>
</tr>
</thead>
</table>
| H        | 3   | • Dextre: $200M USD (FY2008) (CBC, 2008)  
• Apollo Lunar Roving Vehicle: $100M USD (FY 2008) (converted from 1978) (Williams, 2005; Williamson, 2008)  
Approximate cost of an integrated system: $250M USD (FY 2008) |

**Description:** In addition to the general benefits of using robotic systems, the need for astronauts to be physically involved in unloading/stowage operations is significantly reduced. Therefore, the risk of injuring an astronaut due to unintentional load drop or pinching is significantly reduced. Furthermore, because cargo handling is a physically demanding task, the incorporation of robotic systems will substantially decrease the risk of astronaut fatigue and over exertion.

**Effects on Risk:** In addition to the general benefits of using robotic systems, the need for astronauts to be physically involved in unloading/stowage operations is significantly reduced. Therefore, the risk of injuring an astronaut due to unintentional load drop or pinching is significantly reduced. Furthermore, because cargo handling is a physically demanding task, the incorporation of robotic systems will substantially decrease the risk of astronaut fatigue and over exertion.

**Feasibility:** A roving vehicle capable of carrying cargo should not be hard to develop, but it would require outfitting with the appropriate robotic arm to handle various types of cargo, while also being robust enough to handle heavy loads.

### 4.6 Legal and Ethical Perspectives of Astronaut-Robot Coexistence

The presence of Man in outer space and on the Moon has been a driving factor in the development of classical international space law. Article V of the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, (herein referred as the ‘Outer Space Treaty’) recognizes the safety of humans in space by declaring that astronauts are “envoys of mankind” and urges States “to render to them all possible assistance in the event of accident, distress, or emergency landing on the territory of another State Party or on the high seas.” In addition, the Outer Space Treaty obliges States to immediately inform the other States Parties or the United Nations of “any phenomena they discover in outer space, including the Moon and other celestial bodies, which...
could constitute a danger to the life or health of astronauts” (Outer Space Treaty, 1967). The spirit of astronaut safety was reiterated in Article 10 of the 1979 Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (herein referred as the ‘Moon Agreement’) (Moon Agreement, 1979). Through these treaties the international community has demonstrated their concern for astronaut safety, and has declared a collective responsibility for ensuring the safety and wellbeing of astronauts. Although robotics is not mentioned in any of the international treaties, the quest for astronaut safety is one of the reasons that have prompted the introduction of robots.

The importance of human safety in space extends beyond international law. National laws have significantly advanced regulations on crew safety. For instance, the American National Standards Institute USA developed a set of safety standards important to crew safety. Since the 2003 Columbia tragedy, NASA has been testing robotic devices for inspection and repair duties. Some NASA officials were of the opinion that it was “…risky to an astronaut overboard to eye or repair damage in out-of-the-way locations on a space plane. In fact, a space walker could possibly create more damage to the sensitive tiles in attempting to survey or fix the heat-thwarting material” (David, 2003). The NASA Space Agency Engineers speculated that “The Columbia disaster may hasten the day of having free-flying robot inspectors in an astronaut’s tool kit,” (David, 2003). NASA has since been working on strengthening regulations for crew safety.

The safety of astronauts continues to impact the development of legislation and regulation. The use of robotics in space is a new concept that has not been exhaustively regulated and needs to be addressed in a legal context. During the course of space law development, drafters of the primary space treaties did not consider robots coexisting with humans for space exploration missions. They did not, therefore, create provisions to deal with astronaut-robot safety. Nonetheless, numerous concepts have evolved in other spheres of law other than space law, which cover various aspects of astronaut-robot safety. In light of this and for the purposes of in-depth analysis of legal aspects related to astronaut-robot safety and coexistence they are discussed in further detail throughout this section. Analogies are drawn from existing practices in other legal branches, and other potential legal considerations are examined. The discussion hereunder has been limited to astronaut-robot safety with a main focus on robot regulation.

4.6.1 Robotic Safety Standards and Regulations

There are two classifications of regulations that need to be considered when looking at robot-related safety issues: pre-safety and post-safety regulations (Weng et al., 2007). Pre-safety regulations place emphasis on risk assessment and mitigation by putting safeguards on the use and maintenance of robotic systems. Pre-safety regulations exist on a regional, national, and international level; Post-safety regulations are aimed at addressing responsibility distribution. On an international level, the International Standards Organization (ISO) provides for pre-safety rules. For example, rule ISO 10218-1:2006 deals with safety-associated design, protective measures, and industrial robot applications. It also identifies basic hazards associated with robots that should be eliminated so as to reduce risk. Rule ISO 10218-1:2006 also provides safety design guidelines that include rules regarding general machine safety in industrial robot environments. These rules apply to safety-related components of control systems and software design of robot arms and manipulators. (ISO, 2006)

In Europe, the European Cooperation for Space Standardization (ECSS) was established to
develop a coherent, single set of user-friendly standards that are applicable for use in all European space activities. These standards are applicable to pre-safety measures for the manufacturing of robots. An example of national regulations that offer pre-safety measures is found in the industrial robot safety guidelines published by the British Health and Safety Executive Office in 2000 for installation, commissioning, testing, and programming of robots. These national regulations are intended to ensure safety during human-robot co-existence. In most cases, development of pre-safety regulation is largely a government responsibility. In the future, if countries cooperate in the development and manufacturing of robots for the purpose of space exploration, there will be a need to harmonize safety standards, especially if robots are to interact with humans. In that regard, there is a need to re-examine the importance of having a specific, comprehensive and all-inclusive set of regulations that can encompass the different safety standards for future human-robot coexistence.

4.6.2 Development of Robot Legal Rules

Montaner (2000) stated that “…scientific technological activities cannot continue developing without legal rules.” Generally, industrial robots are designed to perform specific tasks that are simply a set of pre-defined instructions that cannot be altered by the robot in response to changing environments. More advanced NGRs, however, will have complex systems that can detect changes in their environment. These systems will result in increased interaction with the environment, similar to human reaction. The emergence of Safety Intelligence (SI) (described as “a system of AI restrictions whose sole purpose is to provide safety parameters when semi-autonomous robots perform their tasks”) in NGRs will likely require designers and manufacturers to consider potential hazards associated with the complexity of new robotic systems (Weng et al., 2007). This means that new restrictions standards, regulations and even laws will need to be developed to ensure the safety, standardization and quality assessment of NGRs, especially those intended to function autonomously (Lyons, 1999).

Although there is currently no existing SI system implemented in any robot, there have been numerous references to the proposal of one by science fiction writer Isaac Asimov, based on his three laws of robotics. They are said to have been the basis for the European Robotics Research Network (EURON) Robotics Roadmap (Weng et al., 2007). In addition, Korea is developing plans to establish a code of conduct for roboethics which is centered on these laws (Lovgren, 2007). However, some robot manufacturers and scholars are against the idea of giving robots morals, or drawing a code of ethics, as suggested by proponents of Asimov’s school of thought (Kerr, 2007). Nonetheless, whether Asimov’s laws or other ethical codes are considered, key contentious issues incumbent to safety concerns need to be addressed.

One specific problem is the ability of robots to “think abstractly” (Weng et al., 2007). Abstract thinking enables humans to interpret and react to human communication. This includes the ability to discuss and understand expressions like metaphors or body language. For example, a robot could not understand an expression of pain on an astronaut’s face to render assistance if the astronaut is unable to operate the robot. This reiterates Asimov’s description of robots as "logical but not reasonable" (Asimov, 1957). The inability to think abstractly could negatively impact the robot’s ability to improve crew safety. Another problem is that of “decision making” in reference to doctrinal reasoning powers. For instance, an autonomous robot would have to interpret the concept of “safety” in order for it to decide when and how to react to dangerous stimuli. For humans, ethical and moral reasoning enable us to distinguish between right and wrong. Critics argue that “…in conflicts involving doctrinal reasoning and morality, the Three
Laws (of Asimov) may become contradictory or at risk of being set aside in favor of human requirements” (Hirose, 1989). Lastly, the problem of legal protection in terms of human robotic co-existence requires review. It has been contended that if Asimov’s Laws are used as a guideline, enforcement would be an arduous task because they are devoid of legal value (Weng et al., 2007). All of these aspects of robotics will need a new branch of law and new policy frameworks ahead of any legal challenges that may ensue.

4.6.3 Liability of Astronaut-Robot Coexistence

Liability is important as safety issues are mostly related to the responsibility of averting accidents and the prevention of damage. In addition, liability clearly identifies obligations, rights and remedies of parties, especially where insurance matters are concerned. Under international law, liability with respect to space activities governed by the Outer Space Treaty and the 1971 Convention on the International Liability for Damage Caused by Space Objects (here in referred to as ‘Liability Convention’) (Liability Convention, 1971). These two treaties extend the liability of States in the event that damage is caused by an object of one launching State, to persons or property onboard such a space object by a space object of another launching State. Liability under national law is mostly government by law of tort as stipulated in respective domestic legal systems (e.g., the law used in industrial accidents, which calls for responsibility for damage caused to another person).

Liability is incumbent in the discussion of safety under astronaut-robot coexistence on the Moon. The rights and responsibilities of robots with different levels of AI will need to be clearly identified based on self awareness issues to assist in future liability regimes (Weng et al., 2007). As mentioned in Section 1.3.2, in the case of an accident involving a human and a robot occurred in Japan, the Japanese national liability regime was important for compensation. In case such accidents occur on the lunar surface, a liability regime is needed to identify the party responsible for tort for compensation purposes. Thus far, under some national laws, human space flight requirements for crew liability regulations aim to protect the public and the USA Federal Government. Under these regulations, the astronauts consent to "liability cross waivers" that do not allow them to hold a claim against the USA government for damages during space flight (FAA, 2005).

Cross waiver liabilities have been used by most space faring nations and in the Inter-Governmental Agreement (IGA) governing the ISS. (IGA, 1998) A sound liability regime would be instrumental in increasing the safety standards that impact crew safety. The current international liability regime is limited to general liability and does not include safety issues related to astronaut-robot coexistence on the Moon. Analogies can, however, be drawn from the ISS liability regime on astronaut-robot coexistence and other industrial terrestrial practices dealing with safety where robots and humans co-exist. There is certainly a need for a new framework outlining the rights and responsibilities related to liability on astronaut-robot coexistence in order to enhance safety standards.

4.6.4 Dispute Resolution

Dispute resolution is a key element of any legal system. The Outer Space Treaty and the Moon Agreement do not have specific dispute settlement mechanisms for conflicts on the Moon. The current dispute resolution mechanism relies mainly on general international law which is weak and devoid of enforcement mechanisms. Article 18 of the Moon Agreement, however, allows
for further developments within which dispute resolution could be considered. Some of the challenges that could arise in astronaut-robot coexistence relate to the jurisdiction of any dispute resolution institution in case of a dispute. The developments that come with the use of robots on the Moon may also generate disputes that will need to be addressed. For example, in the case where an astronaut dies in the “hands” of a robot belonging to another State, the dispute resolution mechanism to be pursued will need to be identified. The appropriate dispute resolution institution with the jurisdiction to deal with the case will also have to be determined. According to the Outer Space Treaty provisions dispute resolution can be pursued under general international law mostly under the International Court of Justice (ICJ); however, certain problems exist that are inherent in such a legal body. The jurisdiction of the ICJ is limited to the consent of both States in order for the case to be heard by the court, and the process of the court is lengthy. Furthermore, its enforcement mechanisms are weak (ICJ-34, 1945). Dispute resolution mechanisms need to be identified or set up by cooperating States before going to the Moon. Countries could highly benefit from the example of the IGA of the ISS.

### 4.6.5 Planetary protection

“If something is intrinsically valuable, then any moral agent has a moral reason to try to bring it into existence or to preserve it if it exists already.” Regan D. (1986) Planetary protection denotes the practice of protecting the celestial bodies within the Solar system from the Earth environment and ecosystem, while aiming to protect Earth from life, substances or other hazardous materials that could be brought back from the various celestial bodies (Rummela, 2004). It also refers to policy and scientific approaches of reducing the chances of life being transported on spacecraft from one planet to another (Cockell, 2005). The purpose of planetary protection policies is to ensure that relevant missions are in full compliance with protection policies and requirements. Article IX of the Outer Space Treaty, declares that States have the obligation to conduct all exploration without harmful contamination and creating adverse changes to the environment of the Earth. Article 6 of the Moon Agreement requires states to take measures to prevent disruption of the existing balance of the environment on Earth through introduction of extraterritorial matter. Moreover, states undertaking lunar exploration have the responsibility of protecting the lunar environment. Although robots could be employed to assist in planetary protection, for example, through waste management the robots themselves as they become inoperable may pose additional hazards to astronauts during EVA activities.

In terms of planetary protection, a comparison of the benefits and disadvantages of using robots on the lunar surface needs further attention. The Committee on Space Research (COSPAR) has been responsible for developing planetary protection policies (COSPAR, 2008). That notwithstanding, very little on the subject of contamination by robots has been done. COSPAR has, however, influenced the planetary protection policies of various space agencies. For instance, the USA passed the NASA Policy Directive NPD 8020.7F (1999), which states that the Earth must be protected from the potential hazard posed by extraterrestrial matter carried by space flight returning from another planet. This provides a platform where protection of the Earth from returning robots can be implemented. There is definitely a need for a systematic approach to curb disposal problems that may arise when the robot population on the Moon increases. Lastly, issues of extraterrestrial life are very significant in lunar exploration. To date, it has been difficult to prove that the Moon and other celestial bodies are absolutely lifeless. An increase in the number of robotic systems increases the chance for the introduction of microorganisms on the Moon or destruction by the robots. Legal regimes for planetary protection need to be expanded and harmonized to include safety issues related to astronaut-
robot co-existence vis-à-vis the protection of lunar and terrestrial ecosystems.

4.6.6 Ethical Considerations for Safety of Human-Robot Coexistence

Ethics is defined as moral principles of action, concepts of risk, and acknowledgment of other people based on respect for all mankind, is a significant part of the harmonious and integrated development of scientific and technological progress. Societal concerns are not only confined to living and working on the Moon but also include the impact of the coexistence of humans and robotics. The entire discussion on safety centers on the dignity of humans and the general public perception of the worth of life. Unlike the price of a robot which can be calculated, the value of life cannot be quantifiable since it varies from society to society. It is said to lie between zero and infinity (ISU, 2005). This figure is heavily influenced by the ethical and cultural values of a society. It is from this concern that the international community, under the aegis of United Nations Educational, Scientific and Cultural Organization (UNESCO), unanimously and by acclamation adopted the Universal Declaration on the 1997 Human Genome and Human Rights were (UNESCO, 2000). UNESCO also coined the term “bioethics” which refers to the social, cultural, legal and ethical implications of technological developments, scientific research and discoveries (Pompidou, 2000). In addition to the legal issues already discussed, ethical issues related to astronaut-robot coexistence must be considered.

4.6.7 Robotic Future: AI and Robot Rights

Acknowledging the scope of this study and the robotic systems proposed, it is evident that AI will not be a feasible technology to be implemented within Phases 1 and 2. However, as robotic technology and their capabilities continue to advance robot AI could be a realistic possibility. Designers and manufacturers of NGRs intend to create robots that have capabilities similar to those of humans. This refers to the theory of Human Based Intelligence (HBI), which accords robots specialized capabilities enabling them to adapt to unstructured environments and work more closely with humans. There is, strong opposition to the development of HBI by some researchers who are resisting what has been termed as a “humanoid complex” trend, by insisting on the functional goal of a robot: to invent useful tools for human use (Weng et al., 2007). Other opponents of the HBI theory argue that goal-oriented robots do not require what humans refer to as “awareness,” therefore HBI should not be pursued Also related to safety, and important in the debate is the issue of safety intelligence, which raises the question of pre- and post-human-robot interaction responsibilities. If indeed the robots will be given roles identical to ones inhabited by humans, will they also be entitled to assume rights like those of humans? How can these rights be claimed? Robot rights have engaged not only futurists, but also lawmakers. For instance when the Hawaii Judiciary developed a comprehensive planning program, a futures research component, it identified the question of robot rights are one of the areas of emerging issues to be discussed (Sugimoto, 1981). At the moment however, robots are still regarded, as inanimate objects which lack the entire element that match those of a human or living organisms. On those grounds, they are devoid of rights and cannot claim any rights. But there will definitely be a paradigm shift with the advent of HBI and AI. According to Christopher Stone, for a thing to be a holder of legal rights, a certain criteria has to be fulfilled before it is legally recognized as, worth with dignity hence claim rights (Stone, 1974). Policy makers and legislators have to be prepared to deal with these developments. Although general in nature the trickledown effect will by extension affect space exploration and in particular safety issues particular to astronaut robotic coexistence.
4.6.8 Towards the Establishment of an Astronaut (Robo-)Ethics Code

The question of ethics in human-robotic interaction has evolved to initiatives to codify ethical issues related to human-robot coexistence. The Korean Ministry of Commerce, Industry and Energy (MCIE) is set to adopt a Robot Ethics Charter that will guide robot users and manufacturers with ethical standards to be programmed into robots. It is geared towards addressing issues surrounding human control over robots; human dependency on robot interaction; legal issues, such as protection of data acquired by robots; and machine identification for determining responsibility distribution. If adopted, the Charter will become a landmark official set of ethical guidelines for robotics (Weng et al., 2007).

EURON, is a private organization devoted to creating resources and exchanging knowledge about robotics research to create a systematic assessment procedure for ethical issues involving robotics. Recently, the EURON Committee has developed a “Roboethics Roadmap” (EURON Roboethics Roadmap, 2006). The Roadmap is mostly human-centered rather than robot-centered. In the Roadmap, members of the robotics community are categorized into three categories: (1) Those not interested in or those who don’t perceive that they have a moral and social responsibility monitor their work, (2) those interested in short-term ethical questions (i.e., those who respect the thinking behind implementing laws), and (3) those interested in long-term ethical concerns (i.e., those who express concern for such issues as the “digital divide” between world regions or age groups.) (Weng et al., 2007).

According to the EURON Roboethics Roadmap, several questions arose, as to whether the Asimov’s proposed Three Laws of Robotics should be used as a guideline for establishing a code of roboethics. Should roboethics represent the ethics of robots or of robot scientists? To what extent should embodying ethics in robots go? And to what extent should robots exhibit “personalities” or express “emotions”? These kinds of questions, although not directly linked to the coexistence of robotics with astronauts, are inextricably linked to the ethical and psychological effect in the conscience of a crewmember that may be working hand in hand with a robot.

In 2004, the Japanese government unveiled a framework of expectations for NGR coexistence with humans wherein safety issues related to robots assisting human beings both physically and psychologically was considered (International Robot Fair Organizing Office, 2004). All these efforts are geared towards developing frameworks for ethical standards that will ensure the safety of human-robot coexistence. All of these are individual initiatives of nations. In case countries embrace international cooperation while returning to the Moon they will need to develop a uniform code of ethics relating to astronaut-robot coexistence. Nonetheless, it will be very difficult to come up with a uniform ethical standard because of the intricacies of measuring moral values of humans in different societies. There is a need for a systematic approach to ethical issues involving robotics encompassing the models pursued by Japan, Korea, EURON, USA, and others.
4.6.9 Legal Recommendations

Following the above discussion, recommendations are as follows:

- There is an inherent need to develop concise laws and regulations that accommodate the astronaut-robot coexistence in space exploration.
- There is a need to re-examine the importance of having a specific and all-inclusive regulation that encompasses the different safety standards for future human-robotic coexistence. A safety regulation model that emphasizes the role of Safety Intelligence (SI) during the pre-safety stage needs to be developed. Among other things, regulations should stipulate criteria for safe interaction with humans. A similar situation has been proposed for terrestrial NGRs (Weng et al., 2007). This would also go hand in hand with the establishment of the International Space Exploration Safety Board (ISESB), whose mandate will include the aforesaid recommendations.
- Development of a new branch of law (i.e., robot law or regulation) is vital to tackle the advancing robot technology in terms of astronaut-robot coexistence. Policy and regulatory issues must be settled to prevent a future legal crisis.
- Legal regimes for planetary protection need to be expanded and harmonized to include safety issues related to astronaut-robot co-existence vis-à-vis the protection of lunar and terrestrial ecosystems.
- A detailed liability framework outlining the rights and responsibilities related to liability on robot astronaut coexistence in order to enhance safety standards should be developed.
- Dispute resolution mechanisms need to be identified or set up by cooperating States before going to the Moon. Countries could highly benefit from the example of the Inter-Governmental Agreement (IGA) of the ISS.
- Establishment of a systematic approach to ethical issues involving robotics encompassing the models pursued by Japan, Korea, EURON, USA and others should be considered.
5 INTERNATIONAL SPACE EXPLORATION SAFETY BOARD (ISESB)

In its early stages, space exploration was essentially a matter of national interest and endeavor. Starting with the space race in the 1960s between the Americans and Soviets, the space field has been mainly an issue of national politics. However, since that time the socio-political climate of the world has substantially changed, leaving more room for international collaboration. Evidence of this can be found beginning in the Apollo-Soyuz joint mission in 1975, which served as a signal of a break in the Cold War between the two space powers, and most recently in the ISS (Klotz, 2006). If national pride and prestige were the main drivers for space missions of the past, they must now share their position as prime objectives for going back to the Moon with goals of the international community, intent on exploration, advanced technology testing, and possible extraterrestrial colonization. Additionally, to establish a lunar base requires huge financial investment that is prohibitive to most space agencies acting independently. International cooperation is now commonplace in space exploration and seems to be a viable answer to further lunar base plans.

As discussed in the previous chapters, several space agencies have developed long-term plans to go to the Moon (see Section 2.1) and most are contemplating international cooperation. It is important to recognize that international cooperation and the resulting agreements between nations can have a direct impact on crew safety. On the one hand, international cooperation can increase crew safety by combining the best technologies and ideas as safety protocol and risk mitigation strategies are developed. On the other hand, countries or agencies may not have the same criteria or concerns with respect to safety. Harmonization between agencies and a clear framework will be required to guarantee the highest level of safety as tasks and facility responsibilities are allocated.

Some initiatives regarding international cooperation in order to increase safety, especially in human spaceflight, have been undertaken by the International Association for the Advancement of Space Safety (IAASS). They believe that such issues must be addressed under international cooperation (Space Travel, 2007). They observe, however, that significant space safety issues are still addressed only at the national level. This lack of consideration for safety issues at a global level could be a major weakness of future lunar programs. To this end, the creation of an International Space Exploration Safety Board (ISESB) is proposed (hereafter also referred to as the "Board"), with the main objective to harmonize safety standards between space collaborators.

This chapter will first provide an analysis of the potential players most likely to take part in an international lunar program initiative, vis-a-vis their position toward human space missions, space safety policies, and current geopolitical issues. Following this analysis, the chapter will successively discuss the organizational structure of the Board as well as alternative financing mechanisms. Legal issues dealing with the structure and jurisdiction of the Board will be addressed, followed by possible ISESB outreach programs toward the general public and the world’s space agencies.
5.1 International Cooperation

Space agencies have different expectations regarding global space exploration initiatives, as well as different perceptions and standards of safety. To be able to design an organization capable of addressing safety concerns related to the establishment and operation of a lunar base, it is crucial to first understand the expectations of each agency with respect to such a collaboration. The geopolitical environment of each potential player will also need to be addressed due to the potential impact on any future partnerships.

5.1.1 USA

The United States deserves particular attention, not only because it was the first nation to put a man on the Moon, but also because it is currently the only country that is actively planning a manned lunar mission. Proceeding from the recent Vision for Space Exploration as announced by President George W. Bush on January 14, 2004, NASA has developed an architecture for a future lunar base. For that purpose, NASA has been allocated a large budget dedicated to space exploration in comparison to other space agencies. In the Vision for Space Exploration, the place of international cooperation is clearly mentioned: President Bush wants to "promote international and commercial participation in space exploration to further USA scientific, security and economic interests" (NASA, 2004).

Capabilities and Limitations

Recent studies present the USA as a natural leader for any collaboration efforts towards the establishment of a lunar base given its enormous and visible technological superiority (Schaffer, 2008; Blamont, 2005). However, given the leadership role that the USA has played in past space exploration efforts, it is reasonable to wonder whether the USA has a vision of broad cooperation with every space faring nation or plans on selecting only some of them. One concern that the USA has regarding cooperation is preventing any one partner from appearing on a lunar mission's critical path (Blamont, 2005). Moreover, what characterizes the USA in space collaboration is its firm determination to maintain its independence and to cooperate only if partners can contribute technological capabilities (Schaffer, 2008).

Hence, potential partners have approached the call for international cooperation by President Bush in his 2004 presidential directive with care. In fact, numerous agencies show skepticism toward this project of collaboration and the ability of the USA to collaborate (Dupas and Logsdon, 2007). The main reason behind this skepticism is based on American security concerns and the interests of its government. Proposing an allegiance between numerous space actors without addressing how the USA would maintain its current security and foreign policies exposes the veritable dichotomy of USA intentions. This contradiction was confirmed by the then NASA Administrator Sean O'Keefe when he reinforced that the "new cooperative space initiative was very much going to be a USA led endeavor, much like the President envisioned in order to meet USA exploration objectives" (O'Keefe, 2004). If this is the case, it is likely that the USA would choose its partners very carefully vis-a-vis the current geopolitical environment.

Following President Bush’s directive, NASA began several informal discussions with other space agencies including the topic of establishing a lunar base. A Global Exploration Strategy was drawn up in 2006 led by NASA with the participation of 14 space agencies (Schaffer, 2008). However, since NASA has come up with its own lunar architecture based on the Global Exploration Strategy, the issues regarding a global mission are no longer the same. Several...
reports and articles indicate that the novelty in USA plans would alter any previous collaboration agreements and that the USA would not collaborate with every willing space agency having plans to go back to the Moon (Schaffer, 2008; ESTEC-ESA, 2006).

Despite American promotion of international cooperation in space exploration, the degree of participation of other partners is not yet defined. Moreover, with changes to the USA government looming in the next presidential election, the priorities and orientation of the government could rapidly change, potentially resulting in modifications to any plans to return to the Moon. It is therefore essential to clearly determine what the USA criteria are for collaboration. Based on these criteria, the capacities and limits of other space agencies, including those of developing nations, will be analyzed in order to determine which agencies are most likely to participate in a USA-led lunar initiative, or if they will be led by another emerging leader in space exploration.

**Geopolitical issues**

Collaboration with the USA will be deeply impacted by geopolitical issues. As mentioned earlier, the joint Apollo-Soyuz mission in 1975 was seen as evidence of the ending of the Cold War with Russia (Klotz, 2006). In the current geopolitical scheme, China has become the main concern of the USA. China is now the third nation to have put a man into orbit and proffers increasing capabilities as a result of its growing economy. However, foreseen civilian cooperation between the two nations has come into question after China's anti-satellite (ASAT) test in 2007. The USA voiced strong disapproval of the test on the grounds that it was against international law with respect to the placement of weapons in space (NewScientist, 2007). Ties between the Chinese and American space industry have suffered as a result of Chinese military involvement in space initiatives. USA International Traffic in Arms Regulation (ITAR) regulations now restrict any transfer of space technology between China and the USA (Sabatier, 2007). Any collaboration with the two economic powers is thus difficult to foresee. Additionally, the USA and China disagree on a number of other political and ethical issues including human rights and weapons proliferation. Given the potential benefits of a lunar mission, however, it is conceivable that the two nations could set aside their differences for the purpose of pursuing a joint lunar mission (Klotz, 2006).

**NASA's "Safety Culture"**

The losses of the shuttles Challenger (1986) and Columbia (2003) were tragic but NASA learned from these failures. Following the loss of Challenger, the NASA administrator at that time, Daniel S. Goldin, affirmed that safety was NASA's highest priority. He also emphasized, however, that there would always be risks to crewmembers, for which preparations had to be made (Broad, 1996). In this context, the risk of a loss of human life continues to be accepted to a certain degree as part of exploration missions. As Goldin stated it, "Human beings have always taken great risks to reap great rewards" (Broad, 1996). However, the state of public opinion on the acceptance of risk, following the Columbia tragedy, is questionable.

In an effort to centralize the treatment of specific safety issues, NASA established the Office of Safety and Mission Assurance (OSMA) and made it responsible "for the oversight on an agency-wide basis for the safety, reliability, maintainability, and quality assurance (SRM&QA) of all policies and procedures in this regard" (Pelton and Marshall, 2006; NASA, 2003). However, following the Columbia tragedy, the Columbia Accident Investigation Board found that NASA's "safety culture" had become "broken". The Board concluded that safety problems were mainly due to the lack of responsibility taken by individual engineers. Workers tended to consider safety
concerns as the responsibility of OSMA and were not sufficiently vigilant in addressing safety at their own level. (Pelton and Marshall, 2006)

Despite such examples of administrative problems, NASA has successfully addressed safety in more pragmatic ways by forming numerous panels which address specific safety concerns, such as those of the ISS (IISFT, 2007).

**USA position toward a collaborative framework**

Based on interviews with NASA representatives, as well as the White House, it has been concluded that the USA would likely veto the formation of any committee responsible for making programmatic or budgetary decisions (Schaffer, 2008). This information is crucial not only for collaborative lunar mission design, but is also important in the design of the ISESB. If the USA were included as a partner in a cooperative framework, gaining their full participation would likely require that the ISESB produce only recommendations and not binding documents.

5.1.2 **Europe**

ESA considers the return to the Moon as a very likely intermediate step to reaching Mars (ESTEC-ESA, 2006). In connection with this, ESA is currently defining an exploration program named Aurora, dedicated to the development of technology and the establishment of missions to the Moon and Mars, all of which can be done by involving other countries. Given its long history of collaboration, there is a high probability that Europe will join any future lunar initiative, but perhaps not as a major player. Without any distinct political vision, entering such a far-reaching project would be quite complicated for ESA. Moreover, ESA's focus on the robotic exploration of Mars and their conservative vision of human space missions are likely to change these plans in the near future (Dupas and Johnson, 2007). Given the current situation, Europe isn't likely to play a major role in a cooperative framework, but priorities could change with political orientation and impetus.

Another question for ESA member states is whether they would collaborate jointly under ESA's direction, or if they would collaborate as individual states. Again, the absence of a unique political vision shared by every member state makes decision-making difficult; this is well known as one of ESA's largest weaknesses. The member states could decide to join independently any collaborative framework. Sweden, for example, has announced plans to colonize the Moon independently (Haine, 2006). For the most part, however, such plans appear unfeasible without international cooperation.

**Capabilities and Limitations**

Europe has launching capabilities in French Guyana and owns the heavy payload launcher Ariane-5, mainly used for commercial flights. It is, however, limited in its ability to conduct independent human spaceflight missions since it currently has no vehicle for sending and returning astronauts to and from outer space. In this domain, Europe requires cooperation. European astronauts currently depend on the American Space Shuttle and Russian Soyuz vehicles. Recently, however, Europe has begun talks with Russia to potentially develop a new vehicle as an alternative to Orion. The Crew Space Transportation System (CSTS) would permit crew transportation without dependence on the USA (The Engineer, 2007). This project is not completed but it is an excellent example of excellent example of the potential of collaboration to improve space capabilities for future lunar missions. Additionally, Japan also predicted to collaborate with Europe and Russia on the CSTS project (Rayl, 2006). This new kind of
cooperation could be a first step in the next generation of human space flight, shifting from a dependency on the USA to a new level of autonomy.

**Safety Policy**
ESA differs in its approach to safety with respect to the USA (Pelton and Marshall, 2006). This is mainly due to the relatively few manned missions in which it has been involved. A "zero tolerance" policy is still the principal program driver of the agency (Pelton and Marshall, 2006). The risks to an agency associated with the loss of any astronaut have led to ESA's cautious approach to human exploration programs.

### 5.1.3 Russia

According to some, the space race is still alive with Russia also planning to go to the Moon in competition with the USA (Baker, 2007). Russia has shown concern for preserving its national interests, and orientates its plans to return to the Moon towards more independence, especially from the USA (Dupas and Johnson, 2007). Though Russia does not appear to be open to any cooperative framework, it would be open to collaboration under its own leadership (Dupas and Johnson, 2007).

There still remain questions, though, regarding Russia's desire to collaborate with the USA as opposed to competing. Russia and the USA have had a long history of cooperation in space. The 1975 joint Apollo-Soyuz mission signed the beginning of more than 30 years of cooperation in space. The ISS stands as another excellent illustration of collaboration between the two space powers. These examples demonstrate that competition has not been the only driving factor for Russian space activities (America.gov, 2007).

**Capabilities and Limitations**
Russia's major strength lies with its highly reliable Soyuz launcher, which has maintained major transportation of crew and cargo for the ISS for a number of years. Given its capabilities, experience in lunar exploration, and current relationship with ESA and China, Russia could potentially lead future lunar exploration initiatives independent of the USA. As is often the case, however, political climate and agency priorities will likely determine the degree of collaboration sought by Russia.

**Safety policy**
A number of launch pad failures and other incidents have resulted in Russia’s perceived reputation for disregard towards matters of safety (Pelton and Marshall, 2006). However, a number of examples illustrating Russia’s commitment to safety would indicate the contrary.

In the early ages of space exploration, Sergei Korolev, one of the world's leaders in human space flight, asserted that safety was a priority for manned missions (Pelton and Marshall, 2006). This concern for the safety of Soviet crewmembers has been reaffirmed by Dr. Walter Peeters when speaking about the Soviet efforts to send a man to the Moon:

"The Russian lunar module was ready and tested, but the carrier had some problems and they had some explosions at the qualification flights. The commander of the first crew was A. Leonov (the first man who did an EVA). He once told me he was prepared, with consent of his crew, to take all the responsibility and asked permission to go (they knew the Americans were going soon), but it was rejected." (personal communication, Peeters, 2008)
It is possible, as this anecdote illustrates, that the Soviets may indeed have lost the space race because of their concerns for crew safety. Additionally, the Russian Soyuz launcher has maintained an excellent record of reliability, and continued to be used after the Columbia accident as the only launch vehicle for transportation to the ISS (Pelton and Marshall, 2006).

The safety practices of Russia continued to improve after the Cold War era. Their participation in the ISS, for example, obliged Russia to consider international safety programs (Pelton and Marshall, 2006). Their standards were assessed by JAXA and ESA, both of whom came to the conclusion that Russian standards were close to their own. Currently, Russia follows ISO 9000 standards as well as other internationally recognized standard systems. Regardless of perceptions, Russia is a good example of how international cooperation can increase safety.

5.1.4 Canada

Canada is showing interest in joining a lunar exploration initiative, particularly following NASA’s plans. A representative of the Canadian Space Agency (CSA) responsible for planetary exploration stated: “Humans have an innate desire to explore and Canada is such a vast and beautiful wild country that we have a lot of exploration in our history, in our genes” (CTV.ca, 2005).

Canada has vast experiences in international cooperation, most poignantly demonstrated through its participation in the ISS. Canada has a long history cooperating with the USA, and is also trying to strengthen its relations with China (People’s Daily Online, 2005). If the USA undertakes a lunar base mission, Canada is likely to join (Moore, 2006). Moreover, the USA has recognized the potential assets of the CSA for such a mission, as Canada has expertise in working in extreme environment (CTV.ca, 2005).

Capabilities
If no definitive plan or role has been attributed yet, Canada hopes to join this USA mission thanks to its experience and capabilities. Canada was in fact the third space faring nation, by sending its own satellite in 1962, after the Russians and the Americans. Among domains of expertise such as communication, earth observation and astronauts, Canada shows a strong involvement in robotics with capabilities such as the Canadarm.

Canada is a major actor in space exploration as well. In May, the Phoenix mission is predicted to land on the Mars surface (Prentice, 2008). Canada seems therefore to be a serious potential partner for any collaboration framework.

5.1.5 Japan

Japan has shown a desire in recent years to participate in lunar exploration through its adoption of a long-term vision that includes manned flight and a lunar landing (IAC, 2006). It shows interest in enhancing international cooperation in space exploration and especially in manned space missions (Kawaguchi, 2007). Japan has fostered cooperation with the USA, as well as with ESA and Russia since the early 1970s. It is also an active member of the ISS and is currently in the process of delivering the second portion of the Japanese Experimentation Module. In the Asia-Pacific region, Japan initiated the establishment of the Asia-Pacific Regional Space Agency Forum in 1993 and is playing a leading role in Asia’s space sector (JAXA, 2007). It regularly
cooperates with countries like Thailand, Korea, Indonesia, Malaysia, Australia, and even China (JAXA, 2007).

Japan foresees sending independent robotic missions to the Moon first before any manned attempt is made. Subsequent to robotic missions, JAXA plans then to participate in an international manned lunar exploration program with the objective of lunar exploration by Japanese astronauts (Kawaguchi, 2007). Japan is also one of the only countries ready to join a human exploration program under American leadership if they receive a political invitation to do so (Dupas and Johnson, 2007).

Capabilities
Japan is a high-technology leader and has extensive advanced robotic technology. Moreover, Japan has already conducted several manned missions with the cooperation of the USA and Russia. Japan is mainly interested in exploring space and other celestial bodies using its advanced technological capabilities, especially robots (ESTEC-ESA, 2006). For a project such as a lunar base where the presence of robots will considerably aid human activities, Japan's robotic and nanotechnology expertise would be a large asset to any international program (Suzuki, 2006). Moreover, Japan's limited space budget makes international cooperation highly desirable. Japan's willingness to cooperate in large human spaceflight programs is evidenced by their contribution of the Japanese Exploration Module (JEM) "Kibo" to the ISS, and their role in creating a corresponding cooperative framework (Kozawa, 2004).

Safety Policy
With the ISS module "Kibo", Japan made crew safety a priority (Malik, 2007). According to Koki Oikawa, JAXA's development project function manager for the JEM, the human facility was mainly directed by safety issues and mandated evolution of current safety understanding: "JAXA didn't [originally] have that kind of understanding for crew safety. I think that was one of the most challenging requirements" (Malik, 2007).

With respect to its Lunar Exploration Program, Japan considers human safety as a major obstacle for space exploration (Kawaguchi, 2007). However, Kawaguchi also makes it clear that Japan's desire to put an astronaut on the Moon is high.

Concerning standards, particularly with regards to robotics, Japan is willing to develop standards regarding manufacturing and engineering. It is now mainly considering ISO rules, especially ISO 10218-1, which covers safety associated design and industrial robot applications (Weng et al., 2007). The knowledge and expertise of Japan, as a leader in robotic standardization, would be particularly beneficial to a collaborative effort, and could serve as a starting point for the establishment of international standardization.

5.1.6 China
China has recently joint the exclusive club of nations to achieve manned spaceflight. It is currently developing space technologies with the hope of becoming the third largest space power. China considers sending missions to the Moon not only as demonstration of their growing economic strength, but also as a business opportunity that could put the country in a strategic position with entrepreneurs (Gittings, 2002). China, according to its official news agency, considers a lunar probe mission useful in raising national prestige and inspiring the spirit of nationalism (Gittings, 2002). It is therefore questionable whether China would conduct a
manned lunar mission jointly with other agencies or under its own flag. The country has, however, a long history of international cooperation in the development of its space capabilities, especially with Russia.

More than 30 years after the Soviet Union stopped providing technical assistance to China’s space program, China resumed its space cooperation with Russia by signing a deal to provide the training of Chinese taikonauts and technical information about the Soyuz spacecraft's capsule, life support systems, docking systems and spacesuit (Lieggi and Aldrich, 2003).

The Chinese space program has also had interactions with other space faring nations including Western European countries, Brazil and the USA. The Chinese government also promotes international cooperation and exchanges in the space field, highlighting its cooperation experiences with several developing and developed countries (Commission of Science, Technology and Industry for National Defense, 2006).

**Capabilities**

By cooperating with both the Russians and the Americans, the Chinese have developed credible space capabilities. After completing its first manned missions, China launched a lunar orbiting probe in 2007. This probe is only the first stage of the Chinese lunar program, which envisions landing a rover on the lunar surface by 2012 and then completing a manned mission by approximately 2020. (MoonDaily, 2007).

China's current manned space program, named Shenzhou, was developed under a three-step program that involves several test flights followed by a manned launch, the development of a manned space station and the completion of a modern space-Earth transportation system. The Chinese scientific community has also discussed plans for lunar exploration and missions to Mars. (Lieggi and Aldrich, 2003)

The Chinese space program, though small when compared to other major space faring nations, holds a strong position in Asia. However, whether the Chinese space program will be cooperative or competitive will depend on the international dynamic. (Brian, 2003)

**Safety Policy**

Space safety policy has played an important role in China’s space program. Chinese rockets and launch vehicles maintain a good safety record, having experienced only one launch failure. "There has been a fanatical emphasis on quality control." (Brian, 2003)

Concerning space safety standards, China has its own standards system, and there is no indication of major uses of ISO or other systems in the Chinese space sector. This may be because there hasn't been any particular cooperative manned space mission between China and other space faring nations, such as in the case of the ISS.

**5.1.7 Emerging space countries**

While many of the major space faring countries have established early plans to go to the Moon, emerging space faring countries continue to improve their space capabilities. An international lunar base program would likely offer many opportunities for countries other than major space faring countries to participate. By pursuing a broader framework of cooperation that includes emerging space nations, relations between nations can strengthened and resources for lunar
missions augmented. Therefore, it is pertinent to have a general vision of the different plans foreseen by emerging space countries and their existing partnerships.

**India**

India is quickly increasing its space capabilities, and is keen on obtaining the status of a major global space power. It is moving beyond its traditional missions of developing communications and remote sensing satellites to focus on new areas such as navigation. India is also pursuing plans to explore the Moon. The Chandrayaan-1 lunar orbiter is expected to be launched in 2008. In addition, the Indian Space Agency (ISRO) has already signed an agreement with Russia for a Chandrayaan-2 mission, foreseen to land a robot on the Moon by 2011 for exploration of lunar resources (MoonDaily, 2007). These two lunar exploration missions could bring back useful information for a future lunar base. Some reports, although incomplete and controversial, indicate that India is interested in undertaking a manned lunar mission, perhaps by the end of the next decade. This has attracted the attention of the United States as a potential partner in space endeavors, despite a history of rocky relations. (Foust, 2006)

Concerning its experiences in international cooperation, the Indian space program has enjoyed a good relationship with NASA and other USA agencies promoting civil space cooperation. Such cooperation has led to participation in the National Oceanic and Atmospheric Administration (NOAA) space program on aerosol monitoring, utilization of GPS technology to modernize Indian air traffic control, and participation in the international Global Learning and Observations to Benefit the Environment (GLOBE) program of science education. Similar to the Chinese space program, India has also depended on USA and Soviet assistance for developing its own space vehicles. (Bureau, 2006)

**Korea**

North and South Korea have both developed rocket technology for military and civilian applications, but their space programs differ in many important aspects. Neither country is seen as a serious competitor to USA space assets, but a successful USA cooperative engagement strategy with North and South Korea could help achieve USA space policy objectives. (Pinkston, 2006)

**Australia**

Australia has treaty level agreements with several governmental space programs, including NASA's Space Vehicle Tracking and Communications Facilities. Australia is also cooperating with ESA in their space-tracking program, with Russian space research, and with Chinese space commerce and technology activities. (Matthew, 1998)

**Israel**

By independently building and launching its own satellite, Israel has become a member of a small group of countries to have independent launching capabilities, including the United States, Russia, England, Japan, India, France and China. Israel has become significant enough to be accepted into the international community of space researchers, and it has formal space research cooperation agreements with the USA, France, Germany, Russia and the Netherlands. (Israel Ministry of Foreign Affairs, 2008)

**Other countries**

Other emerging space countries such as Malaysia, Nigeria, Algeria, Singapore and Iran continue to develop their space capabilities, and are emphasizing the benefits that come from cooperating
with partner space faring nations. Although smaller emerging space nations do not boast the same level of space capabilities enjoyed by large space players, in the context of an international lunar mission, each may yet contribute with technical, financial or logistic resources.

5.2 ISESB Structure and Mission

Due to their complexity, space engineering systems such as spacecrafts, launch vehicles, probes, robots, and future lunar bases are subject to the probability of component failure, the lack of available data at the system level can be a main constraint to handle their malfunction. Thus, in any space mission it is necessary to identify the system's weakest points, and to estimate the probability of failure in order to determine whether it meets specified astronaut safety criteria, or to set up suitable risk management countermeasures.

It was a common belief that component failures were mainly associated with technical errors or catastrophic failures of engineering systems. However, experience gathered in offshore oil platforms, and nuclear power plants shows that in some cases the root cause of the errors is in the organization structure which could also affect the safety of engineering systems (Paté-Cornell and Dillon, 2006; Khan and Amyotte, 2002; Paté-Cornell, 1990). In the context of a future lunar base, organizational errors and system reliability are key issues to be taken into account when making decisions about crew safety. Using a multiple-attribute model, Figure 5-1 presents a combined approach of the managerial and technical aspects associated with crew safety and robotics in a lunar base scenario. Accidents and their frequency can be generally divided into those that are totally unpredictable (e.g., solar events and space weather conditions), or so rare that humans can decide to live with the risk (e.g., failure of non-essential equipment or other lunar base components), and finally those that are self-inflicted, often through management practices and decision making processes that are bound to generate errors and defects with a much higher probability than generally estimated, and mainly associated with the crew composition and expertise (Paté-Cornell, 1990).

On the other hand, accident consequences are divided into short or long term impacts, and are spread over crew health and environment, delay in schedule, work overload, and consequences in economic, political and public opinion. Also, Figure 5-1 shows the potential role of robotics in the detection of errors, the reduction of the probability of component failure of a lunar base or astronaut equipment (by minimizing technical errors, and improving base maintenance), and as astronauts substitutes for EVAs. In brief, all the issues in Figure 5-1 have an important managerial component that, if not addressed, can compromise whatever astronaut safety gains are achieved from a technical point of view.
However, from the managerial point of view, allocating financial, organizational, technical and human resources to solve astronaut safety problems and to determine if a particular measure will be the most suitable may be difficult because multiple attributes of the engineering systems might affect its safety. Addressing astronaut safety needs a dedicated organization such as the ISESB which, based on decision analysis techniques and international experts' and astronauts' opinions, carries on periodic assessments and risk analyses in order to establish safety levels or standards, and the potential effects that safety alternatives would have on a lunar mission. The following sections will discuss in detail the role of the ISESB, a dedicated organization proposed by the authors that could address astronaut safety needs for space exploration.

5.2.1 Definition and Role of the ISESB

The ISESB should be a worldwide federation of crew safety standards bodies (board member bodies). Based on the spirit of international cooperation and interdisciplinary approach, the ISESB would meet the shared interests of governments, space agencies, industries, private companies and public opinion of ensuring the safety of astronauts during lunar exploration activities. It is important to mention that safety boards are already found in oil industries, chemical and nuclear power plants, and ports and waterways (CSB, 2007; Merrick and Harrald, 2002). The functions of the ISESB will revolve around harmonization and development of safety regulations and implementation strategies. Other functions will be risk analysis and assessment, resource allocation, information awareness and information dissemination. A listing of more specific proposed main functions of the ISESB can be found in Appendix C - Article 7.

5.2.2 Organizational Structure of the ISESB

The ISESB could be progressively developed in three phases in accordance with the evolution of a lunar base, as defined in Section 2.2. In each phase the organizational structure would
change depending on the level of autonomy and the increasing role the board would play in improving crew safety through robotics applications:

- **Phase 1 (Immediate short-term concern):** The first phase encompasses the establishment of the safety board as an independent institution (see Figure 5.2-2), receiving continuous input from space agencies, consultant companies (mainly system engineering manufacturing companies), and the International Standard Organization (ISO). Its mandate will be to examine national crew safety standards, relevant ISO standards, and produce recommendations on how the Board will function. The Board will also provide advice on the harmonization of crew safety standards for lunar exploration, propose funding strategies for the Board where possible, and draft standards or make modifications to existing standards for immediate use by countries preparing to go to the Moon. In Phase 1, the ISESB should be able to conduct its own safety certification, and be completely autonomous on the establishment and management of crew safety standards. Potential stakeholders and members of the safety board include space agencies, private companies (e.g., robot design companies), governmental officials of space faring nations and emerging space countries, astronauts, like-minded organizations or related industries and companies that have safety boards (e.g., nuclear power plants, oil companies, ports and waterways), insurance companies, trade and funding organizations, medical doctors, and experts from the academia.

- **Phase 2 (mid-term concern):** During this stage, the Board should be formed either under ISO or continue as an independent organization, operating according to the terms set out in Phase 1. The board should modify and update safety standards, and work with the ISO, space agencies and other private actors to provide crew safety certification.

- **Phase 3 (Long-term concern):** within this period, the ISESB could constitute a committee of the ISO; crew safety certificates provided by the ISESB could be part of ISO certifications. This committee would be made up of ISO experts and other intergovernmental members. It will not only be for lunar missions but also for other space and interplanetary missions.

During Phase 1 the board constitution begins with a direct link and input requirements for lunar missions from the world's space agencies. In this stage, the ISESB would be composed of the International Safety Assembly whose duties include promotion of international cooperation and adoption of new safety standards; the Safety Standard/Regulation Board which acts as an advisory arm on crew safety and robotics; the Ethical Department, which generally concerns itself with the emerging ethical issues. In addition to those departments, there shall also be three Working Groups: the Robotics Board, Crew Safety Board, and Astronaut/Robot Synergy Board designated to perform actual research and in-depth analysis of the (see Figure 5-2 and Appendix C).
The work of preparing crew safety standards and other regulations would be carried out by the three working groups. Each board member interested in a topic for which a working group has been established (e.g., Robotic, Crew Safety, or Astronaut/Robot Synergy working groups) would have the right to be represented in that group. Governmental and non-governmental organizations, international organizations, space agencies, and private companies working together with the ISESB would take part in the work. The draft on crew safety standards generated and adopted by the three working groups should be circulated among the member bodies for voting. The final adoption and publication of the International Space Exploration Safety Standards as well as other documentation should require the consent of at least 75% of the member bodies.

5.2.3 Other benefits of ISESB

Even though the creation of the ISESB could be perceived as a bureaucratic step in the overall mission design of a lunar base, many advantages of such an institution exist. The main thrust behind this organization would be to advise lunar base designers on how robotics could be used to bring a better balance between avoidance, prevention, and management of astronaut safety hazards, and to encourage the incorporation of safety issues during the design of robotic features, achieving then a complete active and passive management of risks, thereby increasing the safety and reliability of engineering systems (see Figure 5-3). Furthermore, due to its international composition and interdisciplinary approach, the establishment and creation of space exploration safer standards may be used to promote and to harmonize space safety policies, to efficiently allocate financial resources and to justify budgets for manned space exploration missions. Finally, through its structure, procedures, intercultural approach, and suitable flow of information among members, the ISESB could help to improve some organizational errors in the management of astronaut-robot synergy and the lunar base, such as time pressures, missed signals of warning and deterioration of engineering systems, poor learning and transference of experience, poor productivity, and the identification, communication and management of uncertainties (see Figure 5-3). The main focus of this board would be to clearly publicize the idea that robots are a tool for space exploration, rather than human substitutes.
5.2.4 Potential Challenges of Setting up the ISESB

**Competition With Existing Standards**
There are several challenges related to setting up the ISESB. The fact that there are existing standards internationally through the ISO, regionally through, for example, the ESCC, and nationally through various other jurisdictions (e.g., the NASA Safety regulations), agencies might not see the immediate need for a new, more comprehensive safety system. Other options, such as the expansion of the ISO mandate, in order to accommodate the suggested objectives might appear more desirable than establishing a new and independent safety board.

**Problem of Learning Period**
Time may also be an issue. Since several countries have plans to go to the Moon from 2020 onwards, they may want to have substantial experience on the Moon before considering additional safety precautions.

**Failure of Major Space Faring Nations to Approve the ISESB**
Another potential challenge is that space faring nations may not be willing to accept and join the ISESB. Major space players such as the United States who already have their own safety standards may not want to be subject to any other standard. The lack of participation by any major space faring nation, due to a low interest, poor diplomatic relations with other Board members, or disagreement on safety standards, could negatively affect the countries that would advocate the formation of the Board. Additionally, countries might join but not necessarily adhere to the guidelines due to their non-binding nature and lack of enforcement mechanisms.

**Financial Constraints**
As there are no concrete obligations to the funding of the ISESB, countries might not volunteer or commit to funding that will guarantee the sustainability of the Board. Additionally, if the Board receives low membership, the costs associated with its operations might become major hurdles. Furthermore, in the event that the Board wants to perform activities such as
certification, a much greater financial support would be required.

**Differences In Cultural Perceptions**

Just as standards of ethics and morality are different from society to society, so are safety standards. This is also related to the fact that different societies perceive the worth of human life differently. It might be very difficult to reach to a consensus for sensitive safety issues. For instance during the assembly of the ISS, the Japanese government found it uncomfortable to accept the use of the color ‘white’ because it was symbolic for death (personal communication, Walter Peters, 30 April 2008). This example may not be directly related to safety but is illustrative of the potential difficulties in finding uniform standards. Nevertheless, proper lobbying and compromise may be exercised to achieve the goals of the board.

### 5.3 Funding of the ISESB

The ISESB will need to have a budget allocated for its setup and operation. Due to its non-profit nature, the funds raised by the ISESB would be used entirely to cover operational activities such as developing crew safety standards; conducting periodic assessment, risk analyses and decision analyses related with hazards to astronauts; improving crew safety for lunar missions based on robotic applications; researching accident hazards to astronauts; and outreach. Also, funds must be allocated to cover administrative costs of the Board, as well as the payment of medical doctors, experts and other external advisors. According to Dr. Walter Peeters, the functioning of the Board will require an estimated budget between USD 300,000 to 400,000 (personal communication, Walter Peeters, 28 March 2008). The rules to finance the Board, however, need to be established. Four alternative ways of financing the Board and of dividing the contributions between the members are enumerated and detailed below.

#### 5.3.1 Contribution of Financial Resources According to National Gross Domestic Product (GDP)

The first way of financing the Board deals with a partitioning of members according to their GDP. Table 5-1 summarizes the GDP of potential players in a lunar mission. The USA, Japan, Germany and China have the highest GDP, with the USA far ahead of all others. Finances could be thus divided between the USA, ESA, China and Japan, these four being the most feasible members of the program. The Board would decide, based on the GDP of member states, the percentage of contributions required from each country. As a contribution from established space countries to the development of emerging space countries' programs, developing nations joining the Board would be free from financing obligations.

<table>
<thead>
<tr>
<th>RANK</th>
<th>COUNTRY</th>
<th>GDP (trillions of USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>United States</td>
<td>13.79</td>
</tr>
<tr>
<td>2</td>
<td>Japan</td>
<td>5.10</td>
</tr>
<tr>
<td>3</td>
<td>Germany</td>
<td>3.26</td>
</tr>
<tr>
<td>4</td>
<td>China</td>
<td>3.25</td>
</tr>
<tr>
<td>5</td>
<td>United Kingdom</td>
<td>2.76</td>
</tr>
<tr>
<td>6</td>
<td>France</td>
<td>2.52</td>
</tr>
<tr>
<td>7</td>
<td>Russia</td>
<td>1.29</td>
</tr>
<tr>
<td>8</td>
<td>Brazil</td>
<td>1.27</td>
</tr>
<tr>
<td>9</td>
<td>India</td>
<td>1.09</td>
</tr>
</tbody>
</table>
5.3.2 Contribution of Financial Resources According to Space Agency Budget

The second alternative to finance the Board works on the same basis as the GDP option. Participating countries with the most significant space budgets will contribute to the Board's budget, according to a calculated percentage (see Table 5-1). These percentages are based on each agency's annual space budget. As with the GDP financing system, only space faring nations will contribute. Emerging space countries would be free of financial obligations.

Table 5-2: Space Budget of space faring and emerging countries

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>SPACE BUDGET</th>
<th>COUNTRY</th>
<th>SPACE BUDGET</th>
</tr>
</thead>
</table>

5.3.3 Payment of Membership to ISESB

A third potential mechanism for funding the Board could be through memberships fees. Participating countries and companies would pay membership fees according to economics strength. Special membership with low fees to the International Space Exploration Safety Board (ISESB) could be established for emerging space nations or countries with small economies. This would allow even small or emerging space players to remain up to date with the establishment of global crew safety standards policies and programs, and the use of robotics for improving astronaut safety during lunar missions. Membership in like-minded organizations such as the International Organization for Standardization can cost over €12 M (ISO, 2006). However, the final decision of membership costs should be taken up by the International Safety Board Assembly.

5.3.4 Voluntary contributions and donations

Voluntary contribution would be based on the willingness of each of the partners to contribute to the upkeep and operation of the ISESB. Agencies participating in the Board would finance it according to their own criteria. The most likely financiers would be the same as those for the GDP and space budget systems, as the countries with the most significant financing capacities will offer the most substantial support to the Board. Voluntary contributions are also a way for agencies to demonstrate their involvement and interest in the Board. In that regard, emerging space countries would be able to make a donation, even if minimal, showing their participation in and support of the Board.

5.3.5 Others
Other alternative sources of funding for the ISESB include sales of publications and magazines related with astronaut/robot safety protocols and standards, expedition of crew safety certificates, royalties of copyright, and other services to be offered as determined by the Board's members.

5.4 Legal Issues of the ISESB

The importance of establishing the ISESB can be stressed from the lack of common safety regulations between nations to deal with evolving astronaut-robotic systems. Internationally, the ISO has fragmented rules relevant to some areas of astronaut-robotic safety, such as robotic design guidelines and rules that cover general machine safety in industrial robot environments, and safety-associated design and protective measures of industrial robot applications. However, such rules remain very general in nature. Safety standards also differ on the regional and national level. Hence the need for harmonization and development of an all-inclusive regulation that can encompass the different safety standards for future human-robotic applications. A safety regulation model that emphasizes the role of SI during the pre-safety stage also needs to be developed. Among other things, regulations should stipulate criteria for safe interaction with humans. It is on this basis that an ISESB has been proposed to undertake the responsibility of ensuring that applicable safety standards are uniform.

5.4.1 Legal Status of the ISESB

The proposed ISESB shall be an inter-governmental, interagency organization, open to private corporate members and observer members. It shall be governed by a Memorandum of Understanding Establishing the Board which stipulates the terms and condition of the Board. Its mandates shall be to make recommendations and pass guidelines which shall not be binding to the member states; however, member states should be required to act in utmost good faith. The Board shall also have the powers to develop measures to deal with constant defaulters of the guidelines as they deem fit (see Appendix C).

5.5 Outreach and Societies

The ISESB will benefit all sectors of the space industry that are concerned with space safety standards. The Board will be able to offer an interdisciplinary perspective on the technical and political aspects of international safety standards and issues related to the establishment of a lunar mission and future space exploration via the following four channels: individuals, research entities and universities, and public and private bodies.

5.5.1 Individuals

The ISESB will provide an open gateway on the Internet where individuals can have access to daily updated news on space exploration and science mission, current investigation of space related accidents, risk mitigation plans for current and future missions, and the history of the space mission accidents. This free service will be used to raise public awareness of safety in space exploration. Additionally, outreach can be extended to youth via interactive online activities. Students will also be able to leave comments and questions about space exploration safety.
5.5.2 **Research Entities and Universities**

Universities and research institutes are of high importance for the ISESB and its continuing competitive abilities in relation to parameter input, design, and standard and code development. The ISESB can offer scientists inexpensive or free data, and information in exchange for the feedback of research results and/or model and safety standard improvements.

A scientific and technological arena in the form of conferences and institutes promoting discussion of space exploration safety issues will be a vital part of the ISESB. Workshops and seminars can be organized to promote the development and adoption of new safety standards for international space exploration and science missions. Existing conference series on space exploration, astronautics and robotic safety should be profiled as important forums for the ISESB information system. Examples of representative conferences are the International Astronautical Congress which focuses on the space safety, rescue and quality sessions (IAC, 2005), the 2nd International Conference on Human-Robot Interaction (AAAI, 2007), and The World Space Congress in Athens (Worldspace, 2008).

5.5.3 **Public Bodies**

The ISESB will benefit, in terms of public credibility, from association with the ISO and the national space agencies. Outreach to governments and the international community will also be through involvement in space related conferences and congresses. For more regional outreach, Board investigators will regularly visit member states and their respective space agencies and organizations to establish and maintain working relationships.

5.5.4 **Private Bodies**

Publication and presentation to insurance companies and other industries related to astronaut-robot safety will play one of the most important roles as part of the outreach program. ISESB will also be present at international space trade exhibitions in order to promote standardization and harmonization of international space safety standards to private industries and companies. Organization visits and free short training programs will also be available to interested private entities.
6 RECOMMENDATIONS AND CONCLUSIONS

6.1 Recommendations

Based on the preceding sections on the risk analysis of lunar tasks, robotic solutions to improve crew safety, and international cooperation to harmonize space safety standards, ALERTS proposes the following recommendations for future study and implementation.

6.1.1 Lunar Task Safety Risk Analysis

When assessing safety risks for possible astronaut tasks in a lunar mission, it is not possible to assess all the tasks and the risks associated with them. The process includes many uncertainties and requires many assumptions due to the absence of statistical data concerning long-duration human permanence on the Moon. The perception of risk, the levels of acceptance of risk and the definition of risk impact regarding human safety can all be approached differently; for instance, diverse strategies to assess risk are found between space agencies, industries and countries.

Definition of the phase of base development and mission objectives must be performed in order to identify the required astronaut tasks. Risks to crew safety for each task must be identified, as well as the potential robotic participation within a task to increase safety. An analysis of each task-associated risk is done after identification of those tasks in which robots can assist. The probabilities of diseases and injuries estimated in the HUMEX study can provide orientation when determining the likelihood of risks for astronaut task; however, statistics do not exist for every specific risk and assumptions must be made following the existing estimations, but not without applying numerical values to any interpretation of classifications.

The definition of severity must include not only injuries, but also impairment, incapacitation and long term effects or diseases in order to assess safety. The classifications for likelihood and severity presented in Table 3-4 are proposed to achieve the assessment of crew safety risks for astronaut-robotic tasks on a lunar base.

Scoring of risks using a scale similar to that proposed in Table 3-5 allows prioritization of tasks in order to concentrate efforts and resources on those with the highest impact on safety. EVA adds more risk to the analyzed tasks and therefore participation of robots during EVA will have more impact on safety of astronauts performing tasks on the Moon. However, additional work must be done by analyzing robotic applications for non-EVA tasks that were identified. These non-EVA tasks were omitted due to the prioritization performed and the scope of this report. Future studies for a lunar base could also use the approach presented in this report to assess crew safety risks in a more detailed list of tasks and their risks.

6.1.2 Robotic Solution Decision Tree

The decision tree presented in Chapter 4 permits analysis of a large number of lunar tasks in order to obtain one or more robotic platforms for each task that will increase crew safety. However, the use of the decision tree is not limited to the present study. The process is entirely upgradeable and, with further work, could be used to assess a completely different task list, as well as be applied a larger range of scenarios and environments, including more advanced
phases of lunar base development (i.e., Phase 3 and beyond). For the latter situation, additional decision boxes could be added as an extension in order to more precisely identify the robotic solutions. For example, in an equivalent Phase 3 study, the present decision tree could be supplemented with decision boxes more specifically related to ISRU. Moreover, future analyses could also take into account varying degrees of required astronaut involvement and allow for the replacement of astronauts with fully-autonomous robots. ALERTS recommends using the decision tree, as a tool that is open to modification and improvement, continually as robotic systems advance and criteria evolve.

6.1.3 Economic perspective of astronaut/robot synergy

The rationale for a robot/astronaut economic trade-off
As reiterated in various parts of the report, it is essential to take into account the synergy between astronauts and robots before further robotic development. In that vain, a methodology to evaluate robot cost and benefit is proposed. The main issues considered are technology feasibility, cost and benefit. The purpose of this analysis is to provide a general guideline for the decision makers and the potential investors to make trade-offs based on the economic considerations.

Robotic cost benefit synergy calculation
Three aspects are taken into consideration for the synergy calculation: technology, cost and benefit (which are detailed in the following sections). A different weight is attributed to each one. For instance, while evaluating the rating of a robot use, the benefits resulting from saving a human life will get a higher weight than the cost. It is in fact more important to have a safer robot even if costly, rather than a cheaper robot with low safety standards. Following that rationale, the criteria have been attributed these given weights: Technology 30%, Cost 20% and Benefit 50%. The score obtained in each column are aggregated to produce a new score which is then taken as the synergy result.

Based on Table 6-1, if the synergy results are high or very high, the development plan will be accepted, otherwise countermeasures will need to be taken or the action terminated.

This table will be filled with the results obtained from Technology Table 6-2, Cost and Benefit Table 6-4 that describe the technology feasibility, the cost evaluation and the benefit evaluation.
### Table 6-1: Robotic Technology, Cost and Benefit Assessment Standard

<table>
<thead>
<tr>
<th>Standard</th>
<th>RATING CRITERIA</th>
<th>TCB SCORING</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 Technology (30%)</td>
<td>2 Cost (20%)</td>
<td>3 Benefit (50%)</td>
</tr>
<tr>
<td>Very High</td>
<td>80&lt;Average&lt;100</td>
<td>Accept option and payback is foreseeable</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>60&lt;Average&lt;80</td>
<td>Accept option and investment is to likely occur</td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>40&lt;Average&lt;60</td>
<td>Acceptable but further modification required</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>20&lt;Average&lt;40</td>
<td>Uncertain feasibility, need to take countermeasures</td>
<td></td>
</tr>
<tr>
<td>Very Low</td>
<td>0&lt;Average&lt;20</td>
<td>Decline investment</td>
<td></td>
</tr>
</tbody>
</table>

**Technology Feasibility Evaluation**

Table 6-2 shows the different categories of robots in the first column. For each category, an estimation of technology readiness and level of autonomy is given. The result obtained from the aggregation of these figures will be used as input for Table 6-1.

### Table 6-2: Technology Feasibility Evaluation Scheme

<table>
<thead>
<tr>
<th>Category</th>
<th>TRL (70%)</th>
<th>Level of Autonomy (30%)</th>
<th>Result (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>e.g. 40</td>
<td>e.g. 10</td>
<td>e.g. 50</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K/K-Prime</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Technological Scoring keys**

**TRL (0→70%):**

- Feasibility study (10-25), Technology Demonstration (25-50), Flight Heritage (50-70)

**Autonomy Level (0→30%):**

- Complete Teleoperation (1-10), Partial autonomy (10-20), Full autonomy (20-30)
Robot Cost Evaluation

The cost of the robots also gets a score, determined as follows: the lower the cost, the higher the score. A robot having a cost between 1 million and 25 million gets the score “A”. By the same logic, a robot having a cost between USD25 and USD100 million will get the score “B” and so on.

<table>
<thead>
<tr>
<th>Category</th>
<th>Results (100%)</th>
<th>Cost Scoring keys</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>e.g. 85</td>
<td>100 = 1 M&lt;cost&lt;25M</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>80 = 25M&lt;Cost&lt;100M</td>
</tr>
<tr>
<td>K/K-Prime</td>
<td></td>
<td>60 = 100M&lt;Cost&lt;250M</td>
</tr>
<tr>
<td>H</td>
<td></td>
<td>40 = 250M&lt;Cost&lt;400M</td>
</tr>
<tr>
<td>G</td>
<td></td>
<td>20 = Cost&gt;400M</td>
</tr>
</tbody>
</table>

Table 6-3: Robot Development Cost Evaluation Scheme (USD, Millions)

Robotic Benefit Evaluation

The robotic benefit evaluation can be split into society return value and risk reduction (crew safety) for astronauts (such as EVA) when using a robot. Society return values need to be established by experts. The score of risk reduction for astronauts are based on the crew safety risk analysis. Similar to the rationale of the economic trade off, the benefit criteria have different weights which are arbitrarily proposed and can be adjusted by the user. Here 30% is proposed for society values and 70% for crew safety (Table 6-4).

<table>
<thead>
<tr>
<th>Category</th>
<th>Society Values (30%)</th>
<th>Crew Safety (70%)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>e.g. 15</td>
<td>e.g. 60</td>
<td>e.g. 75</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K/K-Prime</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Social Value Scoring Keys (0-30%)
(e.g. spin offs, living standard improvements, cultural changes, contribution to GDP)
High (20-30%), Middle (10-20%), Low (5-10%)

Crew Safety (0-70%): Reduction of Risk Scores
57-70%  ➔ Very High  ➔ 81-100%
43-56%  ➔ High     ➔ 61-80%
29-42%  ➔ Moderate ➔ 41-60%
15-28%  ➔ Low      ➔ 21-40%
0-14%   ➔ Very Low ➔ 0-20%
6.1.4 **ISESB Recommendations**

The analysis of the potential players' attitude toward an international cooperation mechanism (Section 5.1) brought out the willingness of every country to join a collaborative framework. The scope and the cost of such an exploration mission makes cooperation a necessity, placing the safety issue on an international level.

The creation of the International Space Exploration Safety Board (ISESB) is proposed. The organization’s main role would be to advise lunar base designers on how robotics could be used to bring a better balance between avoidance, prevention and management of astronaut hazards, and to encourage the incorporation of safety issues during the design of robotic features. The establishment and creation of space exploration safer standards by the ISESB might be used to promote and to harmonize space safety policies, to efficiently allocate financial resources and to justify budgets for manned space exploration missions.

Furthermore, the Board’s structure and procedures could help to improve some organizational errors in the management of astronaut/robot synergy and the lunar base, such as time pressures, missed signals of warning and deterioration of engineering systems, poor learning and transference of experience, poor productivity, and the identification, communication and management of uncertainties.

In order to accommodate most of the interests of the space faring nations, it is suggested that the Board shall not generate binding decisions, but make recommendations. Space emerging countries are likely to join the Board which needs to be able to accommodate more members. In that regard, space faring nations and especially the USA need to change their approach toward cooperation and modify their expectations to allow space emerging nations to participate. Moreover, following the example of NASA's safety culture, it is recommended to not have safety issues addressed only at a centralized level. Every country part of the Board shall feel responsible, as well as at lower levels.

Five alternatives of the ISESB’s funding are also suggested: contribution of financial resources by national GDP or agency space budget, payment of membership fees, voluntary contributions and donations, and finally other sources of funding such as sales of publications and magazines, as well as certification fees among others. The final decision in fund raising should be taken by ISESB members.

Finally, a draft memorandum of understanding establishing the ISESB has been drawn up and is proposed in Appendix C.

6.2 **Conclusions**

Humanity’s return to the Moon is imminent. According to various space agency plans, manned lunar missions may be launched as early as 2020. It is well understood that crew safety will be paramount in these missions. The ALERTS project was undertaken as a means to address the crew safety concerns associated with the establishment of a lunar base through a multi-disciplinary, systematic approach of assessing the ability of robotic systems to improve crew safety and wellbeing.
This process identified 66 general lunar surface tasks through discussions with industry and a survey of literature. These tasks were categorized by the phases of base development defined by ALERTS and also by the level of involvement of astronauts and robots. Based on these categorizations, ALERTS focused on tasks that would be performed during Phases 1 and 2 (60 tasks), since these periods were deemed to have the greatest impact on agency plans. The task list was narrowed further by selecting only tasks where astronauts would be required to participate but could potentially benefit from the assistance of a robot.

At this stage, the safety risks associated with each task were accumulated and a risk analysis was performed, using proposed, integrated criteria from several expert sources. As a result of the analysis, tasks were prioritized according to their overall level of risk: those tasks with the highest level of risk were given highest priority. From this list of tasks, the top 14 were selected as the focus for the ALERTS project. Of particular note—though not surprising—all 14 priority tasks require EVA.

Subsequent to task prioritization, a decision tree was applied to each priority task in order to make logical and consistent recommendations regarding which particular robotic platform could be used to assist in performing the task. After proving the efficacy of the decision tree, each of the remaining 46 Phase 1 and 2 tasks were also applied to the tree. The combined results were surprising; of those tasks that could be assisted by robotics, 72% can be sufficiently accommodated by only 3 different platforms. This is of significant interest because it shows what type of robotic research would have the greatest impact on crew safety for lunar missions.

A Cost, Technology, Benefit Analysis is proposed to determine which specific technologies merit the most attention by decision makers, and associated grading criteria is suggested. This provides management with an important tool for analytically weighing the different aspects comprising a robot. Principally, this refers to how much a robot will cost, the benefit it will bring in terms of increasing task efficiency and reducing the risk to the crew, and the feasibility of the enabling technology. By comparing these three categories, and using weighted scores, the user can quickly and easily perform a comprehensive trade study as to cost effectiveness of a robotic solution and the increase in crew safety associated with it.

Crew safety is the common theme throughout the ALERTS project, and while the use of technology to increase crew safety has been discussed, there are additional methods to ensure the safety of the astronauts on the lunar surface. To this end, ALERTS proposes the establishment of the International Space Exploration Safety Board, a non-governmental organization that would review and harmonize safety regulations pertaining to human-robot synergy, and would be comprised of representatives of the world’s various space agencies with other organizations and companies holding observer roles. This safety board has the potential to have its role expand into other aspects of space flight and space exploration safety.

As Frank Borman stated, “Exploration is really the essence of the human spirit.” That spirit continues to flourish as humanity anticipates returning to the Moon. By maximizing crew safety, the potential for the success of such future exploration endeavors is greatest. While the ALERTS project was undertaken for lunar exploration, it is easy to draw parallels to other human planetary exploration endeavors. The ALERTS project has identified methods that will increase crew safety and ultimately add to the sustainability of a lunar program through reduction of safety risks to make humanity’s return to the Moon as safe as possible. Üt luna!
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## APPENDIX A: PHASES 1 AND 2 LUNAR TASKS REQUIRING ASTRONAUT PARTICIPATION

<table>
<thead>
<tr>
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<td><strong>Base Construction</strong></td>
<td>Lifting/stabilizing</td>
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</tr>
<tr>
<td></td>
<td>Connecting/disconnecting service lines</td>
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</tr>
<tr>
<td></td>
<td>Joining</td>
<td></td>
<td>S</td>
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<tr>
<td></td>
<td>Handtool tasks</td>
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<td></td>
<td>Connecting modules</td>
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<td>Laying of electrical cables</td>
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<td></td>
<td>Fuelling operations</td>
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<td></td>
<td>Unloading/stowage of resupply cargo</td>
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<td>A</td>
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<tr>
<td></td>
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<td>Navigating</td>
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<td>Repelling/Climbing</td>
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### Robot Operation and Maintenance

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### Public Relations

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### EVA Support

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<tr>
<td>EVA suit maintenance/repair</td>
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<tr>
<td>Pre-breathe prior to EVA</td>
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## APPENDIX B: RISK ANALYSIS

### GENERIC TASKS

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<tr>
<td>2</td>
<td>Radiation exposure (acute) - Bone Marrow Syndrome</td>
<td>B</td>
<td>3</td>
<td>B3</td>
<td>12</td>
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<tr>
<td>3</td>
<td>Radiation exposure (acute) - Gastrointestinal Syndrome</td>
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<td>4</td>
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<td>8</td>
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<tr>
<td>4</td>
<td>Radiation exposure (acute) - CV/CNS</td>
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<tr>
<td>5</td>
<td>Radiation exposure (chronic)</td>
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<td>4</td>
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<td>19</td>
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<tr>
<td>6</td>
<td>Micrometeorite impact</td>
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<tr>
<td>7</td>
<td>Suit tear</td>
<td>B</td>
<td>4</td>
<td>B4</td>
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<tr>
<td>8</td>
<td>Failure of life support</td>
<td>A</td>
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<td>Finger injury</td>
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<td>Vomiting</td>
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<td>Poor visibility</td>
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<td>Lunar dust infiltration</td>
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<td>Psych. stress (performance impairing)</td>
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<td>B3</td>
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<tr>
<td>14</td>
<td>Psych.1 stress (normal activity-related stress)</td>
<td>D</td>
<td>1</td>
<td>D1</td>
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<td>15</td>
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<td>17</td>
<td>Broken visor</td>
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<td>A5</td>
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### EVA

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<td>Tripping/Falling</td>
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<td>Dehydration</td>
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<tr>
<td>21</td>
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<td>22</td>
<td>Fatigue</td>
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### Pedestrian EVA (PEVA)

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<tr>
<td>23</td>
<td>Mechanical failure/get stuck</td>
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<td>24</td>
<td>Navigation system failure</td>
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<td>25</td>
<td>Collision</td>
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### Rover EVA (REVA)

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<td>A1</td>
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### SPECIFIC TASKS

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<td>Electrocution/shock - minor</td>
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<td>EVA+PEVA</td>
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### Connecting/Disconnecting service lines (exterior)

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### CONNECTING/RECONNECTING service lines (exterior)

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<td>Electrocut/shock - minor</td>
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<td>Burns - major</td>
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### Joining
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### Hand tool tasks (exterior)
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<td>Sun glare</td>
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### Laying of electrical cables
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### Unloading/ stowage of resupply cargo
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<td></td>
<td>B</td>
<td>2</td>
<td>B2 6</td>
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<td>A</td>
<td>2</td>
<td>A2 3</td>
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<td>C</td>
<td>4</td>
<td>C4 19</td>
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International Space University, Masters 2008 129
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APPENDIX C: DRAFT MEMORANDUM OF UNDERSTANDING ESTABLISHING ISESB

Preamble

The founding Members herein;

The Italian Space Agency (ASI), British National Space Centre (BNSC), the Centre National d’Etudes Spatiales (CNES), China National Space Administration (CNSA), Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), the European Space Agency (ESA), the Indian Space Research Organisation (ISRO), Japan Aerospace Exploration Agency (JAXA), the National Aeronautics and Space Administration (NASA), and the Russian Federal Space Agency (ROSKOSMOS);

Acknowledging that space exploration missions are inherently dangerous,

Knowing that the presence of humans in space is inextricably significant in space exploration,

Recalling that Astronauts are ‘envoys of mankind’ whose safety is paramount to space exploration,

Recognizing the increasing need and significance of the use of robots in space exploration,

Noting that there exist various international, regional and national safety standards related to astronaut robotic safety,

Reiterating international cooperation under the Outer Space Treaty and other space related documents,

Considering the benefit of collaborating to establish, harmonize, strengthen and expand the development of uniform safety standards for future astronaut-robotic coexistence;

Do hereby endorse the following understanding

Article 1 Purpose

The purpose of this Memorandum of Understanding is to establish the International Space Exploration Safety Board (ISESB) (hereinafter referred to as "the Board"), in order to provide a mechanism for enhanced cooperation among its Members to achieve the objective of meeting the shared interests of governments, space agencies, industries, private companies and international community of ensuring the safety of astronauts during lunar exploration activities.

Article 2 Rationale

The members share a number of common interests in safety issues which may be developed into numerous safety standards useful in space exploration through cooperative research activities. Such activities are likely to increase in frequency and scope in the future. It is highly desirable to exchange information on current research activities so as to identify future cooperative activities. Therefore, the Board is established to identify, plan, and assist in the development and implementation of safety standards that are of mutual interest and benefit to the robot astronaut coexistence.
Article 3 Scope
The Board will identify safety issues of importance to each of the countries undertaking missions to the Moon and other Celestial Bodies. It shall establish departments in accordance with Article 4 to undertake activities listed in Article 7 as appropriate, and initiatives with other organizations and institutions interested in safety issues.

The Board will:
- a) Review all existing safety standards pertaining to astronaut-robot safety internationally, regionally and nationally.
- b) Recommend areas that need harmonization.
- c) Identify emerging safety issues and make recommendations to address them.
- d) Serve as the primary means for exchanging information and plans concerning safety issues.
- e) Identify and evaluate options for debris mitigation.
- f) Any specific cooperative activities endorsed by the Board will be implemented through either working groups in accordance with Article 8 or through other arrangements negotiated between its members.

Article 4 Constitution of Departments
There shall be constituted within the Board the International Safety Assembly, the Safety Standard/Regulation Board, the Ethical Department. Each department shall have its role as hereunder described:

a) International Safety Assembly
   - i. To promote discussion and international cooperation in the development of astronaut/robot safety standards for lunar exploration missions.
   - ii. To adopt new safety standards proposed by the Safety Standard/Regulation Board.
   - iii. To promote the rational use of robotics in lunar missions.

b) The Safety Standard/Regulation Board
   - i. To provide advice and to develop astronaut safety standards for lunar missions.
   - ii. To provide advice and to develop astronaut/robot codes of conduct for lunar missions.
   - iii. To provide advice in adopting regulations for potential dispute resolutions and liability issues related with astronaut/robot interaction.
   - iv. To provide advice in regulating new applications of robotics aimed to improve crew safety.

c) The Ethical Department
   - i. To guarantee that astronaut/robot ethical issues will be incorporated in the design, manufacturing and development of robots for lunar missions.
   - ii. To guarantee that astronaut/robot ethical issues will be included in the development of astronaut safety standards, astronaut/robot code of conduct, as well as any other required regulation.
   - iii. To successfully execute within the organization a progressive ethical policy in the use of robots to improve astronaut safety during lunar missions.
   - iv. To be responsible for executing new astronaut/robot ethical policies.
   - v. To include astronaut/robots ethical issues in the outreach activities of the Board.

Article 5 Membership
a) Members of the Board as of the time of endorsement of this Memorandum of Understanding shall consist of all the founding members listed as listed at the Preamble here in above.

b) Any additional member may join upon the consent of at least 75% of the present members of the
Board.
c) Upon establishment of the ISES B the Board shall select observer members. The Observer members shall include representation from other organizations, like-minded companies, or government agencies in their delegation and other intergovernmental agencies engaged in astronaut-robotics safety.

**Article 6 Membership Criteria**

a) Members are countries or national or international space organizations which are carrying out space activities, or which are manufacturing space related components that are of safety concern.
b) A member should be actively undertaking safety assessments and safety precautions related to human missions to the Moon and other Celestial Bodies.
c) A country is represented in the Board by itself or by one space organization. The delegation of any Board member may, however, be comprised of delegates from other space organizations or other selected agencies of that country or of other countries.
d) Representation from other organizations, like-minded companies engaged in astronaut safety, and robot technology development.

**Article 7 Activities**
The activities of the Board shall be:

a) To provide advice in developing crew safety standard policies for lunar missions.
b) To promote the implementation of safety programs in a lunar base.
c) To provide advice in adopting global astronaut safety standards for lunar missions.
d) To update existent crew safety standards for lunar missions.
e) To promote the creation of an astronaut/robot code of conduct.
f) To set up safety protocol systems to operate robots during lunar missions.
g) To conduct research on accident hazards to astronauts.
h) To conduct periodic assessment, risk analysis and decision analysis related with hazards to astronauts during lunar missions.
i) To promote the inclusion of crew safety issues in robotic design to reduce and prevent astronaut hazards.
j) To promote the use of robotics for improving crew safety during lunar missions.
k) To allocate resources (financial, organizational, technical and human) to improve crew safety for lunar missions based on robotic applications.
l) To promote international cooperation and flow of information in the use of robotics to improve astronaut safety during lunar missions.
m) To provide advice in handling managerial errors in order to improve astronaut safety during lunar missions.
n) To raise awareness about astronaut/robots synergy.
o) To organize and coordinate workshops on the use of robotics for improving astronaut safety.

**Article 8 Terms of Reference for Working Groups**
Working groups shall be established to undertake issues pertaining to crew safety standards and other regulations. The Working groups shall be constituted according to the needs identified by the Board. Each Board member interested in a topic for which a working group has been established shall have the right to be represented in that Working Group. Governmental and non-governmental organizations, international organizations, space agencies, and private companies working together with the Board should take part in the work. The draft on crew safety standards generated and adopted by the three working groups should be circulated among the member bodies for voting. The general parameters of Working Groups (e.g., Robotic Board, Crew Safety Board, and Astronaut/Robot Synergy Board) are hereunder described:
a) To prepare astronauts/robotics safety standards.
b) To promote and to develop technical studies on astronaut/robot synergy.
c) To address new technologies, and operational and procedures guidelines related with the use of robotics to improve astronaut safety.
d) To conduct studies on accident hazards to astronauts and how robots could be used to mitigate them; to propose safer approaches to design robots for lunar missions.
e) To provide technical support for potential dispute resolution.
f) To determine safety technical requirements of robots for astronauts.
g) To promote the participation of the private sector.

**Article 9 Rules of Operation**
The final adoption and publication of the International Space Exploration Safety Standards as well as other documentation should require the consent of at least 75% of the member bodies. The adopted standards or guidelines shall not be binding to the member states but the states shall be required to act in utmost good faith. The Board shall have the powers to develop measures to deal with constant defaulters of the standards or guidelines.

**Article 10 Funding and Other Resources**
Member states to the Board shall decide amongst themselves as they deem necessary the mode of funding either through contribution according to each country, Gross Domestic Product, according to the space budget allocation, or through membership fees. This shall not, however, prevent the board from receiving grants or donations through other options to advance the objectives of the Board.

**Article 11 Withdrawal / Dissolution / Termination of Membership**

a) Any Member may withdraw from the Board by providing written notice to the Board at least 6 Months in advance.
b) Dissolution of the Board may occur at any time by an unanimous vote of all Members, including the Founding Members.
c) The Board by unanimous decision may terminate the membership of a member that is a constant defaulter of the standards developed by the Board if the Board so proves.

**Article 12 Entry into Force / Amendment**
This memorandum of understanding will enter into effect on the date of the last signature of the Founding Members and will remain into effect for a period of 3 years. After which the member states have the discretion to extend, amend, or revise by a two-thirds majority of all Members, including the concurring votes of all of the Founding Members.

IN WITNESS WHEREOF the Founding members have caused their duly Authorized representatives to sign the Originals in English and French Language:

Done on this..................day of.................. Two thousand and..................

At .................................. (Place, Country).

Name of Founding Member and Signature
APPENDIX D: FUNDING SYSTEMS OF A LUNAR BASE

As stated in Section 2.2.9, space projects can be financed through government funding, venture capitalists, business angels as well as public-private-partnership depending on the nature of the projects. Issuance of lunar bonds is one option for funding the lunar base project. To aid in the decision-makers in choosing between the financing options, a decision tree is suggested (Figure D-1).

Figure D-1: Financing Decision Tree

Definitions

A bond is a debt security, issued by authorized organization that owes the holders a debt and is obliged to repay the principal and interest (the coupon) at a later date, termed maturity. The bond market is a financial market where participants buy and sell debt security, usually in the form of bonds. A coupon is a fixed or float rate or inflation link.

Why Lunar Bonds?

The rationale for selecting lunar bonds is in order to assure higher reliability for the crew, the cost of technology development will be high. The bonds can thus provide large financial capability. The length of time until the maturity date is often referred to as the term or tenor or maturity of a bond. The maturity can be any length of time. Some bonds even have a term of up to thirty years. Given the current state of the world economy, the Gross Domestic Product
(GDP) of the entire world is worth approximately $48 trillion (GDP 2006). As of 2006, the size of the international bond market is an estimated $45 trillion, compare to the world financial market, lunar bond capacity are not burden to the World. The lunar bonds generate indicative new way to explore international cooperation because big capacity bonds need collateral. They provide tension-free environment for engineers and developers from financial worries during short durations that maybe imposed by shareholder. As targeted to global financial market, it will be attractive to bond holders in terms of flexibility.

The potential investors in lunar bonds include institutional investors, governments, traders, and individuals. Except for the government, all the potential investors will analyze the value of bonds. The major concern is the safety of their investment. The second one is profit. The substantial guarantee from the international economic organization will greatly improved the lunar bonds creditability. The World Bank is one of the world’s largest sources of funding and knowledge for developing countries. The IMF is an international organization, established to promote international monetary cooperation, exchange stability, and orderly exchange arrangements. The main body that issues lunar bonds should be guaranteed by IMF or World Bank. However these two organizations are essentially dedicated to humanitarian assistance in developing nations, therefore their involvement in this funding strategy is questionable. A SWOT analysis is also proposed (Table D-1)

<table>
<thead>
<tr>
<th>STRENGTH</th>
<th>OPPORTUNITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable Long term money source</td>
<td>New cooperate framework</td>
</tr>
<tr>
<td>Space Agency Partnership and IMF or world bank as Guarantor</td>
<td>Financial innovation push technology innovation</td>
</tr>
<tr>
<td>Concentrated on technology breakthrough</td>
<td>New financial product in the world market</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WEAKNESS</th>
<th>THREAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Everything on paper</td>
<td>Technology risk</td>
</tr>
<tr>
<td>Organization coordinate</td>
<td>Economic instability</td>
</tr>
<tr>
<td>budget control</td>
<td></td>
</tr>
<tr>
<td>Difficulty to find a guarantee</td>
<td></td>
</tr>
</tbody>
</table>
“To conduct a study for increasing crew safety during lunar surface exploration through task allocation between astronauts and robots.”

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