ASSESSMENT OF OPPORTUNITIES IN THE FIELD OF ROBOTICS FOR THE MOON-MARS EXPLORATION INITIATIVE

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Prepared by:

Philip A. Lapp Ltd.
Suite 302
14A Hazelton Avenue
Toronto, Ontario
M5R 2E2

with support from:

Dynacon Enterprises Ltd.
Suite 200
5050 Dufferin Street
Downsview, Ontario
M3H 5T5

Government of Canada Gouvernement du Canada

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TITLE: ASSESSMENT OF OPPORTUNITIES IN THE FIELD OF ROBOTICS FOR THE MOON-MARS EXPLORATION INITIATIVE

AUTHOR(S): Philip A. Lapp
Gabe D'Eleuterio
John D. Keys

ISSUED BY CONTRACTOR AS REPORT NO: 2/91

PREPARED BY: Philip A. Lapp Ltd.
Suite 302
14A Hazelton Avenue
Toronto, Ontario
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1.0 INTRODUCTION

1.1 Background

This report is submitted in fulfilment of Supply and Services Canada (SSC) Contract No. 31016-0-6036/01-SR for a study entitled "Assessment of Opportunities in the Field of Robotics for the International Moon-Mars Exploration Initiative".

On July 20, 1989, the 20th anniversary of the Apollo XI Moon landing, President George Bush announced his vision for an international program to return to the Moon and then undertake a manned mission to Mars. This initiative would chart a course for the United States in space exploration well into the next century.

His proposal calls for Space Station Freedom to be the first critical step, from which would follow the return to the Moon and then the manned voyage to Mars. The program is to be open to international cooperation and is known as the Space Exploration Initiative (SEI). A full description of SEI is available elsewhere, and so it not duplicated here. The reader is referred to "Report of the 90-Day Study on Human Exploration of the Moon and Mars", National Space Council, supported by NASA, November, 1989.

This assignment deals with one of eight studies aimed at assessing Canadian interest and capability in possible participation in the Space Exploration Initiative. The eight companion studies deal with:

Science;
Space Communications and Spacecraft Subsystems;
Planetology, Remote Sensing and Resources;
Robotics;
Life Sciences;
Biotechnology for Life Support;
Energy; and,
Building Sciences.

1.2 Study Objectives

The general objective of this assignment is to provide information and rationale to support the development of long term plans in the area of robotics for human exploration. The specific objectives are as follows.

- To establish the level of interest and potential rationalization of Canadian participation in SEI.
- To identify Canadian opportunities for participation in SEI.
- To identify potential projects and teams to successfully develop the technology.

2.0 METHODOLOGY

The following tasks were undertaken in order to complete the assignment.

- Preparation of a background paper reviewing the NASA activities, to serve as a representative mission scenario.
- Review of significant United States and international relevant robotic and rover technology development.
- Conduct specific interviews and contact a range of potentially interested people by phone and mail.
- Analyze the responses and arrive at an overall assessment of possible Canadian robotic participation in SEI.
- Recommend appropriate Canadian participation in Moon-Mars exploration, together with more in-depth follow-on studies that should be undertaken.

A background paper was prepared and distributed in advance to prospective interviewees. A copy is contained in Appendix 1. This was sent to all persons contacted, along with a guide to the type of information sought. The main points related to the identification of:

- capability;
- missions;
- key robotic technologies; and,
- interest in participation and teaming.

The guide may be found in Appendix 2.

Supply and Services Canada (SSC) included an announcement of the studies in their Bulletin. This resulted in a number of enquiries and expressions of interest in participating in any developing program.

The following groups were sampled for contributions.

- Persons/organizations selected in consultation with the Scientific Authority.
- STEAR contractors.
- PRECARN membership.
- Persons/organizations expressing interest as a result of the SSC announcement.

The breadth of the survey and the fact that some of those contacted solicited information from colleagues or associates resulted in some individuals receiving requests for information twice. In a few cases, more than one individual in a given organization was contacted.

The names and addresses of persons contacted are given in Appendix 3 - a total of 76 persons. The following table summarizes the interviews:

Table 2.1

Interview Summary

	Industry	Public Service	University
Personal	10	4	2
Phone Contact	5	5	3
Letter Reply/Refer	14	4	5
No Reply/Referral	9	2	6
Enquiry	6	0	1

The information collected was collated and organized to identify missions and technologies. Criteria were established to evaluate the findings and set priorities. These were used as a basis for recommendations regarding follow-on actions.

3.0 ROBOTICS OBJECTIVES OF OTHER SPACE NATIONS

An attempt was made to gain a deeper understanding of where other space nations have placed an emphasis, so as to permit the identification of possible niches for Canada. In our admittedly limited searches of other nations now involved in space station - USA, ESA countries and Japan - we were unable to uncover any policy statements on the use of robotics from either NASA or ESA. We did obtain information on the Japanese plans.

In general, US and European agencies appear to accept robotics as a normal tool needed as part of future missions, and not singled out for special treatment. This same lack of special recognition is not shared by many of the major space contractors from these countries. Firms like Martin Marietta, Rockwell International and Thomson CSF have their own robotic technology strategies, and while brochures and journal articles are published by such companies from time to time, marketing and other strategies of value to competitors obviously are kept secret.

On the other hand, Japan has structured its national space robotic efforts very carefully. It recognizes the enormous cost of manned space operations and is therefore concentrating on automation, both to reduce costs and to encourage technology development. The work in space robotics is guided by the Space Robot Forum comprising a 70-member group from government, industry and academia. This group is funded by the National Space Development Agency (NASDA).

Japan plans to develop its own large rocket, shuttle and space station, and explore the Moon followed by Mars. Machines will dominate the tasks, progressing from teleoperation through telerobotics to a third generation where machines work by themselves or with very little human intervention.

Japan expects to launch its first unmanned shuttle (Hope) in the late 1990's. It will be similar to the US shuttle with its main function to be a platform for experiments and transportation. Hope will dock with space structures and satellites.

As part of its contribution to Space Station, Japan is developing a 9.7 m robot arm capable of handling a mass of 7000 kg. There will be a smaller arm at the end with a gripper. This is scheduled for launch in 1997.

The space station will be unmanned and serviced by robots which will be earth-controlled. A free-flying robot will tow satellites and cargo to the station. A serpent arm, 25 m long, will be part of the configuration. No funded work is underway for the third generation technologies visualized, and it is expected that they will build on robotic technologies already developed for terrestrial applications.

Around the turn of the century, Japan plans to launch an unmanned service vehicle for assembly and repair of satellites. Key technologies, sensors, autonomous control, manipulation and teleoperation have still to be developed. Work is underway on this project.

Japan plans an unmanned Lunar Mobile Explorer for launch in 2000. It will collect samples and look for water on the Moon. A manned outpost is planned for 2010. The special robots required for lunar rovers are not being developed at present, but work is being carried out on mobile robots for terrestrial applications. A series of articulated tracked vehicles has been developed, with various locomotion capabilities. Japan's research on walking robotics is considered to be some of their finest. Japan has developed a six-legged teleoperated underwater vehicle for inspection. They also have a vehicle for inspecting nuclear facilities.

A seven-year project, Underground Space Development, has recently begun to develop technologies for building underground storage and supply systems, as well as other facilities. Automation and robotics are key elements in these developments.

One company has formed a research team devoted to lunar base construction using lunar materials and automated machinery. Construction will be done as far as possible with robots under teleoperation.

Japan has been using robots in manufacturing for some time. New developments aim at producing flexible manipulators like snakes, tentacles, elephant trunks, all of which have potential application in space. One such development comprises an arm with eight joints, each with two degrees of freedom that are linked serially and decrease in size toward the tip - a trunk! The arm is integrated with a mobile platform. Further examples are:

- flexible fingers, each with three chambers, controlled with pneumatic servos;
- ladder climbing robots;
- a teleoperated live-power line maintenance robot;
- bipedal walkers;
- a two-arm torso that can stitch together a purse on a sewing machine, turn it inside out, and attach a shoulder strap; and
- an assembly robot intelligent enough to study and complete an assembly task.

Japan's infrastructure for space development is similar to that in the US. Government departments set policies and distribute funds. Private companies develop systems. In some situations the government only provides seed money, the rest comes from the private sector.[1]

4.0 FINDINGS AND ANALYSIS

In developing our findings for the study, a total of 76 persons were contacted in 51 organizations (listed in Appendix 3):

- 28 companies
- 12 government groups
- 11 university groups

[1]Source: Japan Robotics Aim for Unmanned Space Exploration, IEEE Spectrum, December 1990, p. 64-67

The questions generally followed the Interview Guide (Appendix 2) which focused on robotics capability and how it could be applied to a Canadian SEI contribution, and on ideas for such a contribution. The findings draw from verbal and written responses which suggested ideas for specific missions, related technologies and criteria for evaluating suggestions.

We were beset immediately with the question as to whether the technologies where Canada has or could have expertise should be the driver, or whether initially, appropriate missions should be identified for Canada. For the latter, the related technologies would follow; all of which may not fall within Canadian capabilities. In such cases, the formation of strategic alliances with others may be the appropriate approach.

Most groups interviewed were very keen to participate in a Canadian SEI team concept, but we were disappointed in the response to questions calling for new ideas on specific technologies that Canada should exploit. In general, the view was that we should build on current capabilities derived from the Shuttle Remote Manipulator System (SRMS) and space station activities. Most of those interviewed took the position that they would be responsive to specific requirements: "just tell us what you want, and we will respond". In the end, we created the list of technologies ourselves, and they are described in Section 4.4 below.

Interviewees were far more comfortable in suggesting specific missions for Canadian participation in SEI. The strong interest expressed by several groups in starting with candidate missions instead of technologies led us to the approach we chose wherein a list of proposed missions is prioritized against a set of reasoned criteria. A second analysis is made where each candidate mission is evaluated against the technologies needed for the mission. From such analyses, conclusions are drawn which lead to a set of recommendations.

4.1 Missions

The missions selected for evaluation were those in which interviewees expressed an interest. Interest is defined as being willing to spend the time to propose missions for Canadian participation in SEI. No one offered to spend money, although some respondents must have devoted substantial man-hours in their written responses.

Rovers were suggested by several people. They are generic to most missions, and therefore have not been identified separately. Where rovers were identified with an application, the organization making the identification is listed as interested in the mission. The following table lists the suggested missions and organizations that expressed an interest:

Table 4.1

Missions and their Advocates

Mission

1. **Excavation/Mining Vehicle**

System - vehicle or drag line - for mining resources from lunar regolith to support manned outposts and habitats.

Institutions Expressing Interest

- Dynacon
- Ecole Polynique
- Institute for Information Technology (NRC)
- Optech
- Spar Aerospace Ltd.
- Thomson CSF

2. **Service/Repair Vehicle**

A vehicle or depot for servicing and repair of rovers or other installations.

Institutions Expressing Interest

- Alberta Research Council
- Ecole Polytechnique
- Institute for Aerospace Research (NRC)
- Institute for Information Technology (NRC)
- Optech
- Thomson CSF
- Centre de Recherche Industrielle de Quebec

3. **Geophysical/Geological Survey Vehicle**

A vehicle equipped to carry out electromagnetic, radiometric, gravity surveys, and to record the locations at which measurements have been taken. It is also equipped to collect geological samples, store them, possibly perform analyses.

Institutions Expressing Interest

- Alberta Research Council
- ENDEV
- Institute for Aerospace Research (NRC)
- International Submarine Engineering (ISE)
- Thomson CSF

4. Rescue Vehicle

A vehicle equipped to collect vehicles, instruments that must be returned to a central facility for repair. In the longer time frame, humans may have to be rescued from life-threatening situations.

Institutions Expressing Interest

- Ecole Polytechnique
- Institute for Information Technology (NRC)
- Optech
- Thomson CSF

5. Extraction/Processing Plant

A pilot plant capable of accepting material mined from the lunar surface and carrying out subsequent processing and extraction to obtain the desired end products such as oxygen, helium, etc.

Institutions Expressing Interest

- Dynacon
- ENDEV

6. Laboratory Science Facility

An expandable facility for carrying out scientific investigations. These could include astronomy, biological studies, and investigations.

Institutions Expressing Interest

- International Submarine Engineering (ISE)

7. Assembly Factory

An assembly facility located on Space Station or the Moon, capable of taking individual components or subsystems and constructing the end product.

Institutions Expressing Interest

- MacDonald, Dettwiler & Assoc. (MDA)
- Thomson CSF
- University of Toronto
- Dynacon

8. Habitat Construction

Construction of a lunar habitat, making use of local resources, to provide shielding against radiation from solar flares and cosmic sources.

Institutions Expressing Interest

- Alberta Research Council
- Spar Aerospace
- Thomson CSF
- University of Toronto

There were seven companies with suggestions. There are others who said they would like to participate, but had no suggestions. Eleven companies did not reply at all.

4.2 Evaluation Criteria

In order to rank the proposed missions, six independent evaluation criteria were developed. They cover a wide range of perspectives, but are far from exhaustive. Further important criteria may well arise in future, but they could readily be added to, or substituted for the criteria described below.

Criteria were chosen to be:

- Relevant to the subject matter being assessed;
- Sufficient in number to prevent inadvertent de-selection;
- Few enough to avoid all missions ending up with the same ranking; and
- To focus on the technological aspects of the missions.

1. **Builds on existing capability**

   A mission that builds on existing capability is likely to be further up the learning curve and therefore can be undertaken with less cost and at a faster rate.

2. **Links with terrestrial applications**

   There is a better chance of spin-offs if there is a terrestrially related application where work is already underway. There should be a capability to participate in space robotics, and make use of that contribution in terrestrial applications.

3. **Leads to autonomous project**

   Cooperation at the highest levels is necessary, but joint endeavour on projects adds to complexity and can obscure national identity.

4. **National identity**

   A project with which existing Canadian general interests can relate will reinforce those interests. A project in an area foreign to Canadian interests will likely be less well received and may result in fewer long-term benefits.

5. **Acceptability to SEI partners**

   Canada should not try to undertake a mission where it will conflict with strong interests of partners, such as areas where the project is critical to the overall success of the SEI. In these situations, NASA (or another lead agency) will have to reserve the project for its own.

6. <u>**Contains desirable technologies**</u>

Some technologies are more desirable to enhance than others. Projects that involve such desirable technologies should be favoured.

Other criteria were considered and rejected:

- Weighting the criteria, on the grounds that such an exercise requires more broadly based opinion than has been available in this assignment;
- Criteria dealing with regional benefits in Canada, on the grounds that the missions must be much more carefully defined before such criteria become relevant;
- Criteria involving wealth creation on the same grounds as above; and
- Cost, since figures were not forthcoming.

Other criteria were considered and rejected. They included criteria dealing with regional benefits in Canada, on the grounds that the missions must be much more carefully defined before such criteria become relevant, criteria involving wealth creation on the same grounds that such an exercise requires more broadly based opinion than has been available in this assignment.

4.3 Evaluation Summary

The criteria listed above were used to evaluate each of the missions that were suggested to us. The detailed evaluation appears at Appendix 4, and is summarized in Table 4.2.

Table 4.2

Mission Evaluation

	Criteria						
	1	2	3	4	5	6	Score
Excavation/mining vehicle	h	h	h	h	m	m	(16)
Servicing/repair vehicle	l	m	m	l	l	m	(9)
Geophysical/geological veh.	h	h	l	m	m	l	(12)
Rescue vehicle	l	l	l	m	l	m	(8)
Extraction/processing plant	h	h	m	h	m	l	(14)
Laboratory science facility	m	m	m	l	m	l	(10)
Assembly factory	h	m	m	l	l	h	(12)
Habitat construction	m	l	l	l	l	m	(8)

Criteria for Evaluating Suggestions (criteria weighted equally)

1. Builds on existing capability
2. Links with terrestrial applications
3. Leads to Canadian autonomous project
4. National identity
5. Acceptability to SEI partners
6. Contains desirable technologies

Scoring

high - h - 3
med - m - 2
low - l - 1

Ranking		Score
1.	Excavation/mining vehicle	(16)
2.	Extraction/processing plant	(14)
3.	Geophysical/geological vehicle	(12)
3.	Assembly Factory	(12)
5.	Laboratory science facility	(10)
6.	Servicing/repair vehicle	(9)
7.	Rescue vehicle	(8)
7.	Habitat construction	(8)

4.4 Robotic Technologies

The SEI program will depend heavily on "autonomous robotics". It is accordingly appropriate then to review those technologies that will be required, or likely required, for autonomous robotic capabilities and thus impinge on SEI. The following is a list of these technologies with a brief description of each:

AS **Ambulatory Systems.** These systems include all types of mobile vehicle such as wheeled rovers and multilegged robots.

AI **Artificial Intelligence.** This branch of science will have direct application to automonous robotics in the areas of expert systems, dealing with uncertainty, knowledge representation and world modelling, pattern analysis, task and trajectory planning, and learning.

CA **Control Architectures.** The concept of control architecture underlies and supports all of the chip-level technologies which drive the latest developments in pattern recognition and trajectory and motion control algorithms. Control architecture will impinge on parallel-processing capabilities, multitasking operating systems, hierarchical structures, and fault tolerance.

CTAC **Coordinated Two-Arm Control.** This type of control implies two individual robots cooperating in a manner that forces them to act in unison.

FT **Fault Tolerance.** Fault tolerance refers to the ability of detecting system failures. Techniques involve possible reconfiguration to provide tolerance. Fault tolerance may involve health monitoring, failure anticipation, failure/fault detection, diagnosis, redundant resource management, status reporting, and interface to safety management.

FF **Force Feedback.** Force feedback is required in many robotic applications where the robotic system is in contact with the "work" such as in machining. This technology must give consideration to force sensors, control techniques, and task (world) description interface.

FL **Fuzzy Logic.** Fuzzy logic is the generalization of "crisp logic" and can be employed as a systematic framework to deal with uncertainty in sensor data and planning activities.

MPAC **MultiPurpose Applications Console.** This may be considered an integrative technology aimed at interfacing a system via a display terminal to a human operator. In autonomous robotics, MPACs will likely be needed for systems display and teleoperation.

NN **Neural Networks.** The theory of neural networks offers a new approach to pattern recognition and systems modelling based on connectionist principles. It is an attempt to emulate the workings of the brain. Potential applications in autonomous robotics include control, human/machine interface, sensor fusion, sensor-data processing, and chip-level implementations.

OP **Operations Planning.** Operations planning is key to autonomous capabilities from the planning of high-level functions to low-level tasks.

PS **Position Sensing.** Basic position control is a fundamental requirement for all automation devices whose main purpose is to move from one position to another. Hence, the need for position sensors such as optical encoders, synchro-resolvers, and laser interferometers.

RP **Robot Programming.** Programming of robotic systems is critical for an autonomous capability. Robot control languages must be able to interface with task descriptions and must provide support for various types of sensor.

SFo **Sensor Focus.** Sensor focus implies that only those sensors which are required for decision-making are monitored. This concept leads to distributed processing, parallel systems, embedded systems, and methods of focusing on the most important sensors.

SFu **Sensor Fusion.** Sensor fusion is concerned with the integration of various sensory functions including data collection and data processing.

SS **Smart Sensor/Actuator Systems.** There has recently been considerable attention dedicated to the notion of smart sensor/actuator systems. These smart systems will possess the capability of self-diagonistics, self-calibration, local processing capabilities, standardized communications routines, and integration of sensory and processing functions.

ST **Speech Transaction.** This implies the use of voice transactions such as in the output of data to a human listener or voice actuation by a human operator.

SC **Supervisory Control.** This refers to a supervisory model of control where, for example, a robot is commanded to execute a task but a supervisor/operator must intercede if a problem arises. Supervisory control would have a particularly important role in a partially autonomous system.

TS **Tactile Sensors.** Tactile sensing, not to be confused with force feedback, is more like vision processing since it is based on pattern recognition rather than direction/magnitude information provided by force feedback.

TO **TeleOperation.** Teleoperation is the operation of a system at a distance. Canadarm, for example, is teleoperated.

TC **Temporal Control.** Temporal control refers to faster-than-real-time situation to allow the operator or programmer to view the execution of a task beforehand. This could be critical in alleviating operator boredom and fatigue.

TP **Trajectory Planning.** This is the planning of the motion of a robotic system to accomplish a task, generally in the presence of obstacles.

VS **Vision Systems.** A vision capability will be key to autonomous robotics. Issues that must be considered with vision systems are self-focusing and calibration, image preprocessing, feature extraction, object shape synthesis, and image processing hardware.

WM **World Modelling.** Task-level robot programming, as well as the latest techniques in trajectory planning, force feedback and teleoperation, require a robust and malleable model of the "world".

4.5 Mission Scenarios

The technologies listed above are cross-referenced to the mission scenarios in Table 4.3. The scenarios are abbreviated as follows:

ExMi	Excavation/Mining
SeRp	Servicing and Repair
Geo	Geophysical/Geological Survey Vehicle
SeRs	Search and Rescue
ExPro	Extraction and Processing
LaSci	Laboratory Science
Fac	Assembly Factory
Hab	Habitat Construction

In cross-referencing, an attempt has been made to assess the importance of each technology to each mission scenario.

Table 4.3
Cross-Reference of Technologies and Mission Scenarios
Mission Scenario

Technology	**ExMi**	**SeRp**	**Geo**	**SeRs**	**ExPro**	**LaSci**	**Fac**	**Hab**
Ambulatory Systems	H		E	E			D	D
Artificial Intelligence	E	E	H	D	E	H	E	H
Control Architectures	E	E	E	E	E	E	E	E
Coordinated Two Arm Control	E	E	D	D	E	D	E	E
Fault Tolerance	H	E	D		H	D	E	H
Force Feedback	E	E	H	D	E	D	E	E
Fuzzy Logic	H	H	H	H	H	D	H	H
MultiPurpose Applications Console	H	H	H	H	H	H	H	H
Neural Networks	H	H	H	H	H	H	H	H
Operations Planning	E	E	D		E		E	E
Position Sensing	E	E	E	E	E	E	E	E
Robot Programming	E	E	E	E	E	E	E	E
Sensor Focus	E	E	H	H	E	D	E	E
Sensor Fusion	E	E	H	D	E	D	E	E
Smart Sensors	E	E	H	H	E	H	E	E
Speech Transaction		D	D	H		H		
Supervisory Control	H	H	E	E	H	E	H	H
Tactile Sensing	E	E	H	E	E	H	E	E
TeleOperation	H	E	H	E	H	E	D	H
Temporal Control	H	H	D	D	H	D	H	H
Trajectory Planning	E	E	E	E	E	E	E	E
Vision Systems	E	E	E	E	E	E	E	E
World Modelling	E	E	H	D	E	D	E	E

Legend:
E - Essential Technology
H - Highly Desirable Technology
D - Desirable Technology

4.6 Rating Scheme for Technologies

Table 4.3 represents only a cursory attempt at identifying the **technical** importance of each technology to the various missions. However, in assessing how critical the development of a particular technology would be, one must consider other factors as well, namely, **programmatic** and **strategic.** The programmatic factor reflects the fact that some technologies, while being essential to a given mission, may have (or will have) achieved a greater maturity than other essential technologies and therefore would not be as "critical" to develop. The strategic factor is intended to relate the spin-off potential of a particular technology.

Priority Index. A priority index has been used quite effectively by Dynacon to prioritize technologies on the basis of technical, programmatic, and strategic aspects.[2] The numerical index I for each technology is computed as follows:

$$I = T \times P \times S$$

where T, P, and S, represent, respectively, a measure of the technology's technical, programmatic, and strategic importance.

Technical Factor. Since the mission scenarios are far from well defined, it is difficult to attach a number to the technical importance of a technology with a large degree of certainty. Thus, for present purposes, we shall take a score of 1 as corresponding to an essential technology (i.e., a technology which is essential for autonomous capabilities), 0.6 for a

[2] Carroll, K.A., "Autonomous Robotics - Phase I: Requirements and Critical Technologies," Volume I(A), Dynacon Report 28-904/0404, May, 1990.

highly desirable technology, and 0.3 for simply a desirable technology.

Programmatic Factor. The programmatic factor reflects the advancement of a technology and may be expressed mathematically as

$$P = t_{nominal}/t_{required}.$$

Here, $t_{nominal}$ is the length of time that it will nominally take for a particular technology to mature; $t_{required}$ on the other hand is the length of time until the technology will be required. A number of scenario timetables for SEI have been proposed but $t_{required}$ = 20 years could serve as a representative timeframe. For example, if a technology is expected to mature in 10 years, then P = 1/2. As not to bias towards technologies with long lead times, we constrain P to be at most 1. Thus, all technologies that will not mature before they are required are treated equally.

Strategic Factor. The strategic term S measures the potential for terrestrial spin-off on a scale of 0 to 1. A score of 1 implies a very strategic technology with exceptionally good spin-off potential.

4.7 Technology Assessment

An assessment of the programmatic and strategic important of the identified technologies is based on the work of Carroll[3] and is summarized in Table 4.4. Note that this assessment is independent of the mission scenarios. Strategic considerations are concerned with spin-off potential and therefore are truly

[3]ibid

independent of mission scenario; however, programmatic aspects may vary among the scenarios since the missions would not necessarily share the same timetable.

Table 4.4

Programmatic and Strategic Assessment of Technologies

Technology	P	S
Ambulatory Systems	1.0	0.7
Artificial Intelligence	0.63	0.9
Control Architectures	0.35	1.0
Coordinated Two Arm Control	0.50	0.2
Fault Tolerance	0.25	0.2
Force Feedback	0.50	1.0
Fuzzy Logic	0.60	0.8
MultiPurpose Applications Console	0.35	0.1
Neural Networks	0.63	0.9
Operations Planning	0.25	0.9
Position Sensing	0.50	0.1
Robot Programming	0.75	0.9
Sensor Focus	0.60	0.4
Sensor Fusion	0.50	0.8
Smart Sensors	0.60	1.0
Speech Transaction	0.75	0.2
Supervisory Control	0.75	0.9
Tactile Sensing	0.75	0.9
TeleOperation	0.50	0.9
Temporal Control	0.25	0.8
Trajectory Planning	0.40	0.3
Vision Systems	0.25	0.9
World Modelling	0.50	0.9

Priority Assessment. In Table 4.5, the priority index for each technology as it applies to each of the mission scenarios is tabulated. Note that since T, P and S fall between 0 and 1, the maximum value for the priority index is I = 1.

Table 4.5

Priority Indices of Technologies
Mission Scenario

Technology	ExMi	SeRp	Geo	SeRs	ExPro	LaSci	Fac	Hab
Ambulatory Systems	0.42	-	0.70	.70	-	-	0.21	0.21
Artificial Intelligence	0.57	0.57	0.34	0.17	0.57	0.34	0.57	0.34
Control Architectures	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Coordinated Two Arm Control	0.10	0.10	0.03	0.03	0.10	0.03	0.10	0.10
Fault Tolerance	0.03	0.05	0.02	-	0.03	0.02	0.05	0.03
Force Feedback	0.50	0.50	0.30	0.15	0.50	0.15	0.50	0.50
Fuzzy Logic	0.29	0.29	0.29	0.29	0.29	0.14	0.29	0.29
MultiPurpose Applications Console	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Neural Networks	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Operations Planning	0.23	0.23	0.07	-	0.23	-	0.23	0.23
Position Sensing	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Robot Programming	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.68
Sensor Focus	0.24	0.24	0.14	0.14	0.24	0.07	0.24	0.24
Sensor Fusion	0.40	0.40	0.24	0.12	0.40	0.12	0.40	0.40
Smart Sensors	0.60	0.60	0.36	0.36	0.60	0.36	0.60	0.60
Speech Transaction	-	0.05	0.05	0.10	-	0.10	-	-
Supervisory Control	0.41	0.41	0.68	0.68	0.41	0.68	0.41	0.41
Tactile Sensing	0.68	0.68	0.41	0.68	0.68	0.41	0.68	0.68
TeleOperation	0.27	0.45	0.27	0.45	0.27	0.45	0.14	0.27
Temporal Control	0.12	0.12	0.06	0.06	0.12	0.06	0.12	0.12
Trajectory Planning	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Vision Systems	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
World Modelling	0.45	0.45	0.27	0.14	0.45	0.14	0.45	0.45

Technology Ranking. The technologies are ranked in Table 4.6 beginning with the most critical for development and tapering to the least critical. This ranking is obtained by averaging the technology priority indices over the eight mission scenarios and weighting each scenario equally.

Table 4.6

Ranking of Technologies by Priority Index

Technology	I
Robot Programming	0.68
Tactile Sensing	0.61
Smart Sensors	0.51
Supervisory Control	0.51
Artificial Intelligence	0.43
Force Feedback	0.40
Control Architectures	0.35
World Modelling	0.35
Neural Networks	0.34
TeleOperation	0.32
Sensor Fusion	0.31
Ambulatory Systems	0.28
Fuzzy Logic	0.27
Vision Systems	0.23
Sensor Focus	0.19
Operations Planning	0.15
Trajectory Planning	0.12
Temporal Control	0.10
Coordinated Two-Arm Control	0.07
Position Sensing	0.05
Speech Transaction	0.04
Fault Tolerance	0.03
MultiPurpose Applications Console	0.02

It must be emphasized that Table 4.6 considers all the mission scenarios equally and, in this respect, is only meant to provide a guide. Moreover, this is a ranking based on the measure of development which would be required for the identified technologies; it is not a ranking based solely on the importance of the technologies to SEI.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The objectives of this study were laid down to be:

- To establish the level of interest and potential rationalization of Canadian participation in SEI.
- To identify opportunities for Canadian participation in SEI.
- To identify potential projects and teams to successfully develop the technology.

The interviews and contacts made by us have established beyond any reasonable doubt a significant level of interest in SEI participation by not only the "space" community in Canada, but also by the broader group contacted within the automation and robotics community. There were twenty-five persons who made substantial contributions to the study.

We have identified eight missions as possible areas where Canada could participate in SEI. The institutions proposing such missions are listed in Table 4.1 which would be a logical starting point in the formation of teams to develop the technology. In addition, most of those contacted offered their technologies where applicable.

As we worked our way through the robotics community, we were struck with the high level of advancement, enthusiasm and dedication of the engineers and scientists making up this elite and rapidly expanding group. While the field is not new, many of the technologies employed are at the cutting edge of tomorrow's needs. The lists of essential and Highly Desirable technologies for the eight proposed missions in Table 4.3 and the related descriptive paragraphs lay testament to the diversity of applications served by any of the SEI missions. Clearly, participation in SEI provides Canadian industry with technologies required in future markets that could be too costly to acquire by other means. Moreover, as an advanced technology nation, Canada must not be left behind when other nations are going to the Moon and Mars.

Unlike most of the other companion studies, robotics, like automation and remote sensing, is a tool needed to accomplish a mission and not an end in itself. Many of those contacted were skilled in robotics, but not in its application to space. The notion of Moon and Mars exploration, while exciting and capturing the imagination, was novel and foreign to the types of applications being contemplated by many of the practitioners in Canada, save for the limited number of persons in the space industry itself or those involved in the STEAR program.

There was no strong support for the development of rover technology, although vehicles were suggested for a number of missions. (Canada has made a name in snowmobiles which are not an auspicious platform from which to launch a lunar vehicle.) There was some suggestion that we should eschew rovers, since they are expensive, others are far ahead on the learning curve, and Canada does not have the native industry upon which to build.

Conclusions and the recommendations that flow from them are based on our findings and the analysis in the previous section. In essence, they lead to actions and specific strategies for Canadian involvement in an international SEI activity.

5.1 Canadian Space Consciousness

Based on our interviews, the space segment represents a small percentage of the growing universe of automation and robotics practitioners in Canada. While the STEAR program has done much to expand space consciousness within this universe, we were struck with the widespread lack of knowledge of current Canadian space activities and initiatives. This is particularly the case outside of Ontario and Quebec - those very parts of Canada where such activities need to be expanded for space to be a truly national effort.

We conclude that further efforts need to be made to stimulate space interest within the Canadian automation and robotics communities. The forest industries in the west and east coast regions have come a long way in these technologies including rovers, and have expressed an interest in establishing a dialogue with the space community. The appropriate group in the industry is FERIC (Forest Engineering Research Institute), and we recommend that:

1. **CSA explore with FERIC the organization of a meeting of automation and robotics specialists from the two groups in order to exchange ideas, explore the value of future meetings and visits, and thereby expand the awareness of Canadian space interests in regions outside central Canada.**

There are other industries that tend to concentrate in regions outside central Canada, which also are actual or potential users of advanced robotics, but unfortunately are not as well organized in an R and D sense as the forest industries. They include:

- agriculture
- mining and mineral processing
- oceans

Each of these industries have R and D facilities, either in separate companies (such as Noranda), collectively (as, for example, in agricultural machinery), or in government (such as the Bedford Institute of Oceanography). The broad strategy of approaching such institutions, as recommended above for the forest industry, would be a more general approach; but we believe the FERIC suggestion in Recommendation 1 should be tried first, since it is a proposal already on the table.

5.2 Mission Evaluation

The missions summarized in Table 4.1 were elicited from a relatively small group of interviewees in comparison with the massively large response experienced by NASA in casting its net for ideas through the Lunar/Mars Synthesis Group. We have concluded that the mission identification and evaluation process conducted in Sections 4.1 to 4.3 involved too small a team. A larger more balanced group is needed to refine and expand the missions. Moreover, we believe that the criteria should not necessarily all carry the same weight in the mission evaluation. A larger group would give weighting greater credence and validity. A process for weighting was used with some success, we believe, in evaluating the STEAR technologies. We recommend that:

2. **CSA utilize group dynamics by creating a balanced evaluation group (20-24 people) that expands and refines the candidate missions, revisits and weights the criteria, and conducts an evaluation along the lines shown in Table 4.2 and Appendix 4.**

There are only four points separating the first four missions in the ranking associated with Table 4.2. Thus the ranking could be altered easily by altering the weighting of criteria, or by slightly revising the evaluation summaries in Appendix 4. We have concluded that the first four missions should be ranked equally, and that further criteria need to be applied which relate to costs and the ability for Canada to find a partner to share the costs.

5.3 Strategic Alliance

The missions evaluated in this study were not costed because there was little evidence upon which a costing model could be constructed with any degree of confidence. Suffice to say that, with the exception of the science facility which might possibly be sized to fit a cost constraint, the missions examined involve multi-billion dollar facilities. They are likely to be too expensive for Canada to pursue alone.

We have concluded that Canada should seek a strategic partner for most of the missions evaluated, or conversely identify less expensive stand-alone missions which could fit a Canadian purse. SEI is a bold exciting adventure for any nation to join, and the danger of the latter is that a stand-alone, affordable mission may fall short of what is needed to capture the Canadian imagination. We recommend that:

3. **Once the appropriate mission is identified CSA take steps toward the formation of a strategic alliance with another nation such that skills and facilities intermesh, and each partner carries its appropriate share of the costs.**

5.4 Technology Assessment

From Table 4.3, the following missions include 20 or more Essential and Highly Desirable technologies. STEAR is supporting, or contemplating supporting 15 of these.

Excavation/Mining Vehicle
Servicing/Repair Vehicle
Extraction/Processing Plant
Habitat Construction
Assembly Factory

The STEAR technologies cover the Essential and Highly Desirable technologies for the remaining missions:

Geophysical/Geological Survey Vehicle
Rescue Vehicle
Laboratory Science Facility

The following technologies are Essential for all missions:

Control Architectures
Position Sensing
Robot Programming
Trajectory Planning
Vision Systems

The Geophysical/Geological Survey Vehicle will use all technologies (23), 7 Essential, 11 Highly Desirable, 5 desirable.

It can be concluded from the technology assessment that STEAR is important if Canada is to enter SEI. It ends in mid-decade, and is tied to MSS and the extended MSS programs. If there is no follow-on to STEAR even in its present form, Canada's base expertise will be placed in jeopardy. We recommend that:

4. **In support of a Canadian SEI initiative, CSA give early consideration to some form of continuation of the STEAR program beyond mid-decade, in order to preserve and enhance base expertise in relevant technologies, and protect investments already committed through the present STEAR program.**

The above recommendation might be implemented in the following fashion. Initially we believe it is important to insist that the practitioners themselves describe in some detail what is meant by each candidate mission. This could be accomplished through a workshop seminar where the experts are assembled (perhaps 50 or 60 of them) for a 1 to 2 day session. From such a workshop, it should be possible to identify a core group of 20-24 experts (movers and shakers) to form an evaluation committee.

The committee's main role would be to re-visit the mission evaluation process, including a re-assessment and weighting of the evaluation criteria, and in light of the seminar results, select no more than three missions, but hopefully narrow it down to one or two, for detailed examination.

The next step would be to put out a series of RFPs (each in the order of $50K) to practitioners (not consultants) to establish a preliminary mission definition and, most importantly, to form teams that would carry the project forward and be its champion through to success or rejection. CSA would have to form counterpart teams within the Agency and other relevant government institutions.

An appropriate timeframe would be to have such a program dovetail with the current STEAR program. This suggests that the RFPs should be let early in 1992. In this way, Canada should be ready when the time comes to negotiate our position in the overall SEI program.

5.5 Canadian Capability

In our search for appropriate groups and persons to interview in this exercise, we cast a reasonably wide net (76 persons in 51 organizations). Yet during the course of our interviews, we would learn of other groups with automation and robotics capabilities, and time did not permit us to pursue them. We were left with the uncomfortable feeling that there is still a lot of Canadian capability in these technologies unrelated and not interested in space that we have left untapped. However, we believe we have covered the space interests. We have concluded that a more thorough effort should be made to assess Canadian capability and recommend that:

5. **CSA mount an effort to measure and assess the Canadian capability that exists in the field of robotics, irrespective of area of application or discipline.**

We believe we have captured possibly 75% of the Canadian automation and robotics universe in this study. The medical/health care field is where we would explore further, as well as the groups associated with the agricultural, mining and oceans industries referred to in Section 5.1.

Since robotics is so vital to Canada's on-going efforts in space, it may be useful for CSA to find some means of institutionalizing it through regular seminars, workshops, publications, on-line retrieval services, etc. In one way or another, CSA should take such actions as are necessary to attract the robotics community to maintain contact.

Appendix 1
Background Paper

Human Exploration

of the

Moon and Mars

> "...a long-range continuing commitment (is needed for the human exploration of space). First, for the coming decade, for the 1990s, Space Station Freedom, our critical next step in all our space endeavors. And next, for the next century, back to the Moon, back to the future, and this time, back to stay. And then a journey to another planet, a manned mission to Mars. Each mission should and will lay the groundwork for the next."
>
> - President George Bush
> 20 July 1989

Introduction

Thus did President Bush, on the twentieth anniversary of the Apollo XI Moon landing, chart America's course in space for the remainder of this century and the beginning of the next. The target is Mars. The course of exploration, however, will steer past Space Station Freedom and the Moon.

The spirit of exploration is innate to humankind and setting Mars as the goal for exploration in space is a logical next step after the Moon. The Moon-Mars mission is anticipated to culminate in a permanent outpost on Mars by the year 2020.

Needless to say, this mission will represent the most ambitious endeavour in human civilization. Like the Space Station Project, the Moon-Mars mission will require an international effort. To participate in this effort is to make a long-term commitment to science and technology and to take one's place at the vanguard of space exploration. Canada, like all other nations considering their role, must assess its own capabilities, establish its own mandate and chart its own course in this endeavour.

Background

The United States has formally begun the Moon-Mars Exploration Initiative (SEI) by establishing an independent Synthesis Group, chaired by former astronaut and retired Air Force Lt. General Thomas P. Stafford under the joint auspices of the White House and NASA, to establish the goals and assess the needs of the

Moon-Mars mission. From an American perspective, this mission can be seen as a natural extension of the U.S. space program building on the successes of Mercury through the Space Shuttle and now Space Station.

There are myriad challenges facing those prepared to embark on this odyssey. SEI will need to draw from numerous branches of science and technology, from martian geology to the behavioral sciences. The involvement of humans in the exploration will, in particular, require the development of new technologies such as regenerative life support systems, advanced cryogenic hydrogen-oxygen engines, resource utilization in situ, radiation protection and nuclear power systems.

Robotics and automation will be key to many of the required technologies. In fact, manned missions to Mars will be preceded by robotic missions. Robotic manipulators will be needed for the construction of spacecraft, likely to be done in Earth orbit. A high level of automation for systems operations will be imperative even for the manned missions. On the surface of the Moon and Mars, rovers or legged robots will be required as well as other robotic systems.

Canadian Perspective

Canada has been an active participant in the space program since the early 1970s. Space Station Freedom with the Mobile Servicing System with its remote manipulator systems is a direct extension of the development of Canadarm.

At the same time and as part of its Space Station Project, Canada has also solicited ideas from industry and academia through its Strategic Technologies in Automation and Robotics (STEAR) program in many other related areas including user development. STEAR has been very successful in fostering growth in the Canadian scientific and technological communities.

Canada recognizes that SEI is the important next step in space exploration and has accordingly, through the Canadian Space Agency, identified areas of potential involvement. Briefly, these areas are:

- Science
- Space Communications and Spacecraft Subsystems
- Planetology, Remote Sensing and Resources
- Robotics
- Life Sciences

- Biotechnology for Life Support
- Energy
- Building Sciences

The first phase of the Canadian SEI effort will be to conduct a survey of interest and feasibility in each of these areas. The goals of these surveys are:

- To establish level of interest, rationale and appropriate areas of participation;

- To identify potential projects and participants; and

- To establish compatibility with the U.S. SEI effort.

The results of these surveys will provide the basis for the formulation of the Long-Range Space Plan as well as for discussions with NASA.

The second phase will then be devoted to research and development on selected science and technology projects.

The survey in the area of robotics has been charged to Philip A. Lapp Limited.

Mission Profile

Several mission profiles to the Moon and Mars have already been proposed by NASA and U.S. aerospace corporations. The anticipated date of the first martian landing with crew varies from 1999 to 2006. The proposed size of the crew ranges from 4 to 15. All scenarios plan for a permanent outpost in the second decade of the next century. While SEI is expected to make use of Space Station and the Moon as waypoints to Mars, some scenarios forego completely the use of Space Station.

Robotic Needs

Robotics will be an integral part of any scenario. In addition to the use of robotics in the assembly of space systems in orbit, robotics will be needed on the Moon and Mars for:

- building
- mining
- processing
- exploration
- transportation
- rescue operations

Clearly, rover technology will also be vital to the mission. A substantial amount of attention has already been focused on robotics and rover technology for specific use on the Moon and Mars. A brief summary of the systems likely to be needed is given in Table 1.

This summary is intended to provide a skeletal overview of the robotic needs for the Moon-Mars mission. There are, of course, numerous issues to consider for each type of robotic or rover system. There may in addition be other types of systems that will be required. It should also be mentioned that there will be a need for automation other than that supplied by robots; for example, materials processing, which will be essential to the success of the mission, will require a good deal of nonrobotic automation. All these needs must be considered thoroughly.

Table 1 Robotic Systems and Rovers

Type	Size	Description
1. Platform Robot	Small-Medium-Large	For delicate assembly (Small); "Work horse" robot for precision operations (Medium); For large-motion maneuvers (Large); For use in orbital operations and surface operations (e.g., on rovers)
2. Dual-Arm Robot	Small-Medium	For unstructured tasks, e.g., maintenance, processing, laboratory experiments
3. Cherry Picker	Large	For assembly (building) maintenance, rescue operations
4. Autonomous Transport Robot	Medium	For inventory, parts handling, hazardous-materials handling, processing.

5. Planetary Rover	Various	For surface transportation, exploration, rescue operations
6. Insect Robot	Various	Mutilegged robot for surface transportation, exploration, rescue operations
7. Excavation Robot	Large	For site preparation, mining
8. Acquisition Robot	Small-Medium	For soil sampling, analysis

Note: Small implies < 1 m; Medium 1˜ 3 m; Large > 3 m.

Given Canada's international reputation in space manipulator systems, robotics as well as rover technology may be an appropriate area to concentrate Canadian SEI efforts. But this must by no means be the only area Canada should consider.

Concluding Remark

With the advent of the Moon-Mars Space Exploration Initiative, it is time for all potential participants in Canada to consider their role, and that of their country, in space. It is critical that Canada avail itself of this opportunity to remain at the forefront of space exploration. The advances to be made in science and technology will not only be limited to space; indeed, SEI is also intended to yield many tangible benefits in terrestrial spinoff applications.

Appendix 2
Information Guide

Moon-Mars Robotics
Information Guide

1. What is the nature of your capability in robotics.

2. What is the extent of your capability:

   - off the shelf
   - custom
   - notional

3. To what areas in SEI do you believe your capability can be applied.

4. Have you carried out any studies relating to your capability that would apply to SEI.

5. Would you be willing to share your capability with others in order to form a Canadian team.

6. What conditions would you place on membership in a team.

7. Are there specific areas where Canada could make a unified contribution, for example:

   - autonomous mining vehicle
   - assembly factory on space station
   - repair/rescue vehicle on Moon/Mars
   - habitat assembly

8. What should we concentrate on and why.

9. What is the timing and what are the implications for capability.

10. What are potential applications outside of Moon/Mars.

11. What are costs ex-launch.

Appendix 3
Persons Contacted

Dr. J.H.B. Anderson
Oerlikon Aerospace Inc.
225 Boul du Séminaire sud
Saint-Jean-sur-Richelieu
Québec
J3B 8E9
Bus:514 358 2000
FAX:514 358 1744

Dr. Clifford Baronet
National Research Council
Montreal Road
Ottawa, Ontario
K1A 0R6
Bus:613 993 9086

Mr. Hans W. Baumans
Centre de Recherche
Industrielle du Quebec
Boite Postale 2000
succurale Youville
Montreal, Québec
H4P 2X1
Bus:514 383 1550

Dr. Pierre Belanger
McGill University
Dean of Engineering
382-817 Sherbrooke Street West
Montréal, Québec
H3A 2K6
Bus:514 398 7251
FAX:514 283 7897

Mr. Duncan Bena
Sensor Adaptive Machines, Inc.
6360 Hawthorne Drive
Windsor, Ontario
N8T 1J9
Bus:519 944-6641

Mr. Jeff Berryman
B.C. Advanced Systems
Institute
3700 Gilmore Way
Burnaby, B.C.
Bus:604 435 0551

Mr. Bert Blevis
Canadian Astronautics Limited
1050 Morrison Drive
Ottawa, Ontario
K2H 8K7
Bus:613 820 8280
FAX:613 820 8341

Dr. Ron Boorman
N.B. Research & Productivity
Council
P.O. Box 6000
College Hill Road
Fredericton, N.B.
E3B 5H1
Bus:506 452 8994

Mr. Richard Boudreault
Oerlikon Aerospace Inc.
255 Boulevard du Séminaire
St.-Jean-sur Richelieu, Québec
J3B 8E9
Bus:514 358 2000
FAX:514 358 1744

Mr. Ken Bowring
Thompson CSF Systems Canada
18 Auriga
Nepean, Ontario
K2E 7T9
Bus:613 723 7000
FAX:613 723 5600

Mr. K. Carroll
Dynacon Enterprises Ltd.
200 - 5050 Dufferin Street
Downsview, Ontario
M3H 5T5
Bus:416 667 0505
FAX:416 667 0109

Mr. Dave Chamberlain
Dynacon Enterprises Ltd.
200 - 5050 Dufferin Street,
Downsview, Ontario
M3H 5T5
Bus:416 667 0505
FAX:416 667 0109

Dr. Ernest Chang
Alberta Research Council
Advanced Computing & Eng. Dept
3rd Floor
6815 - 8th Street
Calgary, Alberta
T2E 7H7
Bus:403 297 2671
FAX:403 275 3003

Mr. R.M.H. Cheng
Concordia University
Department of Mechanical
Engineering
1455 De Maisonneuve Blvd.W.
Montréal, Québec
H3G 1M8
Bus:514 484 3136
FAX:514 848 8782

Dr. Dale Cherchas
ENDEV Consulting Ltd.
4565 West 6th Ave.
Vancouver, B.C.
V6R 1V4
Bus:604 224 0869
FAX:604 224 8923

Mr. Steve Chumak
Vadeko International Inc.
2600 Argentia
Mississauga, Ontario
L5N 5V4
Bus:416 821 3222
FAX:416 821 2232

Dr. Paul Cohen
Ecole Polytechnique
Dept de genie electrique
Case Postale 6079,
Succursale "A"
Montréal, Québec
H3C 3A7
Bus:514 340 4549
FAX:514 340 4147

Dr. A.E. Collin
PRECARN Associates Ltd.
300-30 Colonnade Road
Ottawa, Ontario
K2E 7J6
Bus:613 727 9576
FAX:613 727 5672

Mr. Alan A. Desroches
Renssalaer Polytechnic
Institute
Center for Intelligent Robotic
Systems
Center for Industrial
Innovation
Suite 8015
Troy, N.Y.
12180-3590

Brig-Gen W.R. Dobson
DND Steering Group on Robotics
& AI
1175 Medoc Court
Orleans, Ontario
K1C 2S6
Bus:613 830 4098
FAX:613 830 9107

Dr. Karl K. Doetsch
Canadian Space Agency
Space Programs Office
Room 205
Building R-105
Montreal Road
Ottawa, Ontario
K1A 0R6
Bus:613 993 0137

Dr. Otto Forgas
MacMillan Bloedel Ltd.
12th Floor
1075 West Georgia Street
Vancouver, B.C.
V6E 3R9
Bus:604 661 8499

Mr. Lars Foyen
Det Norske Veritas Ltd.
1110-10201 Southport Road S.W.
Calgary, Alberta
T2W 4X9
Bus:403 253 3422
FAX:403 259 3452

Mr. Dan Friedmann
MacDonald Dettwiler &
Associates
13800 Commerce Parkway
Richmond, B.C.
V6B 2J3
Bus:604 278 3411

Dr. A. Goldenberg
University of Toronto
Dept of Mechanical Engineering
5 King's College Road
Toronto, Ontario
M5S 1A4
Bus:416 978 2011
FAX:416 978 7753

Mr. Ray Harpell
Softwords (Press Porcepic)
235 - 560 Johnson Street
Victoria, B.C.
V8W 3C6
Bus:604 727 6522
FAX:604 727 6418

Dr. J. Hollerbach
McGill University
Dept of Mechanical Engineering
817 Sherbrooke Street West
Montréal, Québec
H3A 2K6
Bus:514 398 8080
FAX:514 398 7461

Mr. T.E. Howard
B.C. Research
3650 Westbrook Mall
Vancouver, B.C.
V6S 2L2
Bus:604 224-4331

Dr. P. Hughes
Institute for Aerospace
Studies
University of Toronto
4925 Dufferin Street
Downsview, Ontario
M3H 5T6
Bus:416 667 7719
FAX:416 667 7799

Dr. Raymond Hui
University of Toronto
Department of Mechanical
Engineering
Robotics and Automation
Laboratory
5 King's College Road
Toronto, Ontario
M5S 1A4
Bus:416 978 5739
FAX:416 978 5745

Dr. I. Hunter
McGill University
Dept of Biomedical Engineering
3775 University Street
Montréal, Québec
H3A 2B4
Bus:514 398 6740
FAX:514 398 7461

Dr. David Hunter
Canadian Space Agency
National Research Council
Building R-105
Montreal Road
Ottawa, Ontario
K1A 0R6
Bus:613 998 6902

Mr. Robert B. Isaac
Robert I. Robotics Inc.
958 Leathorne St., Suite 5
London, Ontario
N5Z 3M5
Bus:519 686 1003

Dr. Michael A. Jenkins
University of Toronto
Information Technology Res. Centre
D. L. Pratt Building
Room 286
6 King's College Road
Toronto, Ontario
M5R 1A1
Bus:416 978 7204
FAX:416 978 7207

Dr. Serdar Kalaycioglu
Thompson CSF Systems Canada
18 Auriga
Nepean, Ontario
K2E 7T9
Bus:613 723 7000
FAX:613 723 5600

Mr. Tom King
VIRTEK Inc.
450 Phillip Street
Waterloo, Ontario
N2L 5J2
Bus:519 746 7190
FAX:519 746 3383

Mr. Normand Lassonde
Geyser Informatiques Inc.
507 Place d'Armes, Suite 1701
Montréal, Québec
H.Y 2W8
Bus:514 842 5719
FAX:514 285 1138

Mr. Peter Lawrence
Industry Science & Technology Canada
Space Research and Technology Branch
240 Sparks Street
Ottawa, Ontario
K1P 6C9
Bus:613 954 3182

Dr. P.D. Lawrence
University of British Columbia
Dept of Electrical Engineering
Vancouver, B.C.
V6T 1W5
Bus:604 228-5934
FAX:614 228 5949

Dr. Martin D. Levine
McGill University
Dept of Electrical Engineering
3480 University Street
Montréal, Québec
H3A 2A7
Bus:514 398 7115
FAX:514 398 4470

Mr. Jim MacFarlane
International Submarine Eng. Ltd.
2601 Murray Street
Fort Moody, B.C.
V3H 1X1
Bus:604 942 5223
FAX:604 942 7577

Dr. A. Mackworth
University of British Columbia
Dept of Computer Science
2356 Main Mall
Vancouver, B.C.
V6T 1W5
Bus:604 228 4893
FAX:604 228 5485

Mr. Gord Mallory
Spectrum Engineering
Corporation Ltd.
P.O. Box 687
544 McDonnell Street
Peterborough, Ontario
K9J 6X8
Bus:705 743 7520
FAX:705 743 9878

Mr. Pierre Maltais
Canadian Space Agency
Building R-105
National Research Council
Montreal Road
Ottawa, Ontario
K1A 0R6
Bus:613 993 7419
FAX:613 954 2272

M. Pierre Marcotte
Robotics Centre
205 Mgr. Bourget
Levis-Lauzon, Quebec
G6V 6Z9
Bus:418 833 1965
FAX:418 833 4254

Dr. G.F. Marsters
Institute for Aerospace
Research
National Research Council
Montreal Road, Ottawa
K1A 0R6
Bus:613 993 0141
FAX:613 952 7214

Dr. V.J. Modi
University of British Columbia
Dept of Mechanical Engineering
Vancouver, B.C.
V6T 1W5
Bus:604 228 2914
FAX:604 228 2403

Mr. Maher Nessein
Canadian for Frontier Eng.
Research
200 Karl Clark Road
Edmonton, Alberta
T6N 1E2
Bus:403 450 3300
FAX:403 450 3700

Mr. Joe Liadsky, M.Sc., P.Eng.
Optech Inc.
701 Petrolia Road
Downsview, Ontario
M3J 2N6
Bus:416 661 5904
FAX:613 661 4168

Mr. Anthony J. Bosik, P.Eng.
Bosik Consultants Ltd.
Box 613
5460 Old Mill Way
Manotick, Ontario
K0A 2N0
Bus:613 692 4589
FAX:613 692 0871

Mr. S. A. Mayman, P.Eng.
National Research Council
Institute for Information
Technology
Montreal Road
Ottawa, Ontario
K1A 0R6
Bus:613 993 9010
FAX:613 952 7998

Mr. Eric Jackson, P.Eng.
International Submarine Eng. Ltd.
2601 Murray Street
Port Moody, B.C.
V3H 1X1
Bus:604 942 5223
FAX:604 942 7577

Mr. Forrest Livingston, P.Eng.
Hymarc Ltd.
38 Auriga
Nepean, Ontario
K2E 8A5
Bus:613 727 0441
FAX:613 727 1584

Mr. Tom Mitchell, P.Eng.
International Telepresence Corp.
655 West 7th Avenue
Vancouver, B.C.
V5Z 1B6
Bus:604 873 3300
FAX:604 275 2233

Mr. Joe Ploeg
National Research Council
Institute for Mechanical Engineering
Montreal Road
Ottawa, Ontario
K1A 0R6
Bus:613 993 2424

Dr. Ross Pottie
National Research Council
Montreal Road
Ottawa, Ontario
K1A 0R6
Bus:613 993 9245

Mr. Graham Smith, President
Focal Technologies Inc.
40 Thornhill Drive, Unit 7
Dartmouth, Nova Scotia
B3B 1S1
Bus:902 468 2263
FAX:902 468 2249

Dr. Timothy Pryor
Sensor Adaptive Machines Inc.
6360 Hawthorne Drive
Windsor, Ontario
N8T 1J9
Bus:519 944 6641

Mr. Ken Pulfer
Ass'n of Provincial Res. Orgs.
801 - 275 Slater Street
Ottawa, Ontario
K1P 5H9
Bus:613 567 2993
FAX:613 236 3754

Dr. Ian Rowe
SPAR Aerospace Limited
1700 Ormont Drive
Weston, Ontario
M9L 2W7
Bus:416 856 4552
FAX:416 856 4624

Mr. Brent J. Sauder
Macmillan Bloedel Ltd.
4225 Kincaid Street
Burnaby, B.C.
Bus:604 439 8667

Mr. Brian A. Schaefer
Acquired Intelligence Inc.
204 - 1095 MacKenzie Ave.
Victoria, B.C.
V8P 2L5
Bus:604 383 8935
FAX:604 383 2835

Dr. G.S.W. Sincarcin
Dynacon Enterprises Ltd.
5050 Dufferin Street
Suite 200
Downsview, Ontario
M3H 5T5
Bus:416 667 0505
FAX:416 667 0109

Mr. Brigit Smejkal
Canadian Instrumentation &
Research Ltd.
5035 North Service Road
Unit B7/8
Burlington, Ontario
L7L 5V2
Bus:416 332 1353
FAX:416 332 1808

Dr. Y. Stepanenko
University of Victoria
Faculty of Engineering
P.O. Box 1700
Victoria, B.C.
V8W 2Y2
Bus:604 721 8612
FAX:604 721 8676

Dr. Steve Stober
CAE Electronics
8585 Côte de Liesse
St. Laurent
Montreal, Québec
H4T 1G6
Bus:514 340 5392

Mr. Richard Swann
MacDonald Dettwiler &
Associates
13800 Commerce Park Way
Richmond, B.C.
V6V 2J3
Bus:604 278 3411

Mr. Tom Sweeney
Oerlikon Aerospace Inc.
225 Boul. du Seminaire sud
Saint-Jean-sur-Richelieu
Quebec
J3B 8E9
Bus:514 358 2000
FAX:514 358 1744

Dr. R.C. Tennyson
Institute for Aerospace
Studies
University of Toronto
4925 Dufferin Street
Downsview, Ontario
M3H 5T6
Bus:416 667 7717
FAX:416 667 7799

Mr. Christian Tremblay
ENCORE Computer Limited
310 - 1410 Blair Place
Gloucester, Ontario
K1J 9D9
Bus:613 5650

Dr. J. Tsotsos
University of Toronto
Dept of Computer Science
10 King's College Road
Toronto, Ontario
M5S 1A4
Bus:416 978 3619
FAX:416 978 1455

Mr. Gabby Weintraub
CAE Electronics
8585 Côte de Liesse
St. Laurent
Montréal, Québec
H4T 1G6
Bus:514 341 6780

Mr. W.C. Weston
Aerospace Industries Ass'n of
Canada
1200-60 Queen Street
Ottawa, Ontario
K1P 5Y7
Bus:613 232 4297

Mr. Graham Whitehead
Vadeko International Inc.
2600 Argentia Road
Mississauga, Ontario
L5N 5V4
Bus:416 821 3222
FAX:416 821 2232

Mr. Jack Wilson
Robotics Systems International
Ltd.
9865 West Saanich Road
Sidney, B.C.
V8L 3S1
Bus:604 656 1700
FAX:604 656 1161

Prof. Andrew Wong
VIRTEK Inc.
86 - 450 Phillip Street
Waterloo, Ontario
N2L 5C2
Bus:519 746 7190
FAX:519 746 3383

Appendix 4

Evaluation Summary

Evaluation Summary

Mission Title: Excavation/Mining Vehicle

Description: System - vehicle or drag line - for mining resources from lunar regolith to support manned outposts and habitats.

Criterion	Comments	Rank
1. Canadian Capability	Canadian industry is moving toward autonomous mining in terrestrial situations. Some estimates predict this will be available by the turn of the century. Translation to the lunar conditions would be a logical extension.	high
2. Terrestrial Links	Fits with existing forecast of Canadian advances in terrestrial technology, particularly with respect to drag lines. Canada does not possess terrain vehicle design capability.	high
3. Autonomous Project	While others will probably also engage in mining operations on the Moon, this is an activity Canada could undertake autonomously.	high
4. National Identity	Canada is a resource-based country and mining has been an integral part of our economy for many years.	high
5. Acceptability	Will probably not be seen as competition with SEI partners, but utilization of mined resources will have to be negotiated with a user.	med
6. Desirable Technology	Autonomous mining will require development of technologies that should find application on Earth.	med

Evaluation Summary

Mission Title: Servicing/Repair Vehicle

Description: A vehicle or depot for servicing and repair of rovers or other installations.

Criterion	Comments	Rank
1. Canadian Capability	While Canada has robotic capability as a result of Space Station involvement, there is no indigenous vehicle design capability.	low
2. Terrestrial Links	Some links with underwater developments in the service area.	med
3. Autonomous Project	Canada could provide an autonomous vehicle or facility but would have to arrange for customers.	med
4. National Identity	Apart from MSS, Canada is not identified as a country with exceptional capability in servicing.	low
5. Acceptability	Will probably not be acceptable as the sole service facility. There have to be negotiations with potential users to be sure a Canadian facility would be used.	low
6. Desirable Technology	Servicing involves technologies that build on our Space Station contributions and therefore should be applicable to terrestrial situation.	med

Evaluation Summary

Mission Title: Geophysical/Geological Survey Vehicle

Description: A vehicle equipped to carry out electromagnetic, radiometric, gravity surveys, and to record the locations at which measurements have been taken. It is also equipped to collect geological samples, store them, possibly perform analyses.

Criterion	Comments	Rank
1. Canadian Capability	Canada has knowledge required to design and develop instrumentation to perform the surveys. Automated analysis would probably have to be developed.	high
2. Terrestrial Links	Automated surveying fits well with Canadian experience with similar activities terrestrially.	high
3. Autonomous Project	Unlikely Canada could provide the vehicle to carry instrumentation. There is no capability to design and develop terrain vehicles. We would need a partner.	low
4. National Identity	Canada is identified as a country with extensive capability in developing instrumentation for terrestrial exploration, and in carrying out geophysical and geological surveys. Lack of capability to develop a vehicle is a drawback.	med
5. Acceptability	Other countries will develop means of carrying out similar surveys. Subject to agreements on who has what rights to survey what territories Canada's engagement in these activities should be acceptable.	med
6. Desirable Technology	Geophysical/geophysical surveying is not likely to require development of the most desirable robotic technologies.	low

Evaluation Summary

Mission Title: Rescue Vehicle

Description: A vehicle equipped to collect vehicles, instruments that must be returned to a central facility for repair. In the longer time frame, humans may have to be rescued from life-threatening situations.

Criterion	Comments	Rank
1. Canadian Capability	Canada has the capability to undertake terrestrial rescue operations, but this capability is not easily translated to the lunar environment.	low
2. Terrestrial Links	Very few links with terrestrial rescue technologies.	low
3. Autonomous Project	Canada could not provide all components of a rescue vehicle.	low
4. National Identity	Canada has not special recognition for rescue capability.	med
5. Acceptability	SEI partners would not accept Canada as the sole provider of rescue facilities.	low
6. Desirable Technology	A rescue vehicle would have requirements for some desirable technologies, such as advanced arms with collision avoidance control.	med

Evaluation Summary

Mission Title: Extraction/Processing Plant

Description: A pilot plant capable of accepting material mined from the lunar surface and carrying out subsequent processing and extraction to obtain the desired end products such as oxygen, helium, etc.

Criterion	Comments	Rank
1. Canadian Capability	Canadian industry is moving toward automated processing and extraction in terrestrial applications. Canada probably has at least as much capability in these technologies as any country.	high
2. Terrestrial Links	Very closely allied with Canadian terrestrial capability.	high
3. Autonomous Project	Other countries will provide their own processing and facilities. Canada would have to be sure there would be customers for its own facilities.	med
4. National Identity	Canada is identified as a resource-based country with capability in mineral processing and extraction.	high
5. Acceptability	Canada would be accepted by partners as a provider of processing and extraction, but with the caveat that there must be a customer.	med
6. Desirable Technology	The technologies involved in processing and extraction will make use of very few desirable robotic technologies.	low

Evaluation Summary

Mission Title: Laboratory Science Facility

Description: An expandable facility for carrying out scientific investigations. These could include astronomy, biological studies, and investigations relating to resource evaluations.

Criterion	Comments	Rank
1. Canadian Capability	Canada has no special capability in developing science facilities, although there is expertise in developing associated instrumentation.	med
2. Terrestrial Links	Definite links with capability and interest in astronomy. Other areas of science may not have the same stature.	med
3. Autonomous Project	Canada could provide one semi-autonomous project within such facilities.	med
4. National Identity	Canada has an international reputation in astronomy and upper atmosphere physics.	low
5. Acceptability	Canadian contribution of one component of a science facility would be acceptable.	med
6. Desirable Technology	Little use of desirable robotic technologies.	low

Evaluation Summary

Mission Title: Assembly Factory

Description: An assembly facility located on Space Station or the Moon, capable of taking individual components or subsystems and constructing the end product.

Criterion	Comments	Rank
1. Canadian Capability	Canada has robotic capability to undertake the necessary tasks if they are to be performed on Space Station. This builds on MSS capability.	high
2. Terrestrial Links	More linkages with Canada's involvement in Space Station.	med
3. Autonomous Project	Unlikely Canada could provide full service facilities for assembly. Some participation by one or more partners would be required, use of Space Station for example.	med
4. National Identity	Canada has a modest reputation in space technology.	low
5. Acceptability	It is doubtful if major partners would permit Canada to become the sole provider of assembly facilities.	low
6. Desirable Technology	Makes use of the same desirable technologies as does MSS.	high

Evaluation Summary

Mission Title: Habitat Construction

Description: Construction of a lunar habitat, making use of local resources, to provide shielding against radiation for solar flares and cosmic sources.

Criterion	Comments	Rank
1. Canadian Capability	Construction will require removal of materials from the surface and developing techniques for using lunar materials as a base for fabricating components for habitat construction.	med
2. Terrestrial Links	No special links with Canadian construction activities.	low
3. Autonomous Project	Would probably be too large a project for Canada to undertake alone.	low
4. National Identity	No special association with Canadian terrestrial capability.	low
5. Acceptability	It is doubtful if major partners would permit Canada to become the sole provider of habitats.	low
6. Desirable Technology	Makes use of some desirable technologies such as robotic capability developed for MSS.	med