Canadian Space Agency Agence spatiale canadienne

# Evaluation of the Canadian Space Agency's International Space Station Assembly and Maintenance Operations Program

For the period from March 2008 to March 2015

**Project # 14/15 – 02-01**

Prepared by the Audit and Evaluation Directorate

**February 2016**

Canada

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# Acronyms Used in the Report

| | |
|---|---|
| ARLU | Annual Reference Level Update |
| AVU | Artificial Vision Unit |
| BISE | Bodies in Space Experiment |
| CASIS | Centre for Advancement of Science in Space |
| CELTS | Conscious Emotional Learning Tutoring |
| CIGITI | Centre for Image-Guided Innovation and Therapeutic Intervention |
| CoFR | Certification of Flight Readiness |
| CSA | Canadian Space Agency |
| CSii | Centre for Surgical Invention and Innovation |
| CSOC | Common Systems Operating Costs |
| CSSP | Canadian Space Station Program |
| DARPA | Defense Advanced Research Projects Agency |
| DG | Director General |
| ECG | Evaluation Consultative Group |
| ELC | Express Logistics Carrier |
| EBP | Employee Benefit Plan |
| ESA | European Space Agency |
| ESL | Engineering Support Lead |
| EVA | Extravehicular Activity |
| EVR | Extravehicular Robotics |
| FAA | Financial Administration Act |
| FPL | Flight Planning Lead |
| FTE | Full-time Equivalent |
| HEOMD | Human Exploration & Operations Mission Directorate (NASA) |
| HQP | Highly Qualified Personnel |
| HTV2 | H-II Transfer Vehicle |
| IGA | Intergovernmental Agreement |
| IMC | Increment Management Center |
| IP | Intellectual Property |
| ISED | Innovation, Science and Economic Development |
| ISECG | International Space Exploration Coordination Group |
| ISS | International Space Station |
| JAXA | Japanese Aerospace Exploration Agency |
| LEO | Low Earth-Orbit |
| L&SE | Logistics & Sustaining Engineering |
| MBS | Mobile Base System |
| MCB | Multilateral Coordination Board |

| | |
|---|---|
| MDA | MacDonald, Dettwiler and Associates Ltd |
| MER | Mission Evaluation Room |
| MIEMS | Minimally-Invasive Endoscopic Manipulator System |
| MOC | Mission Operations Centre |
| MOU | Memorandum of Understanding |
| MRI | Magnetic Resonance Imaging |
| MSEF | MSS Sustaining Engineering Facility |
| MSS | Mobile Servicing System |
| NASA | National Aeronautics and Space Agency |
| NGC | Next-Generation Canadarm |
| NRC | National Research Council |
| OCS | Operations Control Software |
| OEC | Operations Engineering Centre |
| OECD | Organisation for Economic Co-operation Development |
| OGDs | Other Government Departments |
| OIP | Operations and Implementation Plan |
| O&M | Operations and Maintenance |
| ORU | Orbit Replacement Unit |
| PAA | Program Alignment Architecture |
| PSPC | Public Services and Procurement Canada |
| R-MPSR | Remote Multi-Purpose Support Room |
| R&D | Research and Development |
| RPCM | Remote Power Control Module |
| RWS | Robotic Workstation |
| S&T | Science and Technology |
| SEMC | Space Exploration Management Committee |
| SIS | Space Infrastructure Servicing |
| SPDM | Special Purpose Dexterous Manipulator |
| SP | Sub-Program |
| SSP | Sub-Sub-Program |
| SSRMS | Space Station Remote Manipulator System |
| SST | Space Science and Technology |
| STDP | Space Technology Development Program |
| SVS | Space Vision System |
| TB | Treasury Board |

# Executive Summary

## Background

This report presents the findings of the Evaluation of the Canadian Space Agency (CSA)'s International Space Station (ISS) Assembly and Maintenance Operations Sub-Sub Program (SSP). The evaluation was conducted between December 2014 and February 2016, covering the time period from March 2008 to March 2015.

The Space Station Program began in 1984 as a result of an invitation to "friends and allies" (G7 economies) by then United States (US) President Reagan to contribute to the on-orbit facility. The original partners were the US (lead), Canada, Europe (represented by the European Space Agency (ESA)) and Japan. In 1985 the Government of Canada confirmed its participation in the program and the original Intergovernmental Agreement (IGA) was signed in 1988. An updated IGA was signed in 1998 and included Russia.

Canada's contribution to the ISS is the Mobile Servicing System (MSS). The MSS's main elements are: the Space Station Remote Manipulator System (SSRMS) or the second-generation Canadarm2, a large manipulator arm, launched in 2001; a Mobile Base System (MBS) that transports the Canadian robots and ISS payloads along the length of the station's main truss, launched in 2002; and, the Special Purpose Dexterous Manipulator (SPDM) or Dextre, a two-armed dexterous robot, launched in March 2008. The Artificial Vision Units (AVUs) and Operations Control Software (OCS) were also provided to support on-orbit crew operations of the MSS via the National Aeronautics and Space Agency (NASA)'s Robotic Workstation (RWS), which also falls under the sustaining engineering support responsibilities of the CSA. The MSS is supported by operations and training facilities located at the CSA's headquarters in Saint-Hubert, Quebec, and by an MSS Sustaining Engineering Facility (MSEF) operated by MacDonald, Dettwiler and Associates Ltd (MDA, the prime contractor) in Brampton, Ontario.

In accordance with the provisions of the NASA/CSA Memoranda of Understanding (MOU), Canada is obligated to:

- support the operations of the MSS;
- provide MSS training to crew and ground support personnel;
- develop and implement procedures for operating the MSS in a safe, efficient and effective manner;
- provide logistics and sustaining engineering for each Canadian element throughout the life cycle of the ISS; and
- provide required spares and to repair MSS hardware that fails on orbit.

In return for its contribution of the MSS and for fulfilling its obligations, Canada has the right to utilize 2.3% of the ISS user accommodations for research activities, and 2.3% of the on-orbit crew time to operate them. Canada also has the right to provide Canadian astronauts for 2.3% of the ISS crew flight opportunities.

In addition to its obligations, Canada is required to compensate NASA for 2.3% of the ISS Common Systems Operating Costs (CSOCs). These are the costs attributed to the operation of the ISS as a whole, for which all partners must pay their respective share. The partners have agreed to "minimize the exchange of funds" by providing goods and services in-kind, i.e. barters, to offset their common cost obligations. To date, all cooperating agencies have offset their CSOC obligations through such barters.

The ISS Assembly and Maintenance Operations SSP is an ongoing activity and is funded through the CSA A-base. The MSS Operations budget is managed through the existing CSA financial structure in accordance with all applicable *Financial Administration Act* (FAA) policies. Budgets are decentralized to the managers responsible for the delivery of specific activities. The total budget for the ISS Assembly and Maintenance Operations SSP between 2008-09 and 2014-15 was $323.6 million, while expenditures were $330.6 million.

The scope of the ISS Assembly and Maintenance Operations SSP is the operation and maintenance of the MSS. It is important to note that the evaluation excludes the **ISS Utilization SSP** and the **Human Space Missions Support Sub-Program** (SP). These two components are scheduled to be evaluated later in fiscal year 2016-17.

The ISS Utilization SSP encompasses the implementation of scientific, operational, medical and technological studies in specific areas, such as life sciences, radiation, material or fluid sciences, to be conducted aboard the ISS by Government of Canada organizations, academia or the private sector.

The Human Space Missions Support SP encompasses all activities required to recruit, develop, train and maintain a healthy and highly-qualified Canadian astronaut corps capable of participating in space exploration missions. It also includes all activities directed at mitigating health risks associated with those missions, such as the development of advanced technologies to be used in support of human space missions.

## Approach and Methods

The evaluation team worked closely with an internal Evaluation Consultative Group (ECG), whose members included representatives of the ISS Assembly and Maintenance Operations SSP and the Audit and Evaluation Directorate.

Data sources for the evaluation included: a review of documentation; interviews with 25 interviewees internal and external to the CSA; a follow-up survey seeking quantitative data from the prime contractor (MDA Brampton); and three case studies of technologies that have evolved from the ISS Assembly and Maintenance Operations SSP (NeuroArm, IGAR and KidsArm).

# Conclusions and Recommendations

## Relevance/Need

**Continued Need for the Program**

Canada's involvement in human spaceflight is seen as a positive decision for a whole host of political, scientific, innovation and economic reasons. Canadian astronauts in space have inspired the nation, motivating young would-be scientists and engineers for generations to come.

Canada's decision to participate in the ISS Program represented a logical step in the evolution of a longstanding working relationship between Canada and NASA which dates as far back as 1969 when Canada was invited by NASA to participate in the Space Shuttle Program.

The evaluation found evidence that the decision to participate in the ISS Program was largely motivated by geopolitical concerns. At the time, the US was intent on building a space station with participation from its western allies as a response to the Soviet's Mir space station which was launched in 1986. Canada's invitation to participate was based on its strong track record in supporting the Space Shuttle Program together with Canada's unique expertise in space robotics – a capability that the US did not possess at the time.

Although the decision to extend Canada's participation in the ISS Program to 2024 is viewed by interviewees as a sound one, and endorses Canada's continued involvement in international human spaceflight activities into the future, it does have budgetary implications for the CSA. As the ISS ages, repairs and the need for replacement parts will become increasingly necessary. There was a sense among many individuals interviewed for this evaluation that the ISS could remain operational beyond 2024 and this was viewed positively because it will increase the potential utilization of the ISS for scientific purposes.

Canada's continued participation in the ISS Program will permit increased utilization and will provide Canada with the opportunity to participate in the dialogue about the next steps beyond the ISS, maintaining Canada's involvement in human space flight. This latter point with regard to participating in discussions on what could follow the ISS Program exemplifies the stature that Canada has acquired and enhanced through its participation in the ISS.

The ISS Program continues to provide opportunities for engagement with international partners with like-minded objectives for the peaceful uses of outer space despite conflicts or other geopolitically difficult situations existing on Earth.

**Alignment with Federal Priorities and Roles and Responsibilities**

Based on a review of documentation and the key informant interviews, there is strong evidence that Canada's continued participation in the ISS Program is well aligned with current federal priorities. These priorities are reflected in such documents as *Canada's Space Policy Framework*[1], the *Science, Technology and Innovation Strategy*, and *Budget 2015* which announced the extension of Canada's participation in the ISS Program to 2024. Although very recent and thus outside of the evaluation period, Canada's continued participation in the ISS Program also aligns with the Government of Canada's focus on innovation and science as stated in the recent *Speech from the Throne* (December 2015).[2]

The evaluation found that managing the Canadian portion of the ISS Program is an appropriate role for the federal government as it is an international agreement that can only be signed and managed by the Government of Canada. Furthermore, the evaluation findings indicate that the CSA's responsibility for the program is consistent with its authority under the *CSA Act*, which states that the Agency is authorized "to cooperate with the space and space-related agencies of other countries in the peaceful use of space."

## Achievement of Outcomes

### Immediate Outcomes

**Opportunities for Human Space Flight and ISS Utilization**

Although the ISS Assembly and Maintenance Operations SSP does not have direct influence over availability of opportunities for human space flight or for ISS utilization, the program does directly enable the achievement of these objectives. Evaluation findings indicate that Canada has realized opportunities for human space flight and for utilization which would not be available in the absence of the ISS Program. The ISS Program represents Canada's only opportunity for human space flight, having had six Canadian astronauts visit the ISS.

**Canada's Leadership Role in Space Robotics**

Canada was invited to participate in the ISS Program because of its leadership in space robotics. Participation in the ISS Assembly and Maintenance Operations SSP has served to cement this leadership role; however Canada's leadership in space robotics cannot be taken for granted since other countries are also developing their space robotics capacity. Participation in the ISS Assembly and Maintenance Operations SSP has led to many innovations in Canada's space robotics capacity, the most important of which has been ground control of Dextre and Canadarm2. Canada's leadership in space robotics has

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[1] Canadian Space Agency. (2014). *Canada's Space Policy Framework: Launching the Next Generation*. Retrieved July 20, 2015 from http://www.asc-csa.gc.ca/eng/publications/space-policy/default.asp

[2] Government of Canada. (2015). Making Real Change Happen. *Speech from the Throne to Open the First Session of the Forty-second Parliament of Canada*. December 4, 2015. Accessed on December 17, 2015 at http://speech.gc.ca/en/content/making-real-change-happen

engendered invitations to participate in other missions; however Canada's ability to participate in these other missions has been limited by the availability of funds within the CSA. There is a general sense among interviewees that Canada's leadership role in space robotics is "ours to lose" without ongoing federal government financial support.

**Recommendation 1: The CSA should assess the importance of maintaining Canada's leadership role in space robotics and the measures to be taken if Canada is to maintain a leadership position in space robotics.**

**Canada's Reputation Among Partners**

Evidence from key informant interviews and documentation indicates that Canada's reputation among international partners has been maintained or even enhanced as a result of the innovative solutions for the repair or maintenance of the ISS developed by the Assembly and Maintenance Operations SSP. Although Canada's contribution amounts to only 2.3% of the ISS Program, Canada is seen by its partners as having more influence internationally than its size would suggest.

**Space Sector Capability and HQPs**

There is evidence from interviews and program performance data that the ISS Assembly and Maintenance Operations SSP has directly contributed to employment of highly qualified personnel (HQPs[3]) in Canada over the time period covered by the evaluation. In addition to employment, the SSP has also contributed to the training of HQPs, including astronauts and ground personnel (including Canadian and international).

There is some evidence from interviews with CSA representatives that those working on the ISS Assembly and Maintenance Operations SSP within the CSA believe that their career potential is limited as a result of a lack of other large scale missions within the CSA and in Canada. Career advancement may also be somewhat limited due to the relatively small team within the CSA. There is also some indication from interviews with CSA representatives that Canada may be losing HQPs to the US. We note this is based on only a limited number of interviews and may not be representative of the views of all CSA employees within this SSP.

**Public Awareness of ISS Technology**

The ISS Assembly and Maintenance Operations SSP is not responsible for public awareness of ISS technology – this is the direct responsibility of the CSA Communications and Public Affairs Directorate. Based on statistics provided by the directorate and on the key informant interviews, there is evidence that Canadians are being informed of ISS technology in general through a variety of means, including videos, online information, press releases, public events, etc. The CSA has developed educational tools

[3] HQPs is defined by the CSA, and this evaluation, as scientists, engineers and technicians.

and kits directed at youth for the past three missions involving Canadian astronauts (Thirsk, Payette and Hadfield).

## Intermediate Outcomes

**Transfer of Know-how from the ISS**

Evidence from the interviews, reviews of documentation and case studies undertaken for this evaluation provides strong indication that know-how is being transferred from the ISS Assembly and Maintenance Operations SSP to non-space uses. The evidence, particularly from the three case studies, indicates that the transfer of know-how is a long process, requiring many years (possibly decades) and substantial financial investment. Although the transfer of know-how is occurring, some interviewees believe that Canada is not doing enough to fully reap the benefits of the space robotics technologies developed for the ISS Assembly and Maintenance Operations SSP. However, the CSA is limited in its ability to directly facilitate commercialization of the technologies because the prime contractor has the sole licence for commercialization of the ISS technologies it has developed.

**Recommendation 2: The CSA should assess options for increasing the commercialization and transfer of technologies from the ISS Program to other areas. Discussions should be held with other federal departments and agencies involved as well as with the prime contractor. This assessment should consider best practices and lessons learned from other ISS Program partners, particularly NASA.**

**Industrial Leveraging of ISS Experience**

There is evidence that the prime contractor has been able to leverage its experience on the ISS Assembly and Maintenance Operations SSP to obtain contracts in the space sector both nationally and internationally. MDA has been able to build on relationships developed through its work on the ISS Assembly and Maintenance Operations SSP. In terms of the technologies and products developed as a result of its work in support of the ISS Assembly and Maintenance SSP, MDA reported that it has obtained some revenue from the sale of grapple fixtures to other space agencies and companies. However, MDA reports that there have been no revenues from new products, services or processes although numerous patents have been registered.

**Broadened Space Stakeholder Base**

There is evidence from research reviewed for this evaluation that the inspirational aspects of space exploration contribute, over the long term, to increasing interest in science and technology among youth and the general public. Inspiring youth contributes, over the long term, to an increased proportion of young people pursuing careers in the sciences and engineering. The inspirational element of the ISS Program has been recognized in *Canada's Space Policy Framework*.

### Ultimate Outcome

**Contribution to Social and Economic Growth**

There is evidence that the ISS Assembly and Maintenance Operations SSP has and will continue to contribute to social and economic growth. The linkage between space exploration and social and economic benefits is recognized in the literature on the subject; however attempts to quantify these benefits tend to be unsuccessful because of their long-term nature and the often indirect linkages between space technologies and the ultimate benefits.

### Unexpected Outcomes

The key unexpected outcome stemming from the ISS Program in general (i.e., not specific to the Assembly and Maintenance Operations SSP) is the extent of the international cooperation engendered. The ISS Program has, over the years, overcome political and economic challenges, most notably recent strains to the international community's relationship with Russia. It is notable that despite geopolitical tensions with Russia, cooperation on the ISS has continued, thus keeping lines of communication open between Russia and the international community.

Another unexpected outcome, this one specific to the ISS Assembly and Maintenance Operations SSP, is the visibility of Canadarm2 and Dextre in Canadian and international media.

## Efficiency and Economy

Based on available evidence, the evaluation found that the SSP is being delivered as efficiently as possible. Overall, the SSP has slowly become more efficient over the time period covered by the evaluation because of increased automation and because of the experience/practice of the combined government/contractor program team. Attempts to increase efficiency further through targeted decreases of staff levels may result in an increased risk to the program. Further erosion in staffing levels may also eliminate existing functional redundancy and put the program at risk. No viable options for increasing efficiency of the SSP were identified by the evaluation. The contract with the prime contractor is very tightly managed, as is appropriate for a contract of this size and duration, and profit is monitored and limited as per the contract clauses, thus providing good value to Canadians.

The SSP does not have a risk reserve and based on evaluation findings, there is no clear need to put one in place. The CSA's approach to managing program risks is through reallocating resources internally within the CSA. This process works well because the nature of space projects is such that delays are frequent and thus being able to reallocate resources internally minimizes the lapsing of funds.

## Program Delivery

The evaluation found no evidence of a lack of clarity in the roles and responsibilities of ISS Program partners nor in the roles and responsibilities within the CSA.

The ISS Intergovernmental Agreement (IGA) and MOU documents[4] spell out roles, duties and commitments and responsibilities for the partnership. In addition, the CSA's Operations Implementation Plan provides a detailed program level description of the management structure, organizational responsibilities and key processes that have been put in place by the CSA to meet its ISS MSS obligations.[5]

[4] *Memorandum of Understanding between the Canadian Space Agency and the National Aeronautics and Space Administration of the United States of America Concerning Cooperation on the Civil International Space Station*. CSA, NASA (January 28, 1998).
[5] Canadian Space Agency. (2012). *Canadian Space Station Program Operations Implementation Plan - MSS-Operations*. Revision B (March 14, 2012). (CSA number: CSA-SS-PL-0195)

# 1 Introduction

This report presents the findings of the Evaluation of the Canadian Space Agency (CSA)'s International Space Station (ISS) Assembly and Maintenance Operations Sub-Sub Program (SSP). The evaluation was conducted on behalf of the CSA Audit and Evaluation Directorate by Kelly Sears Consulting Group in collaboration with Beechwood Consulting and Research Inc., BBMD Consulting Inc., and Hickling Arthurs Low Corp. between December 2014 and February 2016. The evaluation is a requirement of the CSA five-year evaluation plan and was conducted in accordance with the Treasury Board (TB)'s *Policy on Evaluation* (2009) requiring that all federal programs be evaluated every five years.

# 2 Background

This chapter provides a brief profile of the ISS Assembly and Maintenance Operations SSP of the CSA.

## 2.1 Overview

### 2.1.1 History and Context

The Space Station Program began in 1984 as a result of an invitation to "friends and allies" (G7 economies) by then United States (US) President Reagan to contribute to the on-orbit facility. The original partners were the US (lead), Canada, Europe (represented by the European Space Agency (ESA)) and Japan. In 1985 the Government of Canada confirmed its participation in the program and the original Intergovernmental Agreement (IGA) was signed in 1988.

In 1994 with the end of the Cold War, the original partners invited Russia to join the program, a US President Clinton initiative. This established the ISS Program and Canada in 1998 signed the updated IGA between the governments of the US, Canada, Russia, ESA Member States, and Japan concerning the Cooperation on the Civil International Space Station. Under the IGA there are four bilateral Memoranda of Understanding (MOU), between the National Aeronautics and Space Agency (NASA) and the "Cooperating Agencies" - Canada, Japan, Europe and Russia. An Act of Parliament, the *Civil International Space Station Implementation Act,* to implement the IGA was approved and signed in 1999.

The ISS is an orbiting research laboratory. The first module of the ISS was launched in 1998 and since then, orbits the Earth 16 times per day. The ISS has been permanently manned since November 2000.

As a full partner of the ISS Program, Canada shares in the responsibility of managing the activities of the ISS with the governments of the US, Russia, Japan and Europe (represented by ESA).

Canada's contribution to the ISS is the Mobile Servicing System (MSS), the external robotic system that has been critical to the successful assembly and maintenance of the ISS since 2001. The MSS's main elements are: the Space Station Remote Manipulator System (SSRMS) or the second-generation Canadarm2, a large manipulator arm, launched in 2001; a Mobile Base System (MBS) that transports the Canadian robots and ISS payloads along the length of the station's main truss, launched in 2002; and, the Special Purpose Dexterous Manipulator (SPDM) or Dextre, a two-armed dexterous robot, launched in March 2008. The Artificial Vision Units (AVUs) and Operations Control Software (OCS) were also provided to support on orbit crew operations of the MSS via NASA's Robotic Workstation (RWS) which also falls under the sustaining engineering support responsibilities of CSA. The MSS is supported by operations and training facilities located at the CSA's headquarters in Saint-Hubert, Quebec, and an MSS Sustaining Engineering Facility (MSEF) operated by MacDonald, Dettwiler and Associates Ltd (MDA, the prime contractor) in Brampton, Ontario.

In accordance with the provisions of the NASA/CSA MOU, Canada is obligated to[6]:

- support the operations of the MSS;
- provide MSS training to crew and ground support personnel;
- develop and implement procedures for operating the MSS in a safe, efficient and effective manner;
- provide logistics and sustaining engineering for each Canadian element throughout the life cycle of the ISS; and
- provide required spares and to repair MSS hardware that fails on-orbit.

In return for its contribution of the MSS and for fulfilling its obligations, Canada has the right to utilize 2.3% of the ISS user accommodations for research activities, and 2.3% of the on-orbit crew time to operate them. Canada also has the right to provide Canadian astronauts for 2.3% of the ISS crew flight opportunities.

In addition to its obligations above, Canada is required to compensate NASA for 2.3% of the ISS Common Systems Operating Costs (CSOCs). These are the costs attributed to the operation of the ISS as a whole, for which all partners must pay their respective share. The partners have agreed to "minimize the exchange of funds" by providing goods and services in-kind, i.e. barters, to offset their common cost obligations. To date, all cooperating agencies have offset their CSOC obligations through such barters.

Canadarm2 was instrumental in the successful completion of the on-orbit assembly of the ISS Program partners' elements into what has become the largest-ever permanently human-tended space station. The addition of Dextre to the MSS enhanced the ISS's robotic capability by expanding the type and range of robotics activities to include more dexterous tasks such as the removal and replacement of various ISS components, critical to the station's continued operations, and to support science and technology demonstrations. Dextre has reduced the need for astronauts to perform Extravehicular Activity (EVA) (or space walks) reducing the associated risk to astronauts. Furthermore, the MBS enables extending the reach of the robots along the ISS truss.

The subject of this evaluation, the ISS Assembly and Maintenance Operations SSP, falls under the CSA's Space Exploration Program, and the ISS Sub-Program (SP).

The scope of the **ISS Assembly and Maintenance Operations SSP** is the operation and maintenance of the Mobile Servicing System (MSS). This includes:

- the Space Station Remote Manipulator System (SSRMS), or Canadarm2;
- the Special Purpose Dexterous Manipulator (SPDM), or Dextre; and,
- the Mobile Base System (MBS), which embodies Canada's contribution to the ISS Program.

[6] *Memorandum of Understanding between the Canadian Space Agency and the National Aeronautics and Space Administration of the United States of America Concerning Cooperation on the Civil International Space Station*. CSA, NASA (January 28, 1998).

Canada's support is expected to continue through its lifecycle, currently confirmed to run through to 2024.[7] Additionally, as of January 2016, Canada also operates and provides sustaining engineering for the Robotic Work Station (RWS).

It is important to note that the evaluation excludes the **ISS Utilization SSP** and the **Human Space Missions Support SP**. These components are scheduled to be evaluated later in fiscal year 2016-17.

The ISS Utilization SSP encompasses the implementation of scientific, operational, medical and technological studies in specific areas, such as life sciences, radiation, material or fluid sciences, to be conducted aboard the ISS by Government of Canada organizations, academia or the private sector.

The Human Space Missions Support SP encompasses all activities required to recruit, develop, train and maintain a healthy and highly-qualified Canadian astronaut corps capable of participating in space exploration missions. It also includes all activities directed at mitigating health risks associated with those missions, such as the development of advanced technologies to be used in support of human space missions.

## 2.2 Governance and Roles and Responsibilities

As stated in the act that established the CSA (S.C. 1990, c. 13), the agency carries out its functions which are, amongst others, to "plan, direct, manage and implement programs and projects relating to scientific or industrial space research and development and the application of space technology". The Government of Canada, through the CSA, has organized its Space Exploration Program such that its SPs including the SSP answer to the mandate and functions of the act.

Upon completion of the ISS Major Crown Project (i.e., building of the ISS), the CSA was directed by the federal government to take responsibility for ISS under its A-base funding.

## 2.3 Resource Allocation

The ISS Assembly and Maintenance Operations SSP is an ongoing activity and is funded through the CSA A-base. The MSS Operations budget is managed through the existing CSA financial structure in accordance with all applicable *Financial Administration Act* (FAA) policies. Budgets are decentralized to the managers responsible for the delivery of specific activities.

The total budget for the ISS Assembly and Maintenance Operations SSP between 2008-09 and 2014-15 was $323.6 million, while expenditures were $330.6 million. The program budget, expenditures and variance for 2008-09 to 2014-15 are detailed in Tables 1-3, overleaf.

[7] Department of Finance Canada (2015). *Canada's Economic Action Plan: Strong Leadership.* See Government of Canada Budget 2015. Accessed on July 22, 2015 at http://www.budget.gc.ca/2015/docs/plan/ch3-1-eng.html

*Table 1: ISS Assembly and Maintenance Operations SSP Budget, 2008-09 to 2014-15 ($000's)*

| | Fund | 2008-09 | 2009-10 | 2010-11 | 2011-12 | 2012-13 | 2013-14 | 2014-15 | Total |
|---|---|---|---|---|---|---|---|---|---|
| ISS Assembly and Maintenance Operations | Salary - O&M | $10,596 | $11,899 | $8,636 | $8,125 | $8,411 | $9,366 | $10,245 | $67,278 |
| | O&M | $33,499 | $34,842 | $34,461 | $30,290 | $28,467 | $38,804 | $34,744 | $235,107 |
| | Capital | $444 | $250 | $250 | $250 | $250 | $ - | $6,358 | $7,802 |
| | Contribution | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| | EBP 20% | $2,119 | $2,380 | $1,727 | $1,625 | $1,682 | $1,873 | $2,049 | $13,456 |
| **Total** | | **$46,658** | **$49,371** | **$45,074** | **$40,290** | **$38,810** | **$50,043** | **$53,396** | **$323,642** |

Source: CSA Finance Directorate, Annual Reference Level Update (ARLU) of baseline years, June 2015.

*Table 2: ISS Assembly and Maintenance Operations SSP Expenditures, 2008-09 to 2014-15 ($000's)*

| | Fund | 2008-09 | 2009-10 | 2010-11 | 2011-12 | 2012-13 | 2013-14 | 2014-15 | Total |
|---|---|---|---|---|---|---|---|---|---|
| ISS Assembly and Maintenance Operations | Salary - O&M | $9,338 | $9,402 | $7,341 | $7,726 | $7,864 | $8,037 | $7,982 | $57,690 |
| | O&M | $44,913 | $39,738 | $32,870 | $32,722 | $29,908 | $37,850 | $41,361 | $259,361 |
| | Capital | $817 | $38 | $61 | $ - | $40 | $8 | $1,172 | $2,135 |
| | Contribution | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| | EBP 20% | $1,868 | $1,742 | $1,468 | $1,545 | $1,573 | $1,607 | $1,596 | $11,400 |
| **Total** | | **$56,935** | **$50,919** | **$41,740** | **$41,993** | **$39,386** | **$47,503** | **$52,111** | **$330,587** |

Source: CSA Finance Directorate, SAP database, June 2015.

*Table 3: ISS Assembly and Maintenance Operations SSP Variation between Budget and Expenditures, 2008-09 to 2014-15 ($000's)*

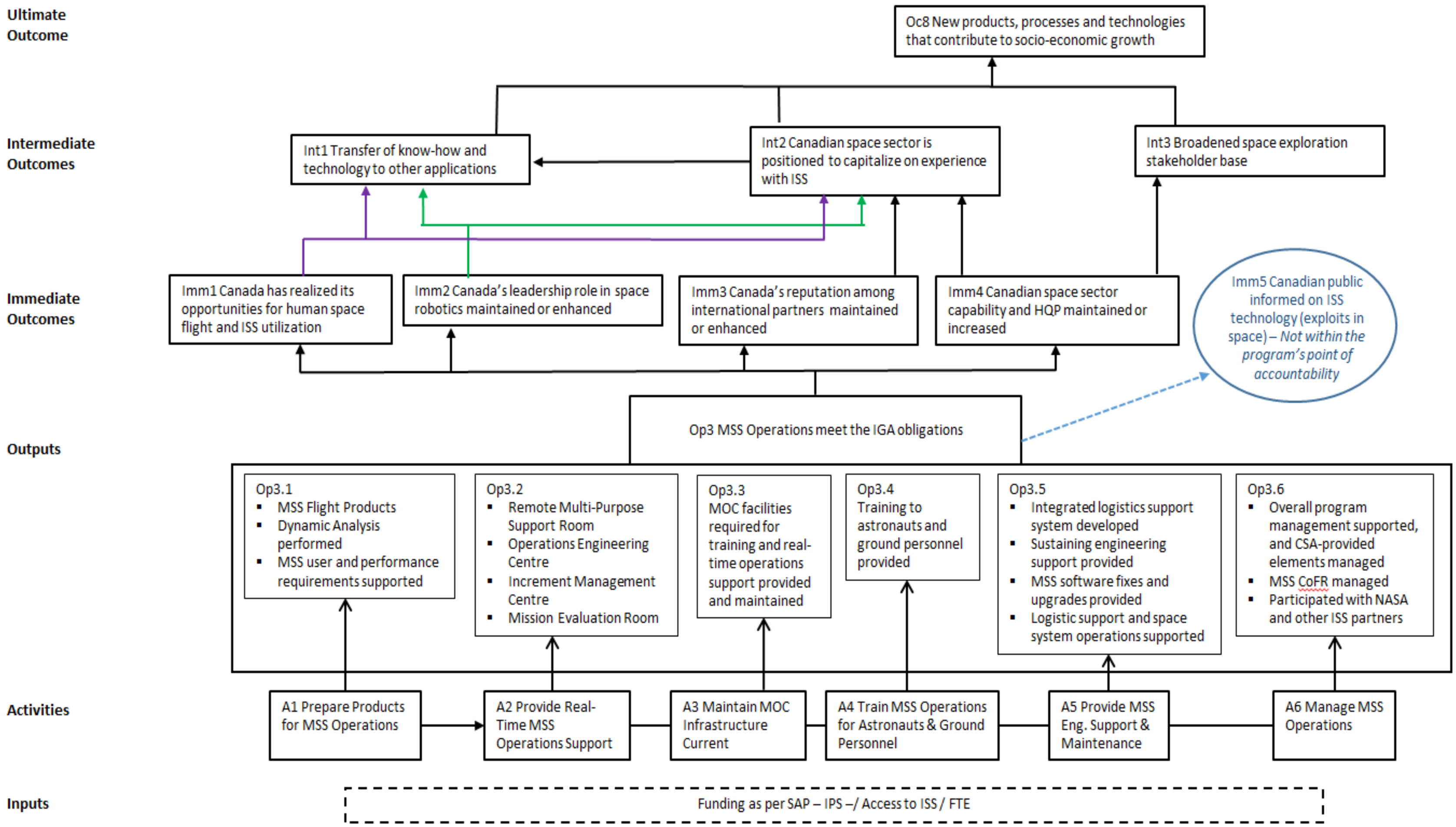
| | Fund | 2008-09 | 2009-10 | 2010-11 | 2011-12 | 2012-13 | 2013-14 | 2014-15 | Total |
|---|---|---|---|---|---|---|---|---|---|
| ISS Assembly and Maintenance Operations | Salary - O&M | $1,258 | $2,497 | $1,295 | $399 | $547 | $1,329 | $2,263 | $9,587 |
| | O&M | ($11,414) | ($4,896) | $1,591 | ($2,432) | ($1,441) | $954 | ($6,617) | ($24,254) |
| | Capital | ($373) | $212 | $189 | $250 | $210 | ($8) | $5,186 | $5,667 |
| | Contribution | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ - |
| | EBP 20% | $252 | $638 | $259 | $80 | $109 | $266 | $453 | $2,056 |
| **Total** | | **($10,277)** | **($1,548)** | **$3,334** | **($1,703)** | **($575)** | **$2,541** | **$1,285** | **($6,943)** |

N.B. Due to rounding, amounts may not sum exactly to totals in Tables 1, 2 and 3.

## 2.4 Program Theory

This section presents the logic model and narrative for the ISS Assembly and Maintenance Operations SSP developed by the consulting team. The logic model developed for the evaluation is strongly aligned with the logic model developed by the CSA Space Exploration Branch for the ISS Assembly and Maintenance Operations SSP. Based on discussions with the Project Authority and the Evaluation Consultative Group (ECG), it was agreed that the logic model should be revised for the purposes of the evaluation in order to provide more detail and granularity with respect to its outputs and outcomes. It was also agreed that the activities and outcomes required some refinement rather than wholescale modification. The logic model narrative is provided in Appendix A.

*Figure 1 – Logic Model for the ISS Assembly and Maintenance Operations SSP*



## 2.5 Prior Evaluations and Audits of the Program

No previous formal evaluations of the ISS Assembly and Maintenance Operations SSP have been undertaken.

An internal audit of the SSP was completed in September 2012.[8] The objective of this audit was to determine whether the management framework in place enabled the program to achieve its objectives and to comply with relevant policies, regulations and guidelines issued by the CSA and the central agencies. The audit concluded that the management framework in place enabled the program to achieve its objectives and to comply with relevant policies, regulations and guidelines issued by the CSA and the central agencies.

The audit identified some opportunities for improvement and provided the following recommendations:

1. Consolidate in a document the information setting out all of the anticipated exceptional costs for extending Canada's participation in the ISS activities to 2020;
2. Improve the documentation for the risk analysis process particularly regarding the assessment of probability and potential impacts on the achievement of expected outcomes;
3. Discuss with the Treasury Board Secretariat (TBS) in order to provide more specific information regarding the indicators used in the Performance Measurement Framework (PMF) for sub-sub-activity "ISS Assembly and Maintenance Operations Program" (1.2.1.1) of the Program Activity Architecture (PAA), and review the indicators if necessary; and
4. Complete the development of the program's Performance Measurement (PM) Strategy and implement it.

All four recommendations have been or are being addressed, and the relevant documentation has been reviewed during the evaluation.

[8] Canadian Space Agency. Audit and Evaluation Directorate. (2012). *International Space Station Assembly and Maintenance Operations Program Management Framework Audit (1.2.1.1). Project #11/12 01-02*. Saint-Hubert, Quebec: Canadian Space Agency.

# 3 Evaluation Approach and Methods

## 3.1 Purpose, Evaluation Issues and Scope

The evaluation of the ISS Assembly and Maintenance Operations SSP is in keeping with the requirements stipulated in the *Policy on Evaluation* and the *Financial Administration Act.* The evaluation report is scheduled to be approved by March 31, 2016, as specified in the CSA's Evaluation Plan 2015-16 to 2019-20.

The evaluation addresses the time period from the certification of Dextre in March 2008 to March 2015. The evaluation period was determined in collaboration with the Evaluation Consultative Group (ECG) members. The evaluation focuses on the five core issues identified in the TB's *Directive on the Evaluation Function* (2009), which includes issues of relevance (continuing need, alignment with federal government priorities, alignment with federal roles and responsibilities) and performance (achievement of expected outcomes, demonstration of efficiency and economy). The specific questions addressed by the evaluation are listed below.

**Relevance**

1. What needs (policy, economic, political, scientific, etc.) led Canada to commit to the ongoing operations and maintenance of the MSS in 1988, i.e., what precipitated the involvement of Canada? Do these needs continue to exist? How have these needs evolved over time?
2. Is the ISS Assembly and Maintenance Operations SSP aligned with federal government priorities?
3. Is the ISS Assembly and Maintenance Operations SSP consistent with federal roles and responsibilities?

**Performance**

4. To what extent has the ISS Assembly and Maintenance Operations SSP achieved its immediate outcomes?
5. To what extent has the ISS Assembly and Maintenance Operations SSP achieved its intermediate outcomes?
6. To what extent has the ISS Assembly and Maintenance Operations SSP achieved its ultimate outcome – new products, processes and technologies that contribute to socio-economic growth?
7. Have there been any unexpected outcomes (positive or negative) as a result of the ISS Assembly and Maintenance Operations SSP?
8. Is the ISS Assembly and Maintenance Operations SSP producing its outputs and outcomes (immediate) in the most efficient manner?
9. Are there any opportunities for improving the overall economy of the ISS Assembly and Maintenance Operations SSP?

**Program Delivery**

10. Are the roles and responsibilities of the ISS Assembly and Maintenance Operations SSP clear and appropriate?

## 3.2 Approach and Methods

### 3.2.1 Approach

The evaluation team worked closely with the ECG. Members of the ECG included CSA managers and staff, including managers of the ISS Assembly and Maintenance Operations SSP and representatives from the Audit and Evaluation Directorate. The evaluation team sought input and feedback from the ECG on key deliverables for the evaluation including: project work plan; evaluation plan; interview guides; case study interview topics and guide; presentation of preliminary findings; and the draft and final reports. The ECG also provided names of individuals to be interviewed.

### 3.2.2 Data Sources

#### *3.2.2.1 Document Review*

A review of existing documentation that relates to the SSP was undertaken to help address all evaluation issues of relevance, effectiveness, efficiency, and economy. The review of documentation included documents provided by the Project Authority as well as publicly available documents identified by our research team. A bibliography is provided in Appendix B.

#### *3.2.2.2 Key Informant Interviews*

In-depth key informant interviews offer the advantages of providing informed opinion and observations on the majority of the evaluation questions as well as assisting in the interpretation and understanding of qualitative and quantitative data from other lines of enquiry.

Seven separate interview guides were developed, one for each category of interviewee. The first few interviews conducted served as a pre-test of the interview guides. Based on these first few interviews, no subsequent modifications were made to the interview guides.

Interviews covered a range of internal and external stakeholders. Internal stakeholders included:

- ISS Assembly and Maintenance Operations SSP Managers – currently responsible for the day-to-day management of the program.
- CSA senior managers – responsible for the overall policy direction of the program, including previous managers of the program.
- Other CSA representatives – involved in providing support for the program, including Finance, Communications and Public Affairs, and ISS astronauts as well as former CSA Presidents.
- Young researchers – who began their career with the ISS Assembly and Maintenance Operations SSP.

External stakeholders include:

- Other Government Departments (OGDs) that are stakeholders in the ISS Assembly and Maintenance Operations SSP – including the Department of Innovation, Science and Economic Development (ISED - former Industry Canada) and Public Services and Procurement Canada (PSPC – former Public Works and Government Services Canada) who are responsible for managing the contract with the prime contractor).
- Industry – MDA, which is the prime contractor for the ISS Assembly and Maintenance SSP, and Neptec, which, although neither a prime nor sub-contractor, developed a vision system which was used for the construction of the ISS.
- NASA – is the principal partner, and oversees the management of the ISS Program.

The following table summarizes the number of interviews completed by category of interviewee. The sampling for the interviews was purposeful[9] – interviewees were proposed by CSA representatives and our project team based on the assumption that they were aware of/familiar with the ISS Assembly and Maintenance Operations SSP. In a few cases individuals proposed had left their position and could not be contacted for an interview, while others indicated after reviewing our interview questions that they were unable to meaningfully respond. A small number of interviewees could not be contacted/were unavailable to be interviewed within the timelines of this evaluation. Wherever possible these interviewees were replaced with another potential interviewee based on whether they were internal or external to the CSA.

[9] Purposive sampling techniques are primarily used in qualitative studies and may be defined as selecting units (e.g., individuals, groups of individuals, institutions) based on specific purposes associated with answering a research study's questions. Maxwell (1997) further defined purposive sampling as a type of sampling in which, ''particular settings, persons, or events are deliberately selected for the important information they can provide that cannot be gotten as well from other choices" (Maxwell, J. (1997). Designing a qualitative study. In L. Bickman & D. J. Rog (Eds.) *Handbook of applied social research methods* (pp. 69-100). Thousand Oaks, CA: Sage, p. 87).

***Completed Interviews by Category***

| **Respondent Category** | **Number of Interviews Completed** |
|---|---|
| CSA senior management | 4 |
| CSA program managers | 5 |
| CSA other (e.g., Communications, former astronauts, former presidents) | 5 |
| Industry (MDA - prime contractor and Neptec) | 5 |
| OGDs | 2 |
| Young researchers/graduate/post-graduate students who worked on the ISS | 2 |
| NASA | 2 |
| **Total** | **25** |

The relative weight of responses was recorded using the following scale. The various opinions and comments provided by the respondents in each group were also analyzed and synthesized.

- "**All/almost all**" – findings reflect the views and opinions of 90% or more of the key informants in the group;
- "**Large majority/most**" – findings reflect the views and opinions of at least 75% but less than 90% of key informants in the group;
- "**Majority**" - findings reflect the views and opinions of at least 50% but less than 75% of key informants in the group;
- "**Some**" - findings reflect the views and opinions of at least 25% but less than 50% of key informants in the group; and
- "**A few**" - findings reflect the views and opinions of less than 25% of key informants in the group.

#### *3.2.2.3 Follow-up Survey*

Some of the information sought from key informants was quantitative. A short survey was completed by the prime contractor.

#### *3.2.2.4 Case Studies*

Case studies were developed in order to provide more in depth analysis of some aspects of the SSP and the technologies that have evolved from ISS Assembly and Maintenance Operations. Three technologies were selected for case studies for this evaluation: NeuroArm; IGAR and KidsArm. It is noted that the development of space and other related technologies requires long lead times, i.e., work on the technologies highlighted by these case studies began prior to the study period. A summary analysis of case study findings is provided in Appendix C.

## 3.3 Limitations

**Most interviewees have a vested interest in the SSP.** This limitation has been mitigated by requiring interviewees to explain their perspectives and provide examples where appropriate. In terms of the overall report, the findings from the key informant interviews were triangulated with findings from other data sources (e.g., document review, literature review, program performance data, financial data and case studies).

**Feedback from the space industry came primarily from one company, MDA.** This was by design as this company has been the prime contractor over the entire period covered by the evaluation. In fact, MDA has been the only prime contractor for ISS Assembly and Maintenance Operations SSP over much of the period of Canada's participation in the ISS Program. Although MDA has participated in this evaluation through key informant interviews and through completion of a follow-up survey, the fact that this information comes from a single firm has implications in terms of confidentiality of information provided. The evaluation team has worked with MDA representatives and the Project Authority in order to protect confidentiality while at the same time maximizing the robustness of the evaluation findings.

**Too early to quantify/assess social and economic benefits of the program.** Due to the very nature of space technologies, the transfer of a technology to other sectors takes many years and is often not directly linked to a particular space technology. In the absence of quantitative data on the social and economic benefits of the technologies developed for the ISS Assembly and Maintenance Operations SSP, the evaluation team has sought to identify and describe these benefits qualitatively.

**Difficulty isolating impacts specific to the program.** As noted above, the ISS Assembly and Maintenance Operations SSP serves to enable the implementation of other elements of the CSA's PAA, specifically the ISS Utilization SSP and the Human Space Missions Support SP. In this sense the ISS Assembly and Maintenance Operations SSP is an operational or enabler program and its primary outcome is the successful operation of the ISS. As a result it is difficult to isolate the impacts of the ISS Assembly and Maintenance Operations SSP from the other ISS programs, or indeed from other CSA programs (e.g., Space Technology Development Program) and other contributors (e.g., funding provided by other ISS partners such as NASA).

**Difficulty calculating return on investment.** Calculating the return on investment of the ISS Assembly and Maintenance Operations SSP and comparisons to other participating partners is a complex undertaking requiring information and data that is not publicly available nor comparable across jurisdictions due to differences in how the ISS Program is delivered by each partner, exchange rate variations, etc.

# 4 Results

## 4.1 Relevance

The continued relevance of the ISS Assembly and Maintenance SSP was assessed by identifying and examining the needs that prompted Canada to continue its involvement in the ISS Program, and by examining whether the ISS Program falls under the authority of the federal government and the CSA.

### 4.1.1 Continued Need for the Program

#### *4.1.1.1 Needs that Prompted Canada's Participation in the ISS*

Key informants within the CSA and NASA who were familiar with the long history of the ISS agreed that the decision by the Government of Canada to participate in the ISS Program represented a logical step in the evolution of the close working relationship between NASA and Canada which began in 1969 when Canada was invited by NASA to participate in the Space Shuttle Program. At the time, a small Canadian company, DSMA Atcon, had developed a robot to load fuel into CANDU nuclear reactors; this robot attracted NASA's attention.[10] In 1975 the National Research Council (NRC) and NASA signed a MOU that Canada would develop and construct the Shuttle Remote Manipulator System, which became known as the Canadarm (i.e. Canadarm1). NRC awarded the contract to Spar Aerospace. The first Canadarm was delivered to NASA in April 1981.

Some senior CSA and NASA representatives explained that the decision by the US and Canada in the mid-1980s to cooperate in building an international space station was largely motivated by geopolitical concerns. The US was intent on building a space station with the participation of its western allies as a response to the Soviet Mir space station which had been launched in 1986. Canada also was attracted to the opportunity to join an "exclusive club" with other G7 nations. Interviewees noted that Canada's invitation to participate was based on its excellent track record in supporting the Space Shuttle Program together with Canada's unique expertise in space robotics – a capability that the US did not possess at the time. NASA interviewees emphasized that Canada's participation was critical. During the design phase it became evident that construction of the space station would require the use of a robotic arm.

Some key informants (both within CSA and external) also noted that participation would enable Canada to reap the technological and socio-economic benefits that would result from the further development of space robotics.

#### *4.1.1.2 Impacts from Extending the ISS Program to 2024*

As outlined in Section 2, Budget 2015 announced the extension of Canada's participation in the ISS mission to 2024. At present, the ISS Program is funded under the CSA's A-base until 2020. The Government of Canada decision to continue ISS participation to 2024 requires that the funding be

[10] http://www.asc-csa.gc.ca/eng/canadarm/beginning.asp

allocated. Consequently, the Agency will need to investigate possible funding mechanisms. While all key informants expressed support for this decision (although some were surprised by the relatively early timing), a few external interviewees observed that there had been little consultation with stakeholders leading up to the announcement. They wondered if Canada might have been able to negotiate a different or better arrangement with NASA had more time been taken (e.g., carve out a broader or greater role on the ISS or establish a role on future missions).

The main issue identified as a result of the extension of Canada's participation is that it may create budgetary pressures within the CSA. Several internal and external informants explained that as the ISS ages, repairs and replacement of parts will become increasingly necessary, i.e. a risk of failure will increase. For example, NASA noted that the eight battery systems attached to the solar arrays are nearing the end of their lives and work is just beginning to replace them (using Dextre), which will continue over the next year. CSA officials stated the CSA and the Government of Canada will need to undertake detailed planning of the potential costs to ensure sufficient resources are made available for the four-year extension period.

CSA and NASA officials noted that the ISS can remain operational for as long as it is technologically (and financially) feasible, i.e., it is conceivable that it could operate beyond 2024 (and could support new missions, as outlined later in this section). As explained by a CSA official, as the ISS Program moved from assembly into full utilization (assembly was completed in 2010), there was – and continues to be – a need to provide industry and researchers with sufficient time to design and carry out experiments on the ISS. The utilization component of the ISS Program is seen as a key driver to reap the full benefits of the ISS and thus the extension of the program to 2024 provides a greater opportunity for all ISS partners to take advantage of those benefits. The US is putting significant effort into maximizing these benefits by outsourcing the management of a piece of its National Laboratory utilization requirements to the Center for Advancement of Science in Space (CASIS).

#### *4.1.1.3 Rationale for Continued Participation in the ISS*

As noted above, Canada has declared its intent to participate in the ISS Program until 2024, and CSA officials indicated that the ISS Program could potentially be extended beyond that date. A CSA representative noted that although Canada could withdraw from the ISS at any time, the IGA would require that Canada provide access to the US (NASA) to all of the Intellectual Property (IP) related to the MSS to allow NASA to continue MSS operations without Canadian participation. (It should be noted that no key informants from the CSA expressed any desire to withdraw.)

One factor justifying Canada's continued participation is to be able to fully exploit the research opportunities on the ISS to advance Canadian technologies through on-orbit demonstration, and to continue to fly Canadian astronauts to the ISS as explained above. A second factor justifying Canada's participation beyond 2020 to 2024 is that it will permit Canada the opportunity to take part in the dialogue between ISS partners that has already started about the next step for space exploration beyond the ISS. ISS partners are discussing this to determine what exploration objectives they may have in common and to develop a schedule focused on the need to begin that work prior to the ISS being decommissioned. The ISS could play a role in supporting another mission, e.g., robotic refueling by serving as a base to carry out technology development activities to mature system designs prior to flying them into deep space. One possible future mission mentioned by key informants would be to establish an outpost at one of the Lagrangian points (points of equilibrium between the Earth and Moon), but which are much further out in space compared to the location of the ISS in low-Earth orbit (LEO). An outpost or habitat at one of these points would be an excellent location to monitor and coordinate communications with another mission on the Moon. It would also be ideal for crisis management, e.g., if an emergency occurred on the Moon. Eventually it could operate as a way station, e.g., to handle tourists to the Moon, or serve as a repair centre for future missions. As noted in the Global Exploration Roadmap,[11] precursor missions to demonstrate capabilities and technologies for lunar missions in sustained fashion support longer-term objectives; specifically reaching Mars.

Industry representatives also noted that Canada's continued participation in the ISS provides an ongoing opportunity to enhance Canadian space robotics expertise. For example, with the shift to utilization, there will be many payloads, some of which will be for internal experiments (i.e., inside the ISS) and some for external experiments (requiring the use of the MSS). Each payload has an engineering element, thus enabling industry (and the CSA) to continue to develop their space robotics capabilities.

### 4.1.2 Alignment with Federal Priorities

Federal priorities in space are identified in *Canada's Space Policy Framework*.[12] Most interviewees both within and outside of the CSA believe that the ISS Assembly and Maintenance Operations SSP is generally consistent with the framework. In fact, the ISS, Canadarm2 and Dextre are featured prominently in the framework document.

The framework has five principles (putting Canada's interests first; private sector at the forefront; partnerships; key capabilities; and, inspiration). Most interviewees stated that the ISS Program aligns with the inspiration, partnerships, key capabilities and innovation themes. They frequently noted that Canada's astronauts program is highly inspirational to Canadians and that the ISS Program is currently the only mechanism that enables Canada to put astronauts in space. Partnerships of course were the basis on which the ISS mission was founded by NASA, Canada and the other cooperating agencies. The ISS Program is somewhat consistent with the key capabilities theme, given its focus on developing Canada's space robotics capability, but it does not support other capabilities such as telecommunications and remote sensing which are supported by other programs at the CSA. Innovation is demonstrated in many ways. One is the evolution of the Canadarm: Canadarm1 was integral to the Space Shuttle Program; Canadarm2 is a critical part of the ISS Program; the Next-Generation Canadarm (NGC) program was instituted for further development of space robotics capabilities; and, opportunities

[11] International Space Exploration Coordination Group (ISECG). (September 2011). *The Global Exploration Roadmap.* Accessed on November 17, 2015 at http://www.nasa.gov/pdf/591067main_GER_2011_small_single.pdf.

[12] Canadian Space Agency. (2014). *Canada's Space Policy Framework: Launching the Next Generation*. Retrieved July 20, 2015 from http://www.asc-csa.gc.ca/eng/publications/space-policy/default.asp

for human exploration beyond LEO currently stands as the logical candidate by extension for this Canadian niche technology. Another example is the increasing reliance of the ISS mission on ground control of the robotics, rather than control by the astronauts, which frees up time for them to work on research instead of routine maintenance tasks. The ISS has also led to the development of several spin-off technologies being applied in the non-space sector (these are discussed in the performance section of this chapter).

The recently released *Science, Technology and Innovation Strategy* supports a need for endeavours such as the ISS and the Assembly and Maintenance Operations SSP. The Strategy refers to recent results from an international survey assessing students' competencies in literacy, math and science, which indicate that Canadian youth perform above the Organisation for Economic Co-operation Development (OECD) average. However, with other countries placing a premium on education, Canada's performance in science and mathematics must keep pace. The Strategy also notes that young people's attitudes toward these subjects are also of potential concern. Only two in five say they would be interested in working in science, technology, engineering and mathematics professions. While education falls within provincial jurisdiction, the federal government can foster and promote an interest in science, technology, engineering and math among young Canadians outside the classroom. The inspirational potential of space exploration aligns with this goal.[13]

A few key informants commented that it could be argued that the ISS Program is less aligned with the "Canadian interests first" theme, given the program is not linked to national sovereignty or security, and that investments in satellite communications and remote sensing would have greater commercial benefits to Canadian industry. Nonetheless, all key informants believe that the program is generally consistent with the *Space Policy Framework*.

Although very recent and thus outside of the evaluation period, it should be noted that Canada's continued participation in the ISS Program also aligns with the Government of Canada's focus on innovation and science as stated in the recent *Speech from the Throne* (December 2015).[14]

### 4.1.3 Alignment with Federal Roles and Responsibilities

All key informants agreed that it is appropriate for the federal government to manage the Canadian portion of the ISS Program, as it is an international agreement that can only be signed and managed by the Government of Canada.

[13] Industry Canada. (2014). *Seizing Canada's Moment: Moving Forward in Science, Technology and Innovation*. Retrieved July 20, 2015 from https://www.ic.gc.ca/eic/site/icgc.nsf/vwapj/Seizing_Moment_ST_I-Report-2014-eng.pdf/$file/Seizing_Moment_ST_I-Report-2014-eng.pdf
[14] Government of Canada. (2015). Making Real Change Happen. *Speech from the Throne to Open the First Session of the Forty-second Parliament of Canada*. December 4, 2015. Accessed on December 17, 2015 at http://speech.gc.ca/en/content/making-real-change-happen

That the CSA is responsible for the ISS Program is consistent with its authority under the *CSA Act*, which states that the Agency is authorized: "to cooperate with the space and space-related agencies of other countries in the peaceful use of space."

## 4.2 Performance

This section addresses the evaluation questions related to performance of the ISS Assembly and Maintenance Operations SSP, including the achievement of outcomes and economy and efficiency.

### 4.2.1 Achievement of Immediate Outcomes

This section presents evaluation findings related to the achievement of immediate outcomes, specifically:

- Canada has realized its opportunities for human space flight and ISS utilization.
- Canada's leadership role in space robotics maintained or enhanced.
- Canada's reputation among international partners maintained or enhanced.
- Canadian space sector capability and HQP maintained or increased.
- Canadian public informed on ISS technology (exploits in space).

It is important to note that although this evaluation is focused on the ISS Assembly and Maintenance Operations SSP, a number of outcomes identified, including immediate outcomes, for this SSP are not within the direct influence of the SSP. Specifically, the SSP does not have an influence over opportunities for human space flight and ISS utilization; and the extent to which the Canadian public is informed on ISS technology. The SSP can assist or enable the achievement of these immediate outcomes, however they fall within the purview of other CSA programs. The outcomes do, however, fall within the influence of CSA's overall involvement with the ISS Program. As mentioned previously, human space flights and ISS utilization outcomes will be covered in greater depth in a distinct evaluation, in compliance with CSA's Departmental Evaluation Plan 2015-2016 to 2019-2020.

#### *4.2.1.1 Opportunities for Human Space Flight and ISS Utilization*

The ISS has had a continuous human presence since November 2, 2000. In 2009, the number of astronauts living on board the space station was increased from three to six. The flight systems provide a safe, comfortable, and liveable environment in which crew members can perform scientific research. These flight systems include habitation accommodations, environmental controls, medical and health support, and computing and data management.[15]

There was consensus among interviewees (both internal to the CSA and external) that the ISS Program is the only opportunity for human space flight available to Canadians. One CSA representative explained

[15] National Aeronautics and Space Administration. (November 2010) Reference Guide to the International Space Station: Assembly Complete Edition. (November 2010). Accessed on August 19, 2015 at: http://www.nasa.gov/pdf/508318main_ISS_ref_guide_nov2010.pdf.

that the ISS Program has given Canada direct involvement in space flight and this is an indicator of the importance of Canada as an ISS Program partner. Another CSA representative noted that it would be difficult and expensive for Canada to get human space flight opportunities through other means – such as through ESA programmes. However, one interviewee external to the CSA noted that without the ISS there could be funds available for other projects that include human space flight – i.e., there are trade-offs.

Canadian astronauts who have been in space over the time period of the evaluation are as follows:

- Julie Payette – July 15 – 31, 2009 (16 days);
- Robert Thirsk – May 27 – December 1, 2009 (188 days); and
- Chris Hadfield – December 19, 2012 to May 1, 2013 (146 days).

The table below summarizes the total number of Canadian astronauts on board the ISS over the time period of the evaluation as well as the total number of Canadian astronaut days in space.

***Table 4: Number of Canadian Astronauts in Space, 2008-09 to 2014-15***

| | 2008-09 | 2009-10 | 2010-11 | 2011-12 | 2012-13 | 2013-14 | 2014-15 |
|---|---|---|---|---|---|---|---|
| Number of Canadian Astronauts in Space | 0 | 2 | 0 | 0 | 1 | 1 | 0 |
| Number of Canadian Astronaut Days on ISS | 0 | 204 | 0 | 0 | 103 | 43 | 0 |

Source: CSA ISS Assembly and Maintenance Operations SSP Performance Data, August 2015.

According to a paper produced by CSA staff in 2012[16], there has been a significant increase in the conduct of MSS operations through Ground Control, thereby freeing up on-orbit crew time for utilization activities. Utilization of the ISS resources continues with Canadian participation in several experiments carried out on board the ISS.

There was agreement among interviewees (internal to the CSA and external) that the MSS operations have consistently met all ISS Program demands. NASA representatives in particular noted that MSS has provided NASA with very good support and the use of Canadarm2 has become routine on the ISS. There was almost complete agreement that MSS operations have been executed "flawlessly". Program performance measurement data and information contained in the CSA's *Departmental Performance Reports* (DPRs)[17] supports this perspective.

[16] Metcalfe, L., M. Ciaramicoli, P. Jean, P. Johnson-Green and E. Tabarah (2012). *Canada and the International Space Station Program: Overview and Status since IAC 2011*. 63rd International Astronautical Congress 2012 (IAC 2012), Naples, Italy, 1-5 October 2012, IAC-11.B2.2.1.
[17] Canadian Space Agency. *Departmental Performance Reports*. Accessed at: http://www.asc-csa.gc.ca/eng/publications/rp.asp#rr

A presentation by CSA managers at the 2009 International Astronautical Conference[18] noted record-setting utilization of the ISS resources with Canadian sponsorship of several on-board experiments. The Bodies in Space Experiment (BISE) continued to gather data assessing the influence of gravity on the perception of up and down and Advanced Plant Experiments on Orbit (APEX) studied the impact of gravity on wood formation. The VASCULAR and HYPERSOLE experiments are studying the effects of microgravity on the human body. Canada has chosen to mainly focus ISS utilization activities on health-related experiments.

The table below summarizes the number of experiments/research projects on the ISS which have involved Canada over the time period under review. It is important to note that the number of experiments performed does not reflect the complexity or scientific value/importance of the experiments. It should be reiterated that the ISS Assembly and Maintenance Operations SSP has no influence over the number of experiments performed on board the ISS except as an enabler of the successful operation of the ISS. Details on the experiments performed on the ISS will be addressed in the evaluation of the CSA's ISS Utilization SSP at a future date.

***Table 5: Number of Experiments/Scientific Research Projects on ISS Involving Canada, 2008-09 to 2014-15***

| | 2008-09 | 2009-10 | 2010-11 | 2011-12 | 2012-13 | 2013-14 | 2014-15 |
|---|---|---|---|---|---|---|---|
| Number of Experiments on ISS | 2 | 7 | 4 | 2 | 4 | 5 | 3 |

Source: CSA ISS Assembly and Maintenance Operations SSP Performance Data, August 2015.

The table below summarizes the number of operational hours for MSS for the time period of the evaluation. The ISS Assembly and Maintenance Operations SSP does not have direct control over the number of operational hours, the SSP responds to the needs of the ISS Program as identified by NASA. Although for the most part the operational needs are identified in advance, there are occasions where the SSP is called upon to perform unexpected operations for things such as repairs to the ISS (e.g., tears in the solar array).

***Table 6: Number of Operational Hours for MSS, 2008-09 to 2014-15***

| | 2008-09 | 2009-10 | 2010-11 | 2011-12 | 2012-13 | 2013-14 | 2014-15 |
|---|---|---|---|---|---|---|---|
| Number of Operational Hours | 570 | 680 | 735 | 545 | 840 | 640 | 600 |

Source: CSA ISS Assembly and Maintenance Operations SSP Performance Data, October 2015.

[18] Sponder, L., G. Leclerc, P. Jean, P. Johnson-Green and T. H. Braithwaite (2010). *Canada and the International Space Station Program: Overview and Status since IAC 2009*. *Proceedings of the 61st International Astronautical Congress (IAC 2010)*, Prague, Czech Republic, September 27 – October 1, 2010. IAC-10.B3.1.3.

#### *4.2.1.2 Canada's Leadership Role in Space Robotics*

##### 4.2.1.2.1 Leadership in Space Robotics

The robotic arms (Canadarm2 and Dextre) onboard the ISS are essential for the following operations: construction and maintenance of the ISS, supporting external ISS experiments, capture of free flying re-supply vehicles and the handling of their delivered payloads, supporting extravehicular activity, and aiding in other scientific activities. These robotic systems can perform simple tasks such as camera positioning, as well as complex tasks such as manipulating and installing 20,000-kg modules. Safety controls and training are key areas required to enable the successful use of robotic systems in the crewed space arena.[19]

There was agreement among interviewees (internal and external to the CSA) who responded to this question that Canada remains the world leader in space robotics and the ISS Assembly and Maintenance Operations SSP has directly contributed to enhancing this leadership position. Some CSA representatives pointed out that Canada was invited to participate in the ISS Program as a direct result of its long standing expertise in space robotics. This perspective is supported by a senior NASA official who explained, "In hindsight maybe NASA or another country could have constructed an arm, but Canada's participation was natural: Canada had the tools and NASA had the utmost confidence in Canada given the experience with the Canadarm on the Space Shuttle." One interviewee noted that although Canada is not the only country with robotics on the ISS, Canada's robotics "get all the headlines" because they do all the highly critical and visible operations. A 2003 evaluation of the Major Crown Project – Canadian Space Station Program supports this perspective. It concluded that the program had enabled Canada to maintain its leadership role in space robotics owing to the success of Canadarm.[20]

Although Canada maintains a leadership position in space robotics, some interviewees (including CSA representatives and those external to the CSA) noted that this leadership position cannot be taken for granted. Other countries such as Japan, Russia and ESA Member States are catching up. Specifically, one CSA representative indicated that the US has a policy that states that NASA must develop robotics – this is part of a presidential directive.[21] This is seen by a few interviewees as evidence of increased competition on the horizon in the area of space robotics. However one CSA representative somewhat disagreed, noting that the fact that other countries are moving into space robotics is not necessarily an immediate threat – it will only be a threat if Canada does not continue to make continuous improvements to Canadarm2 and Dextre and to contribute newer and more innovative robotics systems to future space exploration missions. This interviewee did not believe that at present, other countries are investing heavily in space robotics with the intention of overtaking Canada's leadership position.

[19] Chang, V. and L. Evans (2009). Robotic systems safety. *Safety Design for Space Systems*: 301-318.
[20] Canadian Space Agency. Audit, Evaluation and Review Directorate. (April 2003). *Evaluation of the Major Crown Project – the Canadian Space Station Program (MCP-CSSP). Evaluation Report. Project #02/03-02-01*. Saint-Hubert, Quebec: Canadian Space Agency.
[21] This is supported in documents such as https://spinoff.nasa.gov/Spinoff2010/edu.html.

#### 4.2.1.2.2 Technological Innovations Stemming from the Program

According to interviewees (internal to the CSA and external), ground command was the most tangible and important innovation brought forward by the MSS. This innovation has meant that the majority of operations can now be done from the ground station without needing human, on-orbit guidance from astronauts, thereby freeing up their time for other activities such as science. A 2013 article by Aziz[22] noted that the addition of Dextre increased the capabilities of the MSS, and introduced significant complexity to ISS robotics operations. While the initial operations concept for Dextre was based on human-in-the-loop control by the on-orbit astronauts, the complexities of robotic maintenance and the associated costs of training and maintaining the operator skills required for Dextre operations demanded a re-examination of these concepts. A new approach to ISS robotic maintenance was developed in order to utilize the capabilities of Dextre safely and efficiently, while at the same time reducing the costs of on-orbit operations.

Interviewees noted that ground command of Dextre and Canadarm2 also increased safety for astronauts. A few CSA representatives explained that when Dextre was launched it was designed to be controlled completely from the ground - this met with some resistance at first. Canada made major changes to the software - this was always jointly done with NASA and the contract/agreement with NASA allowed the Canadian team sufficient flexibility to develop these enhancements. A few CSA representatives noted that there is currently huge pressure on NASA on the part of the US government to increase utilization of the ISS and so having the crew free to do experiments has been very beneficial.

One CSA representative explained that when the MSS was first developed and built, there were a set of requirements that had to be met. The system was built to meet these requirements but as early as 2001 there were conditions that led the ISS Assembly and Maintenance Operations SSP to plan and develop enhancements to both make the system safer and increase the probability of mission success. For example, Canadarm2's tip end tends to oscillate when accelerated or decelerated (like a heavy weight at the end of a fishing rod); CSA software engineers solved this challenge by including feedback into the software control system and maintaining tip position accuracy and control.

#### 4.2.1.2.3 Canadian Space Robotics for Other Missions

Interviewees were able to provide examples of missions or projects for which the Canadian space sector has been asked to provide space robotics, although some of the examples go back several years in time. Some interviewees described the Hubble Space Telescope repair for which MDA obtained a contract from NASA to use Dextre's spare arm which was then located at MDA. The key decision for NASA was to de-orbit the Hubble or to service it to extend its life. NASA had considered, and invested in developing, a dedicated robotic servicing mission; but eventually regained confidence in flying the Shuttle to connect with the Hubble Telescope, so the robotic mission was cancelled. Interviewees reported that MDA had successfully carried out some demos that showed the robotic servicing concepts worked.

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[22] Aziz, S. (2013). "Development and verification of ground-based tele-robotics operations concept for Dextre." *Acta Astronautica.* 86: 1-9.

Another example provided by some interviewees (internal to the CSA and external) includes satellite refueling technology, known as Space Infrastructure Servicing (SIS). The idea is that a vehicle would fly up to a satellite, and robotics would be used to fuel and extend the life of the satellite. However one CSA representative noted that the cost of building and launching satellites has come down significantly and this may hinder the commercial prospects for this technology. Industry representatives reported that MDA continues to pursue the market potential for satellite refuelling. These interviewees noted that the technology has been successfully demonstrated and one interviewee indicated that the mindset of commercial satellite operators is changing, making them more open to using SIS. As argued by a few industry representatives, in the future satellites will be built to be serviced in orbit and to be refuelled.

A few interviewees (internal to the CSA and external) described the Artificial Vision Unit (AVU) built by Neptec, which is located on the US laboratory. According to one interviewee, this used to be a key tool, providing additional and accurate position data for payloads on the tip of Canadarm2, used in ISS assembly. It was discontinued in 2010; subsequently, the CSA is considering repurposing the AVU to introduce additional flexibility into the MSS by providing it with greater autonomy which would simplify operations. This is only in the concept phase and is focused on developing new technology for future robotics systems.

One interviewee noted that Canada is frequently invited to participate in missions/projects requiring space robotics. However due to budgetary issues, Canada could not participate. Examples of opportunities where Canadian space robotics were sought out but not used include: robotic systems requirements for the NASA Mars 2020 mission; the US Defense Advanced Research Projects Agency (DARPA) Phoenix mission; and the Lunar Resource Prospector mission. Increased funding would result in more missions and projects making use of Canadian space robotics. In other words, according to this interviewee, the uptake of Canadian space robotics depends on funding by the Canadian government and not on the technology, which is well developed.

#### *4.2.1.3 Canada's Reputation among Partners*

##### 4.2.1.3.1 Reputation among Partners

There was consensus among interviewees (CSA representatives and external to CSA) that Canada's reputation has been enhanced as a result of work performed as part of the ISS Assembly and Maintenance Operations SSP. Specifically, NASA representatives noted that Canada is seen as a strong partner and that NASA, and international agencies, highly value Canadian expertise. A representative from NASA noted the fact that the Canadian Control Centre in St-Hubert, Quebec represents a unique arrangement for NASA (to have a critical function located outside of the US). As further evidence of Canada's positive reputation, a few external interviewees noted that Canada has been offered opportunities to participate in other large space missions and projects because of its expertise is space robotics, specifically the DARPA and Goddard Space Flight Centre, a NASA center, have offered Canada an opportunity to be involved in the next-generation on-orbit servicing project.

A few CSA representatives noted that although Canada contributes only 2.3% of the ISS costs (i.e., Canada is a very small partner in terms of funding), Canada is not treated as a minor partner by NASA – Canada is seen by its partners as having more influence internationally than its size would suggest in terms of its contribution and the importance of the technology it brings to the ISS Program. As noted by Chris Hadfield, "We're the smallest partner on the ISS and yet we have absolutely the most critical role. This has been a real enviable position, and I'm the manifestation of that. We earned the Commander position on ISS, and that can happen again."

##### 4.2.1.3.2 Innovative Solutions for Repair and Maintenance

Interviewees (CSA representatives and those external to the CSA) were able to provide specific examples of innovative solutions for the repair or maintenance of the ISS developed by the ISS Assembly and Maintenance Operations SSP, including:

- Prior to 2008, if there was a truss failure (no power for the MSS), then there would have to be an emergency astronaut walk. A new electrical box has been added to avoid this risk;
- Numerous software upgrades that aim to reduce loads and increase the service life of the robotics system;
- Development of a "shuttle boom inspection system", which directly supported the Space Shuttles' "return to flight" after the Columbia accident;
- Repair of a rip in a solar array using ISS and Shuttle Canadian robotic elements combined with a spacewalk and hand-made tools;
- Development of interfaces for the robotic transfer of payloads, e.g., using the Japanese airlock; and
- Development of workarounds, e.g., removing failed electronics systems that hadn't necessarily been built to be robotically compatible.

Additional innovative solutions for the repair of the ISS developed by the SSP were identified by the review of literature and documentation. An article by Poynter and Keenan (2012)[23] describes how on August 28, 2011, Dextre, supported by Canadarm2, successfully removed a failed Remote Power Control Module (RPCM) from the integrated truss segment of the ISS. These dexterous operations required extreme precision in the ISS's harsh, thermally changing external environment, combined with delicate force sensing and accommodation control and successfully demonstrated the first end-to-end robotic maintenance activity on the ISS.

An article by Rembala (2011)[24] describes how on January 27, 2011, Canadarm2, controlled by crew aboard the ISS, successfully tracked and captured the 10,500 kg free floating Japanese H-II Transfer Vehicle (HTV2) as it drifted within 10 m of the Space Station. After precisely guiding the HTV2 into its

[23] Poynter, L. and P. A. Keenan (2012). *The role of dexterous robotics in ongoing maintenance of the ISS*. *63rd International Astronautical Congress 2012 (IAC 2012), Naples, Italy, 1-5 October 2012, Volume 5 of 14: IAC-12.B3.4-B6.5.6*

[24] Rembala, R. (2011). *The evolution of tele-robotics on ISS and enabling of unmanned on-orbit services. 62nd International Astronautical Congress 2011 (IAC 2011), Cape Town, South Africa, 3-7 October 2011, Volume 4 of 12: IAC-11.B3.4.-B6.6.10*

berthing port on the ISS, Canadarm2 and Dextre robotic systems began the task of unloading ISS spare parts from the HTV2's unpressurized external carrier for transfer and stowage to an ISS Express Logistics Carrier (ELC). These tele-robotic operations, performed by ground operators in the US and Canada, required extreme precision in combination with delicate force sensing and accommodation control and successfully demonstrated some of the most advanced robotic servicing tasks performed in space to date.

A 2010 article by Aziz[25] describes the successful completion of the STS-120/ISS 10A assembly mission. Unlike previous missions that concluded when the Space Shuttle undocked from the ISS, this mission required critical assembly operations to continue after the Shuttle's departure to relocate the Harmony module to its permanent location and activate its systems. The end-to-end mission lasted for almost a month and required the execution of seven space walks, over twenty major robotics operations, and countless hours of ground commanding. The mission included the relocation of the P6 truss segment from the Z1 Node to its permanent location on the P5 truss; a three-day marathon of highly choreographed sequence of robotics operations and space walks, and the reconfiguration of ISS structure to attach Harmony (Node 2) to the US destiny laboratory module; a six-day sequence of complex robotics operations the majority of which were executed after the departure of the shuttle and included an unprecedented amount of ground-commanded robotics operations.

September 2009 marked the first free-flyer capture by Canadarm2 onboard the ISS, an operation that was publicised as a "cosmic catch". The Japanese-built H-II Transfer Vehicle (HTV) was the first of a new class of unmanned transfer vehicles that required the assistance of Canadarm2 to complete their rendezvous with the ISS.[26]

#### *4.2.1.4 Space Sector Capability and HQPs*

##### 4.2.1.4.1 Number of FTEs of Employment

According to data provided to the evaluation team by MDA Brampton, the number of FTEs devoted to MDA's contract associated with the ISS Assembly and Maintenance Operations SSP ranged from a high of 115 to a low of 85 over the time period of the evaluation, of which approximately 75% are considered HQPs.

The total number of FTEs at the CSA employed for ISS Assembly and Maintenance Operations SSP over the time period of the evaluation is summarized in the table below, which includes those from other CSA corporate departments matrixed in.

[25] Aziz, S. (2010). "Lessons learned from the STS-120/ISS 10A robotics operations." *Acta Astronautica.* 66(1-2): 157-165.
[26] Lucier, L. and Smith, C., "Cosmic Catch: Canadarm2's First Capture of a Free-Flying Vehicle – Operational Risks, Considerations, and Results", *Proceedings of the 61st International Astronautical Congress (IAC 2010)*, Prague, Czech Republic, September 27 – October 1, 2010, PaperIAC-10.B6.1.3

*Table 7: Number of CSA FTEs on MSS Operations, 2008-09 to 2014-15*

| | 2008-09 | 2009-10 | 2010-11 | 2011-12 | 2012-13 | 2013-14 | 2014-15 |
|---|---|---|---|---|---|---|---|
| Number of CSA FTEs | 99.0 | 89.0 | 75.6 | 78.1 | 77.3 | 80.3 | 75.5 |

Source: CSA ISS Assembly and Maintenance Operations SSP Performance Data, October 2015.

##### 4.2.1.4.2 Career Impacts Related to the ISS Assembly and Maintenance Operations SSP

All interviewees within the CSA who responded to this question reported positive career impacts as a result of working on the ISS Assembly and Maintenance Operations SSP. In almost all cases, interviewees have spent most of their career working on the ISS Assembly and Maintenance Operations SSP. However a few CSA representatives noted that everyone that becomes part of the team wants to advance/get promoted but there is very little turnover and so fairly limited opportunity for advancement. As noted by a CSA interviewee, "ISS could be a stepping stone to something else but the projects [within the CSA] just don't exist." There is thus evidence that those working on the ISS Assembly and Maintenance Operations SSP within the CSA feel their career potential is limited as a result of a lack of other large scale missions within the CSA. Career advancement limitation may also be due to the relatively small team within the CSA. CSA program managers reported that over the time period of the evaluation, a number of HQPs have left the CSA for employment with NASA or one of its contractors in the US.

Interviewees disagreed on whether skills obtained through working on ISS Assembly and Maintenance Operations SSP are transferable to other areas. Interviewees from outside the CSA who were able to respond agreed that the skills obtained through working on ISS Assembly and Maintenance Operations SSP are transferable to other industries. Being able to list experience with working on the ISS mission is viewed as highly beneficial, as the engineering standards are extremely demanding. One interviewee provided the example of the nuclear industry. The case studies suggest medical robots as another possibility in future. Experience with control theory, vision applications, and targeting on the ISS can also be applied in the nuclear industry (supporting nuclear power plants and decommissioning operation) and in medical robots such as NeuroArm's neurosurgical applications and IGAR's biopsy and ablation procedures in the treatment of tumours.

Opinions of CSA representatives on the transferability of skills from the ISS Assembly and Maintenance Operations SSP to other sectors or other areas within the space sector varied – most feel their skills are not easily transferable. Among those who feel their skills are not transferable, there is a sense that the expertise acquired is quite narrow and that the longer one stays with the ISS Assembly and Maintenance Operations SSP, the more difficult it is to transfer to other areas. As noted by one interviewee, "career potential is very limited because you need someone to leave in order for you to advance."

#### 4.2.1.4.3 Training Provided by the SSP

A key activity undertaken by the ISS Assembly and Maintenance Operation SSP is the training of astronauts and ground personnel.[27] The number of hours of training provided as well as the number of individuals provided with training over the time period of the evaluation is summarized in the table below. We note that the demand for training on the part of the ISS partners is cyclical and can vary significantly from year-to-year. The SSP responds to requests for training – i.e., is not able to influence this indicator. It is worthwhile noting that as the ISS shifts to more ground controlled operations, there has been a corresponding shift to training of ground personnel versus astronauts.

***Table 8: Training Provided to Astronauts & Ground Personnel, 2008-09 to 2014-15***

| | 2008-09 | 2009-10 | 2010-11 | 2011-12 | 2012-13 | 2013-14 | 2014-15 |
|---|---|---|---|---|---|---|---|
| Astronauts (# of hours) | 875 | 490 | 575 | 504 | 375 | 440 | 375 |
| Ground Personnel (# of hours) | 210 | 130 | 75 | 65 | 170 | 145 | 140 |
| # of Individuals Provided with Training | 38 | 27 | 20 | 15 | 37 | 29 | 20 |

Source: CSA ISS Assembly and Maintenance Operations SSP Performance Data, August 2015.

### *4.2.1.5 Public Awareness of ISS Technology*

#### 4.2.1.5.1 Public Awareness of ISS Technology

According to CSA representatives interviewed, the CSA generally does not track communications activities (e.g. web pages hits) specific only to the ISS Assembly and Maintenance Operations SSP – efforts are focused on the ISS overall. They have recently (two years ago) acquired Google Analytics software and this has made it possible to more easily track hits to ISS specific web pages. Statistics for web traffic related to the ISS provided to the evaluation team by the CSA Communications and Public Affairs Directorate are summarized in the table below. Note that spikes in the number of visits correspond to when Canadian astronaut Chris Hadfield was on board the ISS.

***Table 9: Unique Visits to the CSA ISS Website, 2008-09 to 2014-15***

| | 2008-09* | 2009-10 | 2010-11 | 2011-12* | 2012-13 | 2013-14 | 2014-15 |
|---|---|---|---|---|---|---|---|
| International Space Station | 65,785 | 65,770 | 69,025 | 69,425 | 131,644 | 196,327 | 100,523 |

* Note that data are not available for March 2008 and for the period of November to December 2011
Source: CSA Communications and Public Affairs Directorate Performance Data, August 2015.

[27] The CSA and its prime contractor, MDA, conduct MSS training sessions for both astronauts and ground support personnel. A ground infrastructure comprising a MSS simulator, a multi-purpose learning centre, and other training equipment have been built to enable this activity.

CSA representatives reported that available resources during the period of the evaluation have limited the capacity of the Communications and Public Affairs Directorate for planning, implementing and tracking of ISS communications strategies. This is expected to improve shortly with the hiring of new staff.

Since 2011 the CSA Communications and Public Affairs Directorate has been producing short videos related to the ISS and has been tracking the number of times these have been viewed. A list of some of the videos related to ISS Assembly and Maintenance Operations SSP and statistics on the number of times each video has been viewed is presented in Appendix D.

The main types of communications activities undertaken by the CSA are detailed in Table 10. This information is based on a summary analysis of available performance measurement data for CSA communications related to the ISS prepared by the CSA for the evaluation team.

*Table 10: Types of ISS-related Communications Activities Undertaken by the CSA, 2008-09 to 2014-15*

| **PRESS RELEASES AND CONFERENCES** |
|---|
| Press releases/News releases |
| Journalists invited on site at the CSA's headquarters and live broadcasting |
| Interview requests with CSA's spokespersons |
| **WEB UPDATES AND SOCIAL MEDIA ACTIVITIES** |
| Messages, press & news releases, pictures and videos/animations posted on Facebook, Twitter, YouTube and RSS Newsfeeds |
| Live coverage of robotic operations (Dextre, Canadarm2, etc.) on Facebook and Twitter |
| Regular updates of the CSA's website (text, videos and animations) |
| **PUBLIC EVENTS, EXHIBITIONS & LEARNING ACTIVITIES** |
| Learning activities/partnerships with Canadian schools (e.g. in-class experiences, presentations, etc.) |
| Conferences and lectures during public events |
| Exhibitions (partly or mostly on the MSS/robotic) |
| Tours of the CSA's headquarters (ISS infrastructures) |
| **EDUCATIONAL RESOURCES & PROMOTIONAL MATERIAL** |
| Infocards (e.g., Dextre, Canada and the ISS, etc.) to support the CSA's participation in several events and activities |
| Educational resources/kits |
| Modules of Dextre, Canadarm1 and Canadarm2 |

Although the CSA Communications and Public Affairs Directorate has not had a specific overall strategy for communications related to the ISS, it has had strategies for communications related to specific initiatives such as Chris Hadfield's sojourn on the ISS. In addition the Directorate has had communications strategies specific to the MSS such as the 10$^{th}$ anniversary of the MSS which involved documenting CSA staff experiences working on the MSS. When there are major operations undertaken by MSS, a member of the communications team sits in the control centre and provides live commentary – telling the world what is being done and why it's important. For example, when Dextre became the first robot to refuel a mock satellite in space in May 2014, a member of the CSA's Communications and Public Affairs Directorate live tweeted the operations and posted several messages on Facebook.

According to a social media coverage analysis prepared by Influence Communication[28] for the CSA, the key word Dextre was mentioned 1,666 times on Twitter throughout the world between May 22 and 31, 2014, and several space influencers tweeted about Dextre's operations. "The potential scope of those messages is of 21.4 million of views" [loose translation]. A video prepared by the CSA was also viewed about 55,277 times on YouTube (as of March 2015).

According to one CSA representative, NASA works very hard at communications but this interviewee feels that the CSA has been more effective. As noted by Chris Hadfield, "We reached a level of public awareness that was unprecedented, maybe since Apollo 11. The videos we made were seen 50 million times, reaching levels that NASA never achieved. I would send the raw material to CSA communications, who would then turn it around (sometimes within hours) and get it out on social media (e.g., YouTube) so it was accessible to everyone. We also had Music Mondays, where I played and sang simultaneously with 700,000 Canadian youth." CSA Communications and Public Affairs won a national award for this effort, recognized by the Governor General for their work.[29]

#### 4.2.1.5.2 Communications Directed at Youth

The CSA Communications and Public Affairs Directorate produces targeted educational resources and promotional materials related to the ISS and MSS. Educational tools and kits were developed for the CSA's last three ISS missions. Tools included photo cards and posters which were distributed by CSA staff during public events or made available (by order) to individuals and organizations. Statistics (as available) for the number of educational materials distributed are presented in the table below.

***Table 11: ISS Educational Materials Distributed, by Expedition, 2008-09 to 2014-15***

| **Bob Thirsk Expedition 20/21** | **Total Quantity of Materials Distributed to Date** |
|---|---|
| Elementary School | 40,566 |
| High School | 29,434 |
| TOTAL | 70,000 |
| **Julie Payette Expedition STS-127** | |
| TOTAL (no breakdown available – Elementary/High School) | 46,719 |
| **Chris Hadfield Expedition 34/35** | |
| Elementary School | 26,103 |
| High School | 16,906 |
| TOTAL | 43,009 |

Source: CSA Communications and Public Affairs Directorate Performance Data, August 2015.

[28] Influence Communication. *Rapport d'analyse des mentions du robot Dextre sur Twitter réalisé par Influence Communication (22 au 31 mai 2014).* Report presented to the Canadian Space Agency, June 9 2014.

[29] It should be noted that the videos Chris Hadfield refers and the award received by CSA Communications relate to the ISS Utilization and Human Space Missions SSPs, i.e., they are beyond the ISS Assembly and Maintenance Operations SSP.

In addition, approximately 8,624 photo cards of the ISS and 5,417 posters of the ISS were distributed during the evaluation period (April 1, 2008 and March 31, 2015). The current catalogue was put in place in 2012, and estimates from the 2008-2012 period provided by the Communications and Public Affairs Directorate are reported to be conservative. It is likely that a larger number of items were distributed between 2008 and 2012.

One interviewee noted that there used to be a high level communications team for the ISS Program which included ISS partners but they stopped meeting, mostly because of the travel costs. However this committee has been resurrected. Managers of the ISS Assembly and Maintenance Operations SSP have been supportive of this being put in place.

### 4.2.2 Achievement of Intermediate Outcomes

This section presents evaluation findings related to the achievement of intermediate outcomes as depicted in the logic model, specifically:

- Transfer of know-how and technology to other applications.
- Canadian space sector is positioned to capitalize on experience with ISS.
- Broadened space exploration stakeholder base.

#### *4.2.2.1 Transfer of Know-how from ISS*

##### 4.2.2.1.1 Transfer of Know-how to Non-Space Uses

A 2010 report prepared for the European Commission Space Policy and Coordination Unit by Technopolis Group[30] explains that space exploration is unique among space activities in that its primary objective is extending human understanding of space. Therefore its main output is new scientific and technological knowledge generated by extra-terrestrial exploration as well as new knowledge generated as a result of overcoming the significant technological challenges inherent in accessing and exploring the extra-terrestrial environment. Unlike other space activities such as satellite communications, Earth observation and global positioning, which support economic activity via enabling downstream services, space exploration impacts on the economy and society indirectly – through subsequent terrestrial innovation activities based upon the new knowledge and technologies generated for, and by, space exploration.

The evaluation team undertook three case studies of technologies that incorporate know-how from the ISS Assembly and Maintenance Operations SSP. Summary findings from these case studies may be found in Appendix C.

[30] Technopolis Group prepared for the European Commission Space Policy and Coordination Unit. (October 3, 2010). *Summary Report: Space Exploration and Innovation.* Accessed at http://ec.europa.eu/enterprise/policies/space/files/policy/final_technopolis_report_en.pdf.

**NeuroArm**

NeuroArm is a teleoperated magnetic resonance (MR)-compatible image-guided robot. The NeuroArm system comprises two robotic arms capable of manipulating both specially designed and existing microsurgical tools connected via a main system controller to a workstation with a sensory immersive (i.e., virtual reality) human-machine interface.* The surgeon is positioned at a workstation and uses the human-machine interface to interact with the surgical site. The NeuroArm system allows the surgeon to access imaging data without interrupting the surgical procedure while providing the surgeon with the most technologically advanced sensory input available to best facilitate the performance of surgery.

The NeuroArm project began in September 2001. The research team, based at the University of Calgary, investigated other surgical robots under development and approached several potential collaborators. MacDonald, Dettwiler and Associates Ltd (MDA), a company that specializes in building robotics for complicated environments, including the Shuttle Remote Manipulator System (Canadarm) and the Canadian Special Purpose Dexterous Manipulator (Dextre), responded positively to the opportunity to develop a robot for neurosurgery. As a result of the association with a company that had already developed a great deal of teleoperated robotic technology, NeuroArm benefited from the inclusion of knowledge related to the prior aerospace achievements of MDA.

In May 2008, NeuroArm was used for the world's first image guided MR-compatible robotic neurosurgical procedure. The NeuroArm has successfully completed over 60 neurological procedures to date.

The technology that went into developing NeuroArm, the world's first robot capable of performing surgery inside magnetic resonance machines, was born from the Canadarm (developed by MDA for the US Space Shuttle Program), as well as Canadarm2 and Dextre.** As explained by Dr. Garnette Sutherland,

"Many years ago, MDA received the contract to build Canadarm and Dextre on the Space Station. They hired a pile of engineers to go through the process of building these robots. When we had the idea to use a robot for neurosurgery, we gave MDA the requirements, and those same engineers with decades of experience building robots for space began to translate that work into this one."***

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* Human-machine interface is a software application that presents information to an operator or user about the state of a process, and to accept and implement the operators control instructions.

** National Aeronautics and Space Administration (November 18, 2011). NeuroArm: Robotic Arms Lend a Healing Touch. Accessed December 30, 2015 at http://www.nasa.gov/mission_pages/station/research/news/neuro_Arm.htmlhttp://www.nasa.gov/mission_pages/station/research/news/neuro_Arm.html

*** Dr. Garnette Sutherland quote, http://www.nasa.gov/mission_pages/station/research/news/neuro_canadarm/#.Va_3Z4tqkrm

**Image Guided Automated Robot (IGAR)**

IGAR will enable real-time biopsy and therapy of suspected breast lesions in a Magnetic Resonance Imaging (MRI) system. The IGAR Breast Robot is designed for early detection and treatment of breast cancer. The IGAR Breast Robot integrates seamlessly within a Magnetic Resonance imaging system, allowing a radiologist to select a target on a patient's scan and then confidently direct the intervention with millimeter accuracy.*

The IGAR Breast Robot has the potential to transform the care pathway for cancer patients by enabling a "one-stop" system for diagnosis, treatment, and intervention. The IGAR Breast Robot can first perform a biopsy of a suspicious lesion, which can then be followed by ablation of biopsy site margins if clinically appropriate. For lesions or tumours that may require lumpectomy, image guided seed localization in the breast can also be done, improving success rates and avoiding re-incision.

Building on the experience and capacity developed by MDA's involvement in the development of robotics for the International Space Station, the IGAR Breast Robot has benefitted from a rigourous systems engineering approach used in the development of the Canadarm, Canadarm2 and Dextre. The similarities between the Canadarm, Canadarm2, Dextre and the IGAR Breast Robot are in the operating environments and the requirements that needed to be met to achieve full functionality. All of these robots operate in extreme environments (space and inside an MRI machine), both involve expert users (astronaut and surgeon) dealing with delicate objects (mechanical repair in zero gravity and breast biopsies and treatment), both required an ability to be tele-operated and both require extreme levels of safety, durability and redundancy.

The IGAR Breast Robot was developed by partnership between Dr. Mehran Anvari and his team at the Centre for Surgical Invention and Innovation (a non-profit entity hosted by St. Joseph's Healthcare Hamilton and McMaster University) and MDA.

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* Centre for Surgical Invention & Innovation, http://www.csii.ca/robotic_development/igar

**KidsArm**

KidsArm is an autonomous image guided robotic arm for performing anastomosis (reconnect delicate vessels such as veins, arteries, or intestines) on pediatric patients from neonates to 4 years old.* The objective of the KidsArm project was to demonstrate the feasibility (proof of concept) of using an autonomous robotic arm to assist surgeons perform certain procedures many times faster than if they were only using their hands, and with increased accuracy. Key elements of the technology included the vision-based system that can function in an autonomous manner and the software for the control system and collision detection used by the robotic arms, particularly Dextre, on the ISS.

Based on the experience with NeuroArm, MDA approached the medical community to develop similar robotic medical applications based on technologies developed for the robotic arms used on the ISS. Dr. Peter Kim, general neonatal and thoracic surgeon, and co-founder of the Centre for Image-Guided Innovation and Therapeutic Intervention (CIGITI), at SickKids responded positively to MDA's request.

The KidsArm project came to fruition in 2010 when SickKids in collaboration with MDA, facilitated by a $10 million award from the Federal Economic Development Agency for Southern Ontario (FedDev Ontario) and the Ontario Research Fund/Canada Foundation for Innovation, to support the development of an image-guided pediatric surgical robot.

Robots for medical (e.g., KidsArm) and space (e.g., Dextre) operate in unique environments, both require safety monitoring software, and sophisticated control and operator interface. The architectural design is similar, both are intended for critical operations; one for surgery, the other for space operations. KidsArm has ISS heritage in the machines (Anastomosis Tool and Robotic Arm), control system, collision detection and path planning algorithms (Robotic Controller), image guidance framework (Image Processing Unit) and user interface. The experience with control theory, vision applications, targeting on a larger scale for the ISS was applied to KidsArm, the novelty was to make it for smaller applications. The development of KidsArm also benefited from the autonomous operation mode used on the ISS.

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* Looi, Thomas, Benny Yeung, Manickham Umasthan and James Drake. 2013. "KidsArm — An Image-Guided Pediatric Anastomosis Robot", 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) November 3-7, 2013. Tokyo, Japan: 4105-4110.

Interviewees were asked to provide examples of know-how and technology from the ISS Assembly and Maintenance Operations SSP that have been transferred to other industries. Examples provided included NeuroArm and nuclear reactor maintenance.

**NeuroArm** – A few interviewees cited NeuroArm as an example of technology transfer. According to one interviewee, NeuroArm shares the same underlying software as Dextre (e.g., control algorithms, recover from failure, safety critical) as described in the case study developed by the evaluation team.

**Nuclear reactor inspection and maintenance** - MDA has taken its expertise in project management, developed over many years as part of its work on the construction and maintenance of the ISS (and on the Space Shuttle Program) and applied this expertise in a non-space sector: the nuclear industry. For example, MDA has obtained business from the Ontario nuclear power generation company, Bruce Power. Over the past five years this work has involved detailed planning (e.g., storyboarding, mapping out tasks) as part of the maintenance of Bruce Power's nuclear generating station on Lake Huron.

Most recently, MDA supported the inspection and maintenance work during the planned outage of one of the Candu power reactors that took place in August 2015. (The prime contractors were GE and ATS

(Cambridge, Ont.) with MDA as a sub-contractor.) The outage was scheduled for five days, and involved the inspection and maintenance of the nuclear reactor vault. Each day of a shutdown costs millions of dollars in lost revenue, so it is imperative that the work be conducted in an efficient fashion. MDA developed visual storyboards, the sequencing of tasks and the contingency plan. The work involved staging of mock outages and the construction of scale models. MDA indicated that having successfully worked on the ISS (and other space missions) for many years gives the company a high degree of credibility when attempting to obtain business in other sectors. While these planning methods themselves are not likely patentable or saleable, this expertise is enabling the company to obtain contract revenue.

In addition, MDA has developed robotics solutions to carry out inspections of nuclear reactors. For example, in 2010 MDA successfully used a robotics solution to carry out an inspection of the nuclear vault at OPG's Pickering nuclear station.[31] Controlled from a remote work station, operators commanded the highly dexterous robotic solution inside the radioactive chamber. MDA developed a snake robot called "CVIRM" to do the inspection.

A literature review also provided evidence of transfer of know-how from the ISS Assembly and Maintenance Operations SSP to other areas. Articles by Faghihi et al (2013)[32] and Fournier-Viger et al (2011)[33] describe how the intelligent learning agent was developed for the ISS Program. The Conscious-Emotional-Learning Tutoring System (CELTS), a cognitive tutoring agent, whose architecture is inspired by the latest neuro-scientific theories was developed for the ISS Program. The agent is used in a simulation-based tutoring system for learning the complex task of operating Canadarm2. Experimental evaluations have showed that the agent's learning capabilities considerably enhance its adaptation to learners during interactions and consequently improves learners' performance.

A few CSA representatives noted that the uniqueness of the space sector lies in the focus on safety which exceeds what is standard in other industries, particularly when there is human space flight involved. Within the space sector, all potential hazards are identified and the technology is developed in order to decrease all risks to an acceptable level. Each potential cause of risk is identified - and for each cause it is standard to have two controls to mitigate the risk and each control has to be tested and proven. Thus when this technology is transferred to the NeuroArm (for example), then there is very high certainty that potential risk has been reduced to virtually zero. This implies a good potential spin-off into the medical field.

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[31] http://www.mdacorporation.com/corporate/news/pr/pr2010082301.cfm

[32] Faghihi, U., P. Fournier-Viger and R. Nkambou (2013). CELTS: A cognitive tutoring agent with human-like learning capabilities and emotions. *Smart Innovation, Systems and Technologies*. 17: 339-365.

[33] Fournier-Viger, P., R. Nkambou, A. Mayers, E. M. Nguifo and U. Faghihi (2011). An hybrid expert model to support tutoring services in robotic arm manipulations. 7094 LNAI: 478-489. {downloaded: http://www.researchgate.net/profile/Usef_Faghihi/publication/221438932_A_Cognitive_Tutoring_Agent_with_Automatic_Reasoning_Capabilities/links/09e41511198989b653000000.pdf

#### 4.2.2.1.2 Facilitation of Technology Transfer

Despite the success noted in the above examples, a few CSA representatives believe that more could be done to facilitate the transfer of technology from the space sector in general, and the ISS Assembly and Maintenance Operations SSP in particular, to other sectors. One interviewee described attending a recent conference in Boston related to ISS utilization and R&D. Congress in the US has been pushing for the commercialization of the technologies from the ISS Program and helping industry to find ways to commercialize these technologies. Having seen what is being done in the US, this interviewee stated that more should be done in Canada to facilitate the commercialization of ISS technologies. A few interviewees noted that the CSA has focused its ISS utilization efforts on the life sciences, which is seen as a good approach. A few interviewees suggested a coordinated approach between the CSA and ISED to commercialize technologies – including establishing a technology transfer office to assist companies in getting the most out of the technologies. One interviewee further suggested involving universities in the commercialization efforts.

However, as will be discussed in section 4.2.2.2.2, since MDA has a sole licence for the commercialization of the ISS technologies it developed, the CSA can't facilitate the commercialization of those technologies without the approval and willing participation of MDA.

The CSA has set up two platforms for the sharing of information related to patents and technologies, including ISS-related patents and technologies as well as others, called FlintBox[34] and SparkUp (which is now closed). One interviewee from the CSA indicated that the Agency would like to do more to promote these platforms, i.e., communicate their existence.

#### 4.2.2.1.3 Non-Space Patents Linked to the ISS Assembly and Maintenance Operations SSP

A total of 19 unique patents related to NeuroArm, KidsArm and IGAR have been obtained by the prime contractor, MDA. These unique patents amount to a total of 40-50 registered in multiple countries. All of these have either been filed or are in force. Most of the patents are for NeuroArm, followed by IGAR and KidsArm (e.g., smart controls/vision system).

According to findings from the case studies, NeuroArm currently holds eight patents in Canada, one in the European Union and one in Japan. The IGAR Robotic Platform currently holds one Canadian patent, with five additional Canadian and six US patents pending. One patent application has been filed in Canada related to KidsArm.

[34] Flintbox empowers technology communities to connect in a geographic region, building a "Sphere of Innovation" to recognize and capitalize on the valuable relationships and innovation assets in their community. For example, by creating or joining a community "Group" of members with common interests, say tissue engineering or artificial intelligence, users can link to other groups and explore common interests and complementary resources, for a dynamic collaborative effort and to efficiently share related technology projects. http://www.flintbox.com/

#### *4.2.2.2 Industrial Leveraging of ISS Experience*

##### 4.2.2.2.1 Contracts Obtained as a Direct Result of the SSP

Winning contracts depends on a myriad of factors including such things as company location, corporate and team experience, price, and technological expertise. It is thus rarely possible to attribute the winning of specific contracts to a single factor, such as in the case, the ISS Assembly and Maintenance Operations SSP.

In terms of follow-on business obtained by MDA as a result of its contract to support the ISS Assembly and Maintenance Operations SSP, the company has obtained some follow-on contracts with the CSA, including winning a competitive bid in 2015 to replace the MSS cameras. Beyond the CSA, MDA has made numerous sales of grapple fixtures, which must be used by all ISS resupply vehicles and payloads (the value of these contracts was not divulged due to commercial confidentiality).

MDA's work on the ISS has also helped it to build relationships with other space agencies around the world and with other prime contractors, although no formal partnerships have been formed.

MDA's work on the ISS has also helped the company to continue to enhance its space robotics expertise. According to many key informants, MDA is viewed as a world leader in space robotics. The fact that MDA can talk about its long-time practical experience on the ISS is very beneficial when the company attempts to obtain work with other space agencies and prime contractors.

It should be noted that another Canadian space company, Neptec, has benefited from the overall ISS Program – although not directly from the Assembly and Maintenance Operations SSP. Neptec's Space Vision System (SVS) was used on the construction of the ISS. It provided real-time alignment and positioning cues to the Shuttle and ISS crews when they were installing the modules of the ISS. This technology was developed with funding support from the CSA's Space Technology Development Program (STDP).[35] Another Neptec technology, a laser-based sensor used for rendezvous and docking, called the 3D Automated Rendezvous and Docking Sensor (AR&D), has been used by Orbital Sciences Corporation for use in their Cygnus unmanned cargo resupply spacecraft. This technology has been used for the unmanned resupply of the ISS on several occasions. It uses a laser-based 3D sensor and thermal imagers to collect 3D data of its target, which is compared by software with the known shape of the target spacecraft. This technology has other potential space applications, such as for satellite servicing. Neptec has made numerous sales and the market potential is considerable. This technology was developed with support from the CSA STDP program and from NASA.

##### 4.2.2.2.2 Patents and Intellectual Property

According to a few CSA representatives, when the program was first started the IP belonged to the Government of Canada but was licensed back to MDA or anyone else who wanted to use it. MDA does

[35] Neptec's SVS technology is a case study in the CSA's evaluation study of the STDP: *Evaluation of the STDP*, Canadian Space Agency, June 2011. http://www.asc-csa.gc.ca/eng/publications/er-570-2800.asp

not own the IP but the company can use it. One CSA representative reported that MDA has commercialized some patents and provided some royalties to the Government of Canada. The Intellectual Property Management and Technology Transfer department at the CSA tracks and manages this activity. The licences are designed to be to the advantage of industry in order to encourage companies to use and commercialize the technologies. Another CSA representative reported that the CSA is paying more attention to the issue of patents than was the case previously.

MDA has had a no fee licence agreement with CSA up to 2014. Since then, it has been renewed as a royalty bearing licence that will terminate in 2024. Now, as was the case before 2014, MDA is required to report on commercialization. As it was the case before 2014, it is a sole licence, which means that only MDA and the Crown can use the licenced technologies and only MDA can commercialize the technologies (versus an exclusive licence which would have prevented the Crown from using the licenced technologies). According to MDA, this licence structure makes sense as it is in the best position to exploit the technologies. It is however, important to remember that the Crown cannot undertake any ISS technology commercialization activities without MDA's approval and/or participation. Under this licence agreement, MDA has to prove it is trying to exploit the technologies – if it doesn't CSA can revoke the granted rights in the non-space field of use and possibly grant them to another company. While no technologies have been sold, some products have been sold, e.g., variants on grapple fixtures, which have been sold to NASA, Japan, Russia and Italy. So, the spin-offs from MSS have been product sales, not technology.

According to industry representatives, MDA has obtained several patents related to the development of robotics. There are no trademarks, however there are 9-10 patents for robotics interfaces; 3 patents in the US: #5803751: software dock interface; #5458384: robotic Orbital Replacement Unit (ORU) Interface; and #5466025: effector clamping.

In addition, there are patents related to MDA's satellite refuelling business, which stem in part from the ISS work. There are about 10 unique patents (mainly related to being able to capture satellites), with 20-30 registrations in multiple countries.

Despite most interviewees external to the CSA providing an example of technology transfer from ISS Assembly and Maintenance Operations to other areas, a few interviewees perceive that space companies in Canada tend not to be very interested in commercializing technologies beyond the space sector.

#### *4.2.2.3 Broadened Space Stakeholder Base*

A recent report prepared by the International Space Exploration Coordination Group (ISECG) notes that space exploration offers a unique and evolving perspective on humanity's place in the Universe, which is common to all. The report further notes that space exploration is a global endeavor contributing to trust and diplomacy between nations.[36]

The ISECG refers to a 2009 survey conducted by Nature[37] which found that 50% of the internationally renowned scientists who published in the prestigious journal Nature during the previous three years had been inspired by Apollo to become scientists; 89% of the respondents also agreed that human spaceflight inspires younger generations to study science.[38]

A few CSA representatives indicated that the inspirational aspect of the ISS Program and the ISS Assembly and Maintenance Operations SSP is key. Among the main drivers of Canada's participation in the ISS Program early on were inspiration and scientific research/technology development. The inspiration element has been officially recognized in *Canada's Space Policy Framework*.

There was agreement among interviewees (internal and external to the CSA) that public awareness of the ISS Assembly and Maintenance Operations SSP has increased. Interviewees noted that the picture of Canadarm2 and Dextre on the Canadian $5 bill and the media attention of Chris Hadfield's sojourn in space illustrate public awareness. There is also a Canadian stamp illustrating the Canadian flag on the Canadarm. In a poll by the Dominion Institute in 2008 where 3,114 Canadians were asked, "What is Canada's defining, person, event, place, symbol and accomplishment?" the Canadarm was voted as the fifth most popular icon defining Canada, ahead of Niagara Falls and the CN Tower.[39]

A few CSA representatives noted that the ISS accounts for a relatively small portion of the CSA's total budget (approximately 16%[40]) and of the total ISS Program budget (Canada's contribution being of 2.3%), yet Canada receives a disproportionate share of the media attention because of the visibility of Canadarm2 and Dextre.

### 4.2.3 Achievement of Ultimate Outcome

This section presents evaluation findings related to the achievement of its ultimate outcome as depicted in the logic model, specifically: new products, processes and technologies that contribute to socio-economic growth.

[36] International Space Exploration Coordination Group (ISECG). (September 2013). *Benefits Stemming from Space Exploration.* https://www.nasa.gov/sites/default/files/files/Benefits-Stemming-from-Space-Exploration-2013-TAGGED.pdf

[37] The article referred to in the ISECG report may be found at http://www.nature.com/news/2009/090715/full/460314a.html (Accessed July 22, 2015).

[38] International Space Exploration Coordination Group (ISECG). (September 2013). *Benefits Stemming from Space Exploration.* https://www.nasa.gov/sites/default/files/files/Benefits-Stemming-from-Space-Exploration-2013-TAGGED.pdf

[39] Dominion Institute (2014). *101 Things Canadians Should Know about Canada*. http://www.101things.ca.

[40] Average ratio of CSA's ISS Expenditures (provided by Finance) to CSA's actual spending reported in the Departmental Performance Reports over the evaluation period (2008-09 to 2014-15).

#### *4.2.3.1 Contribution to Social and Economic Growth*

##### 4.2.3.1.1 Societal Benefits Stemming from the Technologies

A paper prepared by the ISECG concludes that there are numerous cases of societal benefits linked to new knowledge and technology from space exploration. Space exploration has contributed to many diverse aspects of everyday life, from solar panels to implantable heart monitors, from cancer therapy to lightweight materials, and from water purification systems to improved computing systems and to a global search-and-rescue system. The paper further concludes that though the precise nature of future benefits from space exploration is unpredictable, current trends suggest that significant benefits may be generated in areas such as new materials, health and medicine, transportation and computer technology.[41] This perspective is supported by technologies such as NeuroArm, KidsArm, and IGAR which are described above in section 4.2.2.1.1. More fulsome descriptions of the technologies may be found in Appendix C.

A report prepared by representatives from ISS partner agencies provides descriptions of a variety of benefits to humanity stemming from the ISS. Benefits identified are grouped into human health, Earth observation and disaster response, and global education.

**Human Health** – Throughout its assembly the ISS has supported research that is providing a better understanding of human health, such as aging, trauma, disease and the environment. Several biological and physiological investigations have yielded results, including improved understanding of physiological processes normally masked by gravity and development of new medical technology and protocols driven by the need to support astronaut health. The upcoming evaluation of the ISS Utilization SSP will provide an assessment of the benefits of ISS on human health.

**Earth Observation and Disaster Response** – ISS facilitates Earth observation aimed at understanding and resolving the Earth's environmental issues. The ISS offers a unique vantage point for observing the Earth's ecosystems. Astronauts, using hands-on and autonomous equipment are able to observe and explain what they witness. Astronauts can observe and collect camera images of events as they unfold and may also provide input to ground personnel programming the ISS automated Earth-sensing systems. This flexibility is an advantage over sensors on unmanned spacecraft. A wide range of Earth observation payloads can be attached to the exposed facilities on the ISS's exterior. A prime example is a technology developed by a Canadian company, Urthecast. Two cameras developed by this company have been mounted on the Russian side of the ISS, which take photos and high definition video of the Earth (with potentially a wide range of uses: weather, security, etc.). While this technology is an example of how the existence of the ISS itself can lead to spin-off applications, it is not directly related to the SSP (the CSA has not provided financial support). In addition, the existing international partnerships facilitate data sharing that can benefit people around the world and promote international collaboration.

[41] International Space Exploration Coordination Group (ISECG). (September 2013). *Benefits Stemming from Space Exploration.* https://www.nasa.gov/sites/default/files/files/Benefits-Stemming-from-Space-Exploration-2013-TAGGED.pdf

**Global education** – The ISS has a unique ability to capture the imagination of students and teachers. The presence of human on board the ISS provides a foundation for numerous educational activities aimed at capturing that interest and motivating the study of science, technology, engineering and mathematics. Through continuous use of the ISS, it is expected that the next generation will be inspired.[42]

The three case studies developed for this evaluation support the perspective that over the very long term, space exploration missions such as the ISS benefit society. All three technologies will likely benefit the healthcare system. Direct benefits to patients resulting from robotic surgery may include shorter hospitalization, reduced pain and discomfort; faster recovery time; smaller incisions; and reduced blood loss and scarring.[43]

#### 4.2.3.1.2 Benefits to Canada's Economy

MDA Brampton is the main contractor (i.e., prime) on the ISS Assembly and Maintenance Operations contract and this division is very dependent on this contract. Up to 2011 MDA Brampton also had the NASA Space Shuttle Canadarm contract, however now the only contract is for ISS Assembly and Maintenance Operations.

The benefits to the Canadian economy resulting from the ISS Assembly and Maintenance Operations SSP cannot be quantified fully based on available information. Given the technologies being developed currently which have been described throughout this report, one would expect positive economic impacts including employment and revenues from products sales. The three technologies that are the subject of case studies developed for this evaluation are not yet commercialized and thus there are no revenues to date associated with these technologies. It is very likely that revenues and employment have resulted from MDA's work in the nuclear sector, however this information is considered to be commercially confidential.

#### 4.2.3.1.3 New Products, Processes and Technologies

CSA has granted a sole licence to MDA to use the licensed technology to make, use, disclose, lease, sell or otherwise dispose of products and services. Under this agreement, MDA agrees to invest in R&D, business development and associated activities to develop the technology. For example MDA worked with the University of Calgary to develop NeuroArm. MDA also designed a Light Duty Utility Arm system to inspect and analyze radioactive waste in underground storage tanks. This system consists of a modular, seven-joint manipulator attached to a telescopic vertical positioning mast. A mobile system

[42] Robinson, J ED. Developed by members of the Canadian Space Agency (CSA), European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), National Aeronautics and Space Administration (NASA), and the Russian Federal Space Agency (Roscomos). *International Space Station Benefits for Humanity. 2012. Accessed on July 22, 2015 at* http://www.nasa.gov/pdf/626862main_ISS_Benefit_for_Humanity.pdf
[43] University of Cincinnati, http://uchealth.com/services/robotic-surgery/patient-information/benefits/

deploys the manipulator in the tank. These are both examples of spin-offs of the technologies developed for the robotic suite on-board the ISS.[44]

### 4.2.4 Unexpected Outcomes

As noted by the ISECG, the ISS partnership is a strong example of continuing international cooperation in space exploration. To achieve its core mission, the ISS partnership has overcome political and economic strains. It has demonstrated the diplomatic value of international cooperation in space.[45] This cooperation has gained importance in recent years given the international community's strained relationship with Russia. It is notable that despite geopolitical tensions with Russia, cooperation on the ISS has continued, thus keeping communications between ISS partner countries and Russia open. This perspective was also noted by a CSA representative.

A NASA document also notes the political and diplomatic achievements of the ISS. According to NASA's Reference Guide to the ISS[46], the global partnership of space agencies exemplifies meshing of cultural differences and political intricacies to plan, coordinate, provide, and operate the complex elements of the ISS. The program also brings together international flight crews and globally distributed launch, operations, training, engineering, communications networks, and scientific research communications.

A few CSA representatives noted that Canadarm2 was launched in 2001 and the CSA has consistently been in the media since. As a result, many countries are aware of the CSA and its role on the ISS.

### 4.2.5 Demonstration of Efficiency and Economy

This section assesses whether the ISS Assembly and Maintenance Operations SSP has been able to generate outputs and achieve its outcomes in an economic and efficient manner. The TB's *Directive on the Evaluation Function* defines the demonstration of efficiency and economy as the "assessment of resource utilization in relation to the production of outputs and progress towards expected outcomes." In general, the analysis of efficiency requires assessing relationships between inputs and outputs and/or outcomes, and the assessment of economy concerns the extent to which best use is made of resource inputs to achieve intended outcomes.

We address economy and efficiency by assessing:

- Whether the ISS Assembly and Maintenance Operations SSP is producing its outputs and outcomes in the most efficient manner;
- Whether there are opportunities for improving the overall economy of the ISS Assembly and Maintenance Operations SSP.

[44] Canadian Space Agency, Uses for Robotic Arm Technology: http://www.asc-csa.gc.ca/eng/canadarm/robotic.asp

[45] International Space Exploration Coordination Group (ISECG) (September 2013). *Benefits Stemming from Space Exploration.* https://www.nasa.gov/sites/default/files/files/Benefits-Stemming-from-Space-Exploration-2013-TAGGED.pdf

[46] National Aeronautics and Space Administration. Reference Guide to the International Space Station: Assembly Complete Edition. (November 2010). Accessed on August 19, 2015 at http://www.nasa.gov/pdf/508318main_ISS_ref_guide_nov2010.pdf.

#### 4.2.5.1 *Efficiency of the SSP*

There was general agreement among CSA representatives and external interviewees that the ISS Assembly and Maintenance Operations SSP is being delivered as efficiently as possible. A representative from NASA noted that the Canadian system ground control is situated in St-Hubert, Quebec – which is unique for NASA (to have a critical function located outside of the US). He further noted that this arrangement illustrates the trust NASA has in Canada and in the CSA. This interviewee stated that the fact that the Canada does not have a large team in Houston has saved the CSA money. He also noted that in addition to efficiently delivering ground control operations, the certification program (training) is also efficiently delivered by the CSA.

A few CSA representatives noted that the CSA cannot increase efficiency any further without increasing risks "exponentially." A few of these interviewees noted that there is not a lot of redundancy in terms of staffing within the ISS Program group at the CSA, and from a risk management perspective they probably need a few more staff. One interviewee explained that staff do not take time off/vacations when there is an operation underway – all existing staff need to be involved. This perspective was echoed by an external interviewee who noted that MDA has tried to keep their staffing numbers as low as possible, and sometimes this has meant that they don't have the staff needed when there are deliverables – there have been some delays as a result of this.

Table 12 summarizes the data on expenditures and MSS operational hours over the years and calculates the cost per MSS operational hour for each year. In 2013-14 CSA Finance began to split out the costs associated with the Common System Operating Costs (CSOC). The CSOC costs are the fees associated with the 2.3% share in the ISS allocated to Canada while the remaining costs (excluding CSOC costs) are the costs associated with Canada's obligations to operate the MSS and are thus not direct costs related to the on-going operations of the MSS. As such, the expenditures presented in the table overstate the actual cost per operational hour of the MSS. CSA and external interviewees believe the SSP has become more efficient over time because of increased automation and experience – as similar operations are repeated over time they become routine and thus the cost per hour of operation should have decreased over time.

However, as shown in Table 12, while the cost per hour declined over the first three years, it has since fluctuated. Cost per hour is influenced by two main factors. First, unplanned events can dramatically affect costs. Any on-orbit failure can add millions of dollars to O&M expenditures and consequently the cost per operational hour will increase for that year. Second, if NASA decides to reduce the usage of the MSS (for reasons not related to its performance/availability), then the number of operational hours declines for the year, which increases the cost per operational hour.

*Table 12: Cost per Hour of MSS Operations, 2008-09 to 2014-15*

| | 2008-09 | 2009-10 | 2010-11 | 2011-12 | 2012-13 | 2013-14 | 2014-15 |
|---|---|---|---|---|---|---|---|
| Number of MSS Operational Hours | 570 | 680 | 735 | 545 | 840 | 640 | 600 |
| Expenses (Actual Expenditures) ('000s) | 56,935 | 50,919 | 41,740 | 41,993 | 39,386 | 41,184* | 40,466* |
| Expenses CSOC 2016-2020 ('000s)** | --- | --- | --- | --- | --- | 6,319 | 11,645 |
| Expenditures (Actual) per Hour of Operations ('000s)*** | 99.89 | 74.88 | 56.79 | 77.05 | 46.89 | 64.35* | 67.44* |

Source: CSA ISS Assembly and Maintenance Operations SSP Performance Data, August 2015 and CSA financial data.
*Excluding CSOC.
**CSOC expenses not broken out from total expenditures prior to fiscal 2013-14.
***Costs per hour of operation for 2013-14 and 2014-15 including the CSOC are $74.22 and $86.85 respectively ('000s).

The representative from NASA commented that the CSA has been doing more with Dextre and this has increased efficiency of the ISS Program as a whole and reduced the need for EVA and spacewalks. Offloading more routine tasks to the robots results in more efficient and effective use of astronauts' time. Astronauts interviewed by the study indicated that Dextre makes spacewalks more efficient, provides capability to do things an astronaut cannot do with both hands; without Dextre, spacewalks would be more difficult. These interviewees believe that on-going improvements to Dextre will further this efficiency and effectiveness.

According to an interviewee external to the CSA, the rates paid to the prime contractor are negotiated every year and generally this goes well. The prime contractor's (i.e., MDA) profit is limited as per the contract clauses. The workload tasks are renewed every March, involving a great deal of work between January and March of every year.

#### *4.2.5.2 Overhead Costs*

CSA representatives report that the number of staff who work on ISS Assembly and Maintenance Operations has decreased in recent years (see Table 7 in section 4.2.1.4.1). However, one interviewee noted that such comparisons are not necessarily accurate because some activities have been shifted from the program to corporate services and vice-versa. Nevertheless there is agreement among CSA representatives that the number of staff has decreased and the volume of activity has increased at the same time – meaning that the program is in fact doing more with fewer staff.

A few external interviewees noted that there is lots of administration at MDA, PSPC, and the CSA related to managing the contract – however not much can be done about it given the complexity of the program, value of the contract and the accountability requirements. Recommendations stemming from the audit of the management of the MDA contract completed in 2012 are listed in section 2.5 of this report.

#### *4.2.5.3 Possible Improvements or Increases to Efficiency and/or Effectiveness*

Few interviewees were able to provide suggestions for improving the efficiency and/or effectiveness of the ISS Assembly and Maintenance Operations SSP.

A few CSA representatives reported that they have been asked to outsource the program – meaning shift more work to the private sector (i.e., to MDA). Program managers are currently working on a proposal for CSA senior management on how to do this. However, a few interviewees question whether this will result in increased efficiency or cost savings. Although it is beyond the scope of this evaluation to verify, there is a sense among some CSA interviewees that public servants (i.e., CSA staff) cost less than MDA employees. Another issue with outsourcing more of the activities relates to the international implications of the program – a few CSA representatives noted that there is a need to ensure appropriate government representation at meetings and for oversight purposes given this is an international project. One interviewee external to CSA noted the only way to reduce costs is at MDA.

CSA representatives interviewed were not able to provide suggestions for reducing overhead and input costs for producing outputs without significantly increasing associated risks.

One CSA representative noted that the CSA cannot reduce CSA staff too drastically because CSA needs to maintain some corporate memory. They cannot afford to lose all the expertise they have built up over the years – this could jeopardize CSA's ability to participate in future missions. So this interviewee argues that there is a need to balance staffing between being efficient and as low cost as possible and the need to maintain capacity and making sure to replace people who retire.

#### *4.2.5.4 Value from the SSP and Return on Investment*

There was consensus among interviewees that Canada has received good value from its contribution to the ISS Program. A few CSA representatives argued that the value of the benefits Canada receives from participation in ISS exceed the 2.3% of the cost of the ISS. For example, one interviewee noted that as a partner in ISS Canada is able to access various payloads and facilities – Canada doesn't pay for the facilities.

One CSA representative noted that Canada owes NASA $95 million over the next five years under the Common System Operating Costs (CSOC) and so the CSA has negotiated things like the building of electronic platform spares, and video convertors, among other things. So this will result in fluctuations in program spending of as much as $10 million per year since 2013. This is being spent in Canada rather than through a transfer of funds to the US. As indicated previously in Table 12, in 2013-14 the CSA provided the equivalent of $6,319 million and $11,645 million (actual expenditures) in 2014-15 towards the $95 million the CSA owes NASA under CSOC for 2016 to 2020.

No one interviewed was able to provide a credible assessment of Canada's return on investment nor did the performance data allow for such an assessment to be made.

#### 4.2.5.5 Internal Risk Reserve

According to CSA representatives, there is no internal risk reserve. Most interviewees explained that the program funds its risks from within the CSA, and the CSA always has sufficient surplus to cover the risks. There is a framework for managing risks where the program identifies and quantifies all the risks and they then make a submission to the CSA Executive. There is agreement that this process generally works well because the nature of space projects is such that even with the best planning things happen which impact the budget. By having an internal risk reserve, the CSA would risk lapsing the funds.

A few interviewees explained that any failure on the ISS (and these are unexpected) affects the program's budget. Even if a spare is available, it still costs the program a significant amount to fix.

## 4.3 Program Delivery – Roles and Responsibilities

### 4.3.1 Relationships among ISS Program Partners

The ISS Program is implemented under a multinational IGA that has Treaty status. The IGA and MOU (CSA-SS-CS-0011) provide for each partner to build, operate and maintain the equipment it contributes to the Space Station, and in addition pay a share of the common systems operating costs. Canada's share of the ISS utilization and common systems operating costs was established as 2.3%. The full role and responsibility for Canada in this international program is summarized below.

From Article 7 of the IGA, CSA is responsible for the:

- management of its own program including its utilization activities;
- systems engineering and integration of MSS;
- development and implementation of detailed safety requirements and plans for the MSS; and
- support to the US in planning for and coordination of the execution of the integrated operation of the ISS.

In accordance with the provisions of the NASA/CSA MOU, Canada is obligated to:

- support the operations of the MSS;
- provide MSS training to crew and ground support personnel;
- develop and implement procedures for operating the MSS in a safe, efficient and effective manner;
- provide logistics and sustaining engineering for each Canadian element throughout the life cycle of the ISS; and
- provide required spares and to repair MSS hardware that fails on-orbit

According to a 2014 document on lessons learned produced by NASA, the development of the ISS evolved over time – it changed because of financial constraints, technical issues, and political policy changes. The lesson learned is that it is important to have a good framework for the program that allows for adaptation. The original ISS agreements provided a framework that was not so precise and detailed to be limiting when things started to change, but it had to be clear enough that everyone had common understanding and was working towards the same goals.[47]

Over time, each of the ISS partners has had their share of domestic issues. This makes it important for the partners to understand one another's environments. Many of the issues are discussed at the multilateral coordination board (MCB) – which is the board at the NASA Human Exploration & Operations Mission Directorate (HEOMD) level – and with the NASA administrator and his counterparts at the heads of agency level (HOA). Topics discussed at the MCB and HOA forums include the political environment, space policy, a change in administration, and economic issues that are coming up. The lesson learned from the perspective of managing the project and roles and responsibilities is that open communications between partners is a key element in maintaining strong partnerships.[48]

### 4.3.2 Roles and Responsibilities within the CSA

The ISS Intergovernmental Agreement (IGA) and MOU documents spell out roles, duties and commitments and responsibilities for the partnership.[49] In addition, the CSA's Operations Implementation Plan provides a detailed program level description of the management structure, organizational responsibilities and key processes that have been put in place by the CSA to meet its ISS MSS obligations.[50]

The Director General (DG), Space Exploration, is the responsible manager within CSA for Space Exploration. He is accountable to the President of the CSA for the conduct of the program. The DG chairs the Space Exploration Management Committee (SEMC) to ensure effective coordination of all financial or human resources across the SPs under his authority (International Space Station (1.2.1), Space Exploration Missions and Technology (1.2.2) and Human Space Missions and Support (1.2.3)). The directors are responsible to action the decisions made during the SEMC that pertain to their respective directorate. Managers direct their employees toward the execution and implementation of those activities. A complete description of the governance structure for the ISS Assembly and Maintenance Operations SSP (1.2.1.1) is documented in the CSSP Operations and Implementation Plan (OIP), CSA-SS-PL-0195 (current revision).

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[47] Lengyel, David M, Newman, Stephen J. (September 2014). *International Space Station Lessons Learned for Space Exploration.* http://www.nasa.gov/externalflash/iss-lessons-learned/docs/report_ISSLessonsLearned.pdf
[48] Ibid.
[49] Ibid.
[50] Canadian Space Agency. (2012). *Canadian Space Station Program Operations Implementation Plan - MSS-Operations*. Revision B (March 14, 2012). (CSA number: CSA-SS-PL-0195)

### 4.3.3 Contract Management

Contract support for MSS Operations is provided by a dedicated team from within the CSSP (Project Engineering) and from PSPC resources, supported by the corporate CSA procurements group within Finance. PSPC resources are specifically responsible to support the Logistics & Sustaining Engineering (L&SE) manager in the negotiation and management of the major L&SE Contract with the prime contractor. Contract management must be effected in accordance with pertinent Government of Canada and CSA rules and policies.

The contract with MDA for ISS Assembly and Maintenance Operations SSP is Task Authorization based; all work is subsequently defined and costed as discrete task orders. Work performed under the proposed contract is authorized by the CSA, under the supervision and approval of PSPC acting as the Contractual Authority. With PSPC support services being maintained on-site at the St-Hubert facility, integrated processes are in place to support the development, review and approval of task orders as well as the monitoring and control of the contract cost. Thus, these individual task orders are managed effectively as individual contracts, issued with controlled scope and specific deliverables.

The CSSP, including PSPC support, is equipped with a structured administrative process enabling it to authorize the work to be carried out by the contractor on an "as and when requested basis'' in accordance with the terms and conditions of the contract. Typically, the CSA issues no less than twenty-five Task Authorizations per fiscal year, roughly accounting for the core $27M per year of the proposal. Monitoring and control of the project's technical performance as well as contract cost is in place by way of an established set of tools. These tools have been historically developed and proven to ensure thorough L&SE technical and contract cost management. This was most recently validated by an independent audit performed by CSA's Audit and Evaluation Directorate in April 2012 on the CSSP, specifically aimed at determining whether the management framework is in place to achieve CSA objectives.

There was consensus among interviewees that the roles and responsibilities are clear and appropriate. No issues or challenges with respect to roles and responsibilities were identified.

# 5 Conclusions and Recommendations

## 5.1 Relevance

The evaluation findings strongly indicate that the ISS Assembly and Maintenance Operations SSP remains relevant.

The evaluation found evidence that the decision in the late 1980s to participate in the ISS Program was largely motivated by geopolitical concerns. The US was intent on building a space station with the participation of its western allies as a response to the Soviet Mir space station which had been launched in 1986. Canada was also attracted to the opportunity to join an "exclusive club" with other G7 nations. Interviewees noted that Canada's invitation to participate was based on its excellent track record in supporting the Space Shuttle Program together with Canada's unique expertise in space robotics – a capability that the US did not possess at the time. According to NASA representatives interviewed for the evaluation, Canada's participation was critical to the construction and operations of the ISS. Furthermore, participation in the ISS Program was expected to enable Canada to reap the technological and socio-economic benefits resulting from the development of space robotics.

Although the decision to extend Canada's participation in the ISS Program to 2024 is viewed by interviewees as a sound one, the decision has budgetary implications for the CSA. As the ISS ages, repairs and the need for replacement parts will become increasingly necessary, i.e., risk of failures will increase. There is a sense among many individuals interviewed for this evaluation that the ISS could remain operational beyond 2024 and this is viewed positively because this will increase the potential utilization of the ISS for scientific purposes. It will also ensure that the IP developed under the ISS Program will continue to remain in Canada.

Canada's continued participation in the ISS Program will permit increased utilization (i.e., utilization over a longer period of time) and will provide Canada with the opportunity to participate in the dialogue about the next step beyond the ISS. Possible next steps include such missions as establishing a space outpost further out into space, possibly in the lunar vicinity as a staging post for the ultimate objective of landing a human on Mars in the distant future. Thereby placing Canada among an elite group of nations involved in space exploration.

The SSP is strongly aligned with current federal priorities as identified in *Canada's Space Policy Framework* and *Budget 2015*. The ISS Program is specifically noted in all of these documents.

Given participation in the ISS Program takes place in the context of an international agreement, it is appropriate that the federal government be responsible for managing Canada's commitments. The CSA's responsibility for the program is consistent with the *CSA Act* which states that the Agency is authorized "to cooperate with the space and space-related agencies of other countries in the peaceful use of space."

## 5.2 Performance

The ISS Assembly and Maintenance Operations SSP is an enabler for other CSA programs linking to the ISS Program in the CSA PAA. As such, some of the outcomes and indicators addressed in this evaluation are not within the direct control of the ISS Assembly and Maintenance Operations SSP.

### 5.2.1 Immediate Outcomes

The ISS Program represents Canada's only opportunity for human space flight. Notably the ISS Assembly and Maintenance Operations SSP does not have a direct influence over opportunities for human space flight – the SSP enables Canada to access opportunities for space flight by successfully delivering on its obligations for operations and maintenance of the ISS. Likewise the SSP enables Canada to take advantage of opportunities to utilize the ISS for scientific experiments and research.

The SSP has consistently met all ISS Program requirements with the use of Canadarm2 and Dextre on the ISS becoming routine. The number of operational hours has fluctuated between 545 and 840 hours per year, depending on ISS Program requirements.

There is strong evidence that the SSP has directly enabled Canada to maintain its leadership role in space robotics. In fact, Canada was invited to participate in the ISS Program because of its leadership role in this field and policy decisions made as far back as the 1980s have served to maintain Canada's leadership role in space robotics to the present day. Canada continues to be recognized for its leadership role in space robotics as evidenced by invitations to participate in international missions requiring space robotics. However budgetary challenges at the CSA have limited Canada's participation. Although Canada remains a world leader in space robotics, this position cannot be taken for granted because other countries are working on enhancing their capacity, including the US, Japan, Russia and ESA Member States. There is thus evidence of a need for Canada to actively work to maintain its capacity through participation in space missions involving space robotics.

**Recommendation 1: The CSA should assess the importance of maintaining Canada's leadership role in space robotics and the measures to be taken if Canada is to maintain a leadership position in space robotics.**

There is strong evidence that the SSP has resulted in technological innovations and this has served to maintain Canada's leadership in space robotics. The most tangible and important innovation is the use of ground command to manoeuvre Dextre and Canadarm2. This innovation has decreased the costs of operations and reduced the need to use astronauts, thereby increasing astronaut safety and freeing up time for them to work on other activities, such as science.

There is strong evidence that Canada's reputation among international partners on the ISS Program has been maintained as a direct result of innovative solutions for the repair and maintenance of the ISS developed by Canada. Also, there is evidence that Canada has been able to develop new approaches and technologies in response to evolving needs of ISS partners. Although Canada's contribution represents 2.3% of the total ISS Program, Canada is seen by its partners as having more influence internationally than its size would suggest.

The SSP has contributed to maintaining employment for HQPs at the CSA and at the prime contractor's facility in Brampton, Ontario. In addition to employment of HQPs, the SSP also provides training to HQPs, including astronauts and ground personnel. There is evidence from the interviews that CSA staff believe their career potential is somewhat limited as a result of a lack of other large scale missions within the CSA. There is also some evidence that opportunities for space sector HQPs are limited within Canada and this has resulted in some "brain drain" with Canadian HQPs leaving to work in the US. However, this conclusion is based on only a limited number of interviews.

The ISS Assembly and Maintenance Operations SSP is not directly responsible for public awareness of ISS technology – this is the direct responsibility of the CSA Communications and Public Affairs Directorate. Statistics provided by the Communications and Public Affairs Directorate and the key informant interviews indicate that Canadians are being informed of ISS technology through a variety of means, including videos, online information, press releases, public events, etc. The CSA has developed educational tools and kits directed at youth for the past three missions involving Canadian astronauts (Thirsk, Payette and Hadfield).

### 5.2.2 Intermediate Outcomes

Evidence from the evaluation provides a strong indication that know-how is being transferred from the ISS Assembly and Maintenance Operations SSP to non-space uses in such sectors as health care and the nuclear industry. The evidence, particularly from the three case studies (NeuroArm, IGAR, and KidsArm), indicates that the transfer of know-how is a long process, requiring many years and substantial financial investment. Although the transfer of know-how is occurring, some interviewees feel that Canada is not doing enough to fully reap the benefits of the space robotics technologies developed for the ISS Assembly and Maintenance Operations SSP. However, the CSA is limited in its ability to directly facilitate commercialization of the technologies because MDA has the sole licence for commercialization of the ISS technologies it has developed.

**Recommendation 2: The CSA should assess options for increasing the commercialization and transfer of technologies from the ISS Program to other areas. Discussions should be held with other federal departments and agencies involved as well as with the prime contractor. This assessment should consider best practices and lessons learned from other ISS Program partners, particularly NASA.**

Based on evaluation findings, MDA, the prime contractor for the SSP, has successfully leveraged its experience with the ISS Assembly and Maintenance Operations SSP. Based on interviews with MDA representatives, the evaluation found that MDA has been able to build on relationships developed through its work on the SSP. While MDA has obtained some revenue from the sale of grapple fixtures to other space agencies and companies, the company has not yet obtained any revenues from other products, technologies, services or processes, although numerous patents have been registered.

There is evidence from research in the US that the inspirational aspects of space exploration contribute, over the long term, to increasing interest in science and technology among youth and the general public. Inspiring youth contributes, over the long term, to an increased proportion of young people pursuing careers in the sciences and engineering. The inspirational aspect of the ISS Program has been recognized in *Canada's Space Policy Framework*. There is evidence that CSA's communications and Public Affairs related to the ISS Program have been targeted at inspiring Canadians, particularly youth in elementary and high school.

### 5.2.3 Ultimate Outcome

The evaluation found evidence that the ISS Assembly and Maintenance Operations SSP has and will continue to contribute to social and economic growth. The linkage between space exploration and social and economic benefits is recognized in the academic literature and policy documents of ISS partners; however attempts to quantify these benefits tend to be unsuccessful. Quantifying the benefits of space exploration is challenging because of the long term nature of the benefits and the often indirect linkages between the space technologies and the ultimate benefits.

With respect to the unexpected benefits, key among these is the fostering of international relationships, particularly with Russia. The international community's relationship with Russia has been tense in recent years, however work on the ISS has continued and this has served to keep lines of communication between Russia and other countries open. Another unexpected benefit resulting from the SSP has been the media attention paid to Canadarm2, Dextre and the CSA.

## 5.3 Efficiency and Economy

Based on available evidence, the evaluation found that the SSP is being delivered as efficiently as possible. Overall, there is evidence that the SSP has slowly become more efficient over the time period of the evaluation because of increased automation and because of experience/practice. Increasing efficiency further through decreasing staffing may result in increased risk. Further erosion in staffing numbers may also eliminate existing redundancy in staffing and put the program at risk. No viable options for increasing efficiency of the SSP were identified in the evaluation. The contract with the prime contractor is very tightly managed by the CSA, PSPC and MDA, as is appropriate for a contract of this size and duration, and profit is monitored and limited as per the contract clauses, thus providing good value to Canadians.

The SSP does not have a risk reserve and based on evaluation findings, there does not appear to be a need for putting one in place. The CSA's approach is to manage risks through reallocating resources internally within the CSA. This process works well because the nature of space projects is such that delays are frequent and thus being able to reallocate resources internally minimizes the lapsing of funds.

## 5.4 Program Delivery

The ISS Assembly and Maintenance Operations SSP has clearly defined roles and responsibilities which are documented in various documents. No challenges related to the roles and responsibilities within the CSA, between the CSA and other federal departments (i.e., PSPC) or between Canada and other ISS Program partners were identified.

As noted previously in this report, the ISS Assembly and Maintenance Operations SSP is an enabler program in that it is intended to ensure that the ISS continues to be operational and is being maintained. Although the ISS Assembly and Maintenance Operations SSP does not have direct influence over availability of opportunities for human space flight or for ISS utilization, the program does directly enable the achievement of these objectives. The distinction between the ISS Assembly and Maintenance Operations SSP and the other ISS Program components (Human Space Missions Support – 1.2.3 and ISS Utilization – 1.2.1.2) may thus seem somewhat artificial as the evaluation findings reflect, in some instances, the outcomes for the ISS Program overall rather than just for the ISS Assembly and Maintenance Operations SSP. Some of these outcomes will be covered in greater depth in a distinct evaluation.

## Management Response and Action Plan

| | RESPONSIBILITY ORGANIZATION / FUNCTION | MANAGEMENT RESPONSE | DETAILS OF ACTION PLAN | SCHEDULE |
|---|---|---|---|---|
| RECOMMENDATION # 1 | | | | |
| The CSA should assess the importance of maintaining Canada's leadership role in space robotics and the measures to be taken if Canada is to maintain a leadership position in space robotics. | Director General, Space Exploration (DG-SE)<br><br>with support from Director General, Space Science and Technology (DG-SST) and Director General, Policy (DG-POL) | Management agrees with the recommendation and DG-SE will perform an assessment of Canada's current competitive position and outlook in the field of space robotics.<br><br>DG-SE will recommend how best to position Canada to advance space robotics competencies and capabilities, including for example Canada's potential participation in on-orbit servicing, space infrastructure and planetary exploration missions. | DG-SE will form a team tasked with producing a report on the state of Canada's space robotics, including SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats), technology and cost assessments.<br><br>DG-SE will update mission and technology roadmaps; identify and prioritize technology developments and mission opportunities involving space robotics and related technologies.<br><br>The results of this work will inform government's decisions on future investments in space robotics. | Final report to be released by July 2016<br><br>Final report to be released by September 2016 |

| | RESPONSIBILITY ORGANIZATION / FUNCTION | MANAGEMENT RESPONSE | DETAILS OF ACTION PLAN | SCHEDULE |
|---|---|---|---|---|
| | | | | |
| RECOMMENDATION # 2 | | | | |
| The CSA should assess options for increasing the commercialization and transfer of technologies from the ISS Program to other areas. Discussions should be held with other federal departments and agencies involved as well as with the prime contractor. This assessment should consider best practices and lessons learned from other ISS Program partners, particularly NASA. | DG-SE with support from<br><br>DG-SST and DG-POL | Management agrees with the recommendation and will assess options for improving the commercialization and transfer of ISS technologies, in consultation with industry, other government departments and international partners.<br><br>CSA has already provided an open license to Canadian industry for all Intellectual Property (IP) developed under the original MSS Program. In addition, a license to use the IP developed under the Special Purpose Dextrous Manipulator (SPDM/Dextre) Contract has been granted to MDA Ltd. This has already led to the commercialization of MSS IP through implementation on products like Neuro Arm, Kids Arm and IGAR developed for the medical industry. It is expected that newer developments from this IP will continue in the future. | In consultation with industry and other government departments, taking into account best practices and lessons learned, DG-SE will propose specific actions to augment the economic impacts, spinoffs and day-to-day benefits stemming from space robotics. In relation to Recommendation #1, CSA will strive to prioritize those technologies with the highest potential for socio-economic benefits (multiple applications and multiple destinations). | Presentation to CSA's Executive Committee by November 2016 |

# Appendix A: Logic Model Narrative

## Activities and Outputs

| Activity | Narrative | Outputs[51] |
|---|---|---|
| A1 - Prepare Products for Planned MSS Operations | CSA develops and delivers all the necessary operational products to support planned MSS operations | Op3.1<br>▪ Develop, review and/or verify the **MSS Flight Products** to be used in support of planned MSS Operations. These flight products include:<br>- Procedures,<br>- Station Program Notes,<br>- Flight Rules, and<br>- MSS Recon files and supporting documentation.<br>▪ Performs the **Dynamic Analysis** in support MSS Operations planning and execution.<br>▪ Supports the development of **MSS user and performance requirements**. |
| A2 - Provide Real-Time MSS Operations Support | When operations are underway, then CSA provides real-time operational and technical support both on-site at CSA and at the NASA Johnson Space Center to meet its commitments to be able to continue operations even if problems arise. | Op3.2<br>This activity includes the manning and certification of the following operational positions:<br>▪ **Remote Multi-Purpose Support Room** (R-MPSR)<br>- System, Task and ROBO Flight Controller<br>▪ **Operations Engineering Centre** (OEC)<br>- OEC Lead<br>- Engineering Support Lead (ESL)<br>- Support Engineer |

[51] Outputs' delivery meeting the IGA requirements may be provided in part by private enterprises through contracts awarded by th e CSA's ISS Assembly and Maintenance Operations SSP management.

| Activity | Narrative | Outputs[51] |
|---|---|---|
| | | - Flight Planning Lead (FPL)<br>▪ **Increment Management Center** (IMC)<br>- IP Canada position<br>▪ **Mission Evaluation Room** (MER)<br>- Extravehicular Robotics (EVR) position. |
| A3 - Maintain MOC Infrastructure Current | To carry out the requirement to provide real-time support, CSA has developed a ground infrastructure comprising in part the R-MPSR and the OEC which are connected to the ISS/NASA ground infrastructure. As a result, access to real time ISS telemetry as well as commanding through to the ISS is possible from CSA. | Op3.3<br>Provide and maintain the **Mission Operations Centre (MOC) facilities** required to conduct training and real-time operations support. This includes:<br>▪ development, maintenance, upgrade, reconfiguration, test, verification, validation and certification activities,<br>▪ performing a real-time operation function in support of mission execution by providing real-time system administration, backup, monitoring, reconfiguration and recovery from system failures for all elements of the MOC as required,<br>▪ support procedure development and procedure validation activities. |
| A4 - Train MSS Astronauts and Ground Personnel | In order to meet the Government of Canada priority, CSA and its MSS prime contractor frequently conduct MSS training sessions for both astronauts and ground support personnel. A ground infrastructure comprising an MSS simulator, a multi-purpose learning centre, and other training equipment have been built to enable this critical activity. | Op3.4<br>Provide **training to astronaut and ground personnel**.<br>Training courses provided are:<br>▪ MSS Robotics Operator<br>▪ CAPCOM<br>▪ MSS Mission Controller Part 1<br>▪ MSS Mission Controller Part 2, and<br>▪ MSS Mission Controller Part 3 |
| A5 - Provide MSS Engineering Support and Maintenance | Operation of ISS requires dedicated real time support from the engineering team to monitor system performance and react | Op.3.5<br>▪ Develop an **integrated logistics support system** for the MSS and support the development of the integrated logistics management capability for the |

| Activity | Narrative | Outputs[51] |
|---|---|---|
| | to possible anomalies. | Space Station Program, including re-supply, on-board maintenance and inventory integration.<br>▪ Provision of sustaining engineering support for the MSS including direct engineering support of all on-orbit operations. Support the execution of all MSS maintenance activities as required.<br>▪ Develop and provide regular **MSS software fixes and upgrades** as prioritized by the program. Synchronize the delivery of MSS software with the ISS Program.<br>▪ **Logistics support operations** (including the provision of spares), and **logistics support space system operations** (i.e., post-landing logistics support). |
| A6 - Manage MSS Operations | CSA participates in a number of major ISS Boards and Panels through which all critical ISS decisions are made. This Canadian participation enables CSA to use its influence to ensure Canadian objectives are not compromised. Finally, Canada is responsible to formally certify that the on-orbit MSS and all of its supporting assets (people, facilities, operational products, etc.) are prepared to support specific ISS mission increments. | Op3.6<br>▪ Support the **overall program management and coordination** for detailed design and development of an integrated Space Station and manage tactical and strategic development of the CSA-provided elements.<br>▪ Manage the **MSS Certification of Flight Readiness** (CoFR) activity and ensure that MSS is certified for all ISS increments.<br>▪ **Participate with NASA and the other partners** in Space Station Program management mechanisms. |

### Immediate Outcomes

**Imm1 Canada has maintained or increased opportunity for human space flight and ISS utilization**
In return to its contribution of the MSS and its continuing operations, Canada has the right to utilize 2.3% of the ISS user accommodations for research activities, i.e., science, and 2.3% of the on-orbit crew time to operate them. Canada has also the right to provide Canadian astronauts for 2.3% of the ISS crew flight opportunities.[52] The ISS provides scientists and engineers with on-going access to the unique microgravity environment of space. As a permanent space laboratory, the ISS allows scientists and engineers to use this unique venue to discover or test new materials, crystals and processes. Research is conducted in a variety of fields such as life sciences, materials, Earth observation and astronomy. The expertise on the ISS gained through the Assembly and Maintenance Operations SSP may inform human space flights and ISS utilization.

**Imm2 Canada's leadership role in space robotics maintained or enhanced**
As a result of successfully operating, maintaining and managing the MSS as per the IGA obligations, Canada's leadership role in space robotics is maintained or enhanced with each successful operation using Canadarm2 and Dextre. The MSS, the external robotic system, has been critical for successful assembly and maintenance of the ISS since 2001.

**Imm3 Canada's reputation among international partners maintained or enhanced**
By successfully maintaining, operating and managing the MSS as per the IGA obligations, Canada's reputation for reliability, innovation and technical skill is maintained or enhanced among the ISS international partners (NASA, JAXA, ESA, and the Russian Federal Space Agency).

**Imm4 Canadian space sector capability and Highly Qualified Personnel (HQP) maintained or increased**
The on-going operations of the MSS will contribute to maintaining or increasing the capability of Canada as well as its HQPs in the space sector by providing on-going training and the potential to maintain HQP skills. Canadian space sector capability refers to private companies and the academic community, conceiving missions, developing scientific instruments and analyzing space-generated data. At CSA, HQPs are defined as engineers, scientists and technicians that are employed in the Canadian space sector.[53]

**Imm5 Canadian public informed on ISS technology (exploits in space)** – *Not within the program's point of accountability.*
This outcome is within the mandate of the CSA's Communications and Public Affairs Directorate which is to inform Canadians on the ISS Program, more specifically on MSS operations, its technology, science and astronaut activities and the benefits that accrue from it. This outcome should ultimately lead to Canadians being interested in and inspired by space exploration. There is also literature that supports

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[52] In compliance with CSA's Program Alignment Architecture and Departmental Evaluation Plan 2015-2016 to 2019-2020, CSA's Human Space Missions Support SP and ISS Utilization SSP will be subject to a distinct evaluation.
[53] http://www.asc-csa.gc.ca/pdf/eng/industry/state-2012.pdf, page 17

the idea that such communication contributes, over the long-term, to Canadians, including youth, becoming more interested in the math, science and engineering and thus over time broadening the space exploration stakeholder base and HQPs.[54]

### Intermediate Outcomes

**Int1 – Transfer of know-how and technology to other applications**

This SSP provides the challenge to industry to develop the high level of ingenuity needed in developing technology and operational solutions that allow machines and humans to function in space. This work by the Canadian industry generates know-how and innovative technology that is often applied for other purposes either in space or on Earth. Initially the adaption to a new application may be done on a small scale for a particular purpose. An increased ability to capitalize on experience with ISS, particularly with respect to space robotics (Imm2); increased opportunity to participate in space missions (Imm1) and this further developing and testing technologies will all contribute to know-how from space exploration (and ISS in particular) to other applications.

**Int2 - Canadian space sector positioned to capitalize on experience with ISS**

Canada's experience in manned space flight and research on the ISS (Imm1); leadership in space robotics (Imm2), strong reputation with international partners (Imm3), and capability and pool of highly trained HQPs (Imm4) contribute to Canada's space sector being able to capitalize on its experience with ISS, particularly with respect to accessing international space sector markets. Given the relatively small size of the space exploration program in comparison to that of some other nations, Canada's preferred option is to collaborate as a partner in international space exploration missions led by other space agencies.

**Int3 - Broadened space exploration stakeholder base**

This refers to expanding the number of individuals and types of organizations in Canada who have an interest in space exploration endeavours. On the individual level, this SSP contributes to increasing the number of Canadian citizens engaged in space exploration activities, whether they are specialists (i.e., HQP) or not. At the organization level, this SSP contributes to increasing the number and types of organizations involved in space exploration, whether they are private companies, academic institutions or governmental entities, hence broadening the space exploration stakeholder base. It is hypothesized that the ISS Assembly and Maintenance Operations SSP, by the outputs it delivers, should contribute to inspire Canadian citizens. Increased level of information on the part of Canadians (Imm5) and the capacity and strong contingent of HQPs in the space sector contribute to broadening the space exploration stakeholder base.

[54] International Space Exploration Coordination Group (ISECG), *Benefits Stemming from Space Exploration*, September 2013. http://www.nasa.gov/sites/default/files/files/Benefits-Stemming-from-Space-Exploration-2013-TAGGED.pdf. Accessed March 3, 2015.

### Ultimate Outcome

**Oc8 – New products, processes and technologies that contribute to socio-economic growth**

Some of the products, processes and technologies initially transferred to new applications on a small scale may eventually prove to be so useful that they become commercially viable and make significant contributions to economic growth. Social benefits derive from space exploration via the research and technologies developed for space exploration which are transferable to Earth and which contribute to solving problems on Earth – in areas such as varied as climate change, healthcare, water supply, energy. There is credible literature on these linkages.[55] Space agencies have documented a large number of examples of products, processes and technologies developed for space exploration that have been adapted for non-space consumer products and services. Int2 contributes to this outcome via increased opportunities for spin-offs from work related to the ISS. Int3 contributes because as the stakeholder base increases, it opens new avenues to new participants to expand the economic sphere. Int1 contributes because those adaptations from space-use to non-space use (new consumer products) contribute to job creation in the industry or academic sectors and generate higher economic growth in general.

[55] European Commission – Space Policy and Coordination Unit, Space Exploration and Innovation: Summary Report. October 3, 2010. http://ec.europa.eu/enterprise/policies/space/files/policy/final_technopolis_report_en.pdf. Accessed March 3, 2015.

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# Appendix C: Case Study Summary Findings

**Evaluation of the CSA's International Space Station Assembly and Maintenance Operations Sub-Sub-Program – Case Studies**

**Case Studies: Summary Overview**

**Introduction**

This appendix presents a summary overview, and the case studies, of the three technologies selected for case studies for this evaluation:

1) ***NeuroArm:*** a highly precise robotic arm that works in conjunction with the advanced imaging capabilities of magnetic resonance imaging (MRI) systems to perform neurosurgical procedures.
2) ***IGAR (Image Guided Automated Robot):*** a robotic platform that will enable automated image-guided minimally invasive procedures for the treatment of various conditions. The first platform developed is the IGAR Breast Robot, which integrates seamlessly within a magnetic resonance imaging (MRI) system allowing a radiologist to select a target on a patient's scan and then confidently direct the intervention with millimeter accuracy.
3) ***KidsArm:*** an autonomous image guided robotic arm intended to perform anastomosis (suture/reconnect delicate vessels such as veins, arteries, or intestines) on pediatric patients from neonates to 4 years old.

The case studies cover the following evaluation questions:

- ***Transfer of Know-how and Technology***: Examples of transfer of know-how and technology from the ISS Assembly and Maintenance Operations SSP to other industries/uses (spin-offs);
- ***Commercial Development, Patents, Trademarks:*** Examples of patents and registered trademarks resulting from Canada's participation in this ISS Assembly and Maintenance Operations SSP (focused on non-space);
- ***Sales Prospects:*** Value of follow on sales (revenues) from new products, processes or technologies which resulted from involvement in the ISS Assembly and Maintenance Operations SSP over the past 7 years;
- ***Conferences, Publications, Citations:*** Number of scientific/lay publications/ citations/conferences;
- ***Potential Socio-Economic Benefits:*** Examples of how the program has contributed to socio-economic growth via new products, processes and technologies;
- ***Unexpected Outcomes:*** Positive and/or negative unexpected outcomes as a result of the ISS Assembly and Maintenance Operations SSP;
- ***Follow-on Technology/Product Development***: Profiles the development of any technologies and products that follow-on from the technologies profiled in the case studies.

Each case study was based on a review of relevant documents (e.g., Internet search including project website and media coverage, conference proceedings and academic journals) and interviews with key informants (e.g., principal researchers/investigators from the medical partner and officials/engineers from MDA involved in the project).

**Transfer of Know-how and Technology**

Experience from three generations of robotic systems (Canadarm, Canadarm2, Dextre) developed by MDA for the Shuttle and International Space Station (ISS) that established Canada as the world leader in space robotics was applied to three robots for medical applications (NeuroArm, IGAR, KidsArm). The similarities between the space (Canadarm, Canadarm2, Dextre) and medical (NeuroArm, IGAR, KidsArm) robots are in the operating environments and the requirements that needed to be met to achieve full functionality. The robots operate in extreme environments (space and inside an MRI machine in the case of NeuroArm and IGAR), they involve expert users (astronaut and surgeon) dealing with delicate objects (mechanical repair in zero gravity and breast biopsies and treatment, suturing in pediatric patients from neonates to 4 years old), and custom configurations are required for both space and medical robots with very little margin for error. As well, IGAR and future generations of medical robots require an ability to be tele-operated with extreme levels of safety, durability and redundancy.

The medical device approval process particularly for invasive devices inside the body is very long lasting ten years or longer. Thus, another benefit of the participation of MDA in the development of the three medical robots was their experience going through various regulatory and approval processes with the space robots. Canadarm, Canadarm2 and Dextre all had to go through exhaustive regulatory and approval processes by the US National Aeronautics and Space Administration (NASA), similar to the regulatory approvals required for NeuroArm by the US Food and Drug Administration and by Health Canada.

The level of direct technology transfer from the development of the Canadarm, Canadarm2 and Dextre to NeuroArm, IGAR and KidsArm was the use of the same algorithm blocks in the control software that operate the medical robots. Experience with control theory, vision applications, and targeting on the ISS was also applied to NeuroArm, IGAR and KidsArm.

**Commercial Development, Patents, Trademarks**

Of the three case study technologies, NeuroArm is the furthest ahead in the commercial development process and holds the most patents, followed by the IGAR Breast Robot which is anticipated to be commercially released in 2016.

**Sales Prospects**

As none of the case study technologies have completed the lengthy regulatory and approval process required of medical devices, no revenue has been generated to-date and no data is available on anticipated sales (this includes NeuroArm which is the furthest ahead in the commercial development process).

**Conferences, Publications, Citations**

The number of conference presentations, publications, citations and awards generally reflects the level of commercial development and number of patents associated with each case study technology. For example, NeuroArm has the most with 111 presentations and demonstrations, 39 peer-reviewed publications and 9 monographs and book chapters. NeuroArm was inducted into the Space Technology

Hall of Fame (April 2014) and its principal researcher, Dr. Garnette Sutherland, University of Calgary, was a recipient of the Companion Of The Order of Canada (December 2011).

**Potential Socio-Economic Benefits**

If commercialized, NeuroArm and the IGAR Breast Robot are expected to lead to reduced incidence of surgical complications arising from more accurate positioning, shorter hospitalization and subsequent reduction in costs to the health care system, smaller incisions resulting in reduced risk of infection, reduced pain and discomfort, reduced blood loss and transfusions, faster recovery time and return to normal activities, and minimal scarring. Tele-operation will allow for access to healthcare services in rural and remote areas.

**Unexpected Outcomes**

No unexpected outcomes were noted or found with any of the case studies. There were, however, two unexpected events: one associated with NeuroArm and the other with KidsArm. In the first case, IMRIS, the company which acquired NeuroArm to complete the regulatory and approval process and commercialize the technology, filed for bankruptcy protection in the US. However, it is anticipated that IMRIS will be able to restructure and refinance its operations and continue the development work associated with NeuroArm. In the second case, Dr. Peter Kim, the general neonatal surgeon at SickKids who began work on KidsArm left mid-way through the project to assume a position in the US. Fortunately, his replacement, Dr. James Drake, Head of Neurosurgery at SickKids, ensured the successful completion of the KidsArm project. There were no unexpected outcomes associated with IGAR.

**Follow-on Technology/Product Development**

All three of the case study technologies are developing follow-on technologies/products. The developers of NeuroArm are expanding its current imaging capabilities beyond the MRI to include the use of ultrasound and Catscan technologies, and are developing CellArm which will bring the capability of NeuroArm technology down to the cellular level allowing surgeons to function at a much greater level of accuracy. The developers of the IGAR Robotic Platform are exploring other clinical procedures including lung, liver and kidney biopsy and ablation, as well as tele-operability. The next generation of KidsArm is the Minimally-Invasive Endoscopic Manipulator System (MIEMS) for neurosurgical applications in pediatric patients.

**Findings/Conclusions**

The potential commercial benefit to Canada lies in the experience and expertise developed by MDA and its application to other products and industries. Prior to MDA's involvement with NeuroArm (MDA's first medical robot), their main focus was on the space industry. Now, they are actively pursuing projects in the medical field and the nuclear industry (supporting nuclear power plants and decommissioning operation), based on the capability developed through participation in NeuroArm and other medical robotic projects (IGAR and KidsArm).

**Case Study 1: NeuroArm**

**Introduction**

NeuroArm is a highly precise robotic arm that works in conjunction with the advanced imaging capabilities of magnetic resonance imaging (MRI) systems to perform neurosurgical procedures. The NeuroArm system comprises two robotic arms capable of manipulating both specially designed and existing microsurgical tools connected via a workstation. The surgeon is positioned at the workstation and uses the human machine interface[56] to interact with the surgical site. The human machine interface provides both magnetic resonance images (MRIs) and real-time high definition 3-dimensional (3-D) images of the surgical site. Modified hand controllers enable the manipulators to emulate the surgeon's hand movements while providing the surgeon with haptic[57] force feedback.

The NeuroArm project was preceded by the development of the world's first intraoperative magnetic resonance imaging system (iMRI) within an operating room (1997). Believing that keeping the patient stationary while moving the MRI machine would be safer than moving the patient to the machine, a team led by Dr. Garnette Sutherland from the University of Calgary, created the world's first movable high field magnet. Although iMRI brought a new level of diagnostic imaging to the practice of neurosurgery, it also created a problem. Surgery had to be paused while real-time images of the patient's brain were being acquired. It was at this time when Dr. Garnette Sutherland asked the question, "Wouldn't it be great if we could continue to operate while images are being taken, in the bore of the magnet?" NeuroArm was conceived as a way of continuing to operate as images were acquired in real time.

The NeuroArm project began in September 2001 and was funded by the Canada Foundation for Innovation, Western Economic Diversification, Alberta Advanced Education and Technology and the philanthropic community of Calgary. Dr. Sutherland and his research team approached several potential collaborators and selected MacDonald, Dettwiler and Associates Ltd (MDA). The development of NeuroArm took seven years, from preliminary design review to manufacture and Health Canada regulatory approval; and built to US Food and Drug Administration standards. The initial clinical trial consisted of introducing NeuroArm into surgery in a graded fashion to account for the multiple variables a surgical robot introduces to the operating room. In May 2008, NeuroArm was used for the world's first image guided MR-compatible robotic neurosurgical procedure. To date, the NeuroArm has successfully completed over 60 neurological procedures under clinical trial setting. Dr. Sutherland performed the majority of the neurosurgical procedures, with a small number (3 to 4) of other neurosurgeons now using the technology as well.

NeuroArm is currently in the investigative use step in the approvals process in Canada and the US. The next step in the approval process is further clinical trials. Only after all regulatory approvals have been met will the product potentially be commercialized.

[56] Human-machine interface is a software application that presents information to an operator or user about the state of a process, and to accept and implement the operators control instructions.
[57] Haptic communication recreates the sense of touch by applying forces, vibrations or motions to the user.

**Transfer of Know-how and Technology**

The NeuroArm project was established as a collaborative effort between the University of Calgary and MDA. Drawing on the know-how and technology used on Canadarm, Canadarm2 and Dextre, NeuroArm combines a highly accurate MRI compatible manipulator system, image guidance, end effectors that incorporate modified neurosurgical tools, touch sensors and force feedback hand controllers that provide remote presence and control to the surgeon. The same algorithm blocks in the control software used on the ISS robotic arms operates the NeuroArm.

The design process used in the development of both sets of robotics was the same. The initial step was to create a mission scenario, outlining all of the pertinent requirements and identifying the numerous challenges to be overcome. The operational processes involved overcoming the numerous challenges (e.g. shielding electrical components inside an MRI machine) followed by the identification of anomalies and finally building in the required safety aspects and ensuring systems had built in redundancy capability.

Another benefit of the participation of MDA in the development of NeuroArm was their experience in going through various regulatory and approval processes. Canadarm, Canadarm2 and Dextre all had to go through exhaustive regulatory and approval processes by the US NASA, similar to the regulatory approvals required for NeuroArm by the US Food and Drug Administration and by Health Canada.

**Commercial Development, Patents, Trademarks**

In the time between the preliminary design review and the critical design review (2002), a company was established, NeuroArm Surgical, to hold the NeuroArm Intellectual Property (IP). In 2006, the initial patent was filed and approved in 2007.

In February 2010, IMRIS corporation (a company that develops, assembles and installs VISIUS Surgical Theatres that are used for a variety of medical applications), acquired the NeuroArm technology. The acquisition of the NeuroArm technology resulted in the development of the SYMBIS Surgical System, a neurosurgical robotics program to be used within the VISIUS Surgical Theatres. The SYMBIS Surgical System was still under development, when on May 26, 2015, IMRIS Inc. announced that the Company, its subsidiary NeuroArm Surgical Ltd., and its US subsidiary, IMRIS, Inc. have each filed voluntary petitions under Chapter 11 of the US Bankruptcy Code in the US Bankruptcy Court for the District of Delaware. Chapter 11 bankruptcy allows IMRIS to restructure its finances and operations, while continuing its development activities.

NeuroArm currently holds 8 Canadian patents, 2 US patents, 1 European Union patent and 1 Japanese patent. The name "NeuroArm" is trademarked in Canada (2004). It also held a US Trademark, however, it was abandoned in April 2015.

**Sales Prospects**

As NeuroArm is in the process of obtaining all regulatory approvals in Canada and the US, including further clinical trials, no revenue has been generated to date. As well, given the current Chapter 11 bankruptcy status of IMRIS and NeuroArm Surgical Ltd. no data is available on potential future sales.

In examining trends in related fields, 2013 worldwide sales of medical robots (robot assisted surgery and therapy medical robots) were 1,300 units for a value of $1.2 billion. As well, during the past five years, the Robotic Surgery Equipment Manufacturing industry has exhibited robust growth (10.2% annual growth) due to the proliferation of robotic surgery equipment across the healthcare sector. Moreover, in the five years to 2020, the industry is expected to continue to grow at a strong pace, despite a more stringent regulatory environment.[58]

Interviewees anticipate that IMRIS will be able to restructure and refinance its operations and continue the development work associated with NeuroArm. Based on general trends in the use of medical robots, there is a strong potential for the NeuroArm to generate revenue, (if commercialized) based upon the worldwide exposure it has already received and the technical excellence awards it has garnered.

**Conferences, Publications, Citations**

The NeuroArm team, led by Dr. Garnette Sutherland from the University of Calgary has provided 111 presentations and demonstrations. They have produced 39 peer-reviewed publications and have contributed to 9 monographs and book chapters. Dr. Garnette Sutherland has received a number of accolades for his involvement with the NeuroArm project; e.g., Companion Of The Order Of Canada (December 2011); NeuroArm Inducted into the Space Technology Hall of Fame (April 2014); NASA Exceptional Technology Achievement Medal (July 2015).

**Potential Socio-Economic Benefits**

As the NeuroArm has not been commercialized and is still in clinical trials and the regulatory approval processes, there have not been any additional direct jobs created through the development of the product.

According to interviewees, if commercialized, the use of NeuroArm is expected to lead to a reduced incidence of surgical complications arising from neurosurgery (currently approximately 5% complication rates from elective surgeries) as well as shortening the time required in hospital settings "post surgery", which would lead to a reduction in overall costs to the health care system.

On an individual level, the use of NeuroArm will lead to reduced pain and discomfort associated with neurosurgery and a faster recovery time and return to normal activities.

**Unexpected Outcomes**

No unexpected outcomes were identified.

**Follow-on Technology/Product Development**

The next evolution of the NeuroArm will be to expand its current imaging capabilities beyond the MRI to include the use of ultrasound and Catscan techniques.

The next generation product based on the NeuroArm technology will be a new project called CellArm. CellArm will bring the capability of the NeuroArm technology down to the cellular level, allowing surgeons to function at a much greater level of accuracy (microns instead of millimeters) and perform

[58] IBIS World. Robotic Surgery Equipment Manufacturing in the US: Market Research Report. Accessed on November 18, 2015 at http://www.ibisworld.com/industry/robotic-surgery-equipment-manufacturing.html

additional procedures (e.g. implantation of "molecular vectors" which can change the cell structure) to achieve desired patient outcomes. The CellArm initiative is currently seeking funding and financial support.

**Findings/Conclusions**

Given that NeuroArm (now SYMBIS) has and is being used on patients in clinical trials, and IMRIS develops, assembles and installs VISIUS Surgical Theatres, if IMRIS can successfully exit from bankruptcy protection the potential for fully commercializing NeuroArm/SYMBIS is promising. It is anticipated that IMRIS will be able to restructure and refinance its operations and continue the development work associated with SYMBIS. The University of Calgary has a collaboration agreement with IMRIS on the use and operation of SYMBIS and has received a SYMBIS unit for neurosurgery. Once fully operational and commercialized, SYMBIS has the potential to reap a number of benefits, both from a commercial perspective and a socio-economic perspective.

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**Case Study 2: IGAR**

**Introduction**

The Image Guided Automated Robot (IGAR) is a robotic platform that will enable automated image-guided minimally invasive procedures for the treatment of various conditions. The first platform developed is the IGAR Breast Robot, designed for early detection and treatment of breast cancer, through real-time biopsy and therapy of suspected breast lesions. The IGAR Breast Robot integrates seamlessly within a magnetic resonance imaging (MRI) system, allowing a radiologist to select a target on a patient's scan and then confidently direct the intervention with millimeter accuracy.[59]

The IGAR Breast Robot has the potential to transform the care pathway for cancer patients by enabling a "one-stop" system for diagnosis, treatment, and intervention. The IGAR Breast Robot can first perform a biopsy of a suspicious lesion, which can then be followed by ablation of biopsy site margins if clinically appropriate. For lesions or tumours that may require lumpectomy, image guided seed localization in the breast can also be done, improving success rates and avoiding re-incision.

In 2007, Dr. Mehran Anvari, McMaster University and MacDonald, Dettwiler and Associates Ltd (MDA) started work on creating and honing IGAR. In 2009, the Centre for Surgical Invention and Innovation (CSii), a non-profit entity hosted by St Joseph's Healthcare Hamilton and McMaster University, was established with Dr. Anvari as its CEO. The CSii received $14.8 million in long-term funding from the Networks of Centres of Excellence and approximately $24.3 million in funds and in-kind time, research and equipment from MDA and McMaster University. CSii partnered with MDA as its primary corporate partner for robotic development. In four years CSii has successfully developed and manufactured its first clinical system designed for early detection and treatment of breast cancer in high-risk women (IGAR Breast Robot).

A pilot Phase I clinical trial was completed in Quebec City in March 2014 under the supervision of Dr. Nathalie Duchesne. Results from the pilot trial are extremely promising and demonstrate the accuracy and usability. All IGAR Breast Robot biopsies were successful and no re-biopsies were required. Patients reported extremely low pain scores and excellent cosmetic outcome.

Following the success of Phase I, Health Canada approved a Phase II clinical trial, which was launched in December 2014. Phase II will involve two sites; Quebec City with Dr. Nathalie Duchesne and Hamilton with Dr. Colm Boylan. Up to 100 patients will enroll in the clinical trial. Phase II will be dual armed, and data will be collected from patients who undergo an IGAR breast biopsy and compared against the standard manual biopsy. Assuming clinical validation and licensing, the IGAR Breast Robot is expected to be commercially released in 2016.

**Transfer of Know-how and Technology**

Building on the experience and capacity developed by MDA's involvement in the development of robotics for the Shuttle and the International Space Station (ISS), the IGAR Breast Robot has benefitted from a rigorous systems engineering approach used in the development of Canadarm on the Shuttle and Canadarm2 and Dextre on the ISS, as well as experience developing NeuroArm.

[59] Centre for Surgical Invention & Innovation, http://www.csii.ca/robotic_development/igar

The design process used in the development of both sets of robotics was the same. The initial step was to create a mission scenario, outlining all of the pertinent requirements and identifying the numerous challenges to be overcome. The operational processes involved overcoming the numerous challenges (e.g. shielding electrical components inside an MRI machine) followed by the identification of anomalies and finally building in the required safety aspects and ensuring systems had built in redundancy capability.

The level of direct technology transfer from the development of the Canadarm, Canadarm2 and Dextre to the IGAR Breast Robot was limited to the use of the same algorithm blocks in the control software that operates the IGAR Breast Robot.

**Commercial Development, Patents, Trademarks**

The development of the IGAR robotic platform was established as a partnership between CSii and MDA. MDA has been a committed partner, offering not only their extensive robotics expertise, but knowledge and support in business planning, forecasting, market analysis, and government relations. MDA are keenly invested in the success of CSii and plan to continue to partner with CSii to successfully launch the first commercial system (IGAR Breast Robot), and to the development and building of future platforms.

CSii has built ties with Hologic who have a significant global share of the breast care business and imaging technologies for women's health. Hologic has offered CSii direct access to the market for the commercial launch of the first system. The CSii has plans to expand the affiliations and partnerships (Stryker, Imris, Ethicon) to maximize the success as CSii moves into building two new robots as well as launching additional new programs to improve care.

CSii also has fostered support and partnership of key academic leaders and organizations across Canada (Quebec, Ontario, and Alberta) and internationally (US, France, Netherlands, Israel). Joint research projects have been established with two other Centre of Excellence in Canadian Research organizations (Centre for Probe Development and Commercialization at McMaster University and the Centre for Imaging Technology at Robarts Research Institute at Western University), which will assist in the development of two future commercial products. CSii's relationship with the Ontario Ministry of Health and Long Term Care has allowed CSii to gain much insight into implementation of new technologies and techniques in clinical setting in Ontario. Similar relationships with Ministries of Health across Canada (Quebec, Alberta, BC) are under development.

The IGAR Robotic Platform currently holds 1 Canadian patent, 11 patents pending: five others in Canada and six in the US.

**Sales Prospects**

The IGAR Breast Robot is currently undergoing clinical validation and licensing with plans for commercial release in 2016. It is too early therefore, for any revenue to have been generated; and no data is available on anticipated sales. As noted in the NeuroArm case study, the medical robot industry is expected to continue to grow at a strong pace over the next five years to 2020.

**Conferences, Publications, Citations**

There are no publications or conference presentations associated with the IGAR robotic platform. However, Dr. Anvari, Scientific Director and CEO of the CSii has received a number of accolades for his involvement with CSii and the IGAR Robotic Platform; e.g., International Space Station Research and Development award for Innovation in Biology and Medicine, for his work on an Image-Guided Automated Robot (IGAR) for use in the diagnosis and treatment of breast cancer (July 2015); ORION Leadership award (2010); McMaster University Innovator of the year (2009).

**Potential Socio-Economic Benefits**

As noted on CSii's website, "CSii has already supported the creation and retention of over 24 high paying technical jobs, which will increase significantly with the commercial release of its first system in 2016."

Health care system benefits include: (1) Fewer complications arising from more accurate positioning resulting in shorter hospital stays; and (2) One-stop treatment including diagnosis, biopsy and ablation treatment to eliminate the tumour or lesions, resulting in fewer surgeries, and reducing overall costs to the health care system.

On an individual level, the use of IGAR Breast Robot is expected to result in: (1) Shorter hospitalization; (2) Reduced pain and discomfort; (3) Faster recovery time and return to normal activities; (4) Smaller incisions, resulting in reduced risk of infection; (5) Reduced blood loss and transfusions; and (6) Minimal scarring.

**Unexpected Outcomes**

No unexpected outcomes were noted or found.

**Follow-on Technology/Product Development**

CSii has other innovative robotic systems in their product pipeline with a second system for a variety of clinical procedures including lung, liver, and kidney biopsy, and ablation planned for commercial release in 2020.

Future applications of the IGAR Robotic Platform will include: (1) Image-guided interventions using ultrasound or MRI-ultrasound fusion; (2) Ablation of the lesion (by cryotherapy or an alternative technology); (3) Radioactive seed localization to tag the lesion for surgical removal; and (4) Tele-operability; allowing radiologists to biopsy and treat patients at a distance thereby improving access to care in rural and remote regions.

CSii is conducting preliminary research and phantom tests on other potential functionalities of the IGAR Robotic Platform for a variety of clinical procedures. It will also integrate with other imaging modalities including Catscan and ultrasound.

**Findings/Conclusions**

Given that the IGAR Breast Robot is currently undergoing Phase II clinical trials in Quebec City and Hamilton, the commitment by both partners (MDA and CSii) to fully develop and commercialize the IGAR Breast Robot, CSii's relationships with provincial ministries of health, and CSii's access to the global health care market through its ties with Hologic, the prospects for the commercial release of the IGAR Breast Robot in 2016 are promising.

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## Case Study 3: KidsArm

### Introduction

KidsArm is an autonomous image guided robotic arm intended to perform anastomosis (suture/reconnect delicate vessels such as veins, arteries, or intestines) on pediatric patients from neonates to 4 years old. KidsArm is intended to assist surgeons perform certain procedures many times faster than if they were only using their hands, and with increased accuracy.[60]

Based on the experience with NeuroArm, MDA approached the medical community to develop similar robotic medical applications based on technologies developed for the robotic arms used on the ISS. Dr. Peter Kim, general neonatal and thoracic surgeon, and co-founder of the Centre for Image-Guided Innovation and Therapeutic Intervention (CIGITI) at SickKids responded positively to MDA's request for the following reason.

> In the medical field, minimally invasive surgery (MIS) and laparoscopic tools revolutionized surgical interventions and shortened patient recovery times by allowing surgeons to perform procedures through 3-4 incisions with a diameter up to 1-2 cm. MIS procedures, however, are often more challenging and complex as the surgeon is restricted to laparoscopic tools that do not possess the same flexibility and dexterity as tools used in "open" procedures (done by hand through a large incision). Pediatric patients pose a unique challenge as they have smaller volumes and different tissue properties.[61] SickKids' Dr. Kim felt that a dexterous robotic tool would help overcome these constraints.

The KidsArm project started in 2010 when SickKids, in collaboration with MDA, received $10 million from the Federal Economic Development Agency for Southern Ontario (FedDev Ontario) and the Ontario Research Fund/Canada Foundation for Innovation, to support the development of an image-guided pediatric surgical robot or KidsArm. Unfortunately, mid-way through the project, Dr. Peter Kim left SickKids/CIGITI to assume a position in the US. He was replaced by Dr. James Drake, Director of CIGITI and Head of Neurosurgery at SickKids, who ensured the KidsArm project was completed.

Two-years later in 2012, a functional prototype (alpha version, proof of concept - could you get a robot to sew either simulated vessels or simulated tissue) of KidsArm was successfully built by CIGITI/SickKids and MDA. KidsArm successfully applied 3 sutures autonomously on the side-to-side scenario but had more difficulty with the end-to-end scenario due to the greater deformation and workspace restrictions.

The project's main challenge was that size and volume constraints are more pronounced as children have smaller organs, vessels and targets while the tools are the same or minimally smaller than adult versions. If the end-to-end scenario could be solved, it is expected that using KidsArm would lead to more consistent outcomes for pediatric patients, and the ability to intervene earlier or perform manipulations on a smaller scale than current practices.

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[60] Looi, Thomas, Benny Yeung, Manickham Umasthan and James Drake. (2013). "KidsArm — An Image-Guided Pediatric Anastomosis Robot", 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) November 3-7, 2013. Tokyo, Japan: 4105-4110.

[61] *Ibid.*

**Transfer of Know-how and Technology**

Similar to the experience with NeuroArm and IGAR, the software algorithms used for Dextre stored inside the source integrity server, were reused/adapted for KidsArm. To facilitate the technology transfer process, the relevant Logistics and Sustaining Engineering (LSE) control engineers that worked on the Mobile Servicing System (MSS) were drafted into the KidsArm project to implement these algorithms.

As well, MDA's experience with control theory, vision applications, targeting on a larger scale for the International Space Station (ISS) was applied to KidsArm, the novelty was to make it for smaller applications. The development of KidsArm also benefited from the autonomous operation mode used on the ISS.

**Commercial Development, Patents, Trademarks**

One patent application was filed in Canada related to the vision system used on KidsArm. There are no trademarks associated with the KidsArm project.

**Sales Prospects**

Before KidsArm can undergo clinical trials and be used on patients, further research in real time tracking, better target tracking algorithms, and for the robotic arm to sew effectively is required.

**Conferences, Publications, Citations**

There are two publications and two citations associated with the KidsArm project. Both publications were presented at international conferences.

**Potential Socio-Economic Benefits**

The development of KidsArm involved hiring new engineers, engineers with experience in the robotic arms used on the ISS as well as NeuroArm and IGAR, research engineers, 10 undergraduate students, 2-4 graduate students, and 4-5 clinical investigators (medical doctors).

If KidsArm were approved the benefits would be more consistent outcomes for pediatric patients, and the ability to intervene earlier or perform manipulations on a smaller scale than current practices.

**Unexpected Outcomes**

No unexpected outcomes were identified.

**Follow-on Technology/Product Development**

A next "generation" of KidsArm, the Minimally-Invasive Endoscopic Manipulator System (MIEMS) robot, is being developed by SickKids/CIGITI by Dr. James Drake (who replaced Dr. Kim), but without MDA's participation. MIEMS is a significantly smaller tool at 2mm in diameter compared to KidsArm which is 8-10mm in diameter. SickKids decided to partner with a different company, ESI.

MIEMS has a better chance of being commercialized and applied on pediatric patients for the following reasons: (1) MIEMS falls within Dr. Drake's area of expertise – neurosurgical applications for pediatric patients; (2) MIEMS at 2mm in diameter is significantly smaller than KidsArm which is 8-10mm in diameter; (3) SickKids new partner, ESI, has similar experience to MDA but in medical robots.

If MIEMS is approved the benefits to pediatric patients would be more accurate and faster procedures which would have a direct positive benefit on patient outcomes, and it would allow surgeons (e.g., at SickKids) to perform previously inoperable operations.

**Findings/Conclusions**

Before KidsArm can undergo clinical trials and be used on patients, further research is required. A next "generation" of KidsArm, the MIEMS robot, is being developed by SickKids/CIGITI by Dr. James Drake.

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## Appendix D: Videos Related to ISS Assembly and Maintenance Operations and Viewing Statistics, 2011 to 2015

### CSA ISS Videos, Number of Times Viewed (as of March 2015)

| Date available on-line | Title | Number of Times Viewed |
|---|---|---|
| 2015-03-06 | Dextre changes a pump on the International Space Station | 5,357 |
| 2015-01-20 | Dextre lets CATS out of the bag on the Space Station | 7,630 |
| 2015-01-15 | Canadian Space Technology to Help Sick Children | 12,539 |
| 2014-09-29 | Canadian Space technology helps breast cancer patients | 19,979 |
| 2014-05-20 | Robot, heal thyself: Dextre becomes the first robot to repair itself in space | 55,277 |
| 2014-05-01 | Dextre installs OPALS on the International Space Station | 11,492 |
| 2013-07-03 | The Next-Generation Canadarm | 23,632 |
| 2013-03-03 | Hadfield behind the controls of Canadarm2 | 130,958 |
| 2013-02-27 | Canadarm2's Cosmic Catch: Dragon | 13,540 |
| 2013-02-27 | Dragon's Delivery: Canadarm2 unpacks the capsule's cargo | 3,059 |
| 2013-02-27 | Canadarm2 releases Dragon for its return flight | 130 |
| 2013-01-09 | Dextre tops off the tank: The Robotic Refueling Mission | 17,459 |
| 2013-01-09 | Dextre, Gas attendant: The Robotic Refueling Mission | 4,185 |
| 2012-06-18 | Dextre's Most Dexterous Task: Part 2 of the Robotic Refueling Mission on the ISS | 3,274 |
| 2012-05-25 | Canadarm2 Captures the Dragon | 2,084 |
| 2012-05-25 | Canadarm2 and Dextre | 68 |
| 2012-04-16 | Canadarm2 to Catch SpaceX's Dragon on its Maiden Voyage to the ISS - Part 1 | 26,473 |
| 2012-04-16 | Canadarm2 to Catch SpaceX's Dragon on its Maiden Voyage to the ISS - Part 2 | 3,485 |
| 2012-03-19 | March 9, 2012: Dextre cleans up after a job well done! | 1,477 |
| 2012-03-19 | March 8, 2012: Dextre Releases the Launch Locks | 1,373 |
| 2012-03-19 | March 8, 2012: Dextre makes the cut: Wire Cutting task is a resounding success! | 1,054 |
| 2012-03-14 | Dextre's Robotic Refueling Mission: Day 2 | 1,481 |
| 2011-09-02 | Dextre's First Repair Job on the ISS | 6,369 |
| 2011-08-26 | Circuit-breaker box repair | 3,428 |
| 2011-07-21 | Canadarm2 installs the RRM hardware | 3,170 |
| 2011-07-21 | An overview of STS-135 Canadian robotic operations | 493 |
| 2011-05-27 | The Final Spacewalk and a New Home for the Inspection Boom | 1,108 |
| 2011-05-20 | From Shuttle to Station: Canadian Space Robotics at Work | 1,012 |
| 2011-04-29 | The Installation of the Express Logistics Carrier 3 | 1,429 |
| 2011-04-29 | AMS Installation | 429 |
| 2011-03-17 | Canadarm2 gives spacewalkers a "leg up" | 922 |
| 2011-03-10 | Dextre's final exam | 328 |
| 2011-03-09 | Operating Canadarm2 | 1,046 |
| 2011-03-02 | Dextre is put through its paces on the International Space Station | 2,399 |

Source: CSA Communications and Public Affairs Directorate Performance Data, August 2015.