Orbital Robotics Spiral Evolution for Future Exploration Missions

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ABSTRACT

Much has already been achieved over the past three decades in the field of orbital robotics, including activities conducted on the Space Transportation System ("Shuttle") Program, the Orbital Maneuvering Vehicle ("OMV") Program and the assembly of the International Space Station ("ISS"). NASA and the Canadian Space Agency (CSA) alone have invested over US$2B in such development, with additional millions of dollars invested by other nations. Several flight demonstration missions are also underway to further capabilities in autonomous rendezvous, spacecraft mating, spacecraft servicing, etc; such as DARPA's Orbital Express Program, NASA's DART Program and the Air Force Research Lab XSS-11 Program. More recently, NASA has initiated a robotics program to safely de-orbit the Hubble Space Telescope, with a further mission option to extend its operating life.

This presentation will describe the key orbital robotic technologies and capabilities that are already being deployed on many of the current missions, as well as a "stepping stone" spiral evolution approach for further advancement of those capabilities that are critical to NASA's new Exploration Enterprise. Future NASA Exploration missions that can benefit from such capabilities include:

- Robotic servicing and life extension of other existing spacecraft
- Planned robotic assembly and maintenance of future large orbital observatories
- Orbital robotic construction of staging infrastructure at remote locations
- Orbital robotic construction of large interplanetary spacecraft

More specifically, the presentation will suggest an evolutionary roadmap for critical technologies such as autonomy & remote control, rendezvous and proximity operations, spacecraft capture/mating and on-orbit servicing. The roadmap will reflect the strategy for a near term, affordable and sustainable path to develop additional capabilities that will enable future ambitious robotic missions.

1. INTRODUCTION

January 14th 2004, President George Bush and NASA Administrator Sean O'Keefe announced a new U.S. National Exploration Vision [1]. The fundamental goal of this vision is to advance U.S. scientific, security and economic interests through a robust space exploration program. In support of this goal, the United States will:

- Implement a sustained and affordable human and robotic program to explore the Solar System and beyond;
- Extend human presence across the Solar System, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and,
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.

To implement this vision, NASA plans to conduct the following new activities:

New Space Transportation Capabilities - NASA will initiate Project Constellation to develop a new Crew Exploration Vehicle (CEV) to provide crew transport for exploration missions beyond low Earth orbit. NASA plans to develop the CEV in a step-by-step approach, with an initial unpiloted test flight as early as 2008, followed by tests of progressively more capable designs that provide an operational human-rated capability no later than 2014.

Lunar Exploration - NASA will undertake lunar exploration and demonstration activities to enable sustained human and robotic exploration of Mars and other destinations in the solar system. Starting no later than 2008, NASA plans to launch the first in a series of robotic missions to the Moon to prepare for and support human exploration activities. The policy envisions the first human expedition to the lunar surface as early as 2015 but no later than 2020. These

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robotic and human missions will further science and demonstrate new approaches, technologies, and systems, including the use of space resources, to support sustained human exploration to Mars and other destinations.

Exploration of Mars - NASA will enhance the ongoing search for water and evidence of life on Mars by pursuing technologies this decade for advanced science missions to Mars in the next decade. Also starting next decade, NASA will launch the first in a dedicated series of robotic missions to Mars to demonstrate capabilities that will greatly enhance robotic capabilities and enable future human exploration of Mars. NASA will conduct human expeditions to Mars and other destinations beyond Earth orbit on the basis of available resources, accumulated experience, and technology readiness.

Destinations Beyond - Over the next two decades, NASA will conduct an increasingly capable campaign of robotic exploration across the solar system. The stunning images we have received from Mars are just the beginning. NASA will launch advanced space telescope searches for Earth-like planets and habitable environments around other stars. NASA will explore Jupiter's moons, the asteroids, and other solar system bodies to search for evidence of life, understand the history of the solar system, and search for resources.

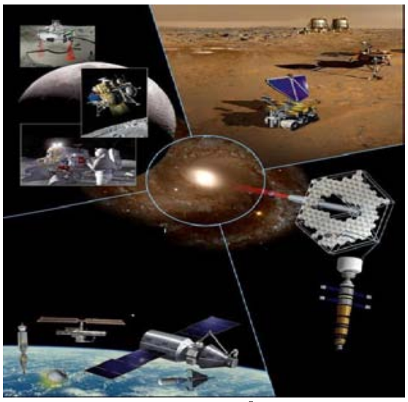

Fig. 1: NASA New Exploration Vision
Human & Robotic Technology Challenges

To support the Exploration Enterprise activities, NASA Code “T” has identified the following Human & Robotic Technology (H&RT) systems challenges [2] that must be surmounted in order to realize both Orbital and Surface Exploration missions:

- Reusability
- Modularity
- Autonomy
- Human Presence in Deep Space
- In-Space Assembly
- Reconfigurability
- Robotic Networks
- Affordable Logistics Pre-positioning
- Energy-Rich Systems and Missions
- Space Resource Utilization
- Data-rich virtual presence
- Access to Surface Targets

2. ORBITAL ROBOTIC SPIRAL DEVELOPMENT

Specific to Orbital Missions, NASA and the Canadian Space Agency have already invested over US$2B in the development of advanced orbital robotics for the past three decades. This has provided the essential foundation to address the Orbital Systems Challenges that have been identified for the new Exploration Plan. Some of the key building blocks relevant to such challenges, and their further evolutionary paths, are described as follows.

2.1 Autonomy and Control

MDA’s technology roadmap for command and control is characterized by

- Transition from teleoperation to automatic scripted control to supervised autonomy
- Continuing reduction in the ratio of operators and ground support crew to number of robotic systems

Current orbital robotic operations, be it on the Shuttle or the International Space Station, rely on proximity teleoperations controlled by on-board astronauts. MDA designed and built the Shuttle Remote Manipulator (SRMS) AFT Flight Deck Robotic Display and Control Station, which has operated flawlessly on the Shuttle fleet for over 20 years. MDA also designed and built the Robotic Workstation (RWS) for the International Space Station (ISS). The RWS (Fig. 2) is the primary on-orbit operator interface for Space Station robotic elements and provides control and televised viewing of Space Station assembly and operations. The RWS was launched on STS-102 and delivered on-orbit in March 2001, and was brought into active service immediately. Since then it has been in almost continuous use. Both of these human-in-the-loop teleoperation systems have the advantage of real-time control and viewing.

Fig. 2: ISS Robotic Workstation

However, as new Exploration missions operate in an unmanned environment or are conducted over long distances, data communication latency becomes a significant problem and direct human-in-the-loop control may not be possible. Human in the loop control of manipulators is known to degrade when round trip communication latencies exceed roughly 0.25 to 0.5 seconds. In the case of Mars missions, the data communication latency ranges from roughly twenty to forty minutes, exceeding a duration that would allow direct human-in-the-loop control of any kind. As a consequence, autonomous capabilities have to be introduced. The level of autonomy depends on the complexity of the operation, circumstances and environment under which it will be performed.

It was with such robotic operational challenges in mind that MDA developed ROSA (Remote Operation for Supervised Autonomy) [3], a new approach for orbital robotics control. The function of this command and control system is to support variable autonomy and allow for introduction of autonomy enhancements over the life of the system. In many cases simple automation will be the first step. ROSA can provide astronauts and operators on the ground with the ability to choose the level of autonomy with which to instruct the system to perform an operation, and to permit the operator to generate operations scripts that seamlessly incorporate mixtures of high and low level commands within a single operation. An operations script can be generated anytime prior to the operation. It will, in general, contain a mixture of goals or tasks and low level commands that control the operation. The use of goals to the greatest extent possible simplifies operations planning. In preparation for an operation the script and appropriate models are loaded. During execution the crew may view the operation. However, the crew need not directly control the execution, but maintains the ability to interfere as required. Architecturally ROSA consists of: 1) sensors to determine the external environment and system state, 2) a behavioral executor to guide operations, 3) an inference engine that invokes and terminates behaviors, 4) an intelligent operations supervisor that controls operations based on high level goals, and 5) a planning and cognitive modeling engine.

ROSA is being deployed by MDA on DARPA's Orbital Express (OE) Flight Program and was the baseline approach for the Hubble Space Telescope Robotic Servicing Mission (Fig. 3). After an extensive NASA safety review of ground control of the Canadarm 2 on the ISS, the first successful ground controlled operation occurred in February 2005. This has opened the door for consideration of a broader ROSA-like framework for more extensive ground-based operations of the ISS robotic systems.

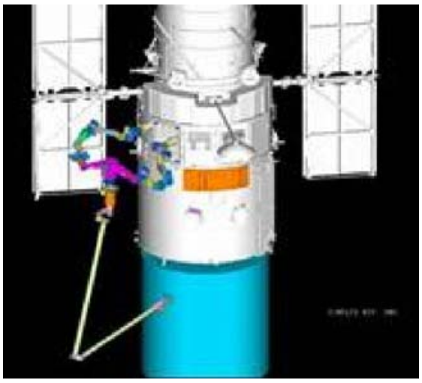

Fig. 3: HST Robotic Servicing

A continuing effort of MDA in the area of command and control is to reduce the ratio of operators and ground support crew required to operate each robotic system. More recently as part of NASA's Exploration Enterprise, a similar goal of moving towards more crew centred operations, where fewer operators control more robotic systems has been highlighted. As robotic systems are imparted with greater degrees of autonomy, there is by definition less operator interaction and operator control over the robot's actions in real time. This may require increased safety awareness as the increased possibility of failures or program errors can place human safety or equipment at risk. With this in mind, MDA recently developed On-orbit Safety Monitor (OSM) [4]. The objective of the OSM project was to develop safety monitoring functions/technologies which will improve the safety of the remote teleoperation of robots where continuous human monitoring is either cost-prohibitive, or not possible. The OSM system is a bundle of functions/technologies to help compensate for the operator's poor situational awareness and mitigate the risks that come with remote teleoperation of robots (eg: ground operations and control of space robotic systems) and/or autonomous operation. OSM's approach is based on using real-time data from a computer vision system for authenticating the synthetic models used for collision detection, and its ability to issue warnings when it detects that safety is being compromised by potential collisions. This will provide systems such as the Mobile Servicing System on ISS with much of the needed situational awareness capabilities that they currently lack.

Future in-space assembly, maintenance and servicing of large spacecraft and infrastructure or construction of large modular systems for lunar or Martian habitation will place demands which cannot be met by current assembly strategies or command and control systems. Presently the ISS assembly process is performed sequentially using only one robotic system, with ground support teams at multiple sites. The current robotic control stations such as RWS are only capable of controlling one robot at a time. They are not designed to control of multiple active robots simultaneously while performing cooperative tasks. Hence a logical next step is the development of a multi-robot control ground planning, training, monitoring and control infrastructure. Such an approach will enable the control and oversight of multiple robots working cooperatively amongst themselves or in the presence of astronauts, as well as the efficient planning and training for safe operations. In addition, such a ground station concept will enable a more centralized approach to orbital robotic operations and move towards the goal of a more crew centred operation.

2.2 Orbital Rendezvous

Autonomous docking or manipulator assisted berthing of space vehicles and modules will play a central role in the anticipated Space Exploration missions. Space vehicles will have to rendezvous and either dock or berth with each other to form larger assemblies or to perform servicing functions. Concepts for Propellant Depots located in LEO staging orbit, the Earth-Moon L1 Gateway and the Sun-Mars L1 Outpost are being developed. All these scenarios involve rendezvous operations of one form or other between two space vehicles, or multiple vehicles, humans and robots working in close proximity. Hence there is an increasing need for high speed, precision 3D and robust sensing capabilities.

Current rendezvous sensing systems utilize radar, camera or lidar (light detection and ranging) technologies. For example, the Russian Progress/Soyuz supply vehicles to the ISS use radar as a rendezvous sensor which, although reliable, has the disadvantage of being large, heavy and power-hungry. The Japanese H-II Transfer Vehicle (HTV) and the European Autonomous Transfer Vehicle (ATV) are expected to deploy retro-reflector based lidar rendezvous technology.

Along with its partner Optech Incorporated, MDA has developed and delivered a Rendezvous LIDAR system (Fig. 4) to the Air Force Research Lab (AFRL) XSS-11 flight demonstration mission which has since begun initial on-orbit operation in May 2005. The mission serves to demonstrate autonomous rendezvous operations and to advance those capabilities needed for a satellite to maintain operations on-orbit without intervention from ground-based mission control teams and assets.

The Optech/MDA Rendezvous LIDAR [5] emits a burst of laser light and steers it using a two-dimensional, fast-scanning mirror. Measuring the time-of-flight and angle of the reflected beam provides the relative position and velocity of a target. This approach has some key benefits over typical methods of obtaining such data as it does not require pre-installed targets (such as retro-reflectors), does not require any external illumination sources and operates under extreme solar illumination conditions. This particular approach provides range and bearing sensing for the long and medium range portion of the rendezvous operation (3km to 50m).

More recently MDA has extended this capability to produce six degrees of freedom pose estimation [6], enabling this sensor to perform a broader rendezvous and docking sensor function with orbital infrastructure with or without rendezvous aid (e.g. the Hubble Space Telescope). Using flight representative avionics, the performance tests of this enhanced system has shown it to be sufficiently accurate to be used as a docking sensor in an automated Hubble Space Telescope docking operation.

As a further evolutionary development, such 3D rendezvous sensing technologies will have to operate at much higher speeds and accuracy, and must be capable of detecting multiple maneuvering objects in close proximity. A large scale orbital infrastructure or spacecraft assembly operation, for example, will likely involve a “network” sensing system that supports the planning, control and monitoring of multi vehicle, multi robot and multi astronauts operating simultaneously.

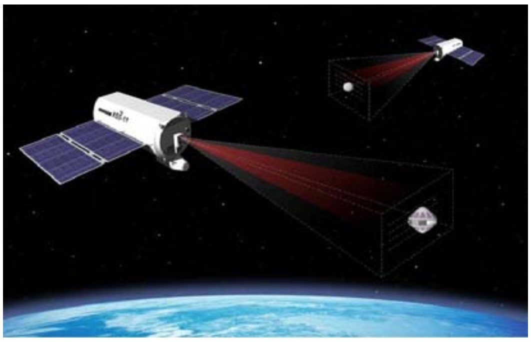

Fig. 4: XSS-11 Rendezvous LIDAR Demonstration

2.3 Orbital Capture/Docking

In-space assembly can be performed by either (1) rendezvous and docking of modules or (2) capture and berthing of modules. This critical phase is sometimes referred to as “The Last 100 m” to imply that this is a separate portion of a spaceflight mission and requires a different, integrated infrastructure.

Direct docking works on the basis that each element provides its own rendezvous support functions such as power, attitude control, propulsion, and command and control. Direct docking technologies have successful deployed such missions as Gemini, Apollo, Shuttle/MIR and Progress/ISS, but has the limitation of being a single function system. As well, most direct docking systems are still fairly large and massive, and must possess an on-board maneuvering capability for rendezvous.

On the other hand, a robotic capture and berth approach for assembly has been well demonstrated on both the SRMS and the SSRMS. The SRMS, for example, has deployed and captured over a dozen free-flying satellites on orbit, including four (4) successful capture and berthing operations of the Hubble Space Telescope to the Space Shuttle. The robotic capture and berth approach has the disadvantage of added size and mass overhead, yet offers the benefit of the many operational functionalities that a robotic manipulator offers. Such functionalities include in-space inspection, repair, maintenance, refueling and re-supply, many of which have been well demonstrated in past Shuttle missions and the upcoming Shuttle Return-To-Flight Program.

The next stage in the evolution of a robotic arms for spacecraft capture and berthing will be demonstrated in unmanned robotic missions such as the DARPA’s Orbital Express Program. Operating aboard the ASTRO servicing spacecraft, the MDA developed robotic arm (Fig. 5) will autonomously capture and berth the client NextSat spacecraft with the aid of a computer vision system. Partially addressing the size and weight penalties a manipulator has presented in the past, the OEDMS achieves this spacecraft retrieval capability with mass, length and power of 71 Kg, 3m and 125W respectively; an order of magnitude smaller than the SRMS. Such unmanned capture and berth capability is also being applied to the potential HST Robotic Mission where the HST is to be mated to a vehicle for servicing.

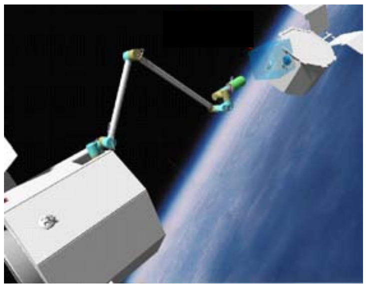

Fig. 5: DARPA Orbital Express Program

A potential evolutionary path for orbital assembly may be to combine the benefits of both direct docking and robotic capture/berthing systems. Such a system may include a simple, standardized low mass mating interface that is supported by a small re-deployable (to another mating interface) free-flyer capture arm. The arm, with its ability to move around the modular infrastructure, can also perform other tasks such as inspection and maintenance. The arm can also be reconfigured such that direct docking to it is also possible. Such a system will have the benefits of reduced overall mass, robustness plus added functionalities. A further extension to such a system may be to integrate smart sensors and intelligent software such that the mating operations can be conducted with minimum human monitoring and control.

2.4 Interfaces for In-Orbit Assembly and Servicing

For the new Exploration missions, in-space assembly capability will be needed across a broad number of systems at a variety of venues including LEO, Earth-Moon L1, Lunar orbit and Mars orbit. Assembly of multiple modular systems will greatly benefit from standardized assembly and handling interfaces characterized by:

- Compatible for both human astronauts and robotic systems
- Minimal additional mass, volume and power required on the spacecraft or orbital infrastructure to enable servicing.

- Robustness for proper mechanical, electrical and fluid mating

As part of the Shuttle and ISS Program, MDA has considerable heritage designing interfaces for robotic assembly and handling (Fig. 6). The Shuttle Remote Manipulator System (SRMS), the Space Station Remote Manipulator System (SSRMS) and the Special Purpose Dexterous Manipulator (SPDM) all have end effectors that have the ability to react structural loads and transfer power and data to a payload. Several interface standards, such as the grapple fixture, micro square interface, and 'H'-fixture, were developed to accommodate a range of payloads sizes. MDA also designed the structural and electrical interfaces used in ISS orbit replaceable units (ORU's), such as the Magnetic V-Guides ORU standard. One particular drawback on the ISS Program, however, is that robotic interfaces, ORU interfaces and astronaut interfaces are *not* all fully standardized, hence increasing both operational and component complexities.

Fig. 6: Shuttle/ISS Robotic Interfaces

To support future Exploration missions, a unified interface standard that adds minimum complexity and mass to modular space and surface systems, while functioning in extreme environments, will likely be required. Such an interface should be capable of meeting all structural, electrical and fluid requirements for an interface between assembled elements, while being highly scalable and reconfigurable to accommodate modules of different sizes and interface requirements. In addition, any reduction in the cost of developing and building a common interface would be broadly realized across several systems.

Through DARPA's Orbital Express (OE) Program, MDA is already establishing a non-proprietary satellite servicing interface standard that can be implemented by any satellite manufacturer. This standard handling and ORU attachment interface is a simpler version of ISS robotically compatible interfaces. At the other end of the spectrum, recent MDA studies and tests of robotic servicing of unprepared spacecraft such as the robotic servicing demonstrations of the HST at GSFC [7] demonstrate that such interfaces can be designed to reduce the overhead or "scarring" required on a spacecraft or orbital infrastructure down to a minimum. The key to achieving this goal is ensuring the robotic system has sufficient dexterity and sufficient levels of perception to provide either an operator or an autonomous control system with the capability to handle these simpler interfaces.

Future designs of these handling interfaces should also focus on dual astronaut and robot compatibility so as to further minimize the servicing overhead. Due to the exceptional dexterity and adaptability of a human (even with the EVA suit), such interfaces will likely still be constrained to a greater degree by the robotic capabilities, with an interfacing adapter for human use. A further extension to such interfaces may be to embed smart sensors and communications links such that all critical interfaces can be better managed with real-time diagnostics and re-configuration capabilities.

2.5 Dexterous Robotics

In addition to large-scale robotic cranes for assembly, smaller more dexterous robots will be required for maintenance and servicing of future exploration systems. This will put a premium on increasingly dexterous robotics characterized by

- Handling and assembly of flexible structures, such as radiators, solar collectors and parasols, requiring more exacting positioning and force/moment control to deal with small tolerance mating and handling of more delicate elements.
- Considerable effort to plan and perform a dexterous task using current state-of-the-art systems.
- Dramatic reduction in robotic timelines and operations processes to meet the large-scale assembly and servicing objectives for future exploration systems.

The Special Purpose Dexterous Manipulator (SPDM) built by MDA was designed to perform on-orbit maintenance of externally mounted ISS hardware (Fig. 7, Fig. 8). It is an advanced two armed robotic system that incorporates automatic collision avoidance and force moment accommodation. Each of the ISS ORU hardware elements is robotically compatible with the SPDM's ORU Tool Changeout Mechanism (OTCM) which consists of a gripper, integrated tie-down bolt torquer and connector mating mechanisms.

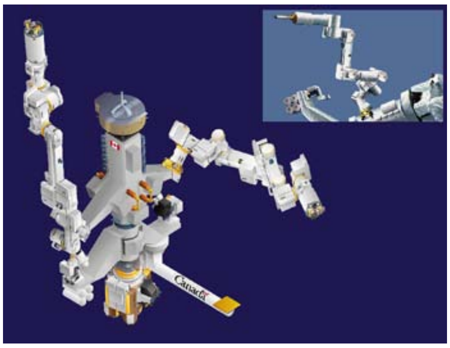

Fig. 7: Special Purpose Dexterous Manipulator

For future Exploration Missions, however, it is envisioned that many dexterous robots will need to be deployed to perform coordinated complex and coordinated tasks. One approach is to develop and deploy even more sophisticated dexterous robots (e.g. humanoids). There are two factors which may indicate that this is not the desired route:

- Lessons learned from 20 years of EVA activity on the Shuttle and more recently on the ISS, show that for each task within each mission, despite the broad capabilities of the astronaut, he still requires a number of specific tools and training to perform these operations
- Increased costs and complexities of producing robust humanoid systems

An alternative approach may be to deploy simple dexterous robots with well defined tasks and capabilities. Such simple robots may not be highly adaptive on their own but working as a group with individual designated capabilities or tools, can provide a robust team capability even under a dynamic working environment. Two more recent developments illustrate the viability of such an approach to dexterous robotic servicing.

MDA is just about to complete flight qualification of the Orbital Express Demonstration Manipulator System (OEDMS) in preparation for its planned on-orbit operation in 2007. Like SPDM, it was designed to service a client spacecraft's robotically compatible ORUs. What sets it apart from SPDM is its cost, mass and power consumption which are one order of magnitude less.

The recent demonstration tests at Goddard Space Flight Centre performed using a ground testbed version of the SPDM (SPDM-GT) to service a full-scale representative model of the HST provide another indication that the generic simpler dexterous robot approach has credibility [7]. In these demonstrations, the SPDM-GT was required to connect a replacement rate gyro and augmentation battery as well as change out guidance sensor and camera elements of the HST. These tasks included door opening, latch/unlatching and connector mate/de-mating which required incremental positioning accuracies of the order of 1-2 mm. Despite the fact that these operations had only been designed to be performed by an astronaut in an Extra-Vehicular Activity (EVA), the generic and dexterous SPDM was able to perform these tasks by augmenting the system with a set of custom tools and an enhanced computer vision system. It was shown that these tasks can be performed using teleoperation or supervised autonomy. As a matter of fact, NASA declared in February 2005 that "A space-flight qualified robot has successfully demonstrated that all life-extension tasks and science instrument change-outs can be robotically performed".

This approach can be further developed to enable more complex tasks such as large scale, unmanned orbital assembly to be accomplished by simple, affordable robot teams. As the robotic team approach matures, further intelligence can be added to the group capability such that they can not only deal with pre-planned tasks and also perform unprepared or contingency tasks as new situation arises. Such robotic teams would also be designed to work safely and cooperatively in an integrated astronaut-robotic environment. The goal is to achieve the ideal human-robotic balance such as to minimize cost, increase safety while maintaining operational robustness.

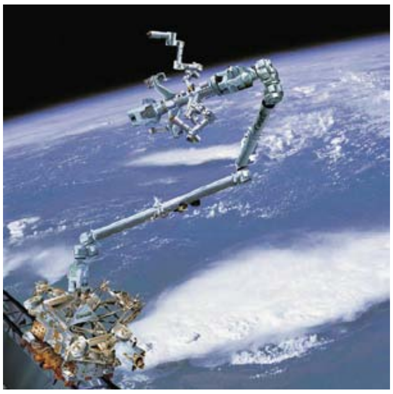

Fig. 8: SPDM on SSRMS

3. CONCLUSIONS

Many of the Exploration orbital mission capabilities and technical objectives can be met via an incremental, spiral development approach based on existing technologies and flight systems. Such an approach will contribute to meeting the overarching challenges of higher reliability and safety, increased affordability, improved effectiveness and greater flexibility. Such key developments in Autonomy and Control, Rendezvous, Capture, Berthing/Docking, Interfaces and Dexterous Robotics already fit in well within the objectives and timeframe of the Exploration Human and Robotic Development roadmap as illustrated in Fig. 9. A key next step consideration will be the pace, depth and emphasis for such further spiral development.

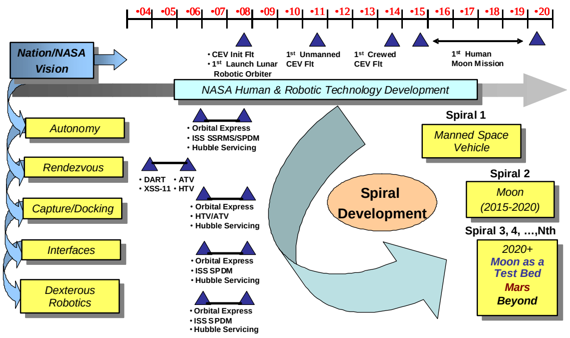

Fig 9: Key Orbital Robotic Spiral Development against Exploration Roadmap

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