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From Past to Future: The Evolution of Robotics Integration in Human Spaceflight Missions

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Abstract

Throughout the past 24 years, the cooperation between human and robotic systems on the International Space Station (ISS) has evolved and has proven invaluable. From both station and robotics maintenance, and mechanical upgrades, to installing science experiments with goals of improving life on Earth, it is evident that this human/robotic enterprise is the way forward for the continued advancement of human space exploration. This paper summarizes the operational trends of the Mobile Servicing System (MSS) aboard the ISS, emphasizing how Canadarm2 and Dextre have contributed to and enhanced the operational longevity and success of the ISS and long-duration human spaceflight. The advancement of the robotic capabilities on the ISS has allowed for more efficient and flexible space operations, while increasing operational capabilities and reducing the need for Extra-Vehicular Activities (EVAs) to perform critical maintenance tasks, which in turn has reduced the risk to human life and enabled better allocation of valuable and scarce human crewmember attention. This well-proven concept is now forming the basis for the future of human space exploration and Human-Robot Interactions (HRI), including for missions associated with commercial human spaceflight and the Artemis Gateway space station in Near Rectilinear Halo Orbit, all of which are developing the foundation necessary for humanity to reach Mars. By highlighting the successful collaboration of human and robotic system from the past and present, this study provides insights into strategies that will pave the way for an accessible and sustainable future of human spaceflight.

Keywords: Space Robotics, Human-Robot Interaction, Canadarm2, Dextre, Extra-Vehicular Activity

Acronyms/Abbreviations

APFR	Articulating Portable Foot Restraint	MCC	Mission Control Centre
ConOps	Concept of Operations	MSS	Mobile Servicing System
EVA	Extra-Vehicular Activity	MT	Mobile Transporter
EVR	Extra-Vehicular Robotics	ORU	Orbital Replaceable Units
HRI	Human-Robot Interaction	OTCM	ORU Tool Changeout Mechanism
ISS	International Space Station	PDGF	Power and Data Grapple Fixture
IVR	Intra-Vehicular Robotics	RWS	Robotic Workstation
LEE	Latching End Effector	SRMS	Shuttle Remote Manipulator System
LEO	Low Earth Orbit	SSRMS	Space Station Remote Manipulator System
LOS	Loss of Signal	SPDM	Special Purpose Dexterous Manipulator
MBS	Mobile Base System	THA	Tool Holster Assembly

1. Introduction

Space robotics is a quickly developing field that has already proven crucial to advancing and enabling space exploration operations, including providing invaluable aid to astronaut crews. Since the first space robotics mission in 1967, the space industry has seen extensive developments in the quantity, category and capabilities of these robotics. Today, space robotics can be divided into three categories: orbital robotics, planetary and lunar robotics, and other Solar System body robotics (i.e. robotics for asteroid-based missions) [1],[2]. The former two categories will be explored, as destinations more accessible for near-future crewed exploration. Within each locational category, space robotics are often also classified by their type of operation, whether the system is a manipulator (i.e. a robotic arm), a rover or other traversal mechanism, or a free-flyer [2],[3]. Finally, space robotics have varying levels of autonomy, from full teleoperation – operated remotely, for example by ground controllers or the astronaut crew – to fully autonomous, something that is of increasing importance as the distance from Earth and the resulting communication lag increase [2].

With crewed space exploration comes challenges and risks to human life. The integration of robotics has filled the gap to perform operations that are not feasible for crews to perform and frees up astronauts to prioritize and perform other mission-critical tasks. Robotics has also been used to either directly aid humans in executing Extra-Vehicular

Activities (EVAs) or replace the need for spacewalks altogether. The Mobile Servicing System's (MSS) Extra-Vehicular Robotics (EVR) role on the International Space Station (ISS) is a prime example of operational demands driving human-robot interaction (HRI) trends in space to promote safety, operational efficiency and overall longevity of spacecraft and missions.

In this paper, the evolution and future of space robotics will be considered, with an emphasis on the current robotics aboard the ISS, considering the impact of robotics on crewed exploration, efficiency, success, and safety.

1.1. History of Space Robotics and Operations

Robotic systems in space and their associated concepts of operations depend on many factors, including: independent operation vs. human collaboration with astronauts, mission needs, and the availability and latency of communication. Efficient and safe space exploration in general relies on space robotics of all kinds. This reliance will continue to grow as the number, scale, complexity, and average distance from Earth to exploration missions all increase.

1.1.1. Orbital Robotics

Orbital robotics – robotics supporting missions in orbit around Earth or another body – are often manipulators or arms with a specialized end effector and have been employed for a vast variety of missions for the purposes of debris removal, satellite and spacecraft capture, berthing and deployment, assembly, servicing, and beyond. Orbital robotics have prominent HRI heritage today. Orbital robotics, predominantly EVR in LEO, began with the 6 degree-of-freedom Shuttle Remote Manipulator System (SRMS, or Canadarm) in 1981, during the Space Shuttle program as seen in Fig. 1, with co-located teleoperation from within the Space Shuttle. These manipulators, built for each of the Space Shuttles, proved to be a key element of NASA's human spaceflight program. While initially conceived as mainly as system for retrieving and deploying payloads, the Canadarm proved to be an invaluable all-purpose space tool used for such critical tasks as constructing the ISS, repairing and upgrading payloads (such as the Hubble Space Telescope), supporting spacewalks, conducting surveys, and a variety of unique, mission-saving tasks. Indeed, SRMS was mission-critical on 72 of the 90 missions that it flew, was used to support 71% of the Space Shuttle EVAs and was needed on 50% of its missions to address or troubleshoot some kind of anomaly [4],[5]. Many manipulators have followed, including for testing and verification of functionality, such as the ground-controlled robot of DLR's 1988 experiment aboard the Space Shuttle, the Robotic Technology Experiment on Spacelab D2 Mission (ROTEX), featuring a robotic arm capturing free-floating objects in orbit [2]. This was followed by JAXA's ETS-VII in 1997, which demonstrated a robotic arm on a primary uncrewed satellite capturing and berthing a secondary satellite, changing out Orbital Replaceable Units (ORUs) and conducting other operations, the first robotic arm aboard a satellite [7]. Later, MDA Space developed the Orbital Express Demonstration Manipulator System that, aboard Boeing's ASTRO satellite, successfully performed the first autonomous satellite capture, demonstrating servicing operations with Ball Aerospace's NextSat in 2007, under contract to DARPA [8].


Fig. 1. SRMS on the Space Shuttle. [6]

Currently, there are numerous manipulators in Earth's orbit, including the Space Station Remote Manipulator System (SSRMS) launched in 2001 and the Special Purpose Dexterous Manipulator (SPDM) introduced in 2008, as part of the MSS aboard the ISS. In 2008, the Japanese Experiment Module (JEM) Remote Manipulator System (JEMRMS) was also added to the ISS' JEM, a system consisting of a Main Arm, and a Small Fine Arm for dexterous operations [10]. The JEMRMS' primary function, with an end effector provided by MDA Space, is to sustain and support payloads on the JEM Exposed Facility (JEF), including transferring, berthing and exchanging payload ORUs [9],[10]. The Chinese space station is also currently home to robotic arms [2].

Intra-Vehicular Robotic (IVR) manipulators have also been employed on the ISS: the humanoid space robot Robonaut2, as seen in Fig. 2, was deployed as the first of its kind on station in 2011 to test robots performing crew tasks within the ISS independently and in collaboration with astronauts, with similar mobility and tool interfaces as humans [13],[14].

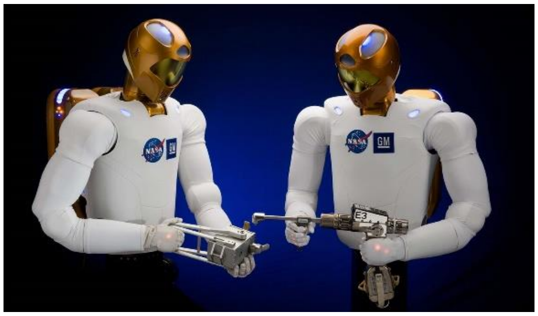
Fig. 2. Robonaut2. [14]

Free-flyer orbital robotics are also prevalent as IVR and EVR for inspection, astronaut aid, and scientific experimentation or demonstration purposes: since 2019, the ISS has been equipped with three Astrobee robots, free-flying autonomous or teleoperated cuboid IVR that traverse the interior of the ISS with cameras and sensors to provide better views of the ISS and monitor the ISS environment for levels of dangerous parameters, including radiation, to keep current and future astronaut crews safe. They also perform station maintenance without crew assistance and have a Robotic Perching Arm to base themselves on station handrails with pan and tilt capabilities [11]. Other EVR free-flyers have been tested, including the 1997 Autonomous Extravehicular Robotic Camera Sprint (AERCam Sprint), a passively-safe system with speed operational limits, which demonstrated extravehicular crew-controlled free-flyer capabilities: it enabled pre- and post-operation inspections, and more flexible camera points of view for operators with attitude hold capabilities outside the Space Shuttle [12].

1.1.2. Planetary and Lunar Robotics

Meanwhile, planetary and lunar robotics missions – commonly in the form of landers and rovers, many with other robotic manipulators for the execution of operations – started with the very first space robotics project, with the 1967 ground-operated Surveyor 3 lunar lander, accompanied by a robotic arm sampler or "scoop" for digging and various surveying instruments to understand the lunar material [15]. Subsequent planetary robotics missions have similarly been purposed for data acquisition and return for scientific research, as well as imagery and exploration of unknown extraterrestrial surfaces. Following the first Surveyor 3 lander, the Soviet Union's Luna 16 mission arrived at the moon in 1970, equipped with robotic arms for drilling and sampling, before the 1970 Luna 17 missions became the first planetary rover, Lunokhod 1, teleoperated from Earth to traverse the moon [3]. Shortly after, in 1975, humanity reached Mars via space robotics: the Viking 1 mission, with a lander equipped with a surface-sampling robotic arm to characterize the Martian soil and environment and investigate through experimentation for traces of life [16]. Planetary exploration has continued to grow from there, with Mars rovers developing autonomous capabilities used alongside teleoperation for terrain navigation, hazard detection and correction. To do so, these robotics have advancing remote sensing and machine intelligence. Robotic manipulators for planetary exploration have also progressed with more advanced technologies and instruments for sample retrieval and analysis, such as Alpha Proton X-Ray Spectrometers and Rock Abrasion Tools featured on the more recent Mars rovers [3]. NASA's inaugural Martian rover in 1996, Sojourner, paved the way for more recent rover technology, as the first planetary robotic system with autonomous capabilities, employing stereo vision [17]. Ingenuity then became the first extraterrestrial helicopter, conducting autonomous flights on Mars from 2021 to 2024, demonstrating controlled flight in a non-Earth environment, with reduced gravity and atmosphere [18]. Presently, operations conducted by planetary robotics revolve around discovery and learning, including sampling, surveying, inspections, data analysis, and transportation.

Despite the vast majority of planetary and lunar missions being uncrewed (aside from the six influential Apollo missions between 1969 and 1972 landing humans on the moon), these uncrewed planetary and lunar robotic systems have provided knowledge and set the foundation for future human exploration with support from robotics, with the goal of landing astronauts at the lunar South Pole by 2027 before establishing a permanent outpost on the moon as a precursor to Martian exploration [19].

1.2. Mobile Servicing System

The MSS is an EVR system with active safety used nearly daily on the ISS by astronaut crews and via ground control from Johnson Space Center and the Canadian Space Agency. It consists of the SSRMS and SPDM, commonly known as Canadarm2 and Dextre, respectively, as well as the Mobile Base System (MBS) and Mobile Transporter (MT). The MBS is a platform providing Power and Data Grapple Fixtures (PDGFs), or interfaces for SSRMS and SPDM to attach to, as well as camera views to aid in operation; it is located on the MT, which traverses along the ISS truss, enabling robotic access across the ISS.

1.2.1. Space Station Remote Manipulator System

The SSRMS, popularly known as Canadarm2, is a nearly symmetrical 17 m long anthropomorphic arm, consisting of 7 degrees of freedom across the shoulder, elbow, and wrist, connected via two booms. A Latching End Effector (LEE) at either end enables SSRMS to attach to grapple fixtures, such as PDGFs, located on the ISS and MBS, allowing "walk offs" to traverse across the station. It can also snare grapple fixtures on SPDM, visiting vehicles, or various payloads.

SSRMS was launched in 2001 and is teleoperated from within the station or from Mission Control Centres (MCCs) on Earth to perform a variety of operations. Its main tasks involve visiting vehicle operations – namely capturing (see Fig. 3), berthing, unberthing and release, and general servicing – ISS assembly and maintenance, EVA support (as described in Section 1.3), payload manipulation, and inspections. Similar to how an astronaut can be maneuvered by SSRMS for EVAs, SPDM can be grappled by an SSRMS LEE and moved about the ISS.

1.2.2. Special Purpose Dexterous Manipulator

SPDM, commonly called Dextre, was launched in 2008, and is a ground-operated dual-armed robot, intentionally designed to perform precise operations to minimize the need for EVAs. It has 7 degrees of freedom per arm in addition to the main Body Roll Joint, a LEE to enable interfacing with and attachment to grapple fixtures around the station, as well as a PDGF that can be grappled by SSRMS for relocation or to access distant locations. SPDM is also equipped with an ORU Tool Changeout Mechanism (OTCM) on both arms, in addition to tools stored in the Tool Holster Assembly (THA) and a platform for payload storage that enable dexterous operations such as ORU and payload Removal and Replacement (R&R) operations, and repair.


Fig. 3. SSRMS capturing Cygnus. [20]

1.3. Extra-Vehicular Activity Risk and Robotics

EVAs, or spacewalks, are activities where astronauts exit a pressurized vehicle in a protective and life-sustaining suit to conduct operations. Historically, EVAs have been performed outside a spacecraft in LEO, first performed by cosmonaut Aleksei Leonov in 1965 during the Voskhod 2 mission, or on the lunar surface, the inaugural lunar EVA occurring with Neil Armstrong and Buzz Aldrin in 1969 during Apollo 11 [21]. In the future, EVAs will also be required in other microgravity environments including the Gateway in a lunar Near-Rectilinear Halo Orbit, and for other planetary and smaller body surfaces, including on Mars. EVAs are performed for various purposes, such as for repair and maintenance – including of the structure, spacecraft and EVR – construction, experimentation, and inspection, and are sometimes contingency spacewalks in the case of off-nominal events. Many protections and redundancies exist to maintain astronaut safety, identified in crew operation and spacesuit requirements. These include electrical current limits, sharp edge and burr mitigation, radiation and carbon dioxide level monitoring requirements, visibility considerations, cognitive and physical workload minimization, limits of time spent in a spacesuit, monitoring and controlling chemical levels and temperatures, all to support and protect crews from the harsh space environments [22]. EVAs are often performed with support from robotics, including SRMS during the Space Shuttle era, and presently SSRMS on the ISS. The manipulator is equipped with foot restraints for the EVA astronaut, such as the Articulating Portable Foot Restraint (APFR) shown in Fig. 4, allowing the arm to ferry the crew member to distant locations on the ISS, including the solar arrays for repair.

Fig. 4. EVA crew member based on APFR on SSRMS. [23]

Despite all required and implemented protections, EVAs are high risk operations for astronauts to perform with the potential for harmful or fatal consequences due to system and hardware failures, human error, operation issues, suit limits, and other unavoidable issues [24]. In fact, out of the 481 EVAs that have been performed between the United States, Russia, and China from the first EVA in 1965 through August 8th, 2024, 20% of EVAs have featured anomalies (such as injuries, EVA suit damage, and ISS hardware malfunction), with 3% of EVAs including injury of the EVA crew, and 0.4% which have seen injury *and* required early EVA termination [25]. Specifically regarding injuries, based on data prior to 2009, the EVA injury rate reached 0.26 injuries per EVA: EVAs are the cause of the most crew injuries in space exploration, exacerbating (and sometimes caused by) the existing physiological and psychological impacts of space, including changes of vision, reaction time, sensorimotor skills, muscle density, and cognitive capacity [26],[27]. The evolution of EVA incidents is depicted in Fig. 5 compared to the total number of EVAs, depicting a decadal reduction in the number of most countries’ EVAs and total incidents since the introduction of SPDM in the late 2000s after an increase in the 2000s, in part due to ISS construction [25]. The progression of total incident and critical incident rates are highlighted in Fig. 6, demonstrating a rough reduction and stabilization in both over time despite some fluctuation.

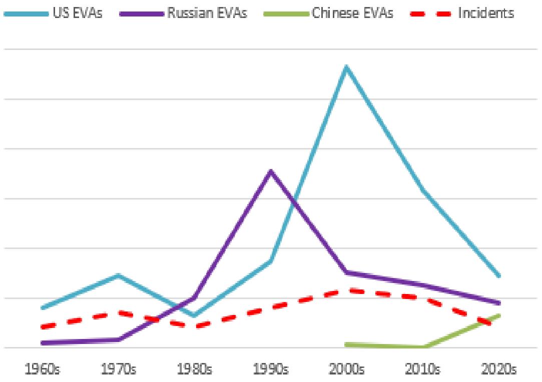

Fig. 5. Total number of EVAs per country and EVA incidents over time. Last data: August 8th, 2024. Adapted from [25].

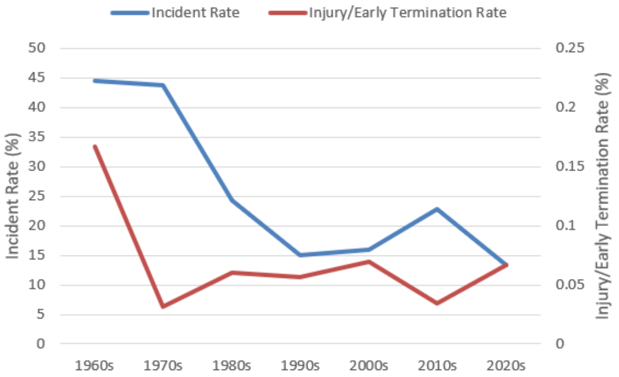

Fig. 6. EVA incident and critical incident rates over time. Last data: August 8th, 2024. Adapted from [25].

Life-threatening anomalies during EVAs have occurred due to EVA suit failure, such as broken cooling systems, ventilation loops, or carbon dioxide scrubbers leading to accumulation of unwanted substances and in turn fogged visors and irritation. EVA suit damage is also of major concern, including punctures and fraying from both over-use and contacting sharp or burred surfaces, leading to burns and fatigue [24]. Another cause of incidents includes Concept of Operations (ConOps) issues, including unsecure safety tethers, repetition leading to skin abrasions, and pre- and during-EVA fatigue [24]. Each issue has the potential for fatal implications.

Evidently, EVAs are some of the most dangerous and harmful facets of crewed space exploration, even within the relative proximity of current low-Earth orbit destinations. EVAs may increase in frequency for long-duration missions up to 24 hours of planetary surface EVAs per week for six-month missions, depending on the chosen ConOps [26]. This will require strategies to accommodate greater mobility for planetary traversal, regolith, radiation, different gravity environments, and associated physiological, metabolic, and psychological strain and fatigue, as well as strategies to avoid injuries when there is higher risk, for example due to microgravity de-conditioning and longer communication delays to ground support [28],[29].

Robotics will be crucial to assisting astronauts in EVAs – and even reducing the necessity for EVAs, as demonstrated by the introduction of SPDM on the ISS. As crewed exploration reaches deep space, HRI will be paramount in supporting EVAs for both physical and psychological tasks, to reduce this great risk to human life, maintain efficiency and consistency, and to enhance safety during missions.

2. Discussion

2.1. MSS Influence on International Space Station Crews

Since 2000, there has been a constant human presence aboard the ISS. The SRMS aided in construction and operations until 2011, overlapping for 10 years with SSRMS, both supporting EVAs and high-load capacity operations to manipulate station modules, payloads, vehicles and other hardware. SPDM was deployed in 2008, with the capability to perform dexterous operations as EVAs had only been able to manage previously. Throughout the lifespan of MSS on the ISS, it has conducted more than 2300 operations.

In considering the evolution of the quantity of MSS operations – where "operations" is defined by events starting on separate GMT dates (each GMT start date could contain up to 3 operator shifts) – it can be compared with the number of non-MSS-supported EVAs performed on the ISS, as depicted in Fig. 7. There was a spike in EVAs in and prior to 2002, largely due to ISS construction, and again around 2007, prior to SPDM's launch in March 2008. Overall, an increasing trend in the number of robotic operations can be identified, while post-SPDM installation, EVAs have decreased and remained below the pre-SPDM 2007 maximum. This proves how EVR operations have increased, initially enabling more operations to occur with the introduction of SSRMS, before reducing astronaut EVA duties through the combined use of SSRMS and SPDM.

It can be noted that, between 2003 and 2005, a decline in all extra-vehicular operations occurred, presumed to be due to a pause in Space Shuttle spaceflight after the Columbia disaster in February of 2003. It is also important to mention that, until 2011, some EVA operations and MSS EVR operations in Fig. 7, Fig. 8, and Fig. 9 may have had support from SRMS. Independent SRMS operations are also not identified in these figures.

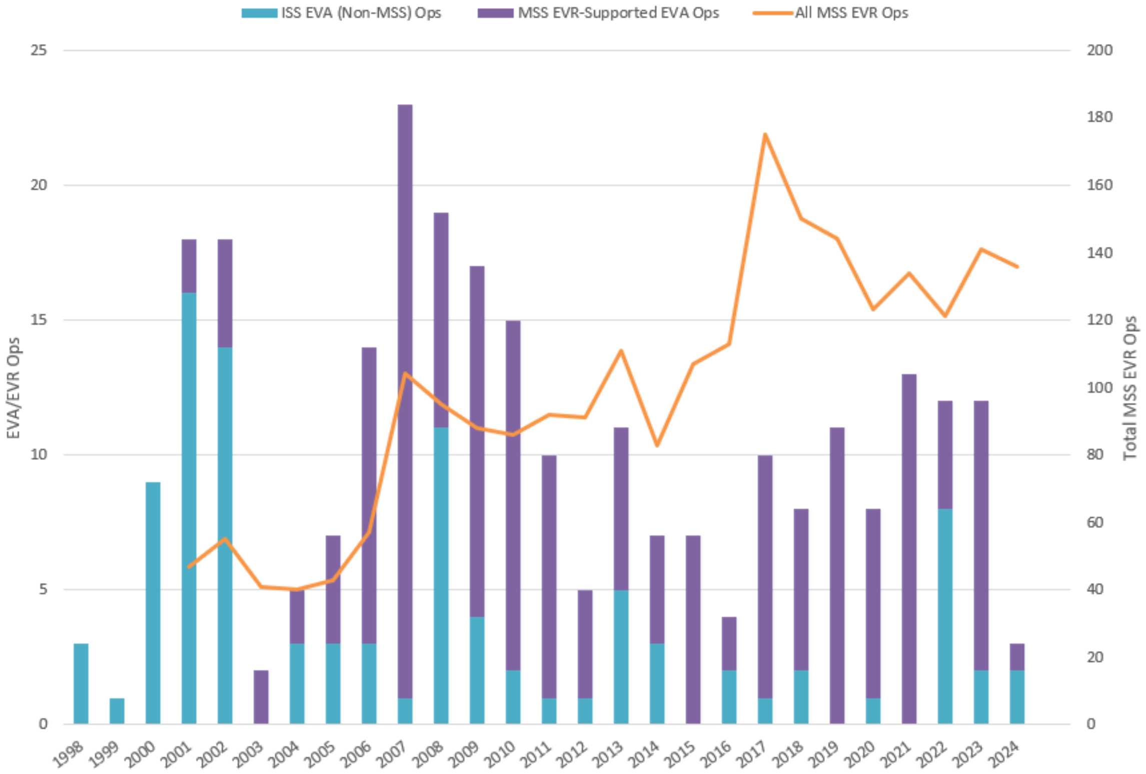

Fig. 7. ISS Extra-Vehicular Operations: EVA vs. EVR Comparison (1998-2024)*. Adapted from [30],[5].

The yearly averages of EVA operations around the installation of SSRMS and SPDM on the ISS can be seen in Table 1:

Table 1. ISS Operation Yearly Average (1998-2024)* [30],[5]

	Total ISS EVA Operations	Total MSS EVR Operations	ISS EVA (Non-MSS) Operations	MSS EVR Only Operations	MSS EVR-Supported EVA Operations
Pre-SSRMS	4.4	0.0	4.4	0.0	0.0
Post-SSRMS and Pre-SPDM	11.4	54.7	4.6	47.9	6.8
Post-SPDM	9.8	116.2	2.5	108.9	7.4

The yearly average of MSS-supported EVAs increased by 6.8 operations with the introduction of SSRMS, compared to the 0.2 operation change for non-MSS EVA operations, further demonstrating the ISS' EVR enabling the completion of necessary EVA operations. This can also be seen with the average number of EVA operations *with* EVR

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[*] Note that MSS EVR data may vary slightly from values due to reporting discrepancies.

support increasing to 7.4 operations per year post-SPDM, in comparison to the average EVA-only operations (with no EVR support) falling to only 2.5 operations per year. Meanwhile, the total EVA average decreased with the addition of SPDM, as the EVR operation averages per year has more than doubled [30],[5].

Out of the total extra-vehicular operations, the percentage of all EVA operations – both with and without MSS EVR support – has decreased with the addition of each MSS robot on the ISS, as the proportion of MSS EVR operations (not including those supporting EVAs) has increased to comprise the majority of operations outside the ISS, visualized in Fig. 8 and Fig. 9.

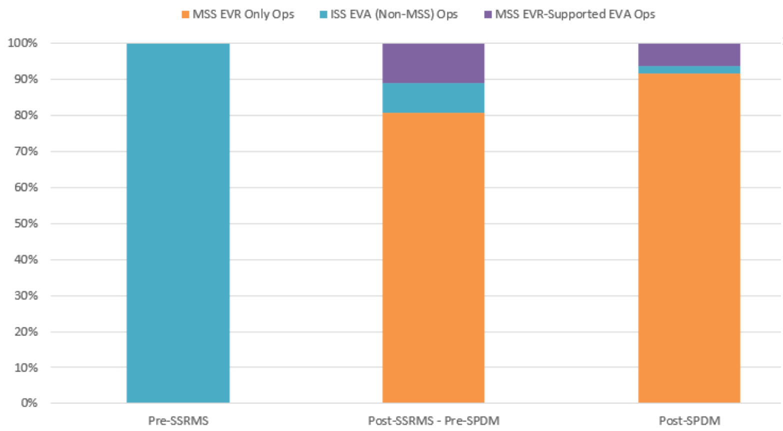

Fig. 8. ISS Extra-Vehicular Operations Distribution Between MSS Robotic Changes (1998-2024)*. Adapted from [30],[5].

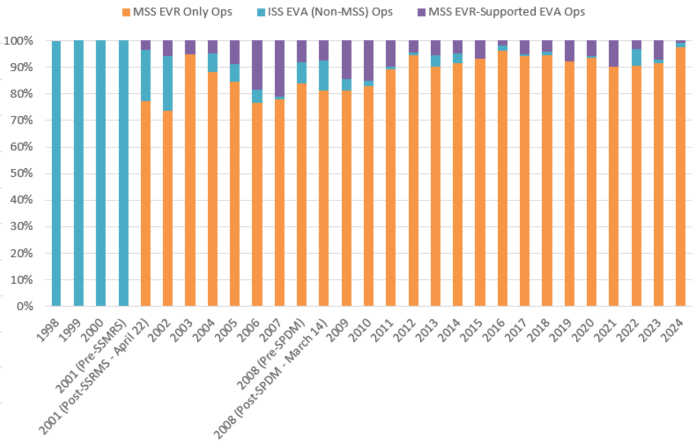

Fig. 9. ISS Extra-Vehicular Operations Distribution Per Year (1998-2024)*. Adapted from [30],[5].

The relative increase of EVR operations and decrease of EVA operations (both with and without MSS support), normalized by the total extravehicular operations in the given period, demonstrates the role of EVR in reducing risky EVA activities, improving the overall safety posture of human spaceflight and contributing to greater efficiency of crew operations with re-distributed and improved time usage.

2.2. Robotics in the Future of Spaceflight

As evidenced by manipulators presently on the ISS, robotics are crucial for performing necessary operations in space. Robotics and HRI will also grow more essential over the next few decades as crewed space missions extend beyond Low Earth Orbit (LEO): immense challenges are posed to human life and habitability with deep space exploration to the moon, Mars, and beyond, requiring support and collaboration with space robotics.

As humans travel farther into the solar system, hazards to human life and productivity increase. The change in environment of deep space travel and planetary or lunar exploration has vast psychological and physiological impacts on humans, including from dust, radiation, nutrition and reduced gravity, as well as limited communication and social isolation [31],[32]. Combined, these influence the crew’s cognitive function, fine motor skills, senses, reaction time, and overall performance, which will create an additional need for robotic assistance in crew operations, and may even necessitate the implementation of robotics intended to mimic social interaction [31],[32],[33]. Other robotic operations involve infrastructure development and construction, EVA support (EVAs), general exploration of the planetary or lunar surface, and scientific experimentation requiring transport and mobility, sensing, sampling capabilities, testing, and analysis, which will require robotic capabilities such as drilling and high load-carrying capacities, as with the previous lunar and Mars robotic missions (described in Section 1.1.2) [31],[34].

Robotics such as the eXploration Large Arm (XLA) and eXploration Dexterous Arm (XDA) currently being designed for the Gateway space station in lunar orbit, as well as the MDA SKYMAKER^{TM} suite of robotic manipulators for commercial partners, are aiming at solving this challenge and providing customizable support and mission operations for future near-Earth and deep space exploration. These systems will have the capability to perform R&Rs and manipulate payloads, and conduct maintenance, relocate modules, and support EVAs on-orbit and on the lunar surface. It is important to note that Gateway will be only intermittently occupied by humans, thereby increasing the importance of robotic capabilities to manage contingencies without crew present, while still requiring HRI when crew is present.

As deep space is occupied by astronauts, crews will contend with communication delays growing from effectively real-time communication in LEO to one-way delays of several seconds for lunar missions, and to up to twenty-two minutes for Mars missions. Based on the Mars mission and expected duration, there is even potential for up to 21 days at a time of communication blackouts [35]. Resupply missions also become increasingly scarce, and missions lengthen with deeper space travel (with ConOps spanning several years) because of travel time [35]. Additionally, EVA durations can extend up to 24 hours in one week. Coupled with a limited number of astronauts per mission and the number of robots and complex operations, autonomy – ideally at a level to be able to operate without human interference and prepare for expected unknowns or issues – is required for both astronauts and robotics, including for HRI and efficiency of life-sustaining operations. Long-term, robotics autonomy in space should target self-contained planning and operation capabilities, while accounting for potential unknowns in the system via active sensing and fault recovery. Autonomy will also reduce the workload for astronauts in-flight, as on ISS two astronauts are typically required to operate MSS robotics from the Robotic Workstations (RWSs) onboard. Not only that, but this will reduce the currently extensive training needed for crew operation as has historically been the norm.

In addition, HRI in the sense of human control modes will require adaptation for future exploration beyond the operation mode with humans-in-the-loop: autonomy on the ground for operation (regardless of distance from Earth) is becoming more necessary for efficiency. For example, as the commercial market grows and the quantity of robotics requiring operation is scaled, it will become infeasible to have dedicated Mission Control Centres with highly-trained operators for every system.

3. Conclusion

Space robotics have advanced significantly over the past 58 years, enabled by both incremental and revolutionary technological developments. Many, particularly SSRMS and SPDM, have proven the significance of robotics in aiding crews and enabling complex, efficient, and reliable operations to reduce dangerous operations, while maintaining and improving the longevity of the astronauts' home in space. Further developments will be needed for future missions including, but not limited to, sensing, artificial intelligence (perhaps including generative AI) such as for mission planning, inspections, and navigation, increased bandwidth and computational capacity, and reliable power production mechanisms for robotic and other use [36],[37]. Robotics will be essential for future crewed exploration, including missions to deep space.

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