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# Extended Reality In U.S. Spaceflight Operations: A Review Of Historic And Potential Future Applications

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***Abstract -*** *Extended reality (XR) concepts and technology have been used by the National Aeronautics and Space Administration (NASA) since the very early days of the U.S. space program, primarily evidenced by the agency's extensive application of XR-enabled telerobotic techniques while conducting remote exploration and space operations [1, 2, 3]. NASA has also leveraged virtual reality (VR), augmented reality (AR), and mixed reality (MR) when facilitating human spaceflight training, seeking ways to ensure astronaut physical and mental health, and designing human-machine interfaces; the agency has further experimented with telepresence applications, which integrate multiple XR disciplines [1, 2, 4]. Here we present a survey of historic and recent XR-related efforts in the U.S. space program and also highlight forecasted uses of such technologies in future long duration (i.e., cislunar and interplanetary) space missions, such as Artemis [5, 6, 7, 8, 9, 10]. Note that this article focuses on human and human-robotic spaceflight operations and does not cover the ubiquitous examples of XR being used throughout NASA for additional science, engineering, analytic, and educational applications [11, 12, 13, 14]. Throughout this review it should be evident that as XR concepts, techniques, and subdisciplines have emerged and evolved, increasingly advanced integrated use cases of the technologies have also manifested.*

***Key Words***: **Technology, Extended Reality, Virtual Reality, Augmented Reality, Robots, Telerobotics, Telepresence, Telemedicine, Telehealth, Human-Machine Interfaces, NASA, Space, Spaceflight, Spacecraft, ISS, Artemis, Gateway, Moon, Mars, Cislunar, Space Exploration, Mars Rovers, Science Fiction, Gaming, Video Games, Cyberspace, Digital Twins, Virtual Worlds, Synthetic Environments, Immersive Worlds**

## 1. INTRODUCTION

Extended reality (XR) is an umbrella term encompassing concepts, technologies, and techniques that enable human-human and/or human-machine interactions within virtual environments (VE) and combined environments featuring real and computer-generated components [3]. The XR domain includes the subdisciplines of virtual reality (VR), augmented reality (AR), and mixed reality (MR). Extended reality also covers mediated remote experiences – such as telepresence and telerobotics – that can be enhanced by VR/AR/MR-associated technologies. This is particularly the case when such implementations include immersive elements that enhance a user's sensation of "presence" within synthetic, augmented, or mixed-reality renditions of distant environments. Many of the concepts underlying and driving the development and evolution of XR methods and technologies have their roots in science fiction [3]. Fittingly, throughout its history the National Aeronautics and Space Administration (NASA) has investigated, developed, and implemented XR techniques to accomplish its space exploration mission [1, 2, 4, 15, 16, 17, 18].

We begin our review of XR technology in the U.S. space program by highlighting notable historic experimental and operational applications of telerobotics, VR/AR/MR, and telepresence in NASA-led human and human-robotic space initiatives. Afterward, we discuss potential uses of XR technology in future space exploration programs, focusing on applications for long-duration cislunar and interplanetary spaceflight endeavors such as *Artemis* [5, 6, 7, 8, 9, 10].

## 2. TELEROBOTICS IN THE U.S. SPACE PROGRAM

Telerobotic operations involve the remote control of robots to perform actions in distant and/or dangerous environments [3, 19, 20]. Telerobots can be operated via various control schemes, some of which are designed to help compensate for distance-related communications delay (i.e., latency), or to assist humans by handling complex processes – thereby freeing the controller to focus on aspects of tasks that require more skill, innovation, or attention. These control methods include [3, 19, 20]:

- Full Autonomy: The robot can operate on its own to accomplish tasks, without operator intervention.
- Supervisory Control/Partial Autonomy: An operator is responsible for defining the higher-level goals for the telerobot based on its current situation. The robot can handle some complex processes autonomously but performs its functions under the overall control of a person using a command-based structure. Useful under conditions with substantial latency.

- Shared Control: The robot has a higher degree of autonomy to dynamically assist the operator in completing tasks.
- Direct or Manual Control: The operator has full control over the system all the time.

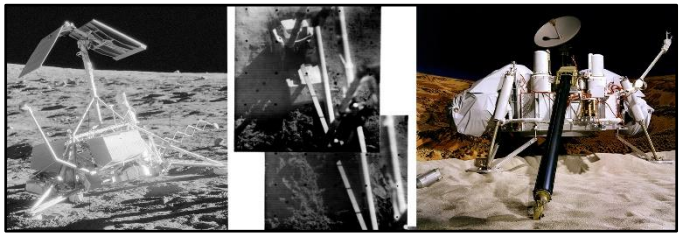

**Fig – 1**: Surveyor 3 and first lunar dig (left, center). Project *Viking* Mars lander replica (right). [24, 30]

Telerobotic systems often rely on XR methods and technologies to provide users with intuitive interfaces featuring more "human-like" sensations and/or realistic recreations of distant or dangerous environments during machine-enabled remote operations [19, 21, 22, 23].

Significantly, the first instance of near real-time supervisory control of a telerobot on an extraterrestrial surface was accomplished by NASA in April of 1967, when the Surveyor 3 lander's mechanical arm was directed to probe the Moon's regolith by Earth-based operators [1, 24]. The honor of teleoperating the first "trench dig" on another world went to JPL engineer Floyd Robertson (see Fig – 1) [25]. Robertson and other operators, guided by the spacecraft's television camera, used the arm's Soil Mechanics Surface Samplers (SMSS) to scoop, manipulate, and ascertain the physical characteristics of surface materials; this was repeated during the Surveyor 7 mission in 1968. In practice, controlling the arm was a step-by-step process, requiring visual verification of results before a new command was issued. Nevertheless, Oran Nicks – then head of lunar flight systems – described this ability "to manipulate the surface the way a person might with his hand" as adding another dimension to exploring [25]. As a result, geologists were able to confirm the presence of highly consolidated material on the lunar surface, paving the way for human explorers during *Apollo* [1, 25].

Incidentally, as the U.S. proceeded with additional robotic precursor missions and then on to the crewed *Apollo* program, the Soviet Union landed and operated the first rover vehicle beyond Earth on 17 November 1970 [26, 27, 28]. During the historic Lunokhod 1 mission, a "five-man team" of Russian operators directly controlled the rover in real-time, successfully driving it across the surface with a top speed of about 100 meters per hour, despite a communications delay of about 5 s round-trip time. The 10 km of lunar surface explored during the lifespan of this first rover was greatly surpassed by Lunokhod 2 in 1973, which covered 37 km using the same direct, real-time driving method. Science operations and surface imaging using the rovers cameras were not conducted while they were moving, but only when stationary. Unfortunately, the time delay ultimately contributed to the malfunctioning of Lunokhod 2, when dust thrown up by an inadvertent descent into a crater interfered with its thermal control systems [26, 28]. Nevertheless, the *Lunokhod* program predicted the utility and feasibility of direct, Earth-to-Moon teleoperations of robotic vehicles [26]. More recently, China applied VR and teleoperation techniques to control lunar rovers during the Chang'e-3 and Chang'e-4 missions to the Moon's near- and far side, respectively, with some facets of these operations reportedly conducted in real-time [29].

Development and application of telerobotic planetary exploration techniques in the U.S. space program continued throughout the remainder of the 20th and into the 21st century, epitomized by multiple Mars surface missions mounted by NASA. Beginning with surface sampling conducted by the *Viking* telerobotic arms, technology and procedures became more advanced with each spacecraft the agency sent to the "Red Planet" (see Fig – 1). Supervisory control remained the primary means of controlling surface robots to compensate for the considerable communications delay to Mars (at times in excess of 40 min) [2, 20, 30, 31]. However, increasing degrees of independence were introduced beginning with the *Mars Pathfinder* mission launched in 1996, which deployed *Sojourner,* the first semi-autonomous planetary rover. Later on, the two *Mars Exploration Rovers* (MER) – *Spirit and Opportunity* – journeyed over 7 km and 45 km, respectively, using autonomous and supervisory control methods [31]. Of interest, based on subjective reporting, D. Chiappe and J. Vervaeke [32] suggested that MER operators experienced sensations of extended-presence and core-presence, as defined by G. Riva and J. A. Waterworth [33].

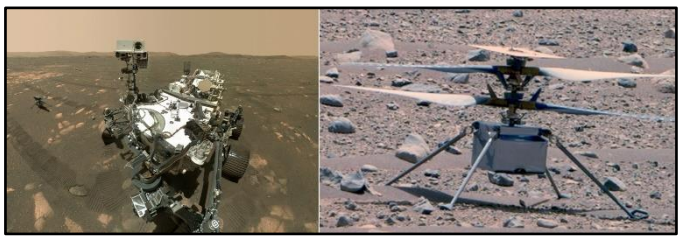

**Fig – 2**: Mars *Perseverance* rover (left) and *Ingenuity* helicopter (right). [31]

By 2024, using a combination of supervisory control and autonomous driving, the Mars *Perseverance* rover – launched in 2020 – had traversed and explored over 30 km of the Martian surface, demonstrating advanced navigation and obstacle avoidance skills [31, 34, 35, 36]. Moreover, after performing the historic first powered, controlled flight on another planet on 19 April 2021, the 1.8 kg *Ingenuity* Mars Helicopter that accompanied *Perseverance* completed 72 exploration flights through the

skies of Mars over nearly 3 years. The helicopter flew autonomously, based on plans that were remotely generated and transmitted by NASA Jet Propulsion Laboratory (JPL) operators. Although it suffered a crash in January 2024, *Ingenuity* greatly surpassed its five-flight mission objective, gathering important imagery and data while demonstrating advanced independent flight control and successful operator-assisted navigation on another planet [31, 34].

Remote manipulation was also utilized throughout the U.S. Space Shuttle (i.e., Space transportation System, STS) program. This is highlighted by the integration of the Canadian Space Agency (CSA)-supplied Canadarm robotic arm aboard 90 shuttle spacecraft flights in 30 years (1981–2011) [1, 37, 38]. Also known as the Shuttle Remote Manipulator System (SRMS), the Canadarm and its various end effectors, manipulation assemblies, and sensor systems was instrumental in performing duties such as spacecraft deployment, repair and maintenance; spaceflight photography and videography; surveys and manipulation of the shuttle cargo bay and its payloads; and astronaut extravehicular activity (EVA) assistance. The Canadarm could be operated in various ways, including visual and camera-aided manual teleoperation by astronauts via the SRMS Control System within the space shuttle cabin, or preprogrammed automatic control [1, 37].

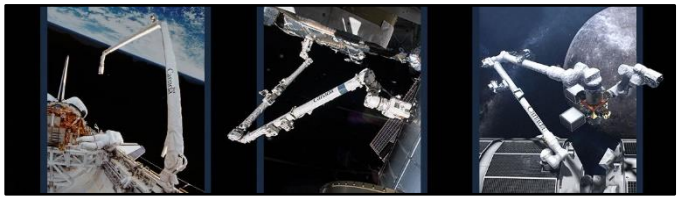

**Fig – 3**: Canadarm and Canadarm2. [37]

The success and legacy of the Canadarm was carried into Canadarm2, also called the Space Station Remote Manipulator System (SSRMS), which has been actively deployed aboard the International Space Station (ISS) since 2001 (see Fig – 3) [1, 37]. Canadarm2, like its predecessor, can be controlled by astronauts aboard the ISS using the station's Robotics Workstation, operated in automatic/preprogrammed mode, or teleoperated by ground controllers [1, 37]. Augmented by the Mobile Base System (MBS) moveable work platform/storage location, and the highly advanced Dextre space robot, the combined SSRMS suite can perform similar duties as the original Canadarm as well as very sophisticated ISS maintenance and operations functions [1, 38].

In the early to mid-2000s, NASA delivered several small, free-flying telerobots called Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) to ISS [39]. These battery-powered, 18-sided polyhedral robots, each about 21 cm in diameter with a mass of about 4.1 kg, were inspired by the autonomous, free-floating "seeker droid" that Luke Skywalker practices his lightsaber skill against in the science fiction film *Star Wars* (1977). Each SPHERES robot is propelled by compressed $CO_2$ gas and can roam about ISS assisting astronauts and conducting experiments sponsored by U.S. and international partner space organizations, corporations, or academic researchers [39, 40]. The SPHERES can be remotely controlled with WiFi or smartphone (i.e., "SmartSPHERES"), are gyroscopically stabilized, and are equipped with cameras and multiple sensors. Additional instruments can be attached to the SPHERES as specified by the intended experiments, such as 3D imagers for autonomous control, object inspection, and scene mapping techniques [39, 40]. In 2018, NASA commissioned the Astrobee project, replacing the SPHERES with three more advanced and highly customizable free-flying robots; each cubic robot is 32 cm on a side and equipped with miniature telerobotic arms (see Fig – 4) [40, 41, 42, 43, 44].

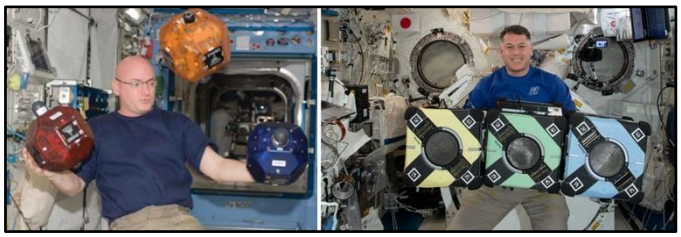

**Fig – 4**: SPHERES (left) and Astobee (right) on ISS. [39, 42]

## 3. VIRTUAL, AUGMENTED, AND MIXED REALITY IN THE U.S. SPACE PROGRAM

Virtual reality (VR) is a subset of XR that – via a combination of technologies – can immerse humans within realistic, three-dimensional (3D), artificially generated worlds or virtual environments (VE) [3, 45, 46]. Augmented reality (AR), like virtual reality, is a subdomain of XR that enhances a participant's perspective by dynamically overlaying digital elements onto their field-of-view (FOV) while allowing them to maintain a sense of presence and interoperability with the actual world [47]. In this way, AR "augments" their perception of the real-world without replacing it. Mixed reality (MR) is similar to augmented reality – however, MR takes the overlay of digital data a step further by allowing a user to interact with both virtual objects *and* actual objects residing in the "real world" [48].

NASA's investigations into the uses of VR technology in human and robotic spaceflight training and operations have been ongoing since at least the 1980s [1,2]. Crewed spaceflight is risky, complicated, and expensive, and the agency discovered that VR could give astronauts realistic training to ensure safety, lower overall costs, and increase the success rates of human spaceflight operations. Similarly, the agency applied VR techniques to prepare for

and conduct robotic planetary exploration programs – especially for landers, rovers, and aircraft sent to Mars – and evaluate data returned from these missions.

Interestingly, NASA itself developed the first low-cost, experimental wide field-of-view (WFOV) virtual reality HMD in the mid- to late 1980s (see Fig – 5) [2, 49, 50, 51, 52]. Known as the Virtual Visual Environment Display (VIVED, pronounced "vivid"), the device used basic, low resolution liquid crystal displays (LCD) made for handheld televisions. The system was invented by Michael McGreevy of NASA's Ames Research Center (ARC) who – as a visionary in the field of early XR – worked at the agency for years "…applying the ideas of visualization and inhabitable spaces to enable the planetary explorers to be where they could not physically go" [53].

**Fig – 5:** NASA VIVED (left); WFOV HMD (right). [51, 52]

In pursuing VIVED, McGreevy and his colleagues aimed to develop a multisensory VE workstation for use in spaceflight teleoperations and telepresence activities [2]. In fact, one of the primary goals of the team was to create a telepresence system that would enable a user to immersively teleoperate robots on other planets [54]. To this end, following VIVED they developed the Virtual Environment Workstation (VIEW), which integrated the EyePhone HMD and DataGloves for input, both developed by Jaron Lanier's company VPL [2, 3]. The VIEW team made advancements in head-coupled displays for gaze-tracking, and the 3D audio technology required for immersive multisensory experiences.

In 1993, NASA used VR technology extensively to prepare astronauts and ground crews for the STS-61 Space Shuttle flight, which was the highly important first mission to service the faulty Hubble Space Telescope (HST) [2, 55]. Instruction using virtual environments supplemented more costly and time-consuming EVA training utilizing physical resources such as the Weightless Environment Training Facility (WETF) at Johnson Space Center (JSC). The VE methods were later assessed to be a contributing factor to the success of the HST repair mission, and elevated interest in using this type of technology in future NASA human spaceflight operations, as pursued by JSC's Virtual Reality Lab (VRL). This was shown in continued use of VR/VE techniques throughout the 1990s and 2000s to conduct training for STS and ISS telerobotic operations (i.e., for Canadarm and Canadarm2), astronaut EVAs, and rescue operations using the Simplified Aid for EVA Rescue (SAFER) unit – a relatively small spacesuit propulsion module for emergency returns to a spacecraft or space station [2, 56, 57].

Johnson Space Center's VRL became the birthplace of NASA's VR-equipped Dynamic Onboard Ubiquitous Graphics (DOUG) system, which was used first on the Shuttle then integrated into ISS systems in the 2010s. As an extension of the VE training devised in the 1990s, DOUG enables virtual reality-immersed EVA crew members on the ground and aboard the station to practice on-orbit EVA procedures, engage with multiple robotic arm operators, and train on EVA scenarios [57, 58]. In 2016, the VRL also deployed the Microsoft HoloLens aboard ISS during *Operation Sidekick* – a program designed to make it easier and more efficient for ground controllers and subject matter experts to "holographically" assist astronauts with spaceflight, maintenance, and payload operations on the station via the HMD's AR/MR capabilities [15, 59].

Since then, a variety of other HMDs and VR/AR devices were used on orbit by NASA and its international partner space agencies during telerobotics testing, multiple scientific investigations, and medical/health experiments [15]. Between 2020 and 2022, for example, an Immersive Exercise Experiment aboard ISS integrated a stationary bicycle with an HMD to help determine if VR could enhance astronaut exercise aboard the station [17, 60]. The system played prerecorded panoramic videos of scenic Earth landscapes and urban environments while astronauts cycled, adjusting the playback speed to match their pedaling. The goal was to provide some additional variation and motivation for astronauts while they performed the two hours of daily exercise required aboard the station to mitigate detrimental effects of prolonged spaceflight (i.e., decreased muscle and bone mass). Additionally, a specially designed Vive Focus 3 HMD was sent to ISS in 2023 to support the study of VR for preventative mental health care; the VR headset was engineered for microgravity use via a collaborative effort between HTC Vive, Nord-Space Apps, and XR Health, and represented the first such use of a device [61].

**Fig – 6:** HoloLens aboard ISS (left); Immersive Exercise Experiment ground testing (right). [15, 60]

The impact of VR on NASA's telerobotic space exploration initiatives has also been substantial. Continuing from their work with VIVED and VIEW, McGreevy and associates built the Virtual Planetary Exploration (VPE) system [2, 50]. This system integrated digital terrain modeling techniques and imagery overlays to investigate the utility of using synthetically generated environments to study data from Mars probes such as *Viking*. Virtual reality technology, including HMDs, enhanced the sense of presence while performing exploration of realistic renditions of the Martian surface derived from the scientific information acquired by the landers. Effectively, this combination emulated physical, in situ exploration of extraterrestrial environments and enabled a type of virtual field research.

McGreevy's efforts with the VPE were inspirational in developing the VR-enhanced tools used by NASA to perform mission planning, remote control, and evaluation of the data returned by interplanetary lander/rover missions from the 1990s to present day [62]. These include the Rover Control Workstation (RCW) developed for the Mars *Pathfinder* program and the follow-on Rover Sequencing and visualization Program (RSVP) that has been used by operators of all subsequent Mars missions. RSVP Includes the Rover Sequence Editor (RoSE) for GUI commanding, and the HyperDrive application for 3D/stereo image and terrain modeling of the VE used to inform, guide, and simulate operations of surface rovers and aircraft [62].

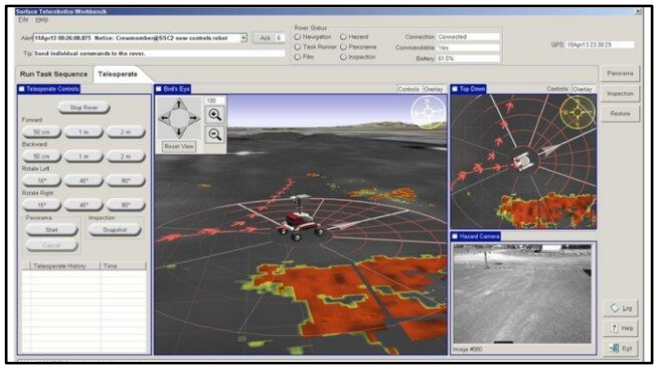

**Fig – 7:** NASA VERVE rover operating system. [66]

Some of the concepts devised by McGreevy and his colleagues were also incorporated into the NASA ARC-developed Visual Environment for Remote Virtual Exploration (VERVE) rover operation system (see Fig – 7) [63, 64, 65, 66]. With VERVE, controllers are provided with real-time, interactive high-fidelity 3D views of a rover's state, task sequence status, and position on a terrain map. In 2013, in an impressive test of space-to-surface robotic teleoperation, astronauts aboard ISS used a laptop equipped with VERVE and the Surface Telerobotics Workbench to remotely control a K10 rover in a simulated "Roverscape" constructed at NASA ARC [66, 67, 68, 69, 70]. Three distinct tests were performed, with three different astronauts operating the rovers for a total of about 10.5 hr; the tests featured intermittent line-of-sight (LOS) communications, latencies between 500 ms and 750 ms, and a combination of direct and supervisory control [69].

Among other tasks, the astronauts participating in the 2013 surface telerobotics tests from ISS conducted a virtual "site survey" and successfully deployed a simulated antenna in the "Roverscape" [69]. While not fully immersive (i.e., in the sense of incorporating XR HMDs, haptics, etc.), this terrestrial analog demonstrated the value of advanced desktop VR techniques to enhance orbital control of a planetary surface vehicle. As highlighted by Terry Fong – NASA Ames Chief Roboticist – the test achieved a number of milestones, including the first [68]:

- Real-time teleoperation of a planetary rover from ISS.
- Real-time supervisory control of a rover from ISS.
- Interactive astronaut control of a planetary rover in a terrestrial analog using a high-fidelity 3D model.
- Use of NASA data networks to connect an astronaut's laptop computer to a remote, surface-based robot.

Overall, this initial experiment exemplified the potential impact of using realistic "virtual world" models to facilitate dynamic human-robotic planetary exploration, and the value of fusing XR-techniques (i.e., VR and telerobotics) toward the development of more advanced space telepresence applications [68, 71, 72, 73, 74, 75, 76].

## 4. TELEPRESENCE IN THE U.S. SPACE PROGRAM

Telepresence typically integrates XR concepts and associated technologies – i.e., VR/AR/MR and telerobotics – to enable a user to interact with physically remote or otherwise inaccessible environments [3]. Ideally, this interaction is intuitive and immersive, with the operator feeling as if they are physically present in the distant location; this usually requires significant sensory input and feedback [3, 77]. Ultimately, telepresence seeks to enhance a human user's sense of "being" when introduced into a replicated distant environment, particularly when conducting remote controlled, computer-mediated operations [3, 78, 79, 80].

Telepresence has many potential applications in space exploration, and NASA has investigated its use across a spectrum of robotic and human spaceflight endeavors, most frequently associated with teleoperation of systems performing planetary exploration or spacecraft operations and maintenance [1, 2, 4]. A review of some of the agency's noteworthy telepresence experiments illustrates the interdisciplinary nature of the field. It further highlights how XR-concepts and technologies can evolve from each other and be combined to address challenges associated with remote exploration.

### 4.1 Telepresence and Robotic Exploration

As noted in our discussion on the associated XR subdiscipline of VR, Michael McGreevy and his team envisioned telepresence applications when developing their pioneering VIVED, VIEW, and VPE systems, including immersive operation of robotic systems on Mars [2, 50, 53, 54]. These ideas likely helped vector NASA to study telepresence enhancements to its robotic exploration and spacecraft servicing initiatives [81, 82].

Throughout the 1980s and 1990s, NASA sponsored the testing of telepresence-operated rovers on Earth that examined the possible benefits of such control for interplanetary probes. Carol Stoker of NASA ARC was an early principal investigator in this field [83]. In 2020, while with NASA's Planetary Systems Branch, Stoker recalled one of the earliest of these surrogate experiments, which took place in the 1980s:

"My first venture in this telepresence area occurred in the late 1980s before we had any access to surface rovers. I worked with a team of roboticists and we got an opportunity to do a field experiment in Antarctica in ice covered underwater environments. We did robotic exploration with underwater vehicles. We purchased a small tethered robotic underwater vehicle and we outfitted it with stereo cameras mounted on a pan and tilt platform and a communication system that would allow the operator on the surface to wear sensors on their head and move the stereo cameras on the rover underwater with their head. The operator wore goggles that put the camera display directly in front of their eyes. This way the operator was telepresent." [84]

**Fig – 8:** NASA/ESA ISS-to-Earth rover control. [87]

NASA and international partner space agencies continued to conduct telepresence tests of this kind into the 21st century – often using underwater, desert, volcanic, and arctic locations on Earth as analog planetary environments [73]. These experiments probed the utility of XR-enhanced control interfaces and telepresence for space exploration, which has remained an area of interest for NASA and many independent researchers [66, 67, 73, 76, 85, 86]. As an example, in November 2019 European Space Agency (ESA) astronaut Luca Parmitano conducted a similar but – in some ways – more advanced experiment than the earlier ISS-based telerobotic operation of the K10 robot with VERVE [87, 88]. From ISS, Parmitano controlled an Earth-based rover in a simulated physical lunar environment constructed in a hangar in Germany. For the first time, the rover was equipped with an advanced 6-degree of freedom (6DOF) gripper with dexterity and mobility equivalent to a human hand (see Fig – 8). Additionally, Parmitano used a haptic, force-feedback controller and real-time video to operate the rover, pick up rock samples, and manipulate them similar to how he might if on the surface with his own hands. Moreover, this was done with the input and advice of a team of expert Earth-based geologists.

Parmitano's successful demonstration of space-to-Earth, haptic-enabled telerobotic specimen collection – all under supervision by Earth-based scientists – highlighted the potential value of collaborative space exploration telepresence [87, 88]. In the words of Aaron Pereira of the German Aerospace Center (DLR) – a NASA/ISS partner:

"This is the first time that an astronaut in space managed to control a robotic system on the ground in such an immersive, intuitive manner… our control interface incorporates force feedback so that the astronaut can experience just what the rover feels, even down to the weight and cohesion of the rocks it touches. What this does is help compensate for any limitations of bandwidth, poor lighting or signal delay to give a real sense of immersion – meaning the astronaut feels as though they are there at the scene." [87]

Thomas Krueger, head of ESA's Human Robot Interaction Laboratory also added:

"Robots can be given limited autonomy in known, structured environments, but for systems carrying out exploratory tasks such as sample collection in unknown, unstructured environments some kind of 'human-in-the-loop' oversight becomes essential. But direct control has not been feasible due to the inherent problem of signal delay – with transmission times constrained by the speed of light… so we have been working towards the concept of humans staying safely and comfortably in orbit around the Moon, Mars or other planetary bodies, but being close enough for direct oversight of rovers on the surface – combining the human strengths of flexibility and improvisation with a robust, dexterous robot on the spot to carry out their commands precisely." [87]

**Fig – 9:** Conceptual low-latency telepresence control of surface robotics from orbiting spacecraft. [26, 89]

Along with the 2016 K10 rover tests, the 2019 experiment conducted from ISS showed how similar systems might be able to facilitate immersive, collaborative, near real-time exploration of extraterrestrial planetary environments from orbiting spacecraft or surface installations [66, 68, 87]. This approach can increase the opportunities for non-astronaut (i.e., Earth-based) scientists, payload, and mission specialists to participate and contribute more dynamically, immersively, and collaboratively during space operations and in situ exploration. Furthermore, it can help to mitigate the expense of frequently deploying astronauts into space or onto a planetary surface for EVAs, concurrently reducing the environmental risks and hazards they might experience when doing so (e.g., radiation exposure) (see Fig – 9) [26, 89, 90, 91].

Nevertheless, it is worth mentioning that expert NASA roboticist Terry Fong [72] indicated that – when it comes to telerobotic operation – "…telepresence (immersive real-time presence) is not a panacea… manual control is imprecise and highly coupled to human performance (skills, experience, training)." Fong [72] suggested that minimizing risk is often more important than ease of operation. Consequently, methods such as supervisory control will still frequently be relied upon in future XR-based human-robot space exploration, even if telepresence operation (i.e., direct, immersive control) of a robotic system is possible.

Along these lines, consideration of the communications delays/latencies associated with a particular teleoperation use case is important in determining whether telepresence (i.e., immersive human-human mediated interaction, or human-machine control) is possible and – if so – how it can be implemented effectively. After decades of practical and experimental applications in the space program, researchers and operators have come to classify teleoperation/telepresence operations into three categories according to relative communication delay/latency [26, 69, 70, 90, 91, 92]. Broadly speaking, these are:

- Low-Latency Teleoperations/Telepresence (LLT): Operations with delays of *less than one second*. In the most exceptional cases LLT can be characterized by near real-time or real-time telerobotic control and/or human-machine or human-to-human telepresence experiences. High bandwidth, continuous communications are typically required to support LLT, particularly if high-definition video or other data intensive media are transferred. In telerobotics, achieving and implementing LLT is most useful for circumstances and tasks which are enhanced by or require having a "human-in-the loop" (HIL), such as interactive exploration, complex spacecraft servicing, or telesurgery. In these cases, high-degree of freedom manipulators, force-feedback controls, and haptic interfaces can facilitate more dexterous and immersive human controls. Examples include NASA and ESA telerobotic/telepresence control of terrestrial rovers from Earth-orbit (i.e., via ISS).
- Moderate-Latency Teleoperations/Telepresence (MLT): Operations with delays on the order of *several seconds*. Under MLT conditions there can be occasional direct/interactive human telerobotic operation, but increased delay may require some supervisor control, step-by-step commanding, or degree of autonomy on the part of the machine. Complex tasks like human directed scouting, surveying, and servicing can still be accomplished, with moderate requirements for communications bandwidth and availability. Examples include the U.S. *Surveyor* robotic lunar surface samplers, and the Soviet Union's *Lunokhod* Moon rovers.
- High-Latency Teleoperations/Telepresence (HLT): Operations with delays on the order of *more than several seconds*. In these cases, methods such as supervisory control, command-based control, and some degree of machine autonomy become more important. There is no live interaction under HLT, and tasks are usually more simplified and scripted than with LLT or MLT. Further, HLT can often be executed with lower bandwidth requirements and intermittent communications. Examples include U.S. interplanetary surface landers, rovers, and aircraft operated on Mars (e.g., *Sojourner*, *Curiosity*, *Spirit*, *Ingenuity*).

These descriptions help us frame and conceptualize the temporal domains associated with XR-enabled space operations, particularly for possible future long duration human-robotic exploration programs (i.e., cislunar and interplanetary), which may involve a combination of LLT, MLT and HLT. In near-future human spaceflight endeavors, however, it is likely that NASA will focus on LLT, which the agency gained additional experience with

during one of its most ambitious and visible telepresence-related programs to date – Robonaut.

### 4.2 Robonaut: Telepresence Robotic Astronaut

Robonaut – which stands for *Robo*tic Astro*naut* – was initiated in the 1990s and centered on the development of an anthropomorphic humanoid robot designed specifically for space operations (see Fig – 10) [2, 54, 93]. Conceived at Johnson Space Center, the effort was precipitated by NASA's conclusion that that maintenance of ISS would require 75 percent more EVA time than had been anticipated [94]. As a possible mitigation strategy, technicians at JSC first invented the Dexterous Anthropomorphic Robotic Testbed (DART) to determine if human-like telerobotic systems could perform some tasks that typically necessitated astronaut spacewalks.

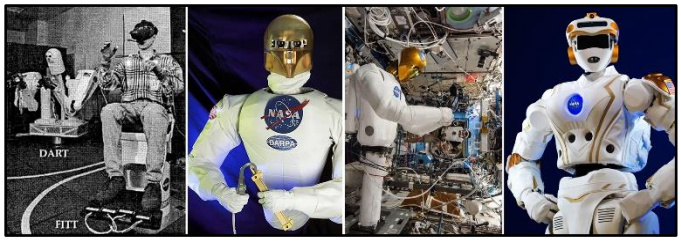


**Fig – 10:** Evolution of Robonaut. From left: DART, Robonaut 1, Robonaut 2, R5 "Valkyrie". [41, 95, 99]

As a precursor to Robonaut, DART was roughly anthropomorphic in that it had a head with two eyes for stereoscopic vision, two arms, and two hands. Significantly, DART was operated via a telepresence interface, including an HMD and hand controllers, which gave the human user a more seamless and intuitive connection with the machine; they could see the environment through DART's eyes and intuitively use its hands to manipulate objects [95]. However, DART was limited in terms of dexterity and was too large and unwieldy to be considered flight-ready [94]. Consequently, the system was evolved into the more humanoid Robonaut, designed from the start be an "EVA-equivalent" robot capable of working with the human-rated spaceflight hardware used by astronauts to perform spacecraft servicing [2, 94, 96].

Robonaut was intended to work alongside its biological counterparts and also perform missions alone, in environments and circumstances that were either too dangerous or not efficient for astronaut duty. Notably, it can operate under manual control, intermittent control, or function completely autonomously for some tasks – consistent with canonical concepts of telerobotic operation [3, 54, 97]. Since its inception, Robonaut has been upgraded physically and in terms of capability – evolving into Robonaut 2, which was operated on ISS by astronauts on the station or remotely by controllers on the ground [98]. Robonaut and Robonaut 2 have been utilized to perform experiments and actual operations both aboard ISS and during EVAs, demonstrating sophisticated telerobotic and telepresence techniques [93, 97, 98]. Development continues, and the program has spawned other human-assisted robotic devices and experimental anthropomorphic robot projects, such as the ruggedized R5 "Valkyrie" humanoid robot, suggesting possible future applications on planetary surfaces [98].

Some NASA officials, researchers, and medical professionals have envisioned using evolved versions of Robonaut or similar telerobotic systems to facilitate human controlled or autonomous clinical duties during future human spaceflight operations [100, 101, 102, 103, 104]. One application, for example, would be robot assisted surgery (RAS) – or *telesurgery* – which has been conducted on Earth for many years, at times telerobotically over great distances [105, 106, 107, 108]. This desire to address medical issues using telerobotics and telepresence techniques reflects one of the NASA first human spaceflight concerns – the health and safety of astronauts – which, arguably, may have been an important catalyst for worldwide *telemedicine* as we know it today.

### 4.3 Telemedicine

While not intrinsically an XR-discipline, or necessarily dependent on XR technologies, telemedicine can integrate facets of telerobotics and telepresence to perform remote health-related functions. This is particularly true, for example, when enhancing a medical practitioner's ability to seem "present" with geographically separated patients, or when providing realistic sensory input to a surgeon performing remote procedures via a teleoperated surgical robot [109, 110, 111, 112]. Contextually, the investigation of this field at NASA (also known as *telehealth*) likely predates telepresence and other XR applications. NASA's initial forays into telemedicine go back to the earliest days of human spaceflight when, in the 1960s, it sought ways of monitoring the health of orbiting astronauts and remotely administering medical care when required [113].

The idea of "healing at a distance" was not a new concept in the 1960s. Historically, telehealth has origins in proposals by some 19th century doctors that suggested the newly invented telephone and telegraph could help mitigate frequent patient visits or draw on the expertise of distant physicians [114]. And – as with other technical advancements – very prescient predictions of technologically-enabled remote medical procedures were speculated in early 20th century science fiction writings, including those by authors E.M. Forster and Hugo Gernsback [115].

However, initial pursuits by NASA during its burgeoning astronaut program are often cited as the first, practical foundational steps toward the development of "telemedicine" – a term coined by Dr. Thomas Bird in 1970

[115, 116]. This field would evolve to encompass many subdisciplines, such as teleradiology, telesurgery, telepathology, and telepharmacology, and become widespread following the maturation of the commercial internet in the 21st century [114, 116, 117, 118]. In addition, some of the major research objectives for telepresence in the space program are derived from this early and continuing need to remotely care for astronauts.

**Fig – 11:** NASA STARPAHC telemedicine project. [113]

NASA began monitoring the physiological and metabolic activity of astronauts during the *Mercury* project, relying heavily on telemetry (i.e., space-to-Earth data links) for transmission of biometric data. Recognizing the importance of observing, understanding, and circumventing the effects of unique spaceflight conditions (i.e., microgravity) on its crews, the agency established the Integrated Medical and Behavioral Laboratories and Measurement Systems (IMBLMS) program in 1964 [113]. The IMBLMS was viewed as instrumental to *Apollo* and subsequent long-duration human spaceflight initiatives. However, health monitoring systems developed under the project were never actually tested during the first Moon program [113, 114, 115, 116].

Nevertheless, the IMBLMS did get a boost in the early 1970s when NASA redirected the technologies toward an Earth-based analog known as Space Technology Applied to Rural Papago Advanced Health Care (STARPAHC). STARPAHC took advantage of strong White House support and successfully demonstrated telemedicine applications in service to rural and indigenous Americans (see Fig – 11). It became the genesis of several follow-on programs and terrestrial NASA testbeds that were key in furthering telemedicine for human spaceflight and also seeding the transition of space technology to public health and humanitarian welfare efforts [113, 119, 120]. Throughout this time, NASA continued to use remote methods to monitor the health of astronauts during all human spaceflight programs, including *Gemini*, *Apollo*, the Space Shuttle, and ISS missions.

The enduring practice of collecting and analyzing medical telemetry from astronauts has been instrumental in improving knowledge of the effects spaceflight conditions on human physiology and facilitating remote and post-mission healthcare for spacefarers [119, 121, 122, 123]. In general, terrestrial supervision of healthcare for astronauts is essential because – at least to this point in the history of human spaceflight – it has not been common practice to include a dedicated doctor as a member of the relatively small crews placed into orbit or sent to the Moon. In fact, the ISS astronaut designated as the Crew Medical Officer is typically an individual without a professional clinical background that has been provided with 60 hours of supplemental medical training [104].

**Fig – 12:** *Star Trek* EMH holographic doctor consults with cyborg Seven of Nine (left); holoported NASA flight surgeon Schmid NASA advises ISS crew (right). [128, 129]

While this might be sufficient for missions in low-Earth orbit (LEO), where the risk of long-term disease/health issues or serious injury requiring immediate on-site surgery might be manageable, it will almost certainly not suffice for more distant, lengthier missions [124]. Consequently, the idea of using telepresence to provide enhanced remote medical guidance and possibly administer medical treatment has been of interest to NASA for decades [113, 125, 126, 127]. As XR concepts have evolved and associated technologies have improved, the agency has been able to experiment with novel ways of augmenting the relative inexperience of the CMO, sometimes leveraging telepresence to deliver terrestrial medical subject matter expertise to astronauts.

In 2021, the agency demonstrated a vision of this when experimenting with a technique called *holoportation*, during which real-time 3D renditions of ground-based medical personnel were transmitted to ISS. Using the mixed reality capabilities of the Microsoft Kinect camera – a device originally designed for video games – NASA flight surgeon Dr. Josef Schmid and his Earth-based colleagues "holoported" to the station to provide medical consultation and interact with astronauts equipped with Microsoft HoloLens AR/MR HMDs. The team showed the potential of immersive, interactive spaceflight telemedical consultation, and also conducted the "first holoportation handshake from Earth in space" [17, 128]. For science fiction fans, this might conjure mental images of the

Emergency Medical Holographic (EMH) program – a virtual, holographic, artificially intelligent medical officer designed to provide contingency clinical support to the crew of *Star Trek: Voyager* (see Fig – 12) [129].

**Fig – 13:** spaceMIRA telesurgery robot controlled from Earth (right), and aboard on ISS (left). [102, 133]

Going beyond holoportation, NASA conducted a groundbreaking initial test of Earth-to-space telesurgery capabilities in 2024 using the Space Miniaturized In Vivo Robotic Assistant (spaceMIRA) surgical telerobot – a spaceflight adapted version of the MIRA Surgical System, manufactured by Virtual Incision Corporation [101, 112, 124, 130]. Of note, MIRA was the first miniaturized robotic-assisted surgery (miniRAS) system developed, and – as of mid-2024 – had been used to perform approximately 30 soft-tissue operations on Earth, specializing in procedures in the intra-abdominal space (i.e., bowel/colon resectioning) [101, 102, 131]. The system is very compact, and requires less set up, teardown and clean-up procedures than larger "mainframe" RAS systems. Precision remote manipulation is facilitated by hand and foot controls, with visualization provided by a specialized console [111, 112, 132, 133].

Specially made to be fit for space travel, the compact spaceMIRA is about 76 cm long – 7.6 cm shorter than its terrestrial counterpart – and weighs about 0.9 kg [130, 133]. The system was launched to ISS in January 2024 to test telesurgery procedures – particularly the effects of microgravity and latency on such operations [101, 102]. During the demonstration, six surgeons controlled the spaceMIRA, precisely using the instrument's two miniature "hands" and cutters to manipulate and dissect a series of rubber bands under tension, which simulated the consistency of human tissue (see Fig – 13) [102, 130]. All operations were deemed successful, with each of the surgeons contending with the round-trip latency of about 0.85 s, roughly the time it took for the commands and video signals to travel to and from ISS, orbiting approximately 400 km overhead [130, 133].

Dr. Michael Jobst, an accomplished colorectal surgeon who was one of the first doctors to use MIRA during medical trials, participated in the space-based RAS demonstrations; as of 2024 he had conducted 15 operations on human patients using MIRA [130]. Dr. Jobst indicated that with spaceMIRA "…you have to wait a little bit for the movement to happen; it's definitely slower movements than you're used to in the operating room" [124]. To help compensate for the delay, ground controllers and technicians experimented with different scaling factors on the terrestrial control console used by the doctors, so that movements performed by surgeons on Earth would be translated into smaller motions executed by spaceMIRA [133]. The lessons learned from this experiment will be carried forward into future telesurgery tests, as NASA works to understand how to effect remote medical procedures on missions at greater distances and of longer duration, such as during *Artemis* and beyond [7, 130, 133].

## 5. EXTENDED REALITY IN FUTURE SPACEFLIGHT OPERATIONS

NASA-sponsored research and planning documents suggest that additional experimental and operational XR-enabled activities will be conducted during future U.S.-led space initiatives, including exploration of the cislunar domain under the *Artemis* program [7, 17, 18, 23; 26]. These efforts will leverage the agency's past achievements, benefit from ongoing academic research in the field, and take advantage of accelerating advancements in commercial XR-associated technologies. Below we briefly highlight several areas in which XR may play a role in supporting future human and human-machine long duration space operations, including those in cislunar space.

### 5.1 Operations and Maintenance

Future astronauts will certainly continue to leverage XR technologies for training and familiarization with spaceflight hardware and procedures. Crews are already utilizing HTC Vive headsets to orient themselves with Gateway via immersion within VR renditions of the future lunar space station (see Fig – 14) [134, 135, 136]. Furthermore, Boeing – one of NASA's "Commercial Crew" spaceflight partners – has modeled the cockpit of its Starliner spacecraft using Unreal Engine, software typically used for gameworld development [137, 138]. The resulting "human-eye resolution" VR simulation enables highly realistic training on Starliner, which is intended to take personnel to the ISS and possibly to the Moon during the *Artemis* program.

Digital twins (DT) are synthetic, virtual analytic models and environments that exchange data with the actual physical systems they replicate [3, 139, 140, 141]. This type of technology may be used to improve synthetic training versions of surrogate space habitats, develop data-enriched interactive mission simulations, and devise collaborative AR/MR-enhanced procedures for astronauts, flight controllers, and scientific investigators [142, 143, 144]. A. Mazumder et al. [141] described how "Experimentable Digital Twins" (EDT) incorporated into

virtual test beds (VTB) and DT-enhanced, haptic telerobotic manufacturing, maintenance, and operations methods have been studied for space applications. These approaches would allow for bidirectional information flow between computer replicas and actual spaceflight hardware [141,145].

**Fig – 14:** Gateway familiarization via HTC Vive HMD. [135]

Augmented reality technology will also be utilized to support operations and maintenance during cislunar and interplanetary human spaceflight missions. NASA has expressed specific interest in outfitting next-generation Moon-bound spacesuits with AR features, primarily to enhance the performance of astronauts conducting EVAs around spacecraft and on planetary surfaces [146, 147, 148, 149]. The agency hopes to streamline task performance by integrating AR capabilities directly into spacesuit helmets, infusing astronauts' views of the "real world" with digital data including technical information, real-time instructions, equipment and system status, and navigational guidance. This may improve the execution of both collaborative and independent duties. An AR interface could, for example, facilitate more immersive and effective assistance from local and Earth-based colleagues and subject matter experts (i.e., with visual cueing), or allow increased autonomy afforded by immediate and intuitive access to information contained in networked databases and reference systems.

To help realize this, an industry technology request for information (RFI) was distributed by NASA's Center Innovation Fund between 2019 and 2021, soliciting an AR system with the ability "…to comfortably display information to the suited crew member via a minimally intrusive see-through display" [146, 150]. As envisioned, the system will be integrated directly into a helmet visor, in lieu of a head-worn device that might introduce equipment integration problems. NASA's codename for this program is the Joint Augmented Reality Visual Informatics System (JARVIS). Notably, the acronym for this project is a nod to the AR/MR-enabled, natural-language artificial intelligence computer system that is integrated into Tony Stark's powered "Iron Man" armor, residence, and "Avengers Tower" in the Marvel Comics and Cinematic Universe franchises [151]. Along with the JARVIS request, NASA released an associated AR-interface software design challenge specifically targeted at colleges and universities called the NASA Spacesuit User Interface Technologies for Students (NASA SUITS); the test week for this program was slated for mid-2025 [150].

In the realm of telerobotics, 50 years of successful joint space operations between NASA and CSA using the Canadian Space Agency's Canadarm (Space Shuttle) and Canadarm2 (ISS) will continue into the *Artemis* program. The agency plans to permanently deploy Canadarm3 aboard the Gateway lunar space station [37, 38]. As its predecessor did aboard ISS, Canadarm3 will be used to move Gateway modules, inspect and repair station elements, assist with visiting spacecraft rendezvous and docking procedures, and facilitate astronaut EVAs and science activities. Similar to Canadarm2, the system will be designed for both autonomous and remote operations (i.e., controlled from Earth or Gateway) [37, 38].

While concrete plans have not been established, NASA officials have further indicated that intravehicular teleoperated and semi-autonomous robots – such as the Robonaut series and Astrobee – are important additions to space station crews [41]. Consequently, it is likely that the agency will deploy similar systems aboard Gateway to assist with and/or conduct maintenance and science operations. Further, since NASA was experimenting with more robust and survivable evolutions of Robonaut (i.e., the R5 "Valkyrie"), it is possible that some similar systems will be adapted to function in and around lunar and planetary surface facilities [99].

Tangentially, NASA may use a mixture of low-, moderate-, and high-latency teleoperations (LLT, MLT, HLT) to remotely control robots aboard and around cislunar and interplanetary spacecraft in the performance of maintenance and science-related functions [4, 26]. A combination of these techniques will likely also be used to operate robots on the surface of the Moon (and/or Mars) to assist with landing site selection and preparation/assessment of outpost locations [26]. Once long-term facilities and equipment are in place, teleoperated robots will probably be leveraged to perform operations and maintenance of them, particularly utilizing orbiting spacecraft (i.e., Gateway) as control platforms [26, 90].

## 5.2 Surface Exploration

In addition to utilizing teleoperated robots to help operate and maintain infrastructure, NASA and its partners will almost certainly investigate and implement LLT-based techniques for surface exploration during *Artemis* and beyond. Recall that the feasibility of XR-enabled LLT for such a purpose was demonstrated by both NASA and ESA in the early to mid-2010s when astronauts controlled terrestrial rovers from ISS [66, 69, 75, 87,]. Given the reduced communications delay from lunar orbit to the Moon's surface (i.e., relative to MLT/HLT from Earth),

astronauts aboard Gateway – for example – will likely exercise similar methods to remotely operate robotic instrumented vehicles and explore the world below them. Doing so will enable them to guide and perform tasks and scientific experiments that benefit from a "human-in-the-loop", but with enhanced system responsiveness and reduced risk. Types of operations may include [26, 69, 90, 91, 152]:

**Fig – 15:** Conceptual view from LLT workstation. [26]

- Crew-Assisted Telerobotic Sample Return: Selection and acquisition of surface samples for return to Gateway and/or Earth for scientific analysis.
- Specialized/Remote-Site Science Operations: Interactive in situ human-machine exploration of regions of the Moon that are particularly difficult (or expensive) for humans to access alone; and/or, which require human judgement, intuition, and/or expertise, but preclude frequent or robust human physical presence. For example, extended exploration of the lunar farside from Gateway via cislunar communications relays, or from crewed vehicles operating near the L2 Lagrange point.
- Lunar Resource Exploitation: Investigation, assessment, and/or extraction of lunar resources in challenging or dangerous locations, such as the potentially volatile/resource-rich permanently shadowed areas of the Moon.

Minimization of delay is highly desired for dynamic exploration, which – intuitively – suggests that line-of-sight communications from lunar orbit should provide the most direct, low-latency path to the surface. That being said, leveraging LLT to perform operations from lunar orbit (or Mars orbit) – for instance – does not preclude also doing so from outposts or habitats located on the surface itself, if the proper communications architectures are available (i.e., surface antennas and satellite relays) (see Fig – 15) [26].

Similarly, XR-enabled LLT operations conducted by astronauts deployed at and around the Moon may be integrated with MLT/HLT operations executed by Earth-based investigators, providing the proper architecture exists. Despite the potential for increased latency introduced by the multiple "links" and users in the communications chain, fusing these approaches may provide opportunities for interactive/immersive human-to-human and human-machine exploration involving both local and terrestrial participants. A variety of control modes – e.g., real-time/direct, interactive/supervisory, and pre-planned/command-based – may be employed to mesh these different domains together [10, 69, 153, 154, 155].

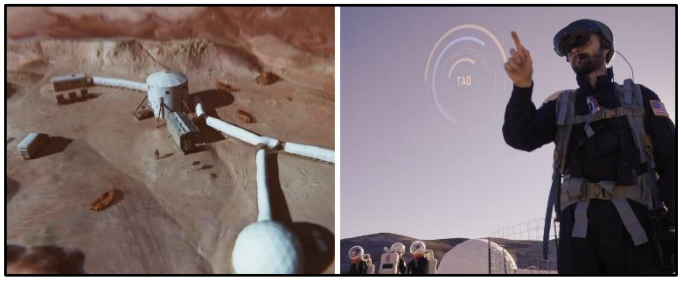

**Fig – 16:** Aerospace Corp *Project Phantom*. [158]

In terms of actual human in situ investigation, the AR enhancements to NASA spacesuits mentioned earlier will probably also aid future surface explorers in coping with unfamiliar extraterrestrial environments. The austere, airless environment of the Moon – for example – challenged the perception of *Apollo* crew members in the 1960s, presenting them with unusual lighting conditions that complicated judgement of size and distance of surface features [156]. K. Rahill [156] tested and confirmed these sensory effects on astronauts – dubbed "lunar psychophysics" – using virtual reality modeling and simulation techniques facilitated by the Unity 3D VR game engine [157]. It is possible that future surface exploration spacesuits will be equipped with AR/MR capabilities that will help astronauts compensate for issues arising from unique geographic and atmospheric phenomena – allowing them to more accurately, safely, and efficiently navigate and explore the landscape during EVAs.

Collectively, VR and AR/MR capabilities (i.e., deployed on the computers of principle investigators and integrated into NASA spacesuits), together with telepresence/telerobotics techniques, may be combined to enhance future collaborative interplanetary exploration. One very exceptional and promising example of this is the Aerospace Corporation's *Project Phantom*, which utilizes VR and AR technologies to dynamically construct a virtual, interactive analog of a remote planetary landscape that can be mutually investigated by both terrestrial researchers and Moon- or Mars-based astronauts (see Fig – 16) [158]. The VR construct provides a means by which

scientists and engineers – called "Phantoms" – can explore and interact with a 3D, reality-based, immersive "digital ecosystem" that has been populated with real-world data via the input of AR-equipped in situ astronauts – called "Explorers". Using their AR-augmented suits, field Explorers can also access notes and annotations placed into the immersive environment by Phantom researchers to guide and inform investigations – thereby enriching the shared exploration system. Developers envision that the system will leverage GPS-like location services, allowing Explorers and Phantoms to inject waypoints, geotag significant findings, and jointly chart courses across a digital planetary landscape that is sustained by current information.

The Aerospace Corporation notes that the system differs from many current "digital twin" applications in that *Phantom* can truly pass data between the virtual and actual worlds bi-directionally, whereas the latter usually focus on updating the synthetic model with real-world information [3, 158]. In other words, when the virtual world is updated by Phantom scientists, deployed Explorers will see those updates overlayed onto their AR-enhance visualizations. Conversely, when Explorers submit information (i.e., images, science data, remote sensing information, etc.) from sensors they carry or deploy, the virtual world is populated with their findings for reference by Phantoms and other Explorers. Presumably, data would also be injected by autonomous and teleoperated robotic vehicles. A *Project Phantom* prototype was tested in a surrogate Martian environment on Earth in 2022, incorporating a simulated Mars-equivalent time delay/latency between when Explorers and drones collected data and when the information was available within the system [158]. In the words of Engineering Specialist Trevor Jahn of the Aerospace Corporation:

"*Project Phantom* connects the real and virtual worlds together, so we can bring the scientific world into the operational space for astronauts on the Moon or Mars… although turnaround time for communication is a factor, it's arguably an improved form of bi-directional communication between astronauts or users on location and whoever is accessing the virtual model. Its potential is undeniable." [158]

Similarly, Don Haddad – Planetary Software Engineer at NASA ARC and research affiliate at MIT's Space Exploration Initiative Extensive – has conducted extensive research further highlighting the potential benefits of using digital twin and XR-technologies to facilitate planetary exploration [159]. As an expert on coupling the real, virtual, and imaginary worlds, Haddad [160] did an outstanding job relating how an immersive, sensor-fed digital twin of a planetary environment could be developed, allowing researchers to explore an information-rich landscape mirroring the actual world. Haddad's work in this area evolved from a previous project constructing a digital twin of a portion of actual terrestrial wetlands in Plymouth, Massachusetts [161]. That virtual counterpart, called *Doppelmarsh,* was populated with information derived from a real-time network of instruments deployed in the physical area it replicated. This produced an "avatar landscape" fabricated from live video, weather and temperature information, and even sensory data that reflected the activity of animals in the area. Among other capabilities, the system allowed a roaming user to toggle between a texturized, realistic perspective and a data-based visualization of the landscape with a capability known as a "virtual lens", or SensorVision [161].

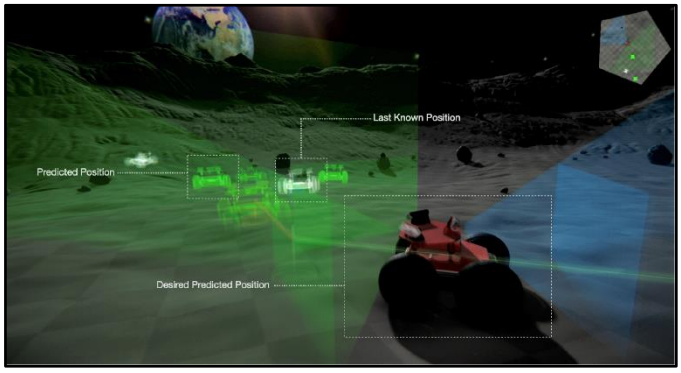


**Fig – 17:** D. Haddad's *Doppelbots*. [160]

The space exploration analog proposed and prototyped by Haddad [160] was called *Doppelbots,* within which a user could drive and operate a virtual, robotic vehicle (i.e., a Doppelbot) that mimicked the performance of an actual rover through a digital twin landscape. Significantly, like *Doppelmarsh*, the *Doppelbots* system was developed using the very popular Unity game engine and is accessible via a video game-like interface, incorporating many interface elements, navigation tools, and other control and visual features that would be very familiar to gamers [157]. According to Haddad [160] , "…these game-inspired elements enrich the user's interaction and enhance their navigation experience within the simulated environment of Doppelbot." In fact, in designing *Doppelbots*, Haddad [160] drew substantial inspiration from real-time strategy (RTS) video games such as *Command and Conquer* – particularly in how the "player" can use a computer mouse to navigate their robot with a "birds-eye" view of the landscape, setting waypoints and chaining commands together. The user interface also provides the operator with a mini-map – a common feature of video games – and allowed toggling between automatic and manual control of the Doppelbot rover.

Similar to the bi-directional information flow that the Aerospace Corporation [158] demonstrated with *Project Phantom*, Hadadd [160] showed synchronization between the virtual Doppelbot rover and it's real-world

counterpart. In doing so, Haddad and colleagues illustrated how the synthetic rendition of the robot could be operated in the *Doppelbots* space while linked with the actual rover performing the same actions in the MIT Media Lab test facility. Moreover, to address the anticipated latencies encountered when performing actions during real-world space operations (e.g., on the Moon or Mars), Haddad [160] envisioned using a novel visualization construct that would allow users to see reflections of the last-known and predicted locations of actual deployed rovers along with the desired position of the user's Doppelbot, all within the digital twin construct (see Fig – 17). This immersive, "4D" depiction of past and possible present locations of surface vehicles provides a very intuitive and responsive space for remote operators dealing with "in-game" lag, so to speak. According to Haddad:

"The integration of the simulated and actual rover in a single environment provides a comprehensive understanding of the rover's status, actions, including simulations of time lag associated with communication. This visualization concept aims to help operators maintain situational awareness… and ensure effective and timely control over space operations and monitoring." [160]

Given these efforts, it is not difficult to see how DT concepts might be integrated with other XR-enabled space operations – such as exploration telepresence (LLT, MLT, and HLT), telerobotics, and AR/MR-enhanced human surface expeditions – to deliver highly enriched, data driven, collaborative human-machine exploration experiences during future cislunar and interplanetary endeavors.

## 5.3 Medical Applications

Space is an extreme environment, and decades of research have revealed that astronauts confront unique physiological challenges that can make living and working there uncomfortable at best and – in the worst cases – life threatening or fatal. In addition to the immediate hazards posed by things such as ionizing space radiation and potential exposure to vacuum, astronauts face lingering biological effects resulting from extended time in closed-loop, microgravity environments [122, 162, 163, 164]. These can include:

- Space motion sickness
- Loss of muscle and bone mass
- Orthostatic intolerance
- Spatial coordination issues
- Eye/vision problems
- Dietary complications
- Respiratory issues
- Increased exposure to microbial contaminants and infection

Beyond the bodily impacts, spaceflight operations also require consideration of the mental health implications of isolation, confinement, and small group dynamics under tremendously stressful conditions [122, 162, 163, 164, 165]. Extreme distance from family, friends, and operational support personnel – and the need to function optimally in life threatening situations for protracted periods of time – exacerbate the psychosociological stressors associated with human spaceflight (i.e., depression, stress, loneliness, boredom). Stays aboard orbital space stations and missions to extraterrestrial planetary bodies of interest can vary from days to years, and all of these potentially debilitating issues – physical and mental – are exacerbated during extended duration missions. Further complicating these problems is the typical absence of substantial specialized medical expertise resident on the space crews [103, 104].

In our review of XR in the U.S. space program we highlighted a few of the numerous experiments that researchers have conducted in space to evaluate the potential merits of XR in addressing the medical needs of astronauts [15, 17, 61, 102, 130]. These investigations and many more like them will undoubtedly continue during *Artemis*, with some use cases seeing operational implementation. Here, based on a review of available literature, we outline several of the most likely ways that XR-associated technologies will be pursued to ensure the physical and mental health of astronauts voyaging to the Moon and beyond.

### 5.3.1 Mental Health

NASA has already experimented with VR HMDs on ISS as a means of improving the mental health of astronauts [61]. Other clinical tests supported that XR (i.e., VR/AR/MR) can be used to help reduce stress by allowing people to temporarily immerse themselves in synthetic, realistic renditions of environments that are comforting or calming to them [17, 165, 166, 167]. Some experiments specifically directed at spaceflight crews indicated that including simulated smells along with the usual visual and auditory facets of VR simulations enhances the sense of presence in such environments [165, 167, 168]. This can improve relaxation effects when astronauts are allowed to virtually "escape" for a time from the relatively small, industrial volumes of their spacecraft. It is possible that NASA will continue to seek ways to apply VR in this capacity, enabling astronauts to occasionally experience more expansive natural or fanciful virtual worlds. Doing so may help them cope with mental health issues that can arise due to long duration confinement, isolation, and distance from Earth. Likewise, using VR/AR to learn new skills (i.e., languages) or play games can be a healthy distraction, help lessen boredom and depression, and improve morale [17, 122, 165].

The vast distances, extended mission times, and high operational tempos associated with spaceflight can result in prolonged periods of time out of contact with family and friends, which can be demoralizing for astronauts. Extended reality devices and methods can assist in enriching communication with loved ones. In a fairly straightforward example, NASA demonstrated that the holoportation technique used to "beam" virtual renditions of physicians to ISS in 2021 could also be used to facilitate immersive family conferences for astronauts, allowing them to feel more present with their loved ones [17].

Moreover, XR may be of particular help when latency or mission parameters preclude dynamic/real-time or frequent contact during long duration space missions. Some proposed communications solutions include rendering virtual avatars of Earth-bound family members that can be used to interact with crew members via VR/AR/MR interfaces [165, 167, 169]. Digital versions of family members might deliver recorded messages to astronauts, for example, or be ported into shared, virtual environments (VE) to facilitate actual or simulated conversations driven by artificial intelligence (AI) [165].

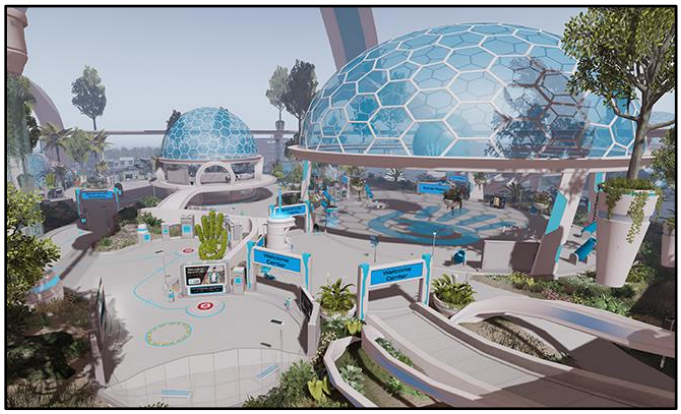

**Fig – 18:** *Second Life* virtual community destination. [170]

D. L. Hansen et al. [169] took these concepts further and considered methods that deliberately tried to account for the increased latencies associated with long distance space travel. They developed an approach called the Designing for Extended Latency (DELAY) Framework, coming up with several XR-like methods to compensate for communications lag in an effort to maintain and enhance feelings of social connectedness, presence, and immersion between astronauts and their distant families. These included [169]:

- A mobile app to facilitate recording and sharing of common experiences (i.e., eating meals, exercising, etc.) between crew members, friends, and family, delivered at appropriate relative times during their days; and 'turn-based' activities that produced shared, integrated videos.
- A concept that delivered pictures to digital "smart frames" or played messages from each other when certain actions were detected (i.e., walking into a room) under an Internet of Things (IOT) type system.
- A video game that allowed crew members and families to meet, play alongside, and battle against AI avatars of one another, with playstyles updated using machine learning (ML).

Similarly, P. Wu et al. [168] conceptualized a system called A Network of Social Interactions for Bilateral Life Enhancement (ANSIBLE). ANSIBLE created shared, group indoor and outdoor virtual environments that astronauts, family, and friends could use for asynchronous interaction via avatars and virtual agents (VA) (i.e., AI-driven avatars) representing each other. In many ways this construct is similar to virtual worlds used in immersive video games and online virtual social communities that have existed since the mid-1990s, including *Worlds Chat*, *Alpha World,* and the thriving *Second Life* VE (see Fig – 18) [170, 171]. Purely AI agents (i.e., "embodied" agents) were also available in ANSIBLE as helpers, consultants, and conversation partners, akin to non-player characters (NPCs) or *bots* in video games [172, 173, 174]. P. Wu et al. [168] envisioned that users and entities could even exchange personal care packages with each other within ANSIBLE. Note that the term ANSIBLE is a tribute to a device from science fiction that enables instantaneous (i.e., "faster than light") communications between any two points in space [175]. The sci-fi "ansible" was invented by author Ursula K. Le Guin, who wrote acclaimed books such as *The Left Hand of Darkness* (1969), and reused by other renown sci-fi writers, including Orson Scott Card, author of the famed novel *Ender's Game* (1977). While not instantaneous, it is possible that systems based on similar concepts to ANSIBLE or DELAY could be used to help alleviate stress associated with the time and distance separating future astronauts and their loved ones.

**Fig – 19:** Intelligent Medical Crew Assistant (IMCA). [179]

### 5.3.2 Physical Fitness

In what some call "exergaming", the integration of XR devices such as stereoscopic HMDs with exercise equipment can increase motivation, enjoyment, and performance – particularly when sensations of immersion and presence are enhanced [176, 177]. One study by S. Grosprêtre et al. [178] also indicated that XR-enabled video games combined with exercise promoted cognitive enhancement. To those ends, it is possible that NASA will install systems like the VR-enhanced stationary bicycle tested aboard ISS during the Immersive Exercise Experiment on Gateway and other future stations, spacecraft, and lunar/planetary surface outposts supporting semi-permanent human occupation [17, 60]. Given space, mass, and power constraints, the agency may consider adapting the concept to other types of exercise equipment, such as a specialized rowing machine [17].

### 5.3.3 Healthcare Delivery

Extended reality technology can offer significant benefits to delivering routine and critical healthcare to astronauts, complimenting and improving the support provided by on-site personnel who may only have peripheral clinical responsibilities, such as the Crew Medical Officer (CMO). Many of the implementations of XR in medical support for long duration human spaceflight operations (i.e., *Artemis* and beyond) will probably be directed at increasing the autonomy of the crew, ideally enabling them to address some health concerns independent of immediate support from Earth. Once again invoking parallels to science fiction, it is possible that a full-fledged EMH-type solution might be available someday in the far future, as depicted on *Star Trek: Voyager* [129]. Until then, extended reality methods supporting remote healthcare for cislunar and interplanetary astronauts may include:

- AR-Guided Medical Procedures: Using AR displays and voice guidance to visually and audibly navigate astronauts through medical procedures. This may be done by using XR-systems that are connected to local virtual libraries and knowledge bases (possibly AI- and/or ML-enhanced), or via XR-enabled cues/instructions from terrestrial doctors. Facets of these capabilities were explored under Operation Sidekick, with remote guidance delivered via the Microsoft HoloLens. Additionally, a Small Business Innovation Research/Small Business Tech Transfer effort solicited by NASA in 2021 called the Intelligent Medical Crew Assistant (IMCA) project resulted in prototype procedures and devices, and a detailed requirements capture (see Fig – 19). [15, 17, 18, 59, 122, 150, 179]
- AR-Facilitated Medical Inventory Assistance: Augmented reality methods might be employed to help space crews without significant medical training inventory medicine and other health-related supplies on future spacecraft and outposts. Two NASA experiments – MedChecker (AR-enabled) and the Autonomous Medical Officer Support Software (AMOS) (non-AR) – suggest that taking advantage of an AR HMD's camera, with appropriate software, could allow astronauts to take stock of medical supplies more efficiently, without ground assistance. [17, 180]
- Holoportation: Transmission of medical expertise to remote space facilities using AR/MR technology may continue, as demonstrated by ISS astronauts and Dr. Josef Schmid (NASA flight surgeon) during the 2021 holoportation experiment. Bidirectional, immersive XR conferencing may help spatially separated medical personnel evaluate astronauts' health issues and provide more effective guidance to address their needs. Further, if also enhanced with AI/ML and virtual agent techniques, this approach might be adaptable to periods/circumstances with higher communications delay. [17, 18, 165]
- Telesurgery: The spaceMIRA experiment conducted in 2024 aboard ISS was a significant step toward illustrating the potential applications of telesurgery in the space program. However, additional research, development, and experimentation is required to develop spaceflight-worthy systems and protocols capable of routinely enabling terrestrial doctors to conduct remote operations for astronauts. This is especially true for cases of high latency. Focus areas include instrument tracking, haptics, scene visualization/recognition, patient monitoring and diagnostics, administration of anesthesia, physician voice recognition/cueing, RAS training/experience, AI/ML and AR/MR integrations, and expansion of telesurgery use cases (i.e., beyond soft tissue abdominal applications). Initially, telesurgery applications may focus on assisting the CMO vs. replacing them. Ultimately, in the absence of an on-site, highly trained surgeon, the deployment of a robot capable of confidently performing autonomous medical procedures would be desired. [101, 102, 104, 181]

As with other XR-enabled space applications, one of the main issues to overcome in space telemedicine is communications delay/latency. However, it is worth noting that future cislunar and interplanetary human spaceflight endeavors will likely include the establishment of space stations (i.e., Gateway) and surface outposts. Consequently, in years to come, it is possible that time-dominant XR-enabled telemedicine scenarios (i.e., telesurgery) could end up being addressed by doctors based at these locations versus Earth, thereby reducing latency for "in-system" healthcare. This would be similar to teleoperating robots from orbiting spacecraft via LLT techniques in the performance of surface exploration of the Moon (or Mars).

## 6. CONCLUSIONS

Science fiction-inspired visions of virtual worlds, intuitive human-machine interaction, and remote "presence" fueled many developments in extended reality technology and techniques [3]. Unsurprisingly, XR has been investigated and applied across a spectrum of use cases throughout NASA's history, including human-machine exploration, personnel training, spaceflight operations and maintenance, and ensuring the health and safety of astronauts [1, 2, 4, 15, 16, 17, 18]. Notably, as this review highlights, aspects of XR (e.g., VR, AR, MR, telerobotics, telepresence) have in many cases evolved synergistically with space exploration requirements, occasionally being directly catalyzed by them (i.e., telemedicine) [50, 52, 69, 75, 76, 113]. Space exploration initiatives also offer fertile ground for advanced integration of XR subdisciplines to address complex scenarios involving human-machine, human-human, and human-environment interaction; this becomes even richer and more interesting when associated fields such as digital twin and video game technology are factored in [156, 158, 160, 161, 165, 168, 169].

Finally, the importance of XR as an enabler for long duration spaceflight is evident, with significant applications in future cislunar and interplanetary exploration, as promised by programs such as *Artemis* – elements of which have been in development since 2010 [7, 26, 71, 86]. The incremental build-up of capabilities on and around the Moon during *Artemis* has been deemed by NASA as "essential to… preparing for human exploration of Mars", and it is likely that XR applications developed to explore our "nearest neighbor" will be ported to the Red Planet [7, 26]. Overall, it is clear that such technology can help our minds and bodies voyage to other worlds – literally and virtually – in highly immersive, intuitive, and collaborative ways. We hope this review stimulates interest and serves as a starting point for continued investigations, particularly those focused on using XR to make the thrill of space exploration more accessible for all of us.

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