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Robotic Pioneers: Helping to Create a Sustainable Presence in Space

INTRODUCTION

Since the very first satellites in space, robotics and automation have played an important role in meeting challenging space mission requirements. Robotic technologies enable the completion of tasks in environments where human presence is non-viable. Many of our most important space missions – one only has to think about the James Webb Space Telescope (JWST), the Voyager missions, or any of the Mars rover missions – are aimed at helping us to understand our universe and answer fundamental questions motivating space research, such as: Where do we come from? Where are we heading? These missions often require operation in the most hostile and distant environments where we cannot send humans and may never be able to do so. Instead of astronauts, however, we can send robotic probes and rovers. Therefore, robotics and robotic platforms are instrumental in meeting some of the most important aims of space research.

Space exploration – the mere act of uncovering what is around us even before conducting science with further goals – has consistently propelled humanity beyond Earth's boundaries and into the expansive cosmos. The allure of space travel and the aspiration for a permanent human presence in space have always sparked wonder and optimism, and it is increasingly evident that robotics stands as an indispensable catalyst in transforming these aspirations into tangible realities. The transformative power of robotic innovation has

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reshaped the landscape of space exploration, opening avenues for a sustainable human presence in space – formerly relegated to the realms of science fiction.

This article delves into the pivotal role of robotics in the pursuit of establishing a lasting human presence in space. Through a historical lens, we explore how robots have played a vital role in enhancing our comprehension of the universe and enabling exploration of distant celestial bodies. We scrutinise the merits of incorporating robots into space missions, ranging from their cost-effectiveness to their resilience in facing the extreme conditions of space.

In the pursuit of establishing a lasting human presence beyond Earth, robots transcend their role in exploration. Their significance extends to becoming essential contributors in constructing and maintaining space habitats for humans, optimising resource utilisation and executing pivotal experiments. These multifaceted tasks lay the groundwork for achieving a self-sustainable presence in space.

This paper is organised as follows: the first few sections summarise a historical perspective of space exploration, including the International Space Station (ISS). The following two sections focus on past and future Mars exploration missions. In the second part of the article, we discuss the various elements regarding the advantages of robots used in space exploration and the collaboration between humans and robots, next we examine the topic of habitat creation. Finally, we conclude by highlighting the future roadmaps of robotic exploration and summarising the main points of the article.

TYPES OF SPACE ROBOTIC ASSETS

Space robotic platforms are specially designed systems that can function in hostile environments. Their complexity and capabilities vary greatly and their purposes are diverse. To make some sense of all these variables, here the author arbitrarily designates a few broad classes of robotic systems according to the missions they are intended to perform. To be noted that some of the missions could be classified into several categories. In terms of taxonomy, space robotics can be broadly categorised into manipulator systems (i.e. robotic arms), mobile systems (i.e. rovers), lander systems (i.e. static probes) and robotic space probes. This taxonomy highlights the diverse roles and functionalities of space robots, each tailored to specific mission requirements.

The first category is robotic arms, which are manipulative structures equipped with joints and end-effectors. These arms are versatile tools used for tasks such as sample collection, maintenance and assembly. They are prominently featured on rovers, landers and space probes to enhance their functionality.

Rovers represent another group of space robotics, serving as mobile platforms equipped with wheels or legs for navigation. These vehicles are designed to traverse planetary surfaces, capturing images and collecting data. Rovers play a significant role in scientific exploration, conducting in-situ experiments and analysing terrain to broaden our understanding of celestial bodies.

The objective of a lander spacecraft is to successfully touch down on the surface of a target planet and then operate autonomously or semi-autonomously to gather and transmit valuable data back to Earth. This data often includes crucial insights into the planetary composition, atmospheric conditions, geological features and other specific scientific parameters.

Finally, space probes are equipped with varying degrees of autonomy, and constitute another integral component of space robotics. These probes are deployed for remote sensing, data collection and analysis. Advanced autonomy allows them to make decisions based on predefined algorithms, adapting to changing conditions without direct human intervention.

BRIEF HISTORY OF SPACE EXPLORATION

Since 1957, when the Soviet Union successfully launched the Sputnik 1 satellite, humans have consistently dispatched robotic emissaries into space, serving as pioneers in the exploration of the vast cosmos beyond Earth. Throughout the years, various forms of robotic spacecraft, including probes, rovers and landers, have journeyed to every planet in our solar system and even ventured into the interstellar medium (Angelo 2007).

In December 1962, the Mariner 2 mission achieved the historic milestone of becoming the world's first robotic space probe to successfully complete a Venus flyby (NASA 2023). It collected measurements based on which it became known that the solar wind streams continuously, it helped to further refine the mass of Venus and noted the high temperatures of the atmosphere of the planet (500 Celsius). The Mariner missions helped to highlight the significant environmental differences between Earth and Venus, and such space agencies became focused on other planets.

In 1970, the Soviet spacecraft Venera accomplished the remarkable feat of landing on the surface of Venus. This marked the first instance of an unmanned probe successfully touching down on another planet and transmitting surface data back to Earth. Due to the conditions prevailing on Venus, attention was turned towards the Moon and Mars and thus space agencies started to optimise for robotic exploration.

One year after the United States' (U.S.') Moon landing, the Soviet Union achieved the first successful deployment of a robotic lunar rover named Lunokhod in 1970. Operating remotely from November 1970 until the summer of the following year, Lunokhod covered almost 10 km across the lunar surface in teleoperation mode (Siddiqi 2018). The Lunokhod Programme pushed the boundaries of rover design, technology, manufacturing and teleoperation.

The NASA Viking mission, commencing in 1968, witnessed successful landings on Mars in 1976. These missions were equipped with robotic technology similar to Mariners 4 and 6. Each Viking spacecraft comprised both a lander and an orbiter. The purpose of these mission series was to build up the knowledge and technology necessary to survive Martian orbit insertion, pass the Entry, Descent and Landing (EDL) stage successfully and deploy landers on the surface in a soft manner.

The list of the most significant robotic missions includes the Voyager probes, which flew by several planets. The probes, even after nearly 50 years, continue to transmit valuable data beyond the heliopause. Both of the spacecraft, Voyager

1 and 2, were launched in 1977, performed flybys of Jupiter and Saturn before Voyager 2 continued to Uranus and Neptune, offering unprecedented insights into the outer planets and their moons, making it the only spacecraft to have done so. Both Voyager crafts are currently journeying billions of kilometres from the Sun, studying particle and magnetic properties of interstellar space. In the summer of 2012, Voyager 1 flew beyond the heliopause and entered interstellar space, the first ever human made object to reach such a feat (NASA Jet Propulsion Laboratory [s. a.]).

Since the early 1970s, the United States and the former Soviet Union undertook challenging missions, sending a plethora of spacecraft to explore neighbouring planets. The list of most prominent missions of this era, of course, has to include the Apollo missions, which primarily focused on human exploration of the Moon, but were equipped with robotic components to help interplanetary travel. These instances exemplify the versatility and far-reaching ambitions enabled by robotic technologies in space exploration initiatives. These missions were characterised by challenging flyby manoeuvres around neighbouring celestial bodies, demonstrating the technological skills of the era.

Despite their limited timelines, the missions achieved remarkable scientific returns. Examples like the Pioneer 10 and 11 missions conducting flybys of Jupiter and Saturn underscore the importance of exploration and discovery that defined the initial phase of interplanetary exploration. These missions, by gathering valuable data about the planets of the solar system, exemplify the adventurous spirit that laid the foundation for subsequent human spaceflight endeavours around the lower Earth orbit and beyond.

ROBOTICS ON THE ISS

Assembly of the International Space Station (ISS) commenced in 1998, marking the beginning of the construction of the most expensive space asset to date (ESA [s. a.]a). Positioned in Low Earth Orbit (LEO), the ISS holds the title of the largest space station ever constructed. Its construction involved a remarkable effort involving most major space agencies, encompassing over 250 Extravehicular Activities (EVAs), commonly known as astronaut spacewalks.

Integral to the assembly process was the utilisation of Canadarm2, a robotic asset developed by the Canadian Space Agency (CSA). Canadarm2 played a crucial role in manoeuvring and assembling various modules of the ISS. Simultaneously, the European Space Agency (ESA) made substantial contributions to the ISS project by investing in developing the Columbus module and its own space-qualified robotic arm. After more than three decades of dedicated work and overcoming substantial delays, the European Robotic Arm (ERA) achieved a significant milestone when it was successfully launched in 2021 (ESA [s. a.]b). Following its launch, ERA underwent in-orbit commissioning the next year, solidifying its role as a valuable addition to the robotic infrastructure of the ISS.

This collaborative effort by multiple space agencies demonstrates the international cooperation and technological advancements that have propelled the construction and operation of the ISS, showcasing the capabilities of both human and robotic assets in the challenging environment of space.

MARTIAN EXPLORATION

Traditional rovers from various space agencies such as NASA's Sojourner, twin rovers Opportunity and Spirit, later on, Curiosity and Perseverance have enabled great discoveries on Mars, but have limitations when it comes to other celestial bodies (e.g. Moon, Phobos, asteroids). We are focusing in this chapter on the Martian case which is of great interest for various reasons: closeness to Earth, vaguely similar temperature and atmospheric conditions.

Sojourner, the inaugural U.S. robotic rover on Mars, touched down on 4 July 1997, and explored the flat terrain of Ares Vallis near its landing site of the Pathfinder Lander. During its brief operational span of two months, Sojourner transmitted 550 images of Mars and collected valuable data on soil composition, wind patterns and weather conditions (Siddiqi 2018). In 2004, NASA's Jet Propulsion Laboratory (JPL) successfully deployed two identical rovers, Spirit and Opportunity, equipped with cameras, computers and specialised scientific instruments. Beyond their expected three-month lifespan, both rovers made groundbreaking discoveries, confirming the planet's past water presence. In 2011, Spirit identified that dust in the Gusev Crater was found to be magnetic, moreover, it also identified rock containing zinc and bromine, indicating the past flow of heated water (Bertelsen et al. 2004). Opportunity transmitted its final data to NASA in June 2018, being operational for a total of 5,111 sols and traversing a total distance of 45.16 km (Platt 2019).

In the frame of NASA's Mars Science Laboratory's mission, Curiosity, a car-sized rover, which landed on Mars in August 2012, remains active after many years. Initially commissioned for a one Martian year mission duration and the capability to achieve at least 20 km, NASA extended Curiosity's tenure indefinitely just six months after landing. Designed to assess the habitability of Mars, Curiosity boasts the largest and most advanced suite of scientific instruments ever sent to the Martian surface (NASA Jet Propulsion Laboratory 2012); it also contains no less than 17 onboard cameras. These instruments can collect rock samples, analyse their composition and structure, and transmit the data back to Earth. The main challenges to its mobility capabilities included issues related to wheel wear, wheel entrapment and progressive wheel sinkage (Rankin et al. 2020).

Building on the previous successful missions, in July 2020, the Perseverance Rover embarked on its journey to the Martian surface. While resembling its predecessor, Curiosity, Perseverance boasts an enhanced wheel design and is equipped with a drill for collecting samples from Martian rocks and soil. Additionally, Perseverance carries the Ingenuity helicopter, the first vehicle to take flight on another planet. This small helicopter faces the unique challenge of flying in the atmosphere of Mars, which is only 1% as dense as Earth's. Enduring harsh conditions, including overnight temperatures plunging to −70 °C, Ingenuity was designed to conduct four planned 90-second flights. Perseverance landed successfully on Mars in February 2021, equipped with an array of technology, including 23 different cameras. Ingenuity is meant to be a 30-day technological demonstrator, originally designed for 5 flights at an altitude between 3–5 m. The successful performance in the challenging Martian environment is outnumbering any previous expectations: in January 2024, Ingenuity had its 72^{nd} flight during which it suffered rotor damage on a featureless terrain (NASA Jet Propulsion Laboratory 2024).

Various static landers without mobile platforms have played a crucial role in advancing our scientific understanding of extraterrestrial environments. For instance, NASA's InSight mission made significant contributions by measuring Martian earthquakes, providing valuable insights into the interior structure of the Red Planet (Yana et al. 2023). Static landers, with their specialised and fixed functionalities, have emerged as indispensable instruments in deciphering the enigmas of celestial bodies within our solar system and farther afield.

The ExoMars Mission, spearheaded by the ESA and previously in collaboration with Roscosmos, has its goal set on exploring Mars and uncovering potential evidence of past or present life. This comprehensive mission consists of two integral components: the ExoMars Trace Gas Orbiter (TGO) and the ExoMars Rover, aptly named the Rosalind Franklin Rover. The TGO was launched in 2016 and it is a hybrid science and telecom spacecraft that serves as an orbiter around Mars. It is equipped with scientific instruments (i.e. NOMAD, ACS, CASSIS, FREND) to study the Martian atmosphere, particularly focusing on trace gases like methane.

The Rosalind Franklin Rover, being part of the second mission phase, is designed to search for signs of the origins of life on Mars. It carries a 2-metre-long drill instrument to collect samples from below the Martian surface. The rover is equipped with a large suite of scientific instruments, including infrared spectrometers, ground penetrating radar and high-resolution cameras, to analyse the composition of the Martian soil (Vago et al. 2017). As such, the ExoMars Rover was meticulously designed and engineered for navigating through highly demanding terrains relative to its platform's capabilities, all the while prioritising the rover's safety (Winter et al. 2015). The core scientific objectives of the ExoMars mission encompass comprehending the Martian environment, probing potential traces of past or current life, and delving into the planet's geological makeup. Focused on exploring a region of significant scientific interest, the rover leverages its mobility and drilling capabilities to augment the mission's capacity for acquiring vital data (Gao 2016). The ExoMars mission represented a collaborative effort between ESA and Roscosmos, the Russian space agency in the quest to unlock the mysteries of Mars. Unfortunately, the project was further delayed and ESA announced that the launch of the rover has been suspended and delayed to at least 2028 (ESA 2023).

Zhurong stands out as China's maiden Mars rover mission being an integral part of the Tianwen 1 orchestrated by the China National Space Administration (CNSA). Its journey commenced with a launch on 23 July 2020, culminating in a successful orbital insertion on 10 February 2021, and a well-executed soft landing on Mars on 14 May 2021. This historic achievement not only marked China as the third nation to achieve a Mars soft landing but also secured its position as the second country to deploy a rover, following in the footsteps of the United States. Exploration activities officially kicked off on 22 May 2021.

Designed for a 90-sol lifespan, Zhurong exceeded expectations, operating for 347 sols (356.5 days) after deployment. Unfortunately, it became inactive on 20 May 2022, due to approaching sandstorms and the onset of Martian winter.

SAMPLE RETURN MISSIONS

The NASA–ESA Mars Sample Return (MSR) Campaign is a response to the long-running scientific objective to better understand Mars. By acquiring and returning to Earth an uncontaminated set of Mars samples, scientists will have access to the extent of science instruments available in terrestrial laboratories, unlocking new possibilities in exobiology, interplanetary geology and supporting our search for the origins of life (Muirhead et al. 2020). The plan involves a multi-step approach that spans several missions over more than a decade. The proposal envisions collecting these samples using a series of small, cylindrical, titanium tubes – 43 in total.

As of September 2022, the NASA–ESA plan has received approval for implementation. The mission involves three key phases (Haltigin et al. 2022):

Sample collection mission

Perseverance rover, part of the Mars Sample Return campaign, serves as the sample collection mission.

It gathers the Martian samples and prepares them for retrieval.

Sample retrieval mission

- This mission involves several components, including a Sample Retrieval Lander, Mars Ascent Vehicle, Sample Transfer Arm and two Ingenuity-class helicopters.
- The lander facilitates the safe landing and deployment of necessary equipment.
- The Mars Ascent Vehicle lifts the collected samples from the Martian surface.
- The Sample Transfer Arm transfers the samples to the Earth Return Orbiter (ERO).

Return mission

- The ERO, a crucial part of the mission, is responsible for transporting the collected samples from Mars to Earth.
- The return is anticipated around 2033, marking a historic moment in planetary exploration.

NASA's OSIRIS-REx mission was specifically designed and constructed for the investigation and sample collection from the near-Earth asteroid Bennu. Launched in 2016, the spacecraft reached Bennu, conducted extensive observations (Barnouin et al. 2020), and acquired samples from the asteroid's surface which were later delivered to the surface of the Earth. Its primary objective was to contribute insights into the early solar system, the formation of planets, and the potential existence of life's building blocks in asteroids.

The Martian Moons eXploration (MMX) is a forthcoming robotic space probe, scheduled for launch in 2024 (Clark 2020), with the primary objective of bringing back the first-ever samples from the largest moon of Mars, Phobos. Primarily developed by the Japanese Aerospace Exploration Agency (JAXA) and officially announced on 9 June 2015, the MMX mission encompasses landing and collecting samples from Phobos, possibly once or twice. Additionally, it includes Deimos flyby observations and the monitoring of the climate of Mars. A notable component of the MMX mission is the inclusion of a rover named IDEFIX, representing a collaborative effort between the French Space Agency (CNES) and the German Space Agency (DLR). This rover, weighing less than 30 kg on four wheels, is designed to navigate and explore the surface of Phobos within its unique microgravity environment (Barthelmes 2023). The mission aims to enhance our understanding of the Martian moons, particularly Phobos, by analysing collected samples and conducting observations. The inclusion of the IDEFIX rover will further extend the mission's capabilities, providing valuable insights into the geological and environmental characteristics of Phobos. The MMX mission holds the potential to contribute significantly to our broader knowledge of the Martian system.

Further sample return missions such as Hayabusa and Chang'e underscore significant milestones, so they should not be omitted. Hayabusa, led by JAXA, successfully retrieved and delivered for the first time samples from asteroids Itokawa (2010) and Ryugu (2020), contributing to our understanding of the early solar system. Meanwhile, the Chinese Chang'e 5 mission, operated by CNSA, in December 2020 has returned lunar samples. These endeavours reflect the increased steps that national space agencies are taking in unravelling the mysteries of our solar system.

ADVANTAGES OF ROBOTIC SOLUTIONS

Robotic platforms prove useful in space applications and exploration where the environments are too extreme and offer unparalleled superiority, especially when venturing into environments too challenging and hazardous for human survival without extensive protection. Take the surface of Mars for instance, where temperatures fluctuating from −153 to +20 degrees Celsius, present a formidable challenge for future astronauts. That is why it is more practical to send remote assets first in order to investigate, assess and prepare for the arrival of future astronauts. Additionally, the vacuum of space and the relentless barrage of solar particles, known as solar radiation, create an environment that is deadly to human presence. To overcome these challenges, space assets are meticulously engineered, subjected to rigorous testing, and built with strict requirements and safety margins. This meticulous approach ensures their resilience in the face of harsh conditions, making scientific missions feasible despite the complexity and potential delays associated with developing cutting-edge technologies.

In contrast to robotic systems, human spaceflight introduces a myriad of complexities that significantly escalate mission costs. The fundamental need for life support systems becomes imperative to guarantee the safety and well-being of astronauts, whether stationed aboard the International Space Station (ISS), prospective lunar bases, or potential Martian missions. Unlike robots, humans demand protection against extreme temperature variations and radiation exposure. They rely on a stable and continuous supply of air and water, necessitating sophisticated life support infrastructure. Moreover, human habitats must meticulously maintain constant pressure and temperature, adding layers of intricacy to space missions. The delicate equilibrium between sustaining human life and the inherently harsh space environment markedly amplifies the financial investment required for human spaceflight endeavours.

Robotic systems, on the other hand, sidestep these intricate challenges associated with human missions. They operate in environments where humans would face insurmountable difficulties without extensive protection measures. Robots do not require life support systems or meticulous habitat conditions.

This inherent advantage allows for streamlined mission planning and execution, resulting in cost-effective exploration of space. The absence of ethical, political and certification considerations, which are inherent in human spaceflight, further contributes to the efficiency of robotic missions. As robots navigate and gather data in the frontiers of space, they simultaneously contribute to the advancement of knowledge that can be leveraged to make future human flights safer and more informed. The synergistic relationship between robotic exploration and human spaceflight endeavours ensures a strategic and complementary approach to unravelling the mysteries of the cosmos.

On the ISS, where there is constant human presence, robotic arms handle heavy lifting tasks, showcasing the efficiency and precision of operation manipulator systems. Cargo transportation is facilitated by various cargo spacecraft, including from ESA, Japan, the United States and the Russian Federation, further emphasising the integral role of robotic systems in the logistics and functionality of space exploration endeavours. The advantages of robotic platforms extend beyond cost-effectiveness to encompass enhanced safety, endurance and adaptability in environments hostile to human life.

Moreover, robots play a pivotal role in space exploration and other environments that are deemed harsh and inhospitable for human presence. Their ability to operate in these challenging conditions stems from several key advantages that are summarised hereafter.

Extreme temperatures

In space and on celestial bodies like Mars, temperatures can vary widely, ranging from scorching heat to bone-chilling cold. Robots are equipped with materials and components designed to withstand these extreme temperature fluctuations, having extensive thermal protection and insulation, but not in need of life support systems, which is a complex and highly costly system of any spacecraft.

Radiation exposure

The void of space is filled with cosmic radiation, including solar and cosmic rays. Research studies of exposure to various doses and strengths of radiation provide strong evidence that cancer and degenerative diseases are to be expected from exposures to galactic cosmic rays (GCR) or solar particle events (SPE). Robots are vulnerable to some extent to the adverse effects of radiation. Their electronic components can be shielded and hardened to withstand radiation, allowing them to operate for extended periods in environments where humans would face significant health hazards.

Microgravity and low-gravity environments

Robots are not affected by the physiological challenges associated with microgravity or low-gravity environments, such as those on asteroids or moons. Human bodies undergo changes in bone density, muscle mass and cardiovascular function in microgravity conditions, making long-term human presence challenging. Robots, on the other hand, can navigate and perform tasks without the constraints of these gravitational limitations.

Planetary mobility

Planetary surfaces, especially those of Mars or the Moon, can be rugged and difficult to traverse. Robots can be designed with advanced mobility systems, such as wheels, legs, or even hopping mechanisms, to navigate challenging terrains without the constant need for human intervention (Rubio et al. 2019). This adaptability enables them to explore inaccessible areas where human mobility would be restricted. It is envisaged that mobile platforms will greatly support astronaut missions on the surface of the Moon or Mars (O'Shea 2023), similar to the Lunar Roving Vehicles (LRV) during the Apollo missions. LRVs allowed human explorers to cover more terrain and increased the range of science activities.

Harsh atmospheric conditions

Environments with corrosive atmospheres, such as the acidic clouds of Venus, would pose significant challenges to human survival. Robots can be constructed using materials resistant to corrosive elements, allowing them to endure and operate effectively in atmospheres that would be detrimental to human health.

Long duration missions

Robots can operate for extended periods without the need for life support systems, food, or rest. This endurance is particularly valuable for missions requiring prolonged exploration or monitoring, where human presence would be logistically challenging and economically impractical. For example, the most optimised transfer from Earth to Mars is about 9 months, during which there are several issues which needs to be solved for future astronauts to travel to the surface of Mars: shielding and protection for humans against radiation from the Sun, the psychological effects of long-term travel, and bringing enough supplies for a return mission.

Precision and repetitive tasks

Robots excel at performing precise and repetitive tasks with unwavering accuracy. In environments where monotony or precision is required, robots can outperform humans, contributing to efficient data collection, assembly, or maintenance tasks. Martian rover missions (e.g. Mars Exploration Rover missions, Curiosity) have been constantly conducting repetitive tasks, including drilling, sample collection and analysis.

By leveraging these advantages, robots become indispensable tools for space exploration and other applications in environments hostile to human life. Their versatility and adaptability make them ideal candidates for pushing the boundaries of scientific and engineering discoveries.

SAFETY ASPECTS

Safety stands as a paramount consideration in the planning and execution of exploration missions, especially as humanity embarks on groundbreaking Artemis Accords: a NASA led mission with major partner agencies such as JAXA, U.K. Space Agency (UKSA), United Arab Emirates Space Agency (UAESA), Canadian Space Agency (CSA) and Italian Space Agency (ASI). As of today, Artemis I (2022) was the successful uncrewed test of the SLS and Orion and was the first test flight for both crafts. The Artemis I mission involved placing Orion into lunar orbit before its return to Earth. These crewed missions, scheduled for 2024–2029, mark a historic return to the Moon's orbit after a hiatus of over 50 years. The overarching goal is to not only revisit lunar space but to advance human exploration by laying the groundwork for future lunar surface missions.

The safety protocols implemented in the Artemis Mission are comprehensive and multifaceted. They encompass rigorous spacecraft design, meticulous pre-launch testing and robust emergency contingency plans. Space agencies, in collaboration with private entities like SpaceX, prioritise the well-being and security of astronauts throughout the mission, considering the inherent challenges of space travel and lunar exploration.

As Artemis progresses, the subsequent phase aims to achieve another significant milestone: setting foot on the lunar surface, underscoring the commitment to safety as a fundamental aspect of the mission. Lunar surface operations pose unique challenges, including the abrasive nature of the lunar regolith, the potential for extreme temperature variations, and the need for life support systems in a hostile environment.

The lessons learned from past missions, such as the Apollo program, contribute to the ongoing refinement of safety measures. Advancements in technology, coupled with a wealth of experience, enable space agencies to enhance spacecraft reliability, astronaut training and mission preparedness.

In addition to lunar missions, the emphasis on safety extends to future endeavours, including crewed missions to Mars and beyond. Each step in space exploration is meticulously planned, integrating state-of-the-art safety features to mitigate risks and ensure the well-being of astronauts as they venture into the cosmos as projects that are funded by governmental agencies became risk-averse over the last few decades. The commitment to safety underscores the responsible approach taken by space agencies as humanity ventures into the future frontiers of space exploration.

HUMAN–ROBOT COLLABORATION

Several successful missions have been performed in the last decades within the human-robot interaction topic: such as ESA's teleoperation missions from the ISS. The Multi-Purpose End-to-End Robotic Operation Network (METERON), represents a forward-looking initiative gearing up for the future of space exploration (eoPortal 2020).

NASA has made significant investments in advancing human-like robotics projects, exemplified by initiatives like Robonaut: a dexterous anthropomorphic robotic system (Ambrose et al. 2000). These endeavours aim to integrate humanoid robotics into space exploration activities, capitalising on the dexterity and adaptability of human-like robotic systems. Robonaut, in particular, represents a cutting-edge venture developed by NASA in collaboration with technology partners. Projects such as Robonaut stress the commitment of space agencies to enhancing the capabilities of robotic systems for human–robot collaboration for current and future space missions. By designing robots with humanoid features (e.g. arms, hands and a torso), it aims to create intelligent machines capable of performing tasks in a manner more similar to how humans operate in terrestrial and space environments, moreover, such humanoids can cooperate with astronauts onboard the ISS (Diftler et al. 2011). This includes tasks that demand fine motor skills, intricate tool manipulation and efficient interaction with the surroundings.

Furthermore, support for initiatives such as Robonaut plays a crucial role in propelling the frontiers of artificial intelligence, machine learning, and collaborative endeavours between humans and robots. The aim is to create robots that seamlessly integrate with astronauts, elevating the overall effectiveness and safety of space missions. In the dynamic landscape of evolving technology, the lessons drawn serve as invaluable knowledge, steering the course of next-generation humanoid space robots. This trajectory sets the stage for progressively advanced and adept robotic systems within the domain of space exploration.

HABITAT CREATION

Establishing habitats on other celestial bodies is a critical step in the prospect of future human settlements, and robotic technologies will play a pivotal role in preparing environments that shield astronauts from challenging external conditions, such as temperature variations and atmospheric pressure fluctuations.

As we envision human presence beyond Earth, automated cargo vehicles are anticipated to play a crucial role in transporting the necessary materials and equipment to the lunar and Martian surfaces. These robotic cargo missions will serve as precursors to human expeditions, carrying payloads that include construction materials, life support systems and other essentials for habitat creation.

However, a significant challenge lies in the limited cargo capacity of current launch vehicles available as of the end of 2023. The payload constraints necessitate innovative solutions to optimise resource utilisation and minimise the number of launches required. SpaceX's revolutionary reusable Starship rocket emerges as a promising solution to address this limitation. With an impressive lift capacity of 100 to 150 metric tonnes to orbit, Starship has the potential to substantially increase the payload capacity for cargo delivery to lunar and Martian surfaces.

The deployment of robotic technologies in habitat creation involves a multifaceted approach. Automated cargo vehicles, equipped with advanced robotic systems, can perform precise tasks such as excavation, construction and assembly. Robotic arms and tools, controlled either remotely or autonomously, will be instrumental in preparing the groundwork for human-friendly habitats.

Beyond construction tasks, robots will also be tasked with creating protective environments within habitats. This includes setting up life support systems, ensuring stable atmospheric conditions and establishing energy infrastructure for sustained human habitation. The autonomous nature of these robotic systems is advantageous in executing repetitive or hazardous tasks without the need for direct human intervention.

As technologies continue to advance, the integration of artificial intelligence and machine learning will further enhance the capabilities of robotic systems in habitat creation. These intelligent robots can adapt to dynamic environmental conditions, learn from their surroundings and optimise their operations over time.

In summary, the future of habitat creation on celestial bodies heavily relies on the collaborative efforts of robotic technologies and advanced launch capabilities. By leveraging innovative solutions like SpaceX's Starship and employing sophisticated robotic systems, we are taking essential strides toward establishing sustainable and habitable environments beyond Earth.

In situ resource utilisation (ISRU) emerges as a critical strategy in the pursuit of sustainable human settlements on other celestial bodies. ISRU could provide materials for life support, construction materials, propellants, or energy to spacecraft payloads or space exploration crews. The ability to harness and leverage local resources for habitat creation becomes imperative to overcome the constraints of limited cargo capacity and ensure long-term viability. Robotic technologies play a central role in implementing ISRU, as they can be equipped to autonomously extract, process and utilise available resources on the Moon, Mars, or other destinations. For instance, robots can mine and process regolith to extract essential materials, such as metals and minerals, for construction purposes. This not only reduces the dependency on Earth-sourced materials but also minimises the need for extensive cargo transport, making the establishment of human habitats more cost-effective and sustainable. Another typical proposal for ISRU is the use of a Sabatier process, to produce methane to be used as a propellant on the Martian surface.

Moreover, ISRU extends to the utilisation of local energy sources. Solar panels deployed and maintained by robotic systems can harness the abundant solar energy available on the Moon's surface or Mars, powering habitat operations and reducing reliance on external power sources. By strategically integrating ISRU with robotic technologies, we pave the way for self-sufficient and resilient human settlements on other celestial bodies, where local resources become the building blocks for sustainable habitation and exploration.

NASA is gearing up for human exploration of Mars, and the MOXIE investigation on the Mars 2020 mission addresses a crucial knowledge gap by showcasing ISRU technologies for oxygen production from the Martian atmosphere. MOXIE collects CO_2 from the atmosphere of Mars, uses electrochemical processes to split CO_2 into O_2 and CO, and then analyses the purity of the produced O_2 before releasing it, along with CO and other exhaust products, back into the Martian atmosphere (Hoffman et al. 2022).

FINANCIAL CONSIDERATIONS

Automated robotic assets often outperform initial mission requirements, hence providing further scientific returns for the same asset, as only the cost of operations needs to be covered. One could argue that such machines cost taxpayers substantial amounts of budget, in fact, however, the yearly ESA budget costs European taxpayers less than a cinema ticket per capita (ESA [s. a.]c).

In the first 50 years of space exploration, during the space race, it was entirely financed by states in order to achieve many records such as the first satellite or the first Moon landing. In the last few years, private investors have gained significantly bigger slices of space exploration. One notable example is SpaceX, which revolutionised the rocket market segment with reusable rocket boosters, lowering the unit price per kg across the industry.

Venture capital also reached space companies: in the past few years, significant investment has flowed into the space sector. Consider the year 2021, where both public and private markets injected $10 billion of new capital into space companies (Bland et al. 2022). Numerous leaders and innovators in the space industry have concentrated on fostering internal growth by financing in-house technology for the development and construction of cutting-edge products. As an illustration, SpaceX made substantial investments in the rapid development and launch of Starlink, recognising the opportunity to apply established capabilities from its launch business to establish a satellite-based broadband internet system. The present is a different kind of space race: growth and technology are leveraged by increased capital.

ROADMAPS

In mapping out their trajectory for the coming decades, major space agencies appear to be steering towards sustained exploration, blending both robotic and human-centric initiatives. NASA, distinguished for its dedicated ventures toward Mars, stands ready to further explore the Red Planet. The emphasis lies on elevated robotic missions, integrating sophisticated sampling and analytical capabilities. Extending beyond Mars, the agency directs its focus toward the distant realms of our solar system. Ambitious missions are under consideration to unravel the enigmas surrounding Jupiter, Saturn, Uranus and Neptune, with a detailed examination of their atmospheres and diverse moons on the agenda.

ESA, on the other hand, envisions a lunar future with its ambitious Moon Village concept and having European astronauts on the surface of the Moon by 2030 (ESA 2022), fostering international collaboration for a prolonged lunar presence. Robotic missions are slated to be instrumental in laying the groundwork and offering logistical support for human endeavours on the Moon. As part of ESA's broader scope, deep space beckons, prompting consideration of missions to asteroids, comets and other celestial bodies, opening avenues for groundbreaking discoveries.

JAXA, with its distinct lunar focus, is anticipated to persist in lunar exploration missions, building upon the successes of Kaguya and charting new territories. The prospect of sample return missions is on the horizon, with JAXA eyeing potential targets among asteroids and intercepting comets together with ESA for meticulous scrutiny back on Earth.

Meanwhile, CNSA of China charts a course that encompasses lunar and Martian horizons. Prolonged lunar exploration, with a potential for sustained lunar habitation, is a key facet. Concurrently, the agency contemplates extending its Martian endeavours, integrating robotic missions and pondering the logistics of sample return missions. For China, these upcoming missions are planned to be in a non-cooperative setup.

These trajectories, intricately woven with scientific pursuits, resource utilisation aspirations and preparedness for potential human undertakings, epitomise the evolving landscape of celestial exploration. Anticipated adaptations to these strategic roadmaps will be influenced by the assimilation of cutting-edge technologies, synergistic international collaborations, and novel revelations unveiled through rigorous scientific exploration.

CONCLUSIONS

The possibilities for space robotics reach far beyond its role in aiding human space exploration. It embraces vital functions in upcoming endeavours such as resource extraction from celestial bodies like the Moon and asteroids. Additionally, space robotics plays a pivotal role in conducting secure scientific investigations throughout our solar system with current and future robotic space probes. Achieving these distant objectives necessitates the technology development of sophisticated hardware, and software while scaling up and optimising robotic functionalities. This can be only met with a vast amount of funding from both private and public entities.

Space robotics assumes paramount importance in establishing a permanent presence beyond Earth, undertaking tasks such as scientific research, habitat construction, infrastructure maintenance and other endeavours too hazardous or costly for humans. Realising the full potential of space robotics requires addressing challenges like creating resilient robots capable of withstanding the harsh conditions of space, developing autonomous software for diverse tasks and establishing necessary supporting infrastructure.

In overcoming these challenges, the focus on advanced robot software for space exploration becomes crucial. Companies and institutions are actively engaged in this pursuit, aiming to empower robots for diverse tasks in extreme environments. As humanity ventures further into space, the role of space robotics stands indispensable, shaping the future of space exploration and enhancing our understanding of the universe.

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