REVIEW

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Compliant Robotics in Space: A Prospective Review of Soft and Deformable Systems for Space Missions

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Space exploration demands innovative robotic solutions to address complex challenges. This article provides a forward-looking perspective on the emerging field of compliant robotics for space applications, categorizing these systems into reconfigurable, hyper-redundant, origami-inspired, and soft robots, each offering unique advantages and facing distinct challenges. The review explores in-depth the critical roles these compliant robots can assume, ranging from on-orbit servicing to planetary exploration and beyond. It also addresses material selection, accounting for the harsh conditions of space, and examines the complexities in design, actuation, sensing, and control. The article concludes with a future-focused discussion of emerging trends, challenges, and research directions. This review aims to offer a comprehensive understanding of the current state of the art, positioning compliant robotics as a transformative force in the next frontier of space exploration.

1. Introduction

1.1. Background and Overview

The dawn of space exploration has driven numerous technological advancements and deepened our comprehension of the universe. As we aspire to extend our reach beyond our planet, the challenges we encounter grow increasingly complex. From navigating harsh environments and conducting scientific experiments to constructing and maintaining infrastructure in space, the demands of space missions necessitate highly versatile and robust systems. In this scenario, robotics has emerged as an indispensable field, offering tools and technologies designed to operate in the challenging environment of space. While traditional rigid robots have been the primary choice for space missions for decades, the increasing complexity of tasks and environments has driven the exploration toward more adaptable robotic systems. This shift has led to the rise of compliant robotics, which, with their flexibility and adaptability, promise to address challenges that rigid robots might struggle with.

The overall concept of compliant robotics encompasses their ability to adapt in response to external forces, characterized by flexibility, reconfigurability, and modularity. Compliance refers to a robot's capacity to yield or flex rather than resist external forces. These features enable compliant robots to offer increased safety during human–robot interactions, adapt to uncertain environments, withstand impacts, and potentially reduce weight and energy consumption.

In this article, compliant robotic systems are defined as consisting of soft and deformable robots. Soft robots are primarily made from flexible and stretchable materials, allowing these systems to adapt and respond to their environment effectively. Deformable robots, on the other hand, are characterized by their ability to change shape and configuration to adapt to different tasks and environments. This versatility is achieved through mechanisms such as reconfigurable, hyper-redundant, and origami-inspired designs. Notable examples include origami robots that can fold into different shapes, truss robots that can extend or retract their struts, and tensegrity robots that can alter their shape through changes in tension. The ability to reconfigure provides these robots with a high level of adaptability, making them ideal for various space missions, including exploration, on-orbit assembly, and servicing tasks. **Figure 1** provides a schematic overview of the classifications of these robots, highlighting their growing importance in space applications.

Examples of these capabilities in action include soft robots designed for rapid exploration and intelligent repositioning in challenging terrains, such as those found on Mars.[1,2] In ref. [3], a flytrap-inspired bistable gripper is developed based on origami design for rapid active debris removal. Furthermore, a soft and bistable gripper has been designed for fast capture in space, using structural instability and kinetic energy absorption to achieve dynamic grasping without the need for additional input energy. This approach has the potential to simplify conventional driving devices and accomplish challenging operations in space missions.[4] The reconfigurable integrated multi-robot exploration system has been devised for lunar polar crater exploration missions, showcasing the potential of modular and reconfigurable robots in tackling the complex requirements of

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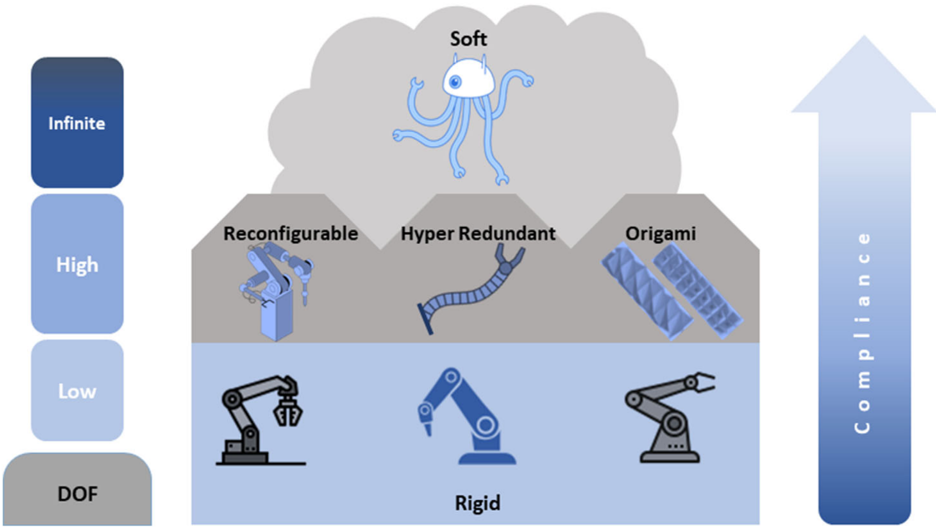

Figure 1. Schematics of robotics in space: rigid, deformable (reconfigurable, hyper redundant, origami), and soft.

crater environment exploration.[5] In ref. [6], the concept of a multiarm robot for on-orbit large telescope assembly represents a significant advancement in the assembly of large structures in space, offering a novel reconfigurable and modular approach that extends the range of possible operations.

The recent Chandrayaan-3 mission, with its soft rover Pragyaan designed for lunar exploration, and NASA's upcoming VIPER mission, aimed at prospecting lunar resources, represent significant advancements in space robotics. Chandrayaan-3's rover, engineered for minimal landing impact, incorporates a modular design, enhancing its resistance against potential failures and showcasing the evolution of sophisticated space robotics.[7–9] VIPER, on the other hand, is set to traverse the Moon's surface, utilizing state-of-the-art robotic systems to survey and analyze lunar resources, thereby paving the way for future crewed missions.[10–12] These missions highlight the requirement for advanced robotics in space exploration, emphasizing the increasing importance of adaptable, robust, and specifically soft and compliant robotics in tackling and operating within the challenging terrains of extraterrestrial environments.

This article presents a comprehensive review of compliant robotics for space applications. We begin by exploring the diverse categories of compliant robots, emphasizing deformable and soft variants. Recognizing the unique challenges of space, we discuss the crucial role of material selection, considering the harsh conditions of the space environment. This review navigates the developmental path of these robots, from conceptualization to operational deployment. In the context of space missions, we highlight the potential roles and contributions of compliant robotics. Looking ahead to future possibilities, we discuss emerging trends and the future prospects of these robots in space exploration. The article concludes with an insightful discussion of the present findings and a summation of the key takeaways. **Figure 2** presents an overview of key issues in compliant robotics in space, which serves as a guide to the structure and organization of the article.

1.2. Key Advantages and Applications

Compliant robotics offer several distinct advantages in space missions, each highlighting their suitability for complex tasks. One significant advantage is safety. The inherent flexibility of compliant robots ensures safer interactions with astronauts and sensitive equipment, significantly reducing the risk of inadvertent damage during operations. This quality is particularly crucial in the confined and delicate environments of spacecraft and space stations, where the slightest error can have severe consequences.

Another major advantage is their compact form factor. In space missions, where every added gram incurs substantial costs and volume is constrained, the ability of compliant robots to be transported in compact forms due to their reconfigurable designs is invaluable. Upon arrival, these robots can expand or be assembled, optimizing space utilization and minimizing payload requirements. This adaptability extends to their energy efficiency as well. Compliant robots optimize energy consumption by leveraging their flexible structures to absorb and release energy efficiently during movement, reducing the overall power requirements which is a critical factor in long-duration space missions.

Adaptability is another significant benefit. The flexibility of compliant robots allows them to navigate intricate and unpredictable environments and withstand harsh extraterrestrial conditions. This adaptability ensures they can perform a diverse array of tasks, from assisting astronauts to servicing space equipment and collecting lunar or Martian samples. Their lightweight nature further enhances their functionality, as the use of lightweight materials reduces payload weight, contributing to the overall cost-effectiveness of space missions.

Furthermore, compliant robots are designed for impact resistance, allowing them to absorb and distribute forces, protecting themselves and other structures from potential impacts. Their modular and scalable nature makes them highly versatile, enabling them to be customized and scaled according to the

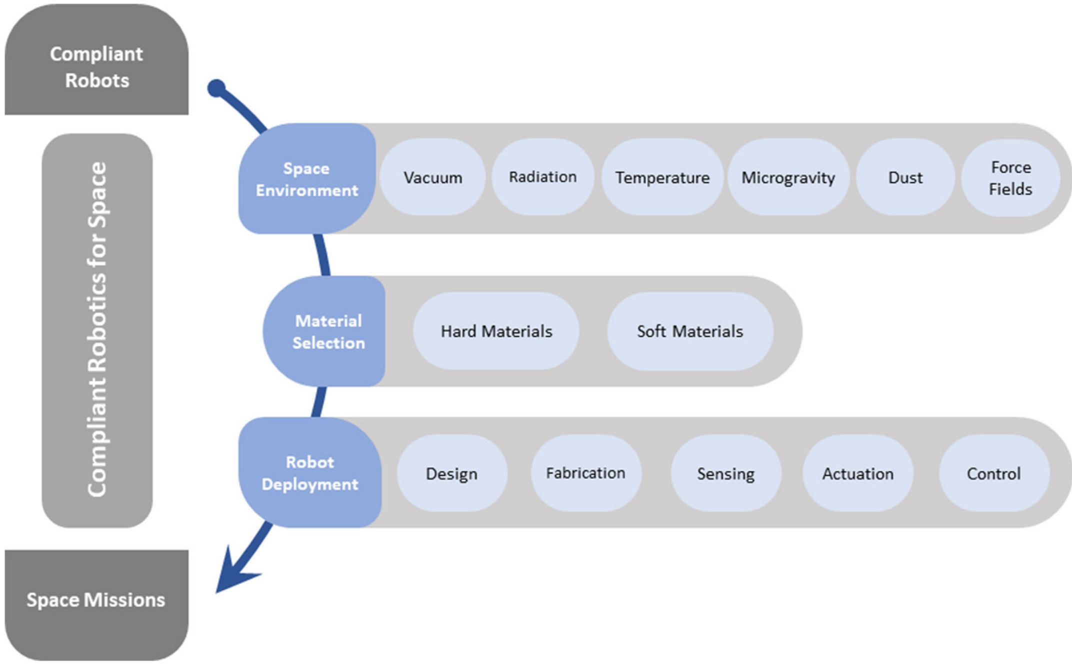

Figure 2. Key aspects of compliant robotics in space, including environmental challenges, material selection, and deployment stages.

specific requirements of different missions. The ease of maintenance and repair is also a noteworthy advantage. These robots are engineered for durability and simplicity, ensuring long-term functionality and minimizing downtime during missions.

Miniaturization addresses the challenges of weight, volume, and energy constraints in space missions by enabling compact and lightweight robotic components.[13,14] Advances in microfabrication and nanotechnology have made it possible to develop systems that function effectively in confined and resource-limited environments.[15–17] MEMS (micro-electromechanical systems) technologies have been applied to create sensors and actuators that offer both precision and lower power consumption, making them suitable for space exploration.[18] Additionally, foldable designs inspired by origami engineering improve packaging efficiency during launch and enable robots to perform complex tasks after deployment.[19,20] Downsized robots are also advantageous for navigating narrow terrains and sharing tasks among multiple systems in planetary exploration.[21,22]

Collaborative robotics enables systems to coordinate tasks such as on-orbit assembly and planetary exploration.[23,24] Decentralized control frameworks and multiagent architectures have been developed to improve coordination in dynamic environments, separating task allocation from environmental constraints and ensuring adaptability.[25,26] Cooperative control methods have demonstrated improved performance in handling challenges like changes in inertial properties and actuator redundancy, particularly in self-assembling robotic systems.[27] Unified motion control architectures have also advanced collaborative motion planning for tightly coupled systems, supporting the precise execution of complex tasks.[28] Modular and reconfigurable robotic systems, which are adaptable to mission-specific needs, further enhance the applicability of collaborative approaches in orbital and planetary missions.[29–31]

Autonomy is essential for space robotics to operate independently in environments where communication delays or limited supervision are common.[32,33] Autonomous systems utilize advanced sensing, onboard processing, and decision-making algorithms to navigate and adapt to unstructured and unpredictable environments.[34–36] Techniques such as reinforcement learning allow robots to adjust to new conditions based on prior interactions, while resilience frameworks ensure reliable operation under unexpected conditions or faults.[37,38] These capabilities are particularly relevant for planetary navigation, resource extraction, and autonomous assembly, where direct human intervention is impractical.[7,11]

Transitioning from their advantages, compliant robots also offer significant applications in space missions. The diverse applications of compliant robotics in space missions are visually summarized in **Figure 3**. Compliant robots assist astronauts with daily tasks, emergencies, and scientific experiments. Their flexibility ensures safe and intuitive interactions, enhancing human operations in space. These robots can handle equipment, perform routine inspections, and conduct complex experiments, augmenting the astronaut crew's capabilities and freeing them to focus on critical mission objectives.

In spacecraft maintenance, compliant robots' adaptability allows them to perform delicate and complex repairs. They can navigate confined spaces within spacecraft, conduct detailed inspections, and execute precise maintenance tasks, ensuring the longevity and functionality of space missions. This reduces the need for risky and resource-intensive human extravehicular activities. The lightweight and compact design of these robots also facilitates their transport and deployment in space missions.

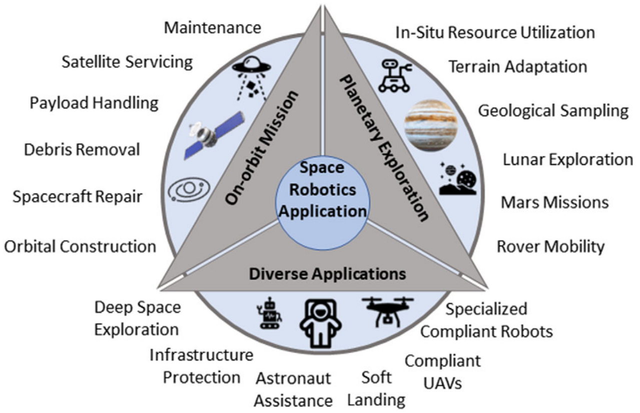

Figure 3. Specific applications of compliant robotics categorized by mission types and operational roles in space exploration.

For sample collection and surface exploration, compliant robots are highly effective due to their ability to adapt to various terrains. They can traverse challenging landscapes, access previously unreachable areas, and collect and analyze samples from planetary surfaces, including lunar and Martian soil. Additionally, compliant robots can contribute to space infrastructure protection and deep-space exploration, highlighting their versatility and important role across a broad spectrum of space applications.

1.3. Literature Review

The field of compliant robotics for space exploration has seen numerous insightful studies across various topics. While many studies have focused on rigid robotics for space applications,[39–41] there is a growing body of research exploring the potential of soft and compliant systems in this domain.[42] For instance, potential applications of continuum and hyper-redundant robots in space are discussed in ref. [43]. Modular and reconfigurable space robot systems in orbital and planetary applications are studied in refs. [29,44]. Origami-based technologies for space structure are discussed in ref. [20]. Also, Zhang et al.[45] studied soft space robotics highlighting the development, challenges, and future prospects of soft robots, including pneumatically actuated, hydraulically actuated, and cable-driven systems. An overview of the autonomy and its resilience in pace missions are detailed in refs. [34,37,38]. Furthermore, information integration in robots for space operations is outlined in ref. [46].

In terms of space exploration and manipulation tasks, compliant robots show promising capabilities.[47] Nan et al. focused on the potential of untethered soft robots for future planetary explorations.[48] Papadopoulos et al.[49] addressed aspects of manipulation and capture in space, such as the dynamics of space manipulator systems, satellites equipped with manipulators, and the contact dynamics between manipulator grippers/payloads and targets. A study on active space debris capturing and removal methods, including the challenges of capturing noncooperative targets and avoiding the generation of additional debris, was presented by Shan et al.[50] Further insights into various methods for active space debris removal, including collective, laser-based, and tether-based techniques, were detailed by Mark and Kamath.[51] Jing et al.[52] offered insights into the configuration and manipulation of soft robots for on-orbit servicing tasks. The development status of space robot technology and the relevant space robot on-orbit assembly technology is discussed in ref. [53]. Furthermore, advances in space robots for on-orbit servicing are reviewed in ref. [54].

Despite these valuable contributions, the application of compliant robotics in space remains a complex field with diverse challenges and opportunities. This article distinguishes itself by not only offering a comprehensive review but also focusing on the inherent adaptability, energy efficiency, and lightweight nature of these robots, shedding light on aspects that haven't been deeply explored in the existing literature. It aims to provide a unique perspective on the potential applications, challenges, and future prospects of compliant robotics in space missions.

1.4. Challenges and Opportunities

While compliant robotics offer numerous advantages, they also face significant challenges. These challenges test the robots' capabilities and create opportunities for innovation. **Figure 4** provides a visual representation of the main challenges faced by space robots and the opportunities they present.

One of the primary challenges in space robotics is the harsh and unpredictable environment. Factors such as extreme temperatures, low pressures, high radiation levels, and microgravity present unique difficulties for robotic operation.[55] The materials used to construct compliant robots must withstand these conditions to ensure effective functionality.[22,56–58] Additionally, robots must be durable enough to endure these demanding conditions, and maintaining them in space presents its own set of difficulties.[59,60] The extreme temperatures, radiation, and vacuum of space further challenge the longevity of compliant robots.[45]

The issue of power supply and energy efficiency is another major challenge common to all space missions. Given the long durations and great distances associated with space missions, maintaining an adequate power supply for the robots can be difficult. This scenario highlights the beneficial energy efficiency of compliant robots.[61] Additionally, a high degree of autonomy is essential for robots to navigate, make real-time decisions, and adapt to unforeseen situations without constant human supervision.[32,33,35,36]

Moreover, the flexible and compliant nature of these robots can also present unique challenges. For instance, controlling the movement and behavior of a soft robot can be more complex than controlling a rigid robot due to the infinite degrees of freedom offered by the soft body. Deformable robots, with their reconfigurable and modular designs, also pose challenges in control strategy due to their ability to change shape and configuration. Designing and implementing effective control strategies for these robots is a significant challenge.[62,63]

These challenges drive technological advancements, leading to innovative solutions and new applications. Although compliant robotics is still in its early phases in space exploration, it holds great promise. As research and development in this field

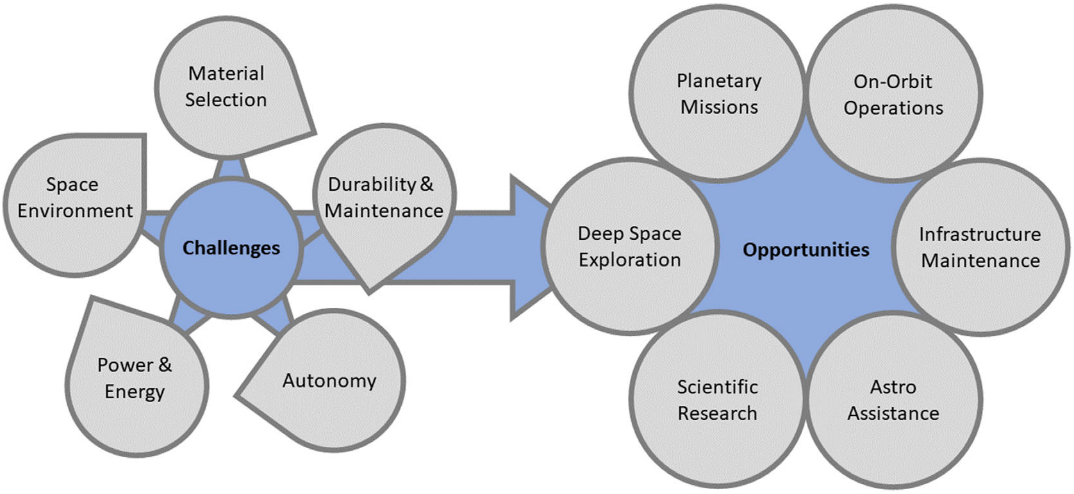

Figure 4. Challenges and opportunities shaping the development of compliant robotics for advanced space missions.

increase, compliant robotics is set to become a key component in the next generation of space exploration. These robots, with their unique adaptability, resilience, and versatility, are well-equipped to handle the various challenges of outer space, potentially improving the capabilities of traditional robotic systems. Their potential roles include intricate on-orbit operations, adaptive planetary missions, and ambitious deep-space explorations. Their skill in maneuvering through difficult terrains, ensuring safe interactions with astronauts, and withstanding the harsh conditions of space emphasizes their importance. Despite significant challenges ahead, ongoing advances in material science, control methodologies, and modular design suggest that compliant robotics could revolutionize future space missions, leading to groundbreaking discoveries and expanding the scope of exploration.

2. Categories of Compliant Robotics for Space

2.1. Overview

Space robotics, as a burgeoning field, encompasses a diverse spectrum of robotic systems, each with unique capabilities and challenges. In this article, we highlight four important categories of compliant robotics that are particularly relevant to space missions: reconfigurable, origami, hyper-redundant, and soft designs. Examples of each of these systems are illustrated in **Figure 5**. These categories provide some of the most promising developments in space robotics, offering distinct advantages and challenges. For a detailed comparison of these different robotic types and their suitability for various space missions, refer to **Table 1**.

Deformable robots, a specialized category within space robotics, are characterized by their adaptability to various missions. Within this domain, we categorize three types, namely reconfigurable, origami, and hyper-redundant robots. Reconfigurable robots offer modularity, redundancy, and mission versatility through interchangeable units.[64–66] Origami robots, with their foldable nature, present solutions for deployment and transportation challenges in space.[67–71] Hyper-redundant robots, integrating elements akin to those found in continuum robotics, distinguished by their significant excess in degrees of freedom, emulate the smooth, flexible motion of biological entities such as snakes and elephant trunks, enabling advanced navigation and maneuverability in complex, unstructured space environments.[43,72] This categorization sets the stage for the exploration in the remainder of this section, focusing on the specific roles, advantages, and challenges of these deformable robots.

This section explores specific categories of compliant robotics. A rich body of literature supports this exploration. An examination of the configuration and manipulation of soft robotics for on-orbit servicing is presented in ref. [52], while untethered soft robotics is the focus of ref. [48]. Insights into soft continuum robots for remote measurement tasks and a comprehensive survey of space robotic technologies for on-orbit assembly are explored in refs. [53,73], respectively. Engineering origami is detailed in ref. [20], while ref. [29] emphasizes the importance of modularity. Achievements and future directions in self-reconfigurable modular robotic systems are outlined in ref. [44], and ref. [74] offers a perspective on these vital characteristics. Together, these works provide a comprehensive view of the current trends and innovations in the dynamic field of space robotics, setting the stage for detailed exploration in the following subsections.

2.2. Deformable Robots

Deformable robotics encompasses a broad and innovative domain within space robotics, presenting versatile solutions to the ever-changing and unpredictable challenges encountered in space missions. Unlike traditional robots, these systems are composed of individual robotic units capable of altering their configuration, thereby transforming their form and function to meet specific needs. This adaptability and the ability to reconfigure enable them to perform a wide range of tasks, often eliminating the need for multiple specialized robots. The intrinsic flexibility of deformable robots not only enhances mission

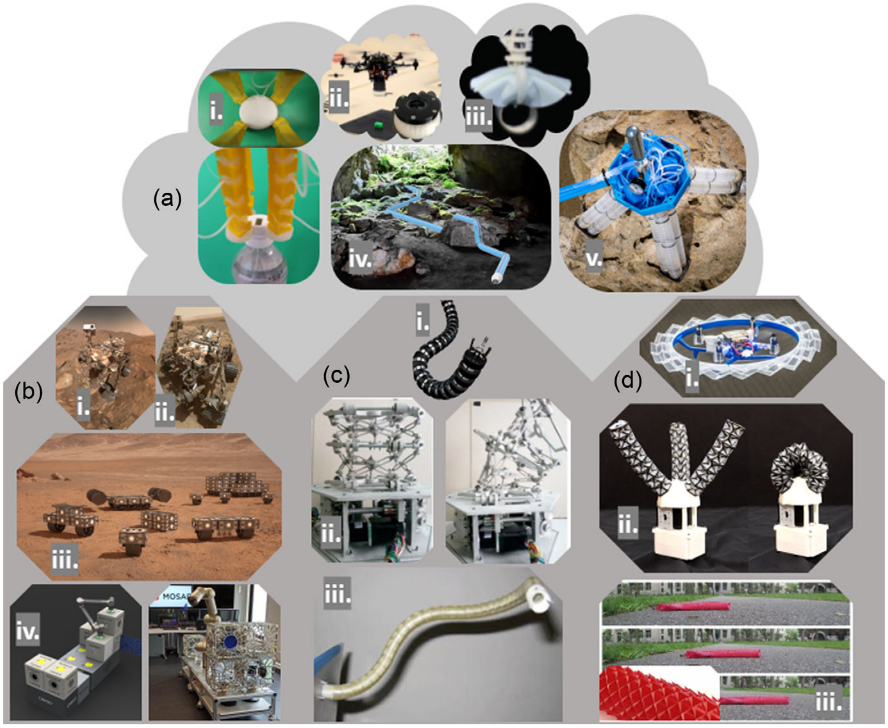

Figure 5. Examples of soft, reconfigurable, hyper-redundant, and origami robotics with potential for space implementations. a) Soft robot; i) Topology optimized bending-twisting soft gripper. Reproduced with permission.[217] Copyright 2022 ASME. ii) TRIGGER: A soft universal jamming gripper for aerial grasping. Reproduced under the terms of the CC-BY-4.0 license.[130] Copyright 2023, IEEE. iii) Octopus-Inspired Soft Robotic Gripper. Reproduced under the terms of the CC-BY license.[386] Copyright 2024, Research. iv) Soft growth navigating robot. Reproduced under the terms of the CC-BY license.[387] Copyright 2021, Research. v) A soft quadruped robot utilizing pressurized air for walking. Reproduced under the terms of the CC-BY license.[388] Copyright 2021, AAAS. b) Reconfigurable modular robot; i) NASA's Mars Curiosity rover,[389] NASA, public domain. ii) NASA's Mars Perseverance rover.[385] Copyright NASA, public domain. iii) Hassell and Eckersley O'Callaghan Mars habitat concept, NASA 3D printing centennial Challenge, 2018.[390] Copyright NASA and Hassell and Eckersley O'Callaghan, publicly available. iv) MOSAR modular satellite reconfigurable space applications services NV/SA concept.[330] Copyright 2020 MOSAR, publicly available under EU Horizon 2020 Project guidelines. c) Hyper-redundant robot; i) A tendon-driven continuum robot. Reproduced under the terms of the CC-BY license.[391] Copyright 2020, Frontiers. ii) Continuous robot designed for non-cooperative target capture in initial contraction state (left) and ultimate bending state (right). Reproduced under the terms of the CC-BY license.[392] Copyright 2021, MDPI. iii) Hyper-redundant articulated robotic medical probe.[393] Reproduced under the terms of the CC-BY license. Copyright 2006, NCBI. d) Origami robot; i) Rotorigami.[366] Reproduced under the terms of the CC-BY license. Copyright 2018, AAAS. ii) Underactuated origami-based robotic gripper with fully open (left) and closed (right) fingers. Reproduced under the terms of the CC-BY license.[394] Copyright 2020, IEEE. iii) Soft crawling robot with kirigami skin.Reproduced under the terms of the CC-BY license.[395] Copyright 2018, AAAS.

success rates but also contributes to greater efficiency and resource optimization in space exploration and operation.

However, these advantages come with inherent challenges. Deformable robots are often constructed from hard or semihard materials, giving them structural stability and durability. The joints and actuators, on the other hand, may be made from softer materials, allowing for flexibility in movement. Balancing these material properties to achieve the desired functionality and performance in the harsh space environment can be complex. The design, control, and stability of these systems present additional challenges that must be addressed to fully realize their potential in space applications.

2.2.1. Reconfigurable Robots

Reconfigurable robots, an important part of deformable robotic systems, consist of multiple identical or heterogeneous units called modules. Unlike traditional robotic systems, these modules can operate independently, communicate with each other, and connect or disconnect, transforming the robot's overall form.[64,66,75,76] This reconfigurability, classified into structural, functional, and hybrid modularity, offers unique advantages in space applications.[29,74]

The technology considerations for implementing modularity in space robotics encompass design principles like commonality, standardization, and scalability; manufacturing techniques from traditional machining to additive manufacturing; system architectures affecting functionality, flexibility, and robustness; and rigorous testing methodologies.[77–79] These considerations ensure adaptability, efficiency, fabrication of complex components, reliable performance in the harsh space environment, and compatibility with space standards. Together, they underline the potential and challenges of reconfigurable and modular robots in future space exploration and operation.[29]

Table 1. Overview of robotic types in space exploration.

Robotic Type	Description and characterization	Key advantages	Challenges	Applications
Soft	Composed of highly compliant materials, safe interaction, damage resilience. Mimics biological systems for grasping, manipulation, and locomotion.	Safety, high adaptability to varying conditions, efficient locomotion, enhanced grasping capabilities.	Control complexity, durability in space conditions, achieving variable stiffness.	Astronaut interaction, debris capture, volatile environment exploration, rugged terrains.
Reconfigurable	Composed of independent and reconfigurable modules, high adaptability. Autonomy, structural, functional, and hybrid modularity.	Scalability, versatility, redundancy.	Control complexity, communication challenges, stability concerns.	Swarm robotics, large-scale exploration, crevice exploration.
Hyper redundant	Inspired by biological systems, offers high flexibility and adaptability. Extensive range of motion, maneuverability.	Excellent conformability, confined space accessibility.	Complex control systems, material constraints.	Tight space exploration, manipulation tasks, soil sampling.
Origami	Utilizes principles of Japanese paper folding, lightweight, compact, adaptable. Kirigami principles for complex transformations.	High portability, reconfigurability, simplicity, compact and lightweight for transportation.	Material selection, precise actuation, complex folding patterns.	Compact transport, variable environment exploration, deployable structures.
Rigid	Traditional form of robotics, featuring predefined shapes and hard materials. Characterized by strength, durability, and limited flexibility.	High load-bearing capability, predictable behavior.	Lack of adaptability, heavy weight.	Exploration rovers, robotic arms for space stations.

In space missions, reconfigurable modular robots provide a resilient solution to the risk of mission-wide failure from a single complex robot.[55] They offer redundancy, coupled with their self-reconfigurable nature, allowing them to adapt to diverse mission requirements. For example, the same set of modules can be reorganized into various forms for planetary exploration, manipulation tasks, or crevice exploration, fulfilling multiple roles with a single set of components.[80,81]

Additionally, reconfigurable modular robots offer cost-effective, scalable solutions, suitable for tasks ranging from detailed inspections to large-scale construction in space.[55,82] The autonomy of such robots is important in space missions, enhancing adaptability and resilience, and enabling real-time response to changes. This autonomy allows individual modules to act collaboratively, though achieving it requires sophisticated algorithms and robust communication, adding complexity.

However, substantial challenges persist. As the number of modules increases, the control complexity increases, complicating coordination, communication, and cooperation. The variable stability of these systems, due to their ability to morph, can also be concerning in the microgravity environment of space. These challenges must be balanced with flexibility and stability to fully leverage the potential of reconfigurable and modular robots in space applications.

2.2.2. Origami Robots

Origami robots present a unique solution to some of the most challenging problems in space robotics, particularly regarding deployment and transportation.[83,84] Origami, the traditional Japanese art of paper folding, has been adapted into engineering designs that can transform their shape through folding and unfolding processes. When a spacecraft launches, every cubic centimeter and kilogram matter. Origami robots, with their ability to fold into compact forms for launch and then unfold in space, dramatically reduce the space and weight requirements.[68]

The possibilities are virtually limitless when it comes to the shapes and functionalities that origami robots can assume. In the design process, a variety of methods, such as mathematical modeling, simulation, and optimization, are employed to create intricate folding patterns and mechanisms.[85–87] These design methods are supported by advanced computational tools, including CAD software and simulation platforms, that allow for the accurate analysis and visualization of folding processes.[20] They can morph into antenna arrays, solar panels, or reflectors; reconfigure to form manipulators or rover-like structures for scientific exploration;[88] or fold into tiny shapes for passing through confined spaces, such as the interiors of a comet or asteroid.[19] The morphable nature of these robots can thus support a diverse range of scientific missions and payloads, enhancing the versatility and productivity of space missions.[89]

Furthermore, the principles of origami are being applied to develop innovative mechanisms that may be tailored to withstand the extreme environment of space.[90] These mechanisms often require fewer parts, resulting in simpler, more reliable, and more cost-effective systems. For instance, origami-inspired techniques are used to design deployable structures like booms and solar arrays that are lightweight, compact for launch, and capable of deploying reliably in space.[91,92]

Typical origami robots can be further improved for space missions by optimizing factors such as the selection of materials that can endure space conditions, customizing folding patterns and mechanisms to suit specific mission needs, and integrating control algorithms capable of managing variable morphologies.[93] These enhancements are guided by established design methods and tools, enabling the creation of origami structures with precise control over folding angles, material properties, and actuation strategies. Additionally, by incorporating kirigami principles, which combine cutting with folding, origami robots could achieve more complex transformations and functionalities, further expanding the versatility of deformable robotics in space applications.[94,95]

Recent advancements in modular origami robotics highlight their potential for space applications.[19,96–99] These robots, utilizing shape memory alloy (SMA) coils for actuation and inertial measurement unit (IMU) sensors for attitude perception, enable untethered operation with wireless charging and support diverse configurations, including crawling robots, robotic arms, and grippers, via magnetic reconfiguration.[100] Modular soft actuators based on triangular prism origami structures further enhance this versatility. By integrating pneumatic actuation and fatigue-resistant crease designs, these actuators achieve rapid response, compound motions, and programmable functionality, supporting tasks such as gripping, navigation, and obstacle avoidance.[101] Hybrid actuators integrating origami-inspired resilient hinges with rigid facets have demonstrated high load-bearing capacity while preserving deformability, promising applications such as multilayered robotic manipulators.[99] Additionally, SMA-driven active origami structures, such as Kapton membranes, offer high packing efficiency and reliable deployment for solar sails, validated through experimental and numerical analyses.[102]

However, challenges persist. A primary challenge lies in developing materials that are both flexible enough to support folding and unfolding processes and durable enough to withstand harsh space environments, while remaining lightweight to meet launch constraints. Moreover, reliable and precise actuation methods for folding and unfolding remain a nontrivial task. Many origami robot designs also require advanced control algorithms to handle the complexities introduced by variable morphologies, which adds another layer of technical challenge to this field.

2.2.3. Hyper-Redundant Robots

Hyper-redundant robots, akin to biological counterparts such as snakes and elephant trunks, possess a level of kinematic redundancy that vastly exceeds the minimum required for basic manipulative tasks. This significant excess in degrees of freedom enables unparalleled adaptability and performance in complex, unstructured environments. By leveraging their extensive kinematic redundancy, hyper-redundant robots offer a new dimension of versatility in space robotics, facilitating movements and operations previously unattainable with traditional hard robots.[103,104] Recent developments have led to various hyper-redundant and continuum robot designs suitable for space applications, ranging from snake-like robots to tentacle-inspired manipulators.[105,106]

The high flexibility of hyper-redundant robots offers significant advantages in the microgravity environment of space because it allows them to maneuver through confined spaces, grasp objects of various shapes, and maintain stability without relying on rigid structures. In addition to on-orbit servicing, hyper-redundant and continuum robots excel in tasks requiring precise control and delicate handling.[107] For instance, these robots have been used to grasp and manipulate objects with complex geometries. In space habitats, they can navigate through cluttered environments and interact with various objects with a level of dexterity and flexibility that traditional robotic arms cannot achieve. Their ability to wrap around or conform to the shape of an object is particularly advantageous for securing items in microgravity, where simple pushing or pulling actions can cause objects to drift or rotate undesirably.

The design of hyper-redundant and continuum robots also allows them to reach into narrow or confined spaces, making them ideal for inspection tasks in spacecraft where traditional robots may not be able to reach.[108,109] These capabilities have been further extended through the use of magnetic resonance imaging compatible continuum robots, enabling precise positioning and navigation in constrained environments.[110,111] Furthermore, their inherent safety due to their soft and compliant structure makes them highly suitable for close interaction with astronauts.

Their bioinspired design and movement principles also mean that they can potentially navigate and traverse planetary surfaces in ways traditional rovers cannot. This includes the ability to navigate through narrow gaps, moving through rough or slippery terrains, or even climbing vertical surfaces. Particularly, the application of hyper-redundant and continuum robots in space exploration has been extended to areas such as autonomous soil sampling, where their flexible design enables penetration into diverse soil types.[109]

However, the complexity of hyper-redundant robot designs comes with significant challenges. The high degrees of freedom make them difficult to model and control, requiring sophisticated algorithms and computation.[112–115] Recent advancements in design methods have focused on optimizing the balance between flexibility and stability, considering factors such as bending stiffness and load capacity.[43,116] Emerging research also emphasizes the importance of energy efficiency in the design of hyper-redundant and continuum robots, contributing to their sustainability and functional longevity.[104] Furthermore, there are challenges associated with the design and integration of flexible actuators and sensors that can withstand the harsh space environment, retain their functionality over extended periods, and deliver the required level of precision and reliability.[117] The exploration of suitable materials and fabrication methods that can ensure the required levels of durability, flexibility, and lightweight attributes for these robots is essential. Despite these challenges, the unique advantages offered by hyper-redundant robots promise exciting new possibilities for their application in space missions.

2.3. Soft Robots

Soft robotics is a rapidly advancing field that fundamentally challenges the traditional notions of robots as hard, metallic machines. By incorporating soft and often compliant materials into their construction, soft robots exhibit a level of adaptability and safety that is hard to achieve with conventional robotic systems.[118–122]

The main advantage of soft robots lies in their high compliance, which results in inherently safe interactions with humans and their surroundings.[123,124] This property can be extremely beneficial in space, where robots and astronauts often share the same workspace. For instance, in the confined environment of a space station, the risk of accidental impacts is high, and a soft robot could mitigate the potential for harm in these scenarios.[45,125]

Furthermore, their inherent deformability enables soft robots to adapt their shape to a wide variety of tasks. This adaptability can be extremely beneficial in space, where the conditions are unpredictable, and the tasks can be diverse. Soft robots can be designed to mimic biological systems, offering innovative solutions for grasping, manipulation, and locomotion in space applications.[126–128] For example, a soft robotic gripper can conform to the shape of an object to grasp it securely, which is particularly useful in the microgravity of space where objects can easily drift away.[129] The universality in grasping, where the shape of the object or the orientation of the gripper is not critically important, further enhances the utility of soft robots in space. This approach has shown promise in terrestrial applications and holds great potential for future space missions.[130,131]

Their lightweight and flexible designs also make them suitable for tasks such as capturing space debris or exploration of extraterrestrial bodies.[132] Soft robots, inspired by biological creatures, can crawl,[133,134] slither,[135,136] or roll,[137] providing efficient locomotion strategies in challenging terrains, including the rugged, uneven landscapes of other planets or moons.[48,138]

Despite these significant benefits, soft robots also face considerable challenges, especially for space applications. One of the primary challenges is the control of these highly compliant systems. The traditional control algorithms used in rigid robotics often cannot be applied to soft robots due to their continuous deformation and high degrees of freedom. Developing robust, reliable, and efficient control strategies for soft space robots is, therefore, a significant area of research. Moreover, the materials used in soft robots often lack the durability required for space missions, making them vulnerable to harsh environmental conditions, such as extreme temperatures and radiation.[139] In addition, achieving variable stiffness—a trait desirable for many space tasks—is a significant challenge, necessitating the exploration of advanced materials and actuation strategies.[140,141]

Regardless of these challenges, the potential of soft robots in space is only beginning to be realized.[45,142] Ongoing research and development efforts focus on overcoming these barriers, promising exciting new capabilities for future space missions. Their unique advantages could revolutionize space robotics, expanding our abilities for space exploration, infrastructure development, and scientific discovery in the years to come.

As we've explored, the categories of compliant robotics provide innovative solutions for the unique challenges of space exploration. These systems are not just novel but are engineered with precise consideration of materials, actuation, and control systems. Yet, these robots don't operate in isolation; their effectiveness is closely tied to the harsh environmental conditions they encounter in space. The following section will explore the complexities of designing these robots to operate efficiently and reliably in the vacuum of space, under thermal extremes, and in radiation hazards.

3. Design Considerations for Space Robotics

3.1. Space Environment

The space environment, distinct from any earthly setting, presents an intricate variety of challenges for robotics. These challenges are predominantly due to the vacuum of space, the presence of microgravity, a wide range of temperatures, intense radiation, dust, and force fields. In this context, material properties and functionality are critically influenced by the unique conditions of space, particularly shaping the design and operation of compliant robotics which, due to their material composition, may react differently than their rigid counterparts.[143,144] **Figure 6** provides an example of how solar wind interacts with Earth's magnetic field, highlighting the environmental conditions that can affect material properties and the functionality of space robotics.

In space, the lack of atmosphere is a defining feature. This absence results in a vacuum environment, which leads to multiple complications. One such complication is the phenomenon of outgassing, where materials in the robot can release gas in conditions of low pressure or high temperature. Outgassing can affect composite materials like graphite or epoxy, leading to damage to electronic components, sensors, or lenses.[145,146] For soft robots, outgassing may affect the functionality of soft actuators and sensors, with certain compliant materials potentially experiencing degradation or altered performance dynamics in the vacuum of space. Another issue related to the vacuum is cold welding, where mechanical parts can weld together in space due to the absence of a tiny air gap separating them.[147,148] This is particularly challenging for mechanisms that rely on movable parts, and for soft robots that might rely on compliant, layered materials that could be more susceptible to these effects.

Moreover, the absence of an atmosphere in space makes thermal management particularly challenging.[149,150] Unlike on Earth, where heat transfer mechanisms include conduction, convection, and radiation, space relies solely on radiation for heat transfer due to its vacuum nature. When exposed to direct sunlight, spacecraft surfaces can experience temperatures ranging from 97 to 127 °C. In contrast, in the absence of solar radiation, temperatures can plummet to as low as −200 to −150 °C.[151,152] Managing such temperature variations is critical to ensure the operational integrity of space equipment. The lack of an atmospheric medium means traditional convective cooling is nonexistent. As a result, the primary methods of thermal regulation in space are through radiation and conduction between components. This becomes especially crucial for compliant robotics, as changes in temperature can alter the elasticity and functionality of soft materials, with potential effects on their mechanical behavior and longevity.

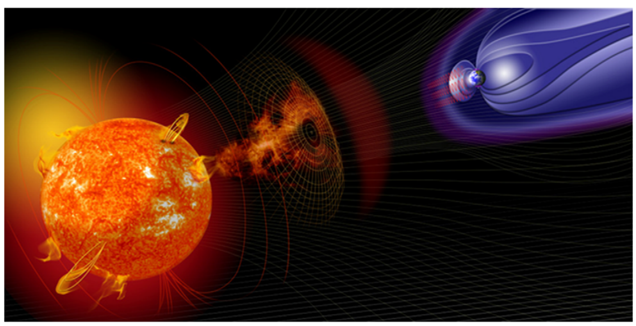

Figure 6. Interaction between solar wind and Earth's magnetic field, illustrating the dynamics of space weather and its impact on the space environment. Image courtesy of NASA.[10]

Furthermore, on celestial bodies like Mars, the surface temperatures vary significantly, averaging between −80 and 0 °C. Such cold environments necessitate the use of heating mechanisms, especially for exterior components like actuators and cameras, to prevent them from freezing.[45] This highlights the importance of thermal management in ensuring the continued functionality of space robots, particularly those made of soft, compliant materials.[153,154]

Microgravity is a significant characteristic of space environments. When considering Earth orbiters, their perceived gravity is a combination of gravitational pull and the forces resulting from their motion. This combined effect means that spacecraft don't experience complete weightlessness; instead, they operate in a microgravity state. This nuanced difference between terrestrial and space conditions leads to varying mechanical behaviors for robots. As many space robots are developed and tested on Earth but operate in space, there's a challenge in ensuring that their models and controls align with both environments. Additionally, in space, the absence of atmospheric resistance means that even minimal forces can cause pronounced changes in the motion of equipment.[155]

Radiation poses a significant challenge in space, far surpassing its effects on Earth.[156] The sources of space radiation are multifaceted. They include X-rays, β-rays, γ-rays, and high-energy particles such as protons, neutrons, electrons, and muons.[157,158] The primary contributors to space radiation in Earth's orbit are Earth radiation belts, solar cosmic rays, and galactic cosmic rays.[159,160] Without the protective shield of a geomagnetic field, high-energy radiation can deeply penetrate space equipment, including compliant robots. While semiconductor components in traditional robots might be disrupted, soft materials, particularly those not tailored for radiation resistance, could degrade rapidly. The Van Allen radiation belts induce effects like charging and sputtering that can adversely affect both electronics and materials. Given these concerns, the selection of radiation-resistant materials, especially those with low atomic mass, becomes very important for compliant space robotics, particularly for components such as actuators and sensors.[161]

Tying back to the advantages of compliant robotics, their adaptive nature allows them to potentially mitigate some of the challenges posed by foreign objects and environmental conditions. For instance, while a rigid robot might suffer structural damage from space dust impacts, a soft robot could deform and absorb the impact without significant damage. This adaptability is particularly important for missions like Chandrayaan-3, which landed near the Moon's south pole—a region characterized by a highland type of soil.[162–164] Also, managing the impact of space dust is crucial for the longevity and effectiveness of the mission's rover and scientific instruments. Unlike Earth's atmosphere, where gravity and weather can settle dust particles, space dust can remain suspended and travel at high speeds. Therefore, the design of robotic systems for such missions must account for these unique challenges, further emphasizing the importance of compliant robotics in space applications.

Space robotics must navigate complex force fields, including gravitational and magnetic fields exerted by celestial bodies. The gravitational force can be represented as $F = \frac{G \times m_1 \times m_2}{r^2}$, where G is the gravitational gain, m_1 and m_2 are the masses of the bodies, and r is the distance between their centers. Soft robots, with their adaptable and modular designs, may have an advantage in navigating these force fields compared to their rigid counterparts. For instance, a soft robot designed for magnetic actuation might adjust its shape and orientation more effectively in a magnetic field than a rigid robot. Recognizing these fields is essential for robots that depend on magnetic actuation or sensors, as they can influence the robot's ability to change shape and respond to external forces. Gravitational forces can fluctuate considerably between different planets and moons, impacting mobility, stability, and energy consumption, with direct implications for the design and performance of compliant systems. Meanwhile, magnetic fields can influence sensors, actuators, and other magnet-sensitive components, necessitating cautious consideration.

Table 2 provides an overview of the key environmental factors in space and their impacts on robotic design.

3.2. Material Selection

Selecting appropriate materials is essential in the design process of robotic systems, significantly impacting performance, survivability, and adaptability to external forces, especially in the harsh conditions of space. This is particularly true for compliant robots, where material properties directly influence their ability to change shape and respond to external conditions. Given the challenges posed by the space environment, detailed in the previous section and summarized in Table 2, it is important to select materials thoughtfully. They must meet the robot's mechanical needs and withstand extreme conditions like varying temperatures, radiation, and vacuum.

The process of material selection in space involves a wide range of factors. These include mechanical properties such as strength, resilience, flexibility, elasticity, and weight, as well as resistance to space environment factors like thermal properties and radiation resistance.[165,166] A hierarchical, performance-based framework has been proposed to optimize the design of multi-fingered soft grippers by balancing material distribution and geometry through parametric and topological optimization techniques, ensuring scalability and task-specific performance.[167] Additional considerations like mass and volume, affecting the cost and feasibility of launch, and practical factors like cost, availability, and machinability of the material, also play an important role in this critical decision-making process.

Moreover, the selection between hard and soft materials can significantly impact the robot's functionality, adaptability, and resilience in the space environment. **Table 3** outlines the typical material choices for key robotic components, including chassis, actuators, sensors, and gears, along with justifications based on their properties and functionalities. This thoughtful selection is important in optimizing performance in various space missions.

The material choice for a compliant robot depends on the specific type of robot and the unique challenges posed by the space environment. For soft robots, materials must exhibit high elasticity and flexibility, commonly achieved through the use of silicone elastomers, thermoplastic elastomers, and shape

Table 2. Environmental factors in space and their impacts on compliant robotic design.

Factor	Impact	Considerations for compliant robotic design
Vacuum	Material degradation, outgassing, cold welding, altered heat transfer.	Use materials resistant to vacuum effects. Consider potential for outgassing and cold welding in design. Incorporate radiative or conductive thermal regulation systems for soft components.
Extreme temperatures	Expansion and contraction of materials, potential thermal shock, degradation of soft material properties, significant temperature swings.	Use soft materials with controlled thermal properties. Incorporate thermal management systems, thermal blankets, and insulation to moderate temperature swings.
Microgravity	Altered mechanical dynamics, reduced gravity effects, precise control challenges.	Design compliant systems for microgravity. Develop control algorithms considering altered dynamics. Implement anchoring techniques for manipulation and consider gravitational variations between celestial bodies.
Radiation	Damage to electronic systems, degradation of material properties, high-energy particle effects.	Incorporate radiation shielding in design, select soft materials resistant to radiation damage. Utilize low atomic mass materials for shielding. Implement fault tolerance in software to mitigate the impact of single event upsets.
Dust (planetary surfaces)	Mechanical wear, optical interference, contamination of instruments, high-speed impact.	Design dust-resistant compliant systems, use protective coatings, and specialized cleaning mechanisms. Consider effects on adaptive capabilities and interactions with external forces.
Force fields	Influence of gravitational and magnetic fields on navigation, sensing, and actuation.	Navigate complex force fields, understanding variations in gravitational forces. Shield and calibrate magnetic-sensitive parts. Consider implications for compliant systems' sensitivity and adaptability.

Table 3. Material selection for different space robotic components: hard versus soft materials.

Component	Material type	Justification
Chassis	Hard (aluminum alloys, titanium alloys)	Chosen for their strength and durability, providing a rigid structure suitable for carrying payloads and withstanding external forces.
–	Soft (silicone elastomers, thermoplastic elastomers)	Selected for flexibility and adaptability to changing shapes, allowing the chassis to conform to uneven terrains or dynamic payloads.
Actuators	Hard (copper, iron, high-strength alloys)	Used in traditional actuator designs for their magnetic and conductive properties, providing robust force transmission and control.
–	Soft (shape memory alloys, pneumatic artificial muscles)	Employed in flexible actuators for their ability to deform and return to their original shape, enabling adaptive and gentle interactions.
Sensors	Hard (silicon for electronic sensors)	Utilized in traditional electronic sensors for their rigidity and stability, offering precise measurements and reliable data acquisition.
–	Soft (polymeric materials for flexible sensors)	Used in flexible, stretchable sensors for their compliance, allowing integration with soft robotic structures and real-time adaptation to environmental changes.
Gears	Hard (steel, brass)	Chosen in traditional gear systems for their durability and resistance to wear, ensuring reliable mechanical transmission.
–	Soft (polymer gears, e.g., nylon)	Employed in compliant systems to reduce weight and noise, allowing for smoother operation and energy efficiency.

memory alloys.[168] These materials not only deform significantly but also return to their original shape upon force removal, offering advantages in damage resistance.[169–171] To ensure long-term reliability in space environments, materials for soft robots must balance adaptability, functionality, and self-healing capabilities. Potential candidates include liquid metals, temperature-resistant elastomers, and smart nanostructured protective coatings, which offer solutions for extreme conditions like radiation and microgravity.[172–175] These advanced materials are particularly suitable for elastic inflatable actuators, antennas, and other critical components in soft robotics for space missions.

However, the intrinsic complexities of soft materials, such as their strong nonlinearity, pose challenges in modeling and design.[123] While soft materials provide unique advantages in flexibility and adaptability, they are generally less tolerant of harsh space conditions like extreme temperatures and radiation.[176] Long-term stability in a space environment, where repair or replacement is often impractical, becomes an essential criterion in material selection.[177] This need for durability requires strict online tests and verification procedures to ensure consistent reliability.

In the case of reconfigurable and deformable robots, materials should be rigid yet deformable, often involving shape memory alloys or flexible plastics. The choice here depends on the robot's specific design and shape-changing mechanisms.[178] Contrastingly, conventional rigid robots, although less frequent in space-compliant robotics, might opt for metals, composites, or rigid plastics. These materials offer high strength and rigidity but can be more susceptible to environmental damage.

Given the variability of space environments, including microgravity and extreme temperatures, materials must also meet specific actuation requirements.[179,180] For instance, light, heat, or magnetic actuation might be considered for missions requiring remote control, while chemically actuated materials could be suitable for extreme planetary conditions.[181,182]

Overall, the material selection for compliant space robots is a multifaceted process. It requires balancing mechanical properties, environmental resilience, and actuation methods, all while keeping in mind the high cost and energy constraints of space missions. Hence, material selection remains a critical aspect of space robotics design and development, demanding comprehensive and systematic protective measures.[183–187]

3.3. Other Specific Requirements for Space Robotics

In addition to the challenges imposed by the space environment and material selection, space robotics must also cater to other mission-specific requirements that are fundamental for successful operation.

3.3.1. Resilience

Owing to the remoteness of space and the specific conditions of vacuum, temperature extremes, and radiation, the resilience of space robots becomes a critical aspect of their design. They need to exhibit high robustness and reliability, capable of functioning efficiently over long durations, with an emphasis on self-repair mechanisms, material tolerance to extreme conditions, and safety protocols to ensure continued functionality and human safety. This demands not only strong design and construction but also the incorporation of fault-tolerant systems and software that can anticipate, withstand, and recover from faults.[38,188,189] Furthermore, technologies such as redundant systems, fault-tolerant algorithms, adaptive materials, and self-healing mechanisms are being developed to enhance resilience.[188,190–194] This enhances the resilience of space robots, making them robust and capable of enduring and recovering from the extreme conditions of space.

3.3.2. Integrated Intelligence

Integrated intelligence in space robotics encompasses a blend of technologies that enable robots to exhibit some cognitive abilities found in human intelligence.[195,196] This fusion involves machine learning, deep learning, natural language processing, computer vision, sensor observation, intelligent control, and more.[197] The goal is to create a robotic system that can perceive its environment, analyze data, make decisions, and perform tasks autonomously.[198,199] Smart materials are integral to this integration, providing robots with the ability to move and adapt independently to various space tasks. Shape memory alloys, responsive polymers, and other adaptive materials enable robots to change shape, orientation, and functionality based on environmental stimuli.[200–203] These materials and intelligent technologies collectively offer unprecedented flexibility and adaptability, making space robots more capable and versatile.

3.3.3. Autonomy

The communication lag coupled with the requirement for robots to operate in remote or inaccessible locations necessitates a high degree of autonomy in space robots. This specific need for autonomy in space is driven by unique challenges such as significant communication delays in deep space missions, rendering real-time control impractical.[204] Therefore, space robots must be adept not only at executing preplanned tasks but also at responding to unexpected situations or changes in the environment without Earth-based intervention.[205,206] The remote and vast nature of space makes it crucial for robotic systems to be capable of high autonomy. Therefore, space robots need to be designed to carry out complex tasks with little to no human intervention. These tasks may include decision-making processes based on sensor data, self-diagnosis and repair capabilities, and adaptive strategies to deal with unexpected scenarios.[34,207–210]

3.3.4. Weight and Volume Constraints

The design of space robots also needs to accommodate the requirements of launch. Robots should be lightweight and compact, given the high costs associated with launching mass into space, and the limited space available on board the spacecraft. Reconfigurable, origami and kirigami designs offer innovative solutions, enabling lightweight and foldable structures that can be expanded or reconfigured in space, thus optimizing both weight and volume constraints.[211]

3.3.5. Limited Energy

Robots should also be energy efficient, considering the limited availability of energy resources in space.[212,213] For example, Chandrayaan-3, like many other space missions, relies on solar power, making energy management a critical aspect of its design. The mission's timing to coincide with the lunar daylight maximizes its operational lifetime, underscoring the importance of energy-efficient design in space robotics. The power systems of the robots must be designed to endure for the intended mission duration, with solar power often used as a primary energy source.[143]

3.3.6. Reliability and Redundancy

Given the extreme difficulty and exorbitant costs associated with servicing or repairing systems in space, space robotics must be highly reliable. Redundancies for critical systems must be included to ensure continued functionality in case of primary system failure. Soft and reconfigurable designs provide excellent options for redundancy, as individual modules can be replaced, and astronauts may repair or even fabricate soft parts, enhancing the system's overall resilience.

3.3.7. Human–Robot Interaction

For robots intended to work alongside human crew members, there are additional safety requirements. These robots should be safe to interact with, necessitating compliant design and careful control of movements. They should also be intuitive to use and potentially capable of learning from their interactions with humans. Soft and compliant robots offer a safer interaction interface, reducing the risk of injury and facilitating cooperative tasks with human crew members.[24,214]

These requirements, while stringent, also represent potential avenues for innovation. The need for autonomy, for example, is driving advances in artificial intelligence and machine learning. Similarly, the demand for lightweight and compact design is encouraging advancements in miniaturization and the development of new materials. Thus, the challenges posed by space exploration are not only being met but are also driving significant advances in robotics and related fields.

Having laid out the intricate design considerations essential for the development of space robotics, what follows is a natural extension that explores how these conceptual designs are translated into functional systems. The journey from concept to operation is a multifaceted process that leverages these design principles, incorporating other crucial elements such as actuation, control, and sensing into the mix. The next section provides a structured framework covering this end-to-end development lifecycle, aiming to furnish a comprehensive understanding of both the theoretical and practical aspects involved in deploying compliant robotics for space missions.

Adapting robotic systems to space missions requires a holistic framework that incorporates both environmental constraints and mission-specific requirements. This involves designing robots that balance trade-offs between weight and durability, ensuring energy efficiency through advanced architectures, and integrating fault-tolerant systems to handle unforeseen challenges. Materials must not only be robust against radiation, vacuum conditions, and extreme temperatures but also maintain compliance and adaptability for various tasks. By combining innovative designs with energy-efficient technologies, space robots can enhance their operational lifespan and reliability, meeting the demands of complex missions while minimizing resource constraints.[34,206,212]

4. From Concept to Operation: Functional Aspects of Compliant Robotics

The development and deployment of compliant robotics for space missions encompass a comprehensive and systematic process. This process spans multiple stages, including concept definition, design and fabrication, actuation, sensing, control, and operational deployment. Each stage addresses unique challenges and considerations specific to the harsh conditions of space, such as material selection for durability, advanced sensing for environmental adaptability, and robust control for autonomy. Insights from previous sections are integrated to ensure these systems meet the demanding requirements of space missions. **Table 4** provides a structured summary of these lifecycle stages, aligning the methodologies and outcomes with the broader discussion in this section.

4.1. Concept

The conceptual stage forms the foundation of the development process. It encompasses visioning, objective setting, and mission planning. During this phase, the high-level goals and strategic outcomes of the robot are defined. This includes determining its functional requirements, environmental considerations (such as specific space conditions), and the desired impact on space missions. For soft and deformable robotics in space, this may include considerations like adaptability, deformability, and modularity. Feasibility analysis is also crucial at this stage to ensure alignment with technological capabilities, budget constraints, and the overarching mission objectives.

4.2. Design and Fabrication

Design and fabrication, often likened to the "skeleton and muscles" of a robotic system, serve as the critical backbone in the development of compliant robotics. This stage is a multistep process encompassing blueprint creation, modeling, material and structure selection, prototyping, assembly, and quality control.[123,215] This becomes particularly crucial for space-compliant robotics. Here, material and design choices must be meticulously evaluated to ensure the system's flexibility, compliance, and adaptability, while also adhering to weight and size constraints for efficient space transportation.[216]

Blueprint creation marks the inception, where a conceptual idea is given tangible structure and form. This involves comprehensive planning and design, factoring in the system's objectives, capabilities, functional elements, power requirements, sensory apparatus, and control mechanisms. Topology optimization can come into play at this stage, enabling designers to create structures that optimize performance under given constraints, including weight and size—factors that are exceptionally vital in the space domain.[217,218] The utility of computer-aided design (CAD) tools is indispensable here, providing the precision and adaptability needed for iterative design improvements.[219]

Modeling is another cornerstone in the design and fabrication process. It involves generating mathematical and computational models to simulate the system's behavior under various conditions, from physical properties like elasticity and deformation to dynamic behavior such as motion and environmental interaction. Given the nonlinear and highly variable nature of materials used in space-compliant robotics, advanced modeling techniques are crucial for predicting and optimizing robot performance in space missions. Both model-based approaches, which rely on detailed mathematical representations of the system, and model-free approaches, which use data-driven methods to learn system behavior without explicit models, play significant roles in this context. Model-based techniques provide precise control and prediction capabilities, while model-free methods, such as reinforcement learning, offer flexibility in adapting to complex and unpredictable environments.[220,221]

Material and structure selection is the stage where the robot's physical architecture is defined. Here, materials are chosen based on a range of factors such as durability, weight, flexibility, and thermal and radiation resistance. The choices are highly

Table 4. Key lifecycle stages in the development of compliant robotics for space missions, highlighting actions, technologies, challenges, and outcomes.

Lifecycle stage	Key actions/focus	Techniques and technologies	Key challenges and considerations	Space mission contributions	Outcomes and deliverables
Concept	• Define mission objectives and robotic vision.	• Advanced AI for mission planning.	• Balancing modularity, adaptability, and complexity.	• Establishes mission-specific design criteria (e.g., radiation tolerance).	• Feasibility studies for adaptable robotic designs.
	• Conduct feasibility studies for modularity and adaptability.	• Payload and environment-specific analysis.	• Addressing budgetary and technological constraints.	• Lays foundation for adaptable, long-duration missions.	• Initial concept designs tailored to mission objectives.
	• Perform high-level system requirements analysis.	• Preliminary concepts for deformable/modular systems.	• Aligning goals with harsh environmental conditions.	• Identifies critical requirements for planetary and orbital tasks.	• Strategic roadmap for subsequent stages.
Design and fabrication	• Select materials and create structural designs.	• Smart materials for thermal/radiation resistance.	• Achieving compliance without sacrificing durability.	• Optimizes designs for efficient transport and deployment.	• Prototypes of lightweight, compliant systems.
	• Perform topology optimization and CAD modeling.	• Additive manufacturing for lightweight designs.	• Meeting weight and size constraints for launch.	• Facilitates in-orbit manufacturing capabilities.	• Fully validated designs ready for manufacturing.
	• Conduct iterative prototyping and compliance testing.	• AI-assisted rapid prototyping tools.	• Ensuring material resilience in extreme conditions.	• Supports versatile applications for planetary exploration.	• Enhanced material libraries for space applications.
Sensing	• Integrate multimodal sensors (e.g., LiDAR, tactile, vision).	• Stretchable sensors for soft robotic feedback.	• Overcoming sensor degradation in radiation and vacuum.	• Enhances environmental perception and navigation.	• High-accuracy sensors tailored for space missions.
	• Ensure real-time environmental data collection.	• High-resolution imaging systems. • Advanced sensor fusion algorithms.	• Ensuring reliable operation in dynamic conditions.	• Supports detailed planetary mapping and resource analysis.	• Comprehensive environmental datasets.
Actuation	• Select actuators (e.g., SMAs, EAPs, pneumatic, motors).	• Shape-memory alloys and electroactive polymers.	• Ensuring precision under microgravity conditions.	• Enables adaptive locomotion on planetary surfaces.	• Actuation systems tailored to specific tasks.
	• Develop modular and hybrid actuation mechanisms.	• Pneumatic systems for soft robotics.	• Designing actuators for resilience in harsh environments.	• Supports complex manipulation tasks in low-gravity settings.	• Modular actuators for versatile deployment.
	• Optimize energy source integration.	• Energy-efficient actuation for extended missions.	• Achieving energy efficiency for long-duration missions.	• Facilitates energy-efficient operation for extended missions.	• Enhanced actuator designs for robust operations.
Control	• Develop strategies for nonlinear and adaptive control.	• AI-based real-time control algorithms.	• Managing latency in deep space operations.	• Enables real-time adaptability for planetary exploration.	• Advanced control frameworks for diverse missions.
	• Implement autonomous and distributed control systems.	• Distributed control for swarm robotics. • Fault-tolerant systems for autonomous operation.	• Ensuring robustness in high-dimensional environments. • Handling communication delays and system failures.	• Enhances mission reliability through autonomous systems. • Facilitates precise navigation and task execution.	• Autonomous systems capable of handling dynamic environments.
Operation	• Deploy, monitor, and maintain robotic systems.	• Fault-tolerant mechanisms for operational reliability.	• Ensuring reliability and safety with minimal human intervention.	• Prolong mission lifetimes through autonomous maintenance.	• Fully operational robotic systems for diverse tasks.
	• Conduct performance evaluations and iterative optimization.	• Autonomous repair techniques for in-orbit servicing.	• Addressing challenges in recycling and disposal of systems.	• Reduces costs via reusable systems and fault tolerance.	• Reliable maintenance protocols for extended missions.
	• Plan end-of-life management strategies.	• Modular designs for streamlined maintenance.		• Addresses sustainability with end-of-life solutions.	• Sustainable practices for long-term space exploration.

mission-specific and are fine-tuned to meet the unique environmental conditions of space.[57,222,223] These considerations were discussed in detail in Section 3.

Emerging trends in orbital manufacturing influence these choices, steering the design of space robotics toward in-space manufacturing techniques like hybrid additive manufacturing.[224,225] This development is leading to designs that are modular and adaptable, suitable for assembly or alteration in orbit, which aligns well with the evolving logistics of space missions.[226–228] Additionally, advancements in volumetric additive manufacturing offer new methods for creating complex parts in microgravity environments, enhancing the potential for manufacturing and assembly capabilities in space.[229–231]

Emerging fabrication methods such as 4D printing and lamination manufacturing are facilitating advancements in more adaptable and reliable soft robotics in space. 4D printing integrates time as a dimension, enabling structures to achieve programmable deformations in response to external stimuli, such as temperature changes, which is particularly beneficial for dynamic space environments.[232,233] Lamination manufacturing offers the potential to create articulated, self-folding structures that are lightweight and capable of adapting to diverse terrains, as demonstrated in Mars mission prototypes.[234,235] These advanced techniques expand the design possibilities for soft robotic components, improving their versatility and functionality in complex space applications.

Prototyping follows, converting theoretical models into functional prototypes. A variety of methods may be employed, such as 3D printing, CNC machining, silicon molding, and laser cutting, suited to the design's complexity and requirements. These prototypes undergo rigorous evaluations to validate their performance under diverse conditions.[236–240] Assembly comes next, where individual components fashioned during the prototyping phase are integrated into a cohesive system. Techniques may range from soldering and welding to modular assembly, depending on the component nature and the overarching design.[241,242] Finally, quality control is imperative for ensuring that the final product meets the initial specifications and can survive the harsh conditions of space. Extensive testing, from structural integrity to functionality tests, validates the robot's readiness for space deployment.

4.3. Sensing

Sensing, often likened to the "nervous system" of robotic systems, is crucial for environmental perception and information processing. It employs technologies such as soft and stretchable sensors, which provide adaptability in space missions.[243,244] Advances in sensing technologies, including 3D perception, state estimation, and data fusion, have enabled the development of sophisticated sensors and methodologies that are essential for autonomous space exploration.[245,246]

These sensors act as the robot's eyes, ears, and touch, offering critical situational awareness in space missions. Their applications range from visual navigation and temperature monitoring to specialized tasks such as LiDAR-based 3D mapping and imaging spectroscopy for environmental analysis.[247–249] Furthermore, the integration of electronic skins has expanded the scope of intelligent interaction in soft robotics.[243,250]

Recent advancements in sensor technologies have pushed the boundaries of their applications in space missions. For example, self-powered and self-healing electronic skins ensure operational reliability under harsh space conditions, extending robot lifespans by mitigating wear and tear.[244,251] These sensors also enable multimodal environmental perception, such as integrating shape-adaptive designs and wireless communication for teleoperation and autonomous interaction.[250,252] With innovations like energy-harvesting mechanisms and temperature-resistant materials, flexible sensors now address critical challenges, including resource efficiency, robustness, and adaptability in space missions.[253–255] These enhancements reinforce the critical role of sensors in enabling resilient and intelligent robotics for exploration, maintenance, and collaborative tasks across diverse mission scenarios.[256]

To ensure efficient utilization of sensor data, robust onboard processing frameworks and algorithms are indispensable. Techniques like real-time data fusion, machine learning models, and reinforcement learning approaches have significantly enhanced the capabilities of robots in object detection, event recognition, and environment modeling, all while optimizing energy consumption.[252,257] These algorithms are particularly critical for overcoming latency and communication challenges during autonomous operations, ensuring responsive and precise control even in distant planetary or orbital settings.[258,259]

Despite these advances, sensor integration faces challenges in the harsh conditions of space. Sensor degradation caused by radiation and vacuum, latency in data processing, and limited bandwidth for transmitting large datasets to Earth require robust solutions.[251,258] Real-time data fusion algorithms, fault-tolerant designs, and radiation-hardened sensors are essential for ensuring accurate and reliable sensing in dynamic and extreme environments. Emerging methods, such as neural network-based sensor calibration and hybrid processing architectures, are being developed to address these issues while enhancing reliability and longevity in space missions.[251]

These advancements in sensing technologies and methodologies not only address the operational challenges of space exploration but also enable diverse applications, including planetary surface mapping, resource identification, and orbital servicing. Through precise environmental perception and adaptive data processing, sensing technologies form a crucial pillar of compliant robotics for space, driving the success of both current and future missions.[251,258]

4.4. Actuation

Actuation, often likened to the "heart" of a robotic system, empowers the robot to interact with its environment, executing actions that range from simple movements to complex tasks such as maintaining balance in variable gravitational conditions. In compliant robotics for space applications, including soft, origami, reconfigurable, and hyper-redundant types, actuation mechanisms are very important and require careful attention to various factors to ensure flexibility, adaptability, and efficiency.[260–262]

Fluidic actuators provide smooth and flexible movements, making them suitable for soft robotics in applications such as on-orbit servicing and planetary exploration.[263] Shape memory alloys offer unique deformation capabilities, enabling reconfigurable structures for adaptive space systems and origami-inspired mechanisms.[264,265] Electroactive polymers (EAPs) respond to electrical stimuli and offer precise control for hyper-redundant and continuum robots in confined space environments.[266,267] Traditional motors are still an option, particularly in reconfigurable and modular robots designed for efficient assembly tasks in space stations.

The choice of the actuator is not a one-size-fits-all decision but rather reflects the specific needs and constraints of a given space mission.[179,268,269] For instance, fluidic actuators, a subset of pneumatic actuators, might be favored for their flexibility in soft robots. SMAs and EAPs, which are often driven by electric signals, could be the preferred choice for applications demanding precise control, such as in origami and hyper-redundant robots. Hydraulic actuators, renowned for their high-force capabilities, might find their way into heavy-duty space tasks. Chemical actuators, although specialized, could be invaluable in missions requiring unique reaction mechanisms.

Energy source selection is another critical dimension of actuation. The chosen energy source must offer sustained power over extended periods, while also being lightweight and compact to minimize the energy required for transportation to space.[270,271] This becomes especially relevant for integrated intelligent robots or untethered systems that demand onboard energy supplies for autonomous functioning.[261,272] Options such as batteries, solar panels, or even nuclear power are carefully evaluated, keeping in mind the specific mission requirements, robot type, and mission duration.

The successful integration of actuation mechanisms in space-compliant robotics calls for a detailed understanding of a range of parameters. This depth of consideration contributes to the creation of more resilient, efficient, and versatile robotic solutions that are fit to navigate the complexities and challenges of the space environment.

4.5. Control

Control mechanisms, often described as the “brain” of robotic systems, enable decision-making, navigation, and execution of complex tasks in space missions. Advanced control systems are essential for managing the high-dimensional, dynamic environments of space, where conventional control strategies often fail.[49,257,273] Microgravity and vacuum environments, alongside extreme temperatures, significantly impact control strategies for soft robots in space. The reduced resistance in microgravity allows even small forces to cause substantial motion, while high-energy radiation can compromise system stability. These factors necessitate robust control algorithms designed for real-time adaptability and resilience.[274,275]

In space robotics, advanced control systems navigate the complexities of high-dimensional, dynamic environments where conventional methods are often insufficient.[49,257,273] Integral to these systems are robust control algorithms and autonomous functionalities. These include advanced guidance, navigation, and adaptive control techniques for managing complex tasks in space, along with innovative actuation methods and fault-tolerant mechanisms that enhance the adaptability and safety of space robotics.[34,276,277]

Advanced strategies such as unified neural output-constrained control and disturbance observer-based control have become important in integrating multiple sensors and actuators for complex spatial tasks.[278,279] NASA’s VIPER mission employed AI-driven control systems for autonomous lunar exploration and soil analysis, demonstrating these technologies’ practical value in space exploration.[10] The integration of AI planning technologies, including Partial Order Causal Link (POCL), hierarchical, and conditional techniques, offers promising capabilities for autonomous spacecraft operation and control, adapting methodologies successfully tested in automated manufacturing domains.[280] Additionally, the integration of methods like dynamic modeling and fuzzy adaptive control[281] and the latest in bioinspired[282] and AI-enhanced control systems[283] reflect a shift toward more sophisticated and adaptable control mechanisms.

Recent advancements in origami robotics have introduced innovative control mechanisms tailored for space applications. Magnetic actuation, for instance, has been leveraged for untethered, distributed control in origami microrobots, enabling rapid shape changes and multifunctionality.[284] For more complex transformations, reconfigurable interactive interfaces facilitate bidirectional communication between virtual and physical environments, allowing for dynamic exploration of design spaces and precise control.[285] Stiffness modulation using shape memory polymers further enhances the configurability and dexterity of underactuated origami robots, making them adaptable to varied space mission requirements.[286] Moreover, OrigamiSats with variable surface reflectivity have been proposed as innovative spacecraft, integrating attitude and shape control through solar radiation pressure. This dual-mode design supports reconfiguration between solar sail and parabolic reflector modes, addressing the unique challenges of coupled attitude and shape dynamics in origami spacecraft.[287]

In the context of soft robotics, controlling infinite degrees of freedom is a significant challenge due to the nonlinear and variable nature of soft materials, making traditional rigid-bodied robot control methods inadequate.[63,288] Model-based control strategies in soft robotics[62] diverge into kinematic and dynamic approaches. Kinematic control, focusing on posture without force considerations, is simpler but less effective for interactive tasks. Dynamic control, incorporating physical forces like inertia and gravity, offers more accurate and versatile control, crucial for space missions.[289–291] In contrast, model-free[292] and learning-based strategies,[293–296] particularly reinforcement learning and Koopman operator approaches, are gaining recognition.[122] Reinforcement learning adapts well to the dynamic and uncertain conditions in space, enabling robots to learn from interactions with their environment.[297,298] The Koopman operator offers a novel way to linearize the nonlinear dynamics of soft robots, enhancing performance and stability against disturbances.[299]

In space environments, latency becomes a critical issue for control. Communication delays between Earth and a robot in space can be extensive, requiring autonomous control systems that enable robots to execute tasks without constant Earth-based supervision.[300–302] This becomes particularly essential for tasks like distant planetary exploration or autonomous on-orbit servicing. Despite technological advances, the latency issue remains a significant bottleneck for real-time control and demands innovative solutions for robust and efficient operation.

Moreover, resistance to harsh space conditions is a critical factor that cannot be overlooked. Control systems must be meticulously engineered using space-grade materials and specialized design principles. Such systems often incorporate robust control mechanisms, including fault-tolerant designs, to counteract the risks associated with single-event upsets and other disruptions. Techniques like radiation-hardened components are specifically integrated to safeguard against the damaging effects of space radiation.[303,304] These features are not just add-ons but are essential for the survival and efficient functioning of the robot in extreme conditions. For a comprehensive overview of the environmental challenges and corresponding engineering considerations, readers are referred to Section 3.

Lastly, adaptability forms a crucial part of the control system in space robotics. This includes the ability of the control system to adapt to changes in the robot itself and changes in the environment, such as variable gravitational fields or unexpected obstacles. Techniques like adaptive control for payload carrying and fuzzy adaptive control have been developed to enhance this adaptability.[276,281] The adaptability of space-compliant robots further extends to learning from experience and adapting over time, essential for long-duration space missions.[34]

4.6. Operation

The operation stage includes deployment, maintenance, performance evaluation, and end-of-life planning. For soft and deformable robotics utilized in space missions, this may include considerations for adaptability and robustness during deployment and maintenance. Ensuring performance consistency, reliability, lifespan, safety, and the overall impact on space missions is crucial. This stage requires careful monitoring, regular evaluations, and potential adjustments or repairs to maintain optimal performance. The end-of-life planning is also vital, considering the disposal or repurposing of the robot at the conclusion of its mission.

For the successful operation of space robotics, system engineering considerations such as modularity, standardization, interfaces, verification, and validation of complex adaptive systems, as well as safety and trust, play a critical role.[40,305,306] High stakes in terms of costs and the increasing complexity of robotic systems demand reliable mission planning and characterizing robotic behavior, especially in multivehicle swarms.

The interconnected stages of concept, design, fabrication, actuation, sensing, control, and operation are crucial for developing compliant robotics for space applications. Each stage contributes to creating resilient, efficient, and versatile robotic systems, particularly in soft and deformable robotics. Meticulous planning ensures these robots thrive in harsh space environments. This section's insights lay the foundation for exploring various categories and forms of compliant robotics, highlighting their potential. The next section will focus on their specific applications in space missions, demonstrating how compliant robotics transform space exploration and drive innovations beyond this field, providing versatile and adaptive solutions for complex challenges.

5. Discovering Space Missions

5.1. Overall Concept

As humanity explores deeper into space, robotic systems must handle increasingly complex roles. These robots serve as our representatives, navigating inhospitable conditions and performing tasks too dangerous or routine for astronauts. In this context, the field of compliant robotics, featuring flexibility and compliance, has become an important area of study. Unlike rigid robots, compliant robots adapt to their surroundings, absorb impacts, and interact safely with humans and systems. Their adaptability, energy efficiency, and lightweight nature enhance mission longevity and affordability, offering unique solutions to space mission challenges.[307]

The potential applications of compliant robotics extend to various destinations and mission concepts. For Earth orbit, they can be employed in space debris removal and on-orbit servicing and assembly, utilizing robotic arms, hands/grippers, and harpoons.[308] On the Moon, compliant robots may facilitate sample return, in situ resource utilization (ISRU), exploration of permanently shaded craters, and preparation for manned bases, employing technologies such as rovers, arms, samplers, and drills.[41,309,310] Missions to Mars may involve aeroshells, airplanes, helicopters, balloons, hoppers, and swarms for tasks like sample return, ISRU, and crewed base development.[311–313] Compliant robotics could also contribute to exploration missions on Venus, Mercury, asteroids, Titan, Europa/Enceladus, and gas giants, utilizing various robotic locomotion techniques like balloons, rovers, hoppers, and cooperative robots.[314]

In space missions, compliant robots, with their inherent compliance and reconfigurability, are capable of performing diverse tasks. These range from delicate manipulations[315,316] and intricate assembly or repairs[317] to robust locomotion and exploration in harsh terrains,[138,318] aligning with the technological needs identified for mobility and locomotion in space missions, such as moving on, into, and above extraterrestrial surfaces using various modes of locomotion like flying, walking, climbing, and more.[40,41,138] The integration of origami-inspired designs, modular components, and the use of materials suitable for extreme conditions allow these robots to be compactly stored for transport and expand once in space, significantly reducing payload requirements.

To illustrate the potential of compliant robots in space missions, consider NASA's Robonaut program. Robonauts are humanoid assistants designed to take over routine or dangerous tasks from astronauts. Robonaut 2, sent to the international space station, features soft, compliant hands that allow it to use the same tools as its human counterparts.[319] This design highlights the robot's dexterity and adaptability, demonstrating the wide-ranging applications of compliant robotics in space exploration.

The rest of this section explores the current state of the art, trends, challenges, and potential of this emerging field in the context of space missions. It examines the unique capabilities of compliant and deformable robots in on-orbit missions and planetary exploration, as well as other diverse space robotic missions. In these varied and challenging contexts, the potential of compliant robotics for space exploration is vast, as summarized in **Table 5**.

5.2. On-Orbit

On-orbit missions, including servicing satellites, removing space debris, and maintaining orbital structures, benefit greatly from compliant robotics.[320,321] These robots, featuring soft, deformable, and modular designs, offer innovative solutions to on-orbit challenges. They enable intricate maneuvers and delicate handling, reducing the risk of damage to fragile spacecraft components by safely absorbing impacts and distributing forces. The ability of these robots to change form, assume compact shapes for navigating narrow passages, extend reach for distant components, or divide into smaller units for multitasking enhances their functionality in various tasks from satellite operations to space station construction.

Deformable robots can be designed for specific purposes such as reorienting satellites, capturing and deorbiting defunct satellites, or conducting repair and maintenance on large space structures.[322–324] Soft robots offer additional benefits with their flexibility and ability to conform to complex shapes, enabling delicate interactions and navigation through constrained environments.[325] The integration of innovative materials and biomimetic design principles in compliant robotics significantly enhances capabilities in satellite servicing, assembly, and inspection. These advancements improve efficiency and safety, setting new standards in on-orbit mission capabilities and reflecting the transformative potential of compliant robotics in space innovation.[29,121,126,326,327]

In the field of on-orbit servicing, compliant robotics are increasingly influential in enhancing mission capabilities. Examples like SMART-OLEV, developed for on-orbit validation and experimentation, utilize magnetic connectors for assembly and disassembly.[328] SUMo, a superagile modular gripper, employs compliant magnetic mechanisms to adapt to different grasping requirements.[329] These innovations, along with the AVERT project, which extends the concept of modularity for autonomous vehicle extrication and transportation, demonstrate the adaptability of compliant robotics for complex on-orbit tasks.[330] These systems facilitate tasks like on-orbit maintenance of spacecraft,[331] debris capture, and the construction and maintenance of space stations.[29] Unlike traditional rigid capture robots, compliant robots integrate innovations such as flying claws[332] and origami-inspired designs,[333] offering more versatility and precision in task execution, with intelligent control encompassing path planning and trajectory tracking.[334,335]

The integration of advanced guidance, navigation, and control mechanisms in compliant robotics is shaping the future of in-orbit space robotic missions. These technologies enable precise task execution, trajectory tracking, and path planning, further enhancing the capabilities of space robots.[273] For example, the robust control of dual-arm space robots has been explored, particularly for complex operations like in-orbit screw-driving, enhancing the precision and functionality of these systems.[336] On the other hand, compliant robotics can be important in future developments of on-orbit assembly and planetary surface material sampling technology. Their adaptability and precision can contribute to the construction of large space structures and the collection of valuable samples from celestial surfaces.[337] Recent advancements in on-orbit servicing have led to the development of novel soft robotic configurations and manipulators, specifically designed for delicate handling and manipulation in space.[52] These innovations have been instrumental in enhancing the efficiency and safety of on-orbit missions, opening new avenues for complex operations previously considered challenging.

5.3. Planetary

Planetary missions involve the exploration and study of celestial bodies in the solar system, including the Moon, Mars, and potentially more distant planets and moons. Compliant robots, with their adaptability and resilience, have the potential to revolutionize these missions.

The unique challenges posed by planetary surfaces, such as rough terrain and slippage, may challenge traditional exploration robots. Recent advancements have allowed for enhanced stability and control, enabling more precise navigation on challenging terrains.[338] Compliant robots, capable of soft landing and adapting to rough and uneven surfaces, traverse various terrains with ease. The evolution of space drones, coupled with compliant robotics' ability to adapt to different terrains and atmospheric conditions, is paving the way for more robust and resilient exploration missions.[339]

Both soft and deformable robots offer unique advantages for planetary missions. Soft robots can conform to terrain, enhancing stability and reducing the risk of becoming trapped, while deformable robots can adapt to different terrains and undertake specialized tasks such as drilling or excavation. Together, they open up new possibilities for exploration and data collection. Compliant robots are facilitating high-speed mobility on planetary surfaces, traversing diverse terrains at higher speeds, and enhancing exploration efficiency.[47,340]

An example of a planetary mission that could leverage compliant robotics is NASA's Mars 2020 mission, where a combination of deformable and soft robots could enhance efficiency and flexibility.[1] Notable examples of recent planetary missions include refs. [341,342], with ref. [343] providing insights into the surface characteristics of Mars. An improved method for property inversion in Martian Tianwen-1 GPR Data contributes to in situ analysis of surface composition,[344] and a high-fidelity simulation for Mars rovers has been developed to facilitate testing and validation.[345] Looking ahead, the integration of compliant robotics in future planetary missions could unlock new opportunities and expand our understanding of the solar system.

The reconfigurable modular approach is also extending to planetary exploration. The modular robotic vehicle concept aims to explore planetary surfaces using a multi-wheeled modular system, capable of reconfiguration for varied terrains and tasks.[29] Other notable examples include the LARRE project, which focuses on locomotion adaptation for rough terrains using a modular and reconfigurable robotic system,[77]

Table 5. Summary of space missions and applications for compliant robotics, highlighting key features, challenges, and technologies.

Area	Techniques/technologies (with examples)	Benefits	Limitations	Space missions (applications)
On-orbit missions				
Satellite servicing	Modular robotic arms (e.g., Canadarm[396]), adaptive control algorithms, compliant end-effectors.	High precision, reduced human intervention.	Requires advanced real-time control, error handling under complex dynamics.	Satellite maintenance, hardware upgrades, thermal blanket repairs.
Debris capture	Hybrid-compliant systems,[355] tethered harpoon mechanisms, net-based capture (e.g., Flying Claws[332]).	Minimizes space debris, prevents collisions.	Challenges in debris trajectory estimation, secure capture mechanisms.	Space debris removal, spacecraft protection.
Construction and maintenance	Modular robotic systems, in-orbit additive manufacturing (e.g., SMART-OLEV[328]).	Enables scalable orbital construction.	Long-term durability of materials in harsh conditions.	Building and repairing space structures.
On-orbit servicing	SUMO grippers,[329] autonomous manipulation tools.	Versatility, real-time adaptability.	Safety concerns in dynamic orbital conditions.	Refueling, component replacement.
Planetary exploration				
Terrain adaptation	Shape-adaptive wheels, reconfigurable chassis (e.g., NASA Mars rovers[385,389]).	Enhanced mobility on uneven terrains.	Energy constraints, durability in extreme conditions.	Geological analysis, planetary scouting.
Drilling and excavation	Percussion drilling robots, soft soil-compliant excavation tools (e.g., Tianwen-1 robots[344]).	Supports subsurface resource utilization.	Susceptible to jamming in dense substrates.	Subsurface sampling, ice extraction.
Planetary mobility	Hybrid wheel-leg mechanisms, high-speed locomotion systems (e.g., Fast-Moving Planetary Rover[397]).	Scalable for diverse terrains.	Limited energy storage for extended missions.	Surface navigation, rapid data collection.
Surface and subsurface exploration	Soft manipulators, bioinspired mechanisms (e.g., Vanguard[398]).	Precise geological data collection.	Remote operation challenges, terrain unpredictability.	Subsurface exploration, soil analysis.
Deep space exploration	Self-assembling robots, energy-efficient actuators, quantum-enhanced navigation systems (e.g., ElectroVoxel[399] Rolling-Jumping Spherical Robot[400]).	Autonomous adaptation to unknown environments.	Communication latency, limited fault tolerance.	Long-duration missions, uncharted space environments.
Space infrastructure protection	Robotic systems for structural health monitoring (e.g., PolyBot[401]), self-healing materials.	Ensures infrastructure durability, reduces interruptions.	Integration challenges with existing systems.	Safeguarding satellites, lunar base maintenance.
Astronaut assistance	Dexterous humanoid assistants (e.g., NASA's Robonaut[319]), robotic exoskeletons, ESA's Meteron.[357]	Reduces astronaut workload, enhances safety.	Reliability concerns under harsh conditions.	Daily task automation, emergency handling, scientific assistance.
Soft landing	Real-time terrain sensing, compliant landing structures (e.g., Chandrayaan-3[163]).	Minimizes landing impact, ensures safety.	Complex precision control for uneven terrains.	Docking, landings on celestial bodies.
Compliant UAVs	Morphing wing drones, rotorigami-inspired systems (e.g.,[366,367]).	Enhanced maneuverability, compact storage.	High energy requirements, control challenges in confined environments.	Surveillance, coordinated swarm behavior, planetary exploration.
Specialized compliant robots for space exploration				
Flapping-wing aerial robots	Aerodynamic efficiency, environmental adaptability (e.g.,[369]).	Adaptable to varied atmospheric conditions.	High design and control complexity.	Aerial reconnaissance, environmental monitoring.
Soft crawling robots	Surface conformity, obstacle navigation (e.g.,[372]).	Versatile mobility on rugged terrains.	Durability challenges, limited payload capacity.	Uneven surface exploration.
Burrowing soft robots	Subsurface penetration, geology analysis (e.g.,[375]).	Enables detailed soil composition studies.	Energy-intensive, susceptible to mechanical wear.	Subsurface exploration, soil sampling.
Jumping robots	High mobility, obstacle navigation (e.g.,[377]).	Overcomes terrain obstacles effectively.	Energy constraints for frequent jumps.	Rapid transit across rough surfaces.
Tensegrity robots	Structural adaptability, resilience (e.g.,[380]).	Operates in variable gravity, navigates complex terrains.	Specialized control requirements, moderate efficiency.	Rough terrain navigation, gravity exploration.

and the Coyote III robot, designed for planetary exploration and equipped with modular wheel-legs to enhance mobility.[346] These innovations underline the significance of compliant robotics in planetary missions, offering flexible solutions for diverse exploration needs.

5.4. Diverse Applications of Compliant Robotics in Space

In addition to on-orbit and planetary missions, compliant robotics have opened new horizons in various fields of space exploration and beyond. This section explores some of the promising applications.

5.4.1. Deep Space Exploration

Compliant robots, with their modularity and intelligent control, hold great potential for deep space exploration. Their adaptability, energy efficiency, and resilience are essential for missions to distant celestial bodies, such as Jupiter's moon Europa. These robots could adapt to various challenges, executing complex tasks autonomously and sustainably, even in remote environments.[54]

Deep space exploration missions venture into uncharted territories of our solar system and beyond, necessitating innovative solutions that can adapt to unknown and complex environments.[347–349] Compliant robots, particularly those with reconfigurable structures, present a promising option for these missions. Efficient decision-making algorithms and high autonomy are important in deep space missions, particularly in uncertain scenarios such as nontethered deep space interferometry. These technologies enable robots to understand their environment, make informed decisions, and improve mission reliability and efficiency.[350,351]

5.4.2. Space Infrastructure Protection

Compliant robotics have the potential to significantly contribute to the safeguarding of essential space infrastructure, such as satellites, space stations, and potential lunar or Martian bases. Their inherent flexibility and adaptability are key for tasks crucial to long-term operational resilience, such as routine maintenance, damage inspection, and immediate repair activities.[352–354]

A notable area of application is the management of orbital debris, where compliant robots are deployed to capture or redirect space junk, thus reducing risks to spacecraft.[355] Their high autonomy enables tasks like regular inspections and immediate preventive actions without constant human oversight, enhancing the safety and integrity of space infrastructure.[356] Moreover, these robots are increasingly used for complex repair tasks, leveraging their dexterity and precision in environments where manual intervention is limited. Their ability to work in the harsh conditions of space and perform intricate repairs ensures the longevity and functionality of crucial space assets.

Additionally, advancements in compliant robotics technology have the potential to develop specialized robots for specific infrastructure protection tasks. These could include robots designed for welding in space, applying protective coatings, and performing structural health monitoring, all of which would contribute to the maintenance and enhancement of space infrastructure.

5.4.3. Astronaut Assistance

Compliant robots, with their adaptable nature, are poised to become invaluable assets for astronauts, assisting in daily tasks, emergencies, and scientific experiments. Their inherent softness and flexibility ensure safe and intuitive interactions with human crew members.

NASA's Robonaut program and the European Space Agency's (ESA) Meteron project are pioneering efforts in this domain, exploring the synergies between astronauts and robots in space environments.[319,357] As future deep space missions necessitate increased astronaut autonomy, the role of compliant robotic assistants becomes even more crucial. These robots can provide real-time support, leveraging advanced algorithms and sensing capabilities to assist astronauts in a variety of tasks, from equipment handling to complex scientific experiments.[358] Modular robotic limbs and exomuscular systems have also emerged as promising tools for astronaut assistance. They can be designed for specific tasks, combining the dexterity of human hands with the precision and strength of robotic mechanisms.[359] These advancements highlight the potential of compliant robotics in amplifying the capabilities of astronauts, ensuring safety, and enhancing overall mission efficiency.

5.4.4. Soft Landing

Soft landing mechanisms are becoming increasingly relevant in the field of space missions. Compliant robotics, characterized by their flexibility and adaptability, are well-suited for facilitating smoother and safer landings on celestial bodies or during docking procedures. India's Chandrayaan-3 serves as a compelling example, with its entirely autonomous lunar descent involving a series of carefully orchestrated phases to ensure a smooth landing. The mission showcases advancements in guidance, navigation, and control systems, providing valuable insights into the design of robust and adaptive landing technologies.[8,163,360]

One significant advantage lies in adaptive touchdown systems. Compliant robots can autonomously adjust to varied surface conditions, making them particularly useful for missions targeting planets or moons with uneven terrains.[361] Moreover, their precision in docking scenarios enhances the safety and efficiency of missions requiring interactions with space stations or other spacecraft. The inherent flexibility in their structure allows for effective absorption of impact energy, thereby reducing risks to mission-critical systems and enhancing the overall integrity of space operations.[362,363]

5.4.5. Compliant UAVs in Space

Compliant UAVs present a novel and promising frontier in space missions, with potential applications in surveillance, exploration, and coordinated swarm behavior. Unlike traditional rigid UAVs, compliant UAVs, such as those employing origami-inspired designs, can adapt to dynamic conditions, absorb impacts, and operate in confined or complex environments.[90,364,365]

A relevant example is the "Rotorigami" system, a rotary origami protective system for robotic rotorcraft, designed to absorb impact forces with its innovative protection system.[366] In addition, the research on morphing winged drones presented in ref. [367] demonstrates significant improvements in UAV agility and energy efficiency, achieved by codesigning their physical structure and control systems. Both works exemplify the integration of adaptive structures with intelligent control in advancing UAV technology. These developments position compliant UAVs as valuable tools for complex space exploration missions, aligning seamlessly with the overarching theme of compliant robotics in adapting to the dynamic and unpredictable conditions of space.

5.4.6. Specialized Compliant Robots for Space Exploration

This section explores a variety of uniquely designed robots, each tailored for specific tasks in the vast scope of space exploration. These robots demonstrate innovative applications of compliant design principles, enhancing their efficacy in the specialized scenarios encountered in space missions.[368]

"Flapping-wing aerial robots" are distinguished by their compliant structure, which enables efficient aerodynamics and adaptability in varied gravitational environments. This makes them suitable for aerial reconnaissance in the diverse atmospheric conditions of different planetary settings, an essential capability for comprehensive exploration and mapping in space missions.[369–371]

"Soft crawling robots" are particularly effective for surface exploration on celestial bodies. Their flexibility allows them to adapt to uneven terrains and navigate complex landscapes, an important trait for probing the surface of planets and moons where traditional rovers may face limitations.[372–374]

"Burrowing soft robots" bring a unique capability to space missions, allowing for subsurface exploration. Their design enables them to penetrate and analyze the geology beneath planetary surfaces, offering insights into soil composition and potential resources, crucial for in-situ resource utilization and understanding planetary formation.[375,376]

"Jumping robots" offer a novel approach to overcoming terrain challenges in space exploration. Their ability to leap over obstacles and traverse rugged terrains can enhance the efficiency of planetary surface exploration, especially in environments where wheeled mobility is impractical.[377–379]

"Tensegrity robots," with their structurally unique combination of tension and compression elements, provide exceptional adaptability and resilience. This makes them well-suited for exploration in environments with variable gravity or rough terrain, where traditional rover designs might struggle.[380–383]

This section explores the diverse roles of compliant robotics in space, encompassing applications from on-orbit servicing to specialized robots and UAVs, while addressing the unique challenges and opportunities within these missions. By examining key features, limitations, and transformative potential, it highlights the field's growing significance in advancing space exploration. Table 5 complements this discussion by summarizing the core aspects and practical applications across various mission scenarios.

6. Future Prospective of Compliant Robotics in Space

In the advancing domain of space exploration, compliant robotics stands as a vibrant frontier, poised to redefine space missions through adaptability, resilience, and multifunctionality. This section summarises the main technological trends that are shaping the field, the prospective impacts on future space missions, the burgeoning research areas that hold promise for unlocking new possibilities, and the collaborative efforts and public–private partnerships advancing the field.

6.1. Technological Trends

Several key trends are steering the evolution of compliant robotics for space applications: 1) Increased autonomy: Leveraging AI and machine learning, autonomous robotic systems minimize human input, setting the stage for fully independent missions and real-time adaptation. 2) Collaborative robotics: Swarm robotics, enabling collaborative work for complex tasks, expands applications to include construction, scientific research, and coordinated exploration. 3) Orbital manufacturing and assembly: In-space manufacturing, particularly for satellite fabrication and assembly, offers new avenues for space mission efficiency, reshaping how spacecraft are built and deployed. 4) Multifunctional systems: Compliant robots with task-switching abilities enhance efficiency and adaptability, supporting diverse assignments through automatic reconfiguration. 5) Human–robot interaction: Advanced AI and sensing technologies foster seamless cooperation between astronauts and robotic systems, enhancing mission efficacy and safety. 6) Miniaturization: The development of compact robotic systems facilitates intricate tasks such as microfracture repair and minute geological examination, broadening exploration possibilities.

6.2. Potential Impact on Future Space Missions

The aforementioned trends are poised to significantly reshape future space missions: 1) Efficiency and flexibility: Compliant robotics optimize mission efficiency and enable ambitious projects with reduced resources, unlocking new potentials. 2) Safety and risk management: By performing hazardous tasks and ensuring delicate manipulation, compliant robots mitigate risks and costs, enhancing mission reliability. 3) Operational agility: Advanced robotics enhance real-time adaptability and responsiveness, improving mission outcomes in dynamic space environments. 4) Cost considerations: Progress in compliant robotics may make space exploration more accessible by reducing financial barriers. 5) Environmentally sustainable practices: Emphasizing waste reduction and energy efficiency, compliant robotics aligns with sustainable space exploration initiatives. 6) Revolutionizing space infrastructure: Development of orbital factories enhances in-orbit operations, transforming space logistics and economics.

6.3. Emerging Research and Its Potential

Intriguing possibilities lie in emerging research for space exploration: 1) Novel materials: Durable and resilient materials, featuring self-healing or adaptive properties, promise to enhance the performance and longevity of space robots. 2) Advanced sensing and control: Innovations in haptic feedback and brain–computer interfaces may lead to unparalleled control and responsiveness. 3) Biomimicry: Emulating natural behaviors leads to adaptive and intuitive solutions, offering unique answers to space challenges. 4) Morphable structures: Shape-altering robots present extensive applicability in diverse space missions. 5) Quantum computing and robotics: Integration with quantum computing could revolutionize real-time decision-making. 6) Ethical and regulatory considerations: Comprehensive standards are pivotal for risk management and responsibility definition in autonomous systems.

6.4. Collaborative Engineering and Public–Private Partnerships

Collaborative efforts and partnerships are essential in advancing compliant robotics for space: 1) Collaborative engineering evolution: Projects like NASA's VIPER encourage innovative solutions through public–private partnerships. 2) Integration with existing systems: Ensuring new technologies can seamlessly integrate with current space infrastructure. 3) Ethical implications: Addressing the ethical considerations of deploying advanced robotics in space, ensuring responsible and fair use. 4) Standardization and interoperability: Developing common standards and protocols for seamless interaction between systems from different organizations. 5) Global cooperation: Promoting international collaboration to leverage diverse expertise and resources, fostering a unified approach to space exploration. 6) Funding and resource sharing: Establishing shared funding mechanisms and resource pooling to support large-scale projects.

As illustrated in **Figure 7**, the future of compliant robotics in space is driven by advancements in capabilities, design, functionality, and technologies, supported by collaborative engineering and emerging research areas that enhance mission capabilities and impact. As technology and understanding continue to evolve, the potential applications of compliant robotics in space will only broaden. These developments hold significant implications for the future of space exploration, heralding an era of innovation and possibilities.

7. Discussion

The field of compliant robotics has experienced substantial growth, with notable applications in space exploration. This discussion seeks to tie together the multifaceted aspects explored in this article, highlighting both the advancements and the ongoing challenges.

Compliant robots, in contrast to traditional rigid counterparts, exhibit a wide range of attributes that are increasingly relevant to space missions, including flexibility, adaptability, and safety. As expanded in **Table 6**, each type of compliant robot offers unique capabilities and faces distinct challenges. Soft robots, with their inherent flexibility, are well suited for tasks requiring delicate handling and precise movements, such as intricate repairs in space. Their capability to perform tasks that require a high degree of finesse positions them advantageously for on-orbit servicing. Unlike rigid robots, which rely on fixed structures and predefined motion paths, compliant robots can navigate complex environments, absorb impact forces, and exhibit resilience to mechanical shocks. Their ability to change shape allows them to undertake a diverse range of tasks that might be unfeasible for rigid robots. However, this adaptability often comes at the cost of more complex control algorithms and real-time adaptability requirements.

Rigid robots, characterized by their fixed structure and high strength, offer high load-bearing capabilities and predictable behavior but suffer from a lack of adaptability and are often heavier. This distinction between compliant and rigid robots highlights the need to carefully consider the specific requirements and challenges of space missions when selecting the appropriate robotic type. Further challenges with compliant robots include complex control strategies and the need for space-compatible materials, which demand innovative solutions. Additionally, the development of low-cost robots is becoming increasingly important in space exploration. These robots offer a cost-effective approach to expanding space missions, making advanced robotic capabilities more accessible.[384]

Transitioning from theoretical concepts to operational, compliant robots involves a complex interplay of design, control, energy efficiency, and real-world adaptability. With the rapidly evolving landscape of machine learning and artificial intelligence, these robots are increasingly capable of autonomous operation. In line with the future prospects outlined in the article, we can expect compliant robots to further capitalize on AI and machine learning for real-time adaptability, especially as research progresses in advanced sensing technologies and brain–computer interfaces.

The choice of materials for compliant robots significantly impacts their capabilities, durability, and operational lifespan, especially in the challenging environment of space. With factors like extreme temperatures, high radiation levels, and vacuum conditions to consider, materials must be selected not only for their flexibility but also for their robustness and resilience. As discussed in this review, the challenge lies in finding materials that can withstand these harsh conditions while retaining the compliant characteristics essential for versatile operation. The ongoing research in adaptive and self-repairing materials, as mentioned in the future prospects, offers a promising avenue for enhancing the resilience of compliant robots in space missions.

The applications of compliant robotics in space are multifaceted, as detailed in Section 5. From planetary exploration to advanced in-orbit servicing, these robots are becoming indispensable tools for a new era of space operations. Soft robots, with their high flexibility, are adaptable for on-orbit servicing and human–robot interaction. Modular reconfigurable robots offer adaptability through reconfiguration, suitable for exploration, assembly, and repair in space. Hyper-redundant robots, with their continuous structure, adapt to confined spaces, making them ideal for inspection and navigation. Origami robots, with their foldable design, provide compact transportation and

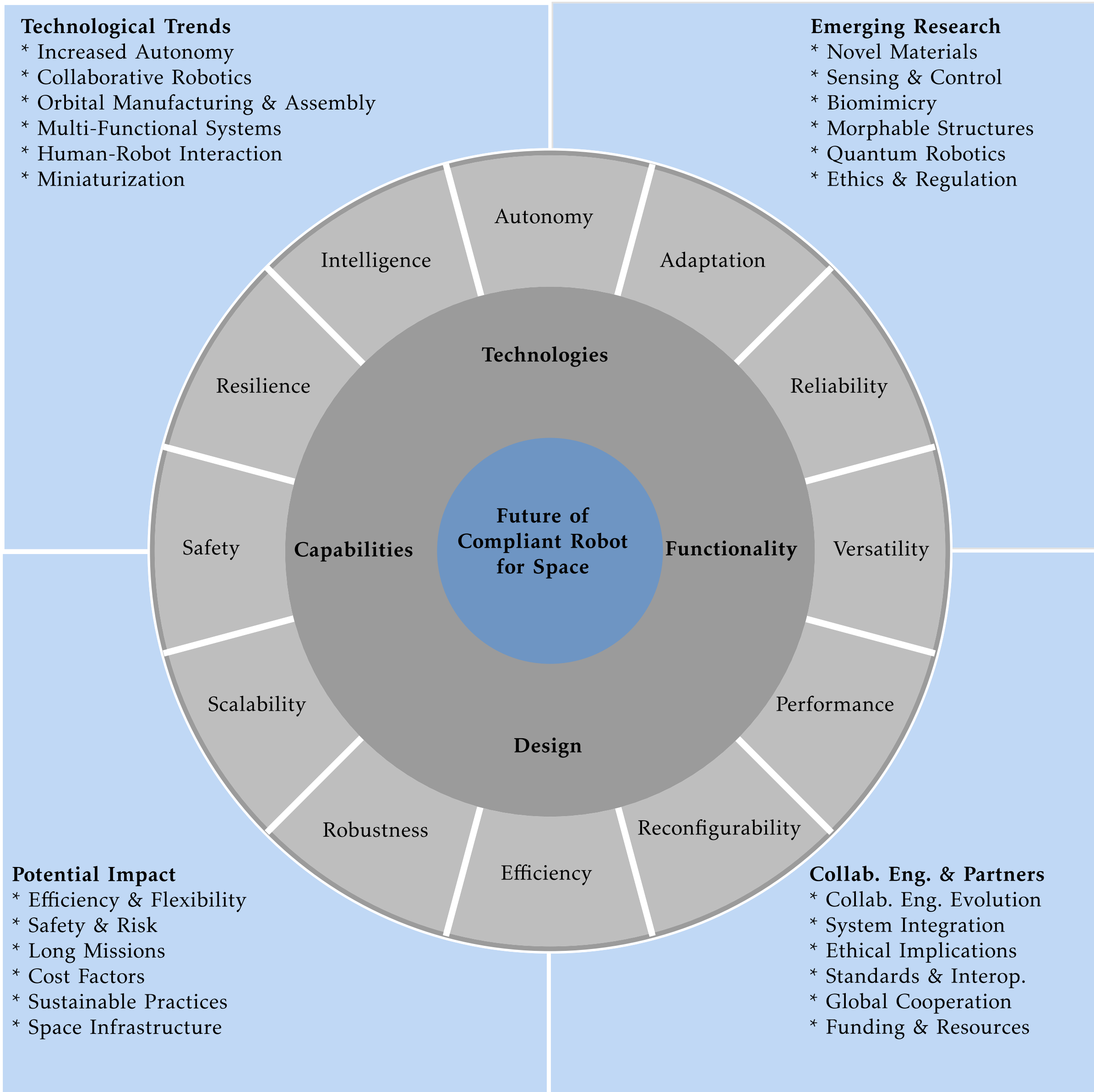

Figure 7. The future of compliant robotics in space. The main prospects are highlighted in the corners: Technological Trends (top left), Potential Impacts (bottom left), Emerging Research (top right), and Collaborative Engineering and Public-Private Partnerships (bottom right). The central ring outlines core focus areas including Capabilities, Design, Functionality, and Technologies, with an outer ring representing their specific advances.

deployment solutions. Moreover, the concept of swarm robotics, where multiple robots work in coordination, offers the promise of scalable and fault-tolerant systems. It is worth mentioning that rigid robots, although limited in adaptability, still serve crucial roles in heavy lifting and structural assembly. These robots are expected to integrate smart materials for limited adaptability in future missions.

The integration of compliant robotics in space missions influences not only technological advancement but also has educational, cultural, and eco implications. Their use promotes a deeper understanding of robotics and space science, enhancing learning opportunities through interactive educational initiatives and public engagement. In terms of heritage, these technological achievements represent a significant aspect of human progress in space exploration, with their milestones being preserved as part of our collective scientific legacy. Furthermore, the health and safety improvements they bring to space missions, such as handling extravehicular activities or operating in extreme conditions, contribute positively to the overall well being of astronauts. Environmentally, compliant robotics promote sustainable space missions by efficiently conducting repairs and maintenance, thereby reducing the need for new materials and equipment, and minimizing the ecological footprint of human activities in space.

Table 6. Comprehensive summary of compliant robotics types, highlighting their features, challenges, and future prospects for space applications.

Robot type	Techniques/technologies	Space environment adaptation	Development workflow	Space missions	Advantages	Limitations	Future prospects
Soft	Shape-memory alloys (SMAs), electroactive polymers (EAPs), pneumatic actuators, stretchable sensors, machine learning for control.	Highly adaptable to dynamic, shifting conditions; suitable for extreme temperatures and radiation shielding using composite materials.	– Design emphasizes compliance and flexibility. – Soft materials with high elasticity and lightweight structures. – Prototyping with advanced 3D printing and iterative testing.	On-orbit servicing, human–robot interaction, planetary exploration, sample collection in delicate environments.	High adaptability, safe human interaction, and ability to absorb shocks and navigate uneven terrains.	Complex control strategies, limited load capacity, and susceptibility to material degradation in space.	Integration of self-healing materials, miniaturization for specialized tasks, and extended autonomy for deep space missions.
Reconfigurable	Modular architectures, hybrid actuation, distributed AI for autonomous reconfiguration, smart connectors for dynamic assembly.	Adaptable through modularity and reconfiguration; efficient use of compact storage and in-orbit assembly techniques.	– Development focuses on modular design. – Flexible assembly strategies for reconfiguration. – Iterative testing for stability and reliability.	Satellite assembly, orbital construction, repair missions, and multifunctional exploration.	Scalability, versatility for diverse tasks, redundancy for fault tolerance.	Control complexity, communication challenges among modules, and stability during reconfiguration.	Development of more intelligent modular systems, including swarm behaviors for exploration and orbital manufacturing.
Hyper redundant	Continuum mechanisms, advanced kinematic modeling, bioinspired control algorithms, and integrated sensing systems.	Well-suited for confined spaces and adaptable to variable gravitational forces.	– Focus on smooth interaction for tight environments. – Specialized control systems for nonlinear dynamics. – Integration of sensory feedback for precision.	Inspection in confined spaces, navigation through narrow paths, and soil sampling.	High flexibility, excellent maneuverability, and precise control in restricted environments.	Material limitations, control system complexity, and moderate energy efficiency.	Haptic feedback integration, brain–computer interface development, and further miniaturization for microenvironments.
Origami	Folding mechanisms, lightweight materials, energy-efficient designs, and self-deploying structures.	Compact folding for efficient space transport; thermal stability through insulating materials.	– Lightweight and compact design principles. – Emphasis on foldable and deployable mechanisms. – Testing focused on deployment reliability.	Compact transportation, deployable structures for planetary exploration, and temporary shelters.	High portability, simplicity in transport, and reconfigurability for variable environments.	Limited robustness, complex folding/unfolding mechanisms, and reduced load capacity.	Innovations in self-deploying mechanisms and multifunctional origami designs for future missions.
Rigid	Traditional actuators, high-strength alloys, advanced servo motors, and precise machining techniques.	Robust design for heavy lifting, strong resistance to extreme conditions, and minimal deformation.	– Development emphasizes durability and strength. – Structural optimization for high-load missions. – Rigorous testing for mechanical stability.	Heavy lifting, structural assembly, and surface mobility in planetary missions.	Reliable performance, high load capacity, and predictable operation under extreme stress.	Lack of adaptability, higher weight, and energy-intensive operation.	Incorporation of smart materials for partial adaptability and enhanced energy efficiency.

To effectively integrate compliant robotics into space missions, it is essential to consider their adaptation to the unique challenges of extraterrestrial environments. These adaptations involve balancing design trade-offs, such as minimizing weight while maintaining durability, and ensuring compatibility with extreme environmental conditions like radiation, thermal cycling, and vacuum. For example, using advanced materials like temperature-resistant elastomers or radiation-hardened coatings can enhance durability without significantly increasing mass. Similarly, compact and modular designs inspired by origami principles can address payload constraints while maximizing functionality.

Additionally, mission-specific requirements must guide the development of energy-efficient systems and autonomous capabilities. Lightweight actuators, low-power sensors, and decentralized control frameworks are critical to optimizing energy consumption and ensuring long-term functionality in resource-constrained missions. By aligning design and operational strategies with these constraints, compliant robotics can evolve into more reliable and efficient solutions for future space exploration.

The future landscape of compliant robotics is intricate, blending technological trends, unresolved challenges such as complexity in control and adaptability, and ethical dilemmas. As we venture further into space, the ethical implications of deploying autonomous robots, especially in environments that may potentially harbor life, should also be carefully considered. Interdisciplinary collaboration among mechanical engineers, material scientists, computer scientists, and ethicists becomes increasingly vital to tackle the diverse challenges and fill the existing gaps in compliant robotics for space applications. These multifaceted considerations call for concerted research efforts and thoughtful discourse to propel compliant robotics to new heights in space applications.

In addition to interdisciplinary collaboration, the evolving landscape of space exploration increasingly highlights the importance of partnerships between governmental agencies and private companies. The NASA VIPER project, as a case in point, demonstrates how such collaborative efforts can drive technological advancements in challenging missions.[385] These collaborations bring together diverse expertise and resources, promoting innovation in robotics and other space technologies. The VIPER project, leveraging commercial capabilities for lunar exploration, exemplifies how this collaborative model can be instrumental in overcoming the complex challenges of space missions. Such partnerships are likely to become important in the future development and deployment of compliant robotics, enabling more efficient, cost-effective, and innovative solutions in space exploration.

On the other hand, the field of compliant robotics in space applications faces significant limitations. Key among these are the gaps in technology readiness, particularly the lack of extensive testing in space conditions, raising concerns about long-term reliability. Rigorous testing, both in simulations and actual space environments, coupled with feedback integration into the design and development process, is crucial for addressing these durability and functionality issues. Another major challenge is integrating these robotics into existing space systems due to compatibility issues in hardware and software. Standardization of components and communication protocols is essential for smoother integration and operability across different missions. Addressing these limitations requires an interdisciplinary approach, blending expertise from mechanical engineering, material science, computer science, and ethics. This collaborative effort is key to advancing compliant robotics in space, ensuring they meet current demands and are adaptable for future explorations.

Building on the technological and integration challenges, the practical application of compliant robotics in space presents its own unique set of difficulties. These challenges are closely linked with the technological ones, as the logistical complexities of transporting and deploying these robots in space directly impact design and operational strategies. Similarly, operational challenges, including ensuring reliable performance in harsh space conditions, are compounded by the need for advanced control algorithms and space-compatible materials. Maintenance, another critical area, often requires innovative solutions due to the limitations of human intervention in space.

As this discussion has highlighted, compliant robotics address specific demands of space exploration, with each robotic type offering distinct capabilities and facing particular challenges. By examining their design features, environmental adaptations, technological approaches, and mission roles, this section outlines their role in advancing space missions. Table 6 provides a comparative summary of key aspects and future prospects.

8. Conclusion

In this article, we have examined the evolving role of compliant robotics in space exploration. Their adaptability, flexibility, and safety, rooted in diverse designs like reconfigurable, hyper-redundant, origami-inspired, and soft robots, equip them uniquely for the demands of space. These robots stand as promising solutions for challenges in autonomous operations, self-repair, and energy management in space. Despite progress, ongoing challenges in material resilience, control complexities, and energy efficiency guide future research directions. As space exploration advances, compliant robotics are poised to become essential, driving a transformative phase in our journey into the cosmos.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Hamed Rahimi Nohooji: conceptualization: (equal); investigation: (equal); writing—original draft: (lead). **Holger Voos**: conceptualization: (equal); investigation: (equal); supervision: (equal); writing—original draft: (supporting).

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deformable robots, hyper-redundant robots, origami robots, reconfigurable robots, soft robots, space environment adaptation, space robotics

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