CEAS Space Journal
https://doi.org/10.1007/s12567-024-00576-6

ORIGINAL PAPER

# Robotic upcycling and recycling: unraveling the era of sustainable in-space manufacturing

**Mini C. Rai**[1] · **Manu H. Nair**[1] · **Dirk Schaefer**[2] · **Renaud Detry**[3] · **Mithun Poozhiyil**[4] · **Justyna Rybicka**[4] · **Shan Dulanty**[4] · **Josie Gotz**[4] · **Maximo A. Roa**[5] · **Roberto Lampariello**[5] · **Shashank Govindaraj**[6] · **Jeremi Gancet**[6]

Received: 21 August 2024 / Revised: 21 August 2024 / Accepted: 7 November 2024

**Abstract**

Advancements in material science, manufacturing and sensor technologies, Artificial Intelligence, and the Internet of Things have paved the way for fabricating new parts using additive manufacturing in microgravity conditions. NASA has successfully demonstrated 3D printing onboard the International Space Station (ISS), though at a minor scale. Nevertheless, the parts built onboard the ISS were returned to Earth for further testing and verification. The logistics of bi-directional transportation of raw materials from Earth to ISS and 3D-printed parts from ISS back to Earth is complex, expensive, and slow. Harnessing materials from space to establish in-orbit manufacturing as a sustainable process is both technically and economically challenging. The potential to reuse, repurpose or recycle space debris is not well studied, though there is an increasing momentum in Active Debris Removal (ADR) missions. Unlike the standard research or review paper, this is a visionary paper in which the authors explicitly address the intersection between space debris removal and in-space manufacturing. This paper defines a pathway towards implementing an operational in-orbit manufacturing and debris removal model. For the first time, the authors introduce the application of Cloud-Based Design and Manufacturing (CBDM) for in-space manufacturing in this paper. The paper aims to define a roadmap towards implementing a space operational model for in-orbit manufacturing and debris removal. Future enabling technologies that will leverage the advances in robotics, automation, and Space 5.0-based solutions to create a new environmentally friendly and economically profitable orbital ecosystem are presented. The authors analyze the pros and cons of robotic ADR, upcycling and recycling space debris for on-demand manufacturing in orbit and present a systematic approach to implementing in-orbit manufacturing as a new frontier. Recommendations are made to establish an imminent Earth-independent space logistics and supply chain system for operating an orbital factory or warehouse that will help realize a suite of in-orbit manufacturing, maintenance, and assembly missions.

**Keywords** Mission design · Space debris · Sustainability · Materials · Manufacturing · Robotics · Space 5.0

## 1 Introduction

Ever since the launch of Sputnik—the first artificial satellite—humanity has witnessed the construction of the biggest orbiting spacecraft - the International Space Station (ISS)—amongst other remarkable accomplishments in space, such as the Apollo lunar mission and a multitude of orbiter and rover missions to the Moon, Mars, asteroids and beyond. According to various forecasting bodies, such as Wall Street and Bank of America, the space economy is projected to grow into a multi-trillion-dollar market by 2040 [1]. However, there is a growing concern about the alarming amount of space debris, a serious threat posed to operational satellites, and the long-term sustainability of outer space activities.

The first documented case of an accidental collision between two artificial objects in Low Earth Orbit (LEO) occurred in 1996. The incident happened on 24 July when debris from an Ariane launcher hit the French military reconnaissance satellite CERISE. It is a sadly repeating story. In February 2009, the collision between the US satellite Iridium 33 and the derelict Russian Cosmos 2251 resulted in more than two thousand pieces of debris. In October 2016, a retired satellite from the US Air Force, the Defense Meteorological Satellite Program Flight 12, broke up in orbit. More recently, in March 2021, the breakup of Chinese satellite Yunhai-1 was linked to an accidental collision with a small piece of debris just 10-50 cms in length

---

Extended author information available on the last page of the article associated with a Russian Zenit-2 launcher sent into orbit in 1996. These events and many others have created over 40,000 pieces of debris larger than 10 cm orbiting the Earth and over 140 million smaller debris remaining unchartered [2]. This includes the upper stages of rockets launched into orbit, which eventually become debris. The sizes of space junk vary from a few millimeters, such as glass fragments, to several meters, such as the large non-operational Environment Satellite (ENVISAT) by ESA. Natural meteoroids are also space debris. Yet, regardless of whether debris is natural or artificial, it poses a significant threat to current and future space assets.

In the last 60 years, there have been more than 640 fragmentation events (break-ups, collisions, explosions), yielding clouds of debris of all sizes. The European Space Agency (ESA) estimates that there are currently 40500 debris objects larger than 10 cm [3]. This population already forces satellite operators to adjust course to avoid collisions regularly, and impacts with active satellites have already led to multiple fatalities [4–7]. Unfortunately, the debris population continues to grow quickly (Fig. 1). Worse, collisions between debris occur regularly, which creates a self-sustaining cascading effect. Experts fear that past a certain threshold, the vast number of debris will trigger a chain collision reaction, referred to as the Kessler syndrome [8]. This cascading effect may finally render low and geostationary orbits (LEO and GEO) non-operational. Controlling debris and tracking their orbits are widely recognized as critical tasks to maintain sustainable access to space for decades to come [9–11]. As the intensity of the space debris keeps growing, scalable commercial and affordable solutions are needed to realistically control and collect the uncooperative debris with dimensions above 10 cm at least.

A study from 2006 showed that at that time, even if no future launches occurred, collisions between existing satellites would increase the 10 cm and larger debris population faster than atmospheric drag would remove objects [13]. The market opportunity for debris removal and in-orbit servicing is developing and will become a multi-billion-dollar market by the end of the decade. It is conservatively predicted to be valued at ∼ $4.4Bn in cumulative revenues (within a range of $2.3-7.2Bn) by 2030 [14]. The global space debris monitoring and removal market is projected to grow from $942.3 million in 2022 to $1.5 billion by 2029 [15]. Morgan Stanley's Space Team estimated that the roughly 350 billion global space industry could surge to over 1 trillion by 2040 and consider space debris removal as one of the drivers of the new space ecosystem [16]. This requires suitable policies at the government and international level, e.g. the Zero Debris Charter by ESA [17].

Literature review shows that space debris is a major threat and missed opportunity. According to Leonard and Williams [18], the value of orbital debris suitable for re-use is estimated at $1.2 trillion. Even though space debris orbiting around Earth poses a major threat to operational satellites, the extent of space debris could be an immense wealth of resources to be reused for manufacturing newer systems in orbit [19]. However, research on upcycling and recycling space debris for in-space manufacturing is still in its infancy. Although the upcoming ADR missions aim to deorbit space debris, the remnants returned to Earth are non-biodegradable objects, polluting the oceans and affecting marine lives. Likewise, disposing of the bulk of debris in graveyard orbits is also not a sustainable solution in the long term. Therefore, space agencies, stakeholders, regulators, investors, businesses, and academia should join forces to develop cutting-edge technologies to robotically upcycle or recycle space debris for on-demand manufacturing in orbit.

The next major milestone for human exploration is establishing an operational in-space robotic fabrication laboratory with additive manufacturing capabilities for handling various materials (polymers to metals). Recently, the STARFAB

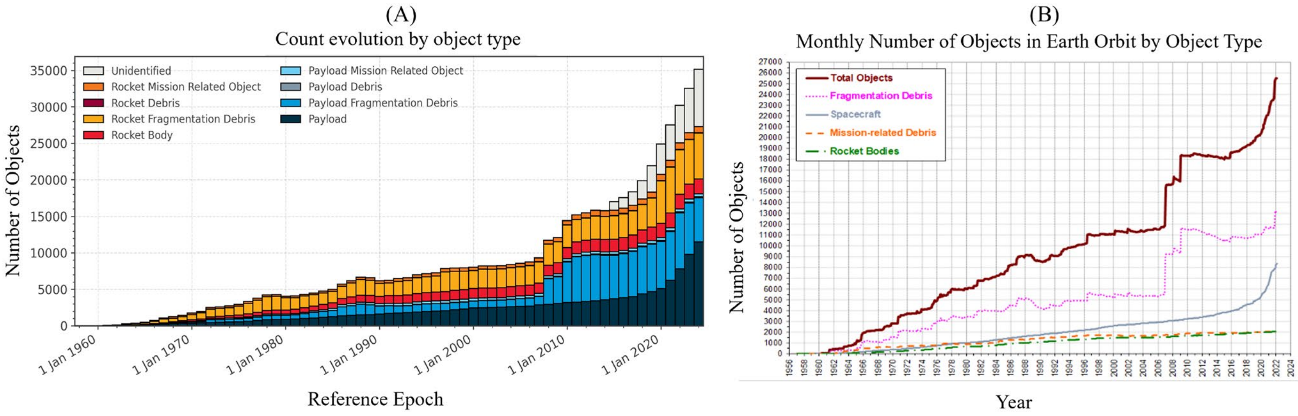

**Fig. 1** (A): Evolution of number of objects in geocentric orbit by object class [3]. (B): number of objects >10 cm in LEO [12]. Steep increases are the result of dramatic fragmentation events. The growth rate of the number of debris is rapidly increasing

project (Fig. 2), funded by the European Commission, officially kicked-off to elaborate a viable concept of an in-space automated warehouse facility to support In-Orbit Servicing, Assembly and Manufacturing (ISAM) applications [20]. However, the aforementioned concept of robotic upcycling, recycling, and sustainable in-space manufacturing sounds like science fiction today, albeit with advancements in space technology. In this paper, we set out a pathway to make this ambitious mission a reality in the decades to come. Initially, we review the state-of-the-art manufacturing in orbit and advancements in robotics with a focus on ADR, followed by a gap analysis in the current understanding of the material science of space debris. Accordingly, a new systems perspective for holistically tackling space debris, harnessing its resources, and additive manufacturing in orbit is presented. With space sustainability at the heart of this paper, the potential scientific, environmental, and commercial benefits of additive manufacturing, upcycling, and recycling in orbit and warehouses in space for implementing on-demand design and fabrication services are presented.

The remainder of this paper is organized as follows: Sect. 2 covers a concise review of the relevant literature mapping the multidimensional subject topics addressed in this paper. The details of the new framework for establishing an orbital space ecosystem and associated critical enabling technologies are described in Sect. 3. Finally, in Sect. 4, inferences are drawn on the technological needs and future directions.

## 2 Scientific and technological review

### 2.1 Robotic active debris capture and removal missions

The Cold War rivalry fuelled a race to develop robotic space technologies. These developments continued after the collapse of the USSR, with former enemies and competitors becoming partners in collaborative scientific projects. Human presence in space is considered a key challenge for all space-faring nations. Therefore, exploration and science missions can and should leverage substantial robotic capabilities for operational excellence and efficiency. Advances in robotic manipulation, control, and grasping technology tremendously increased the range of applications of space robots for planetary and orbital missions, enabling the emergence of whole new classes of missions. Various space robotic manipulators, like the Shuttle Remote Manipulator System, Canadarm-2, Dextre, and the Japanese Experiment Module Remote Manipulator System (JEMRMS), have been critical in the ISS's orbital assembly and other maintenance tasks. Space manipulators have commonly assisted in extra-vehicular activities (EVA) and on-orbit servicing missions. Robotic missions are more reliable, cost-effective, efficient, and safer when compared to human spaceflight. However, it requires the robots to be able to substitute for humans across the operational portfolio, which implies high levels of manipulation dexterity and efficient means to control these robots. Nevertheless, there is an increasing demand for using space robots for large-scale cleaning up of space junk amongst other applications.

**Fig. 2** Artistic impression of STARFAB [20]

Space debris originates in derelict rocket bodies, upper launch stages, and spacecraft abandoned in orbit. Some of these remain intact, but others have collided with one another, corroded, disintegrated, or shed paint flecks, steadily growing the number of objects: 40500 objects greater than 10 cm, 1.1 million objects 1–10 cm, and 130 million 1–10 mm [11]. Objects of all sizes are a threat: Anything larger than a centimeter can severely damage operational spacecraft or launchers [21]. In addition, the larger an object is, the larger the risk of a collision with another, which could lead to a cascading effect discussed above. Objects smaller than a centimeter, including micro-debris composed of paint flecks and solid rocket exhaust particles, force manufacturers to equip spacecraft with heavy shielding; external components, like solar panels, cannot be shielded shielded and have in fact been affected by space debris in several occasions [22].

In the context of space debris removal missions, uncrewed rendezvous and capturing are the only viable solutions. The most accepted concept for removing objects larger than 10 cm is a fleet of debris chasers and refueling stations [23]. The chasers notionally use electric propulsion, although propellant-less chasers that react against the Earth's magnetic field are also under development [24]. Chasers are dispatched to a target, capture it with a designated mechanism [25], de-orbit it or park it on a graveyard orbit, and move on to the next target. However, in flagship ADR efforts funded to date, including RemoveDEBRIS [26], ClearSpace-1 [27], and ELSA-d [28], the focus has largely revolved around the problem of removing a single object.

Handling cooperative and uncooperative targets in orbit poses different types of challenges. The detailed strategy for capturing space debris depends on several factors. If the target is spinning or tumbling, the chaser spacecraft must match this movement, making the approach and capture difficult. It increases the risk of the grappling maneuver going wrong.

Robotic ADR offers many benefits compared to other state-of-the-art debris capture and removal techniques. An exhaustive review of current state-of-the-art debris capture solutions can be found in [29]. Although non-operational legacy satellites were not designed to be remotely serviced in orbit, their salient features could be used to aid in robotic capture and disassembly in a controlled way. This includes ring structures, thrusters, structural beams, fuel tanks, etc. Advancements in robotics and design thinking for disassembly open up opportunities to test novel disassembly methods and create feasible solutions. A gripper-based capture is more deliberate than a harpoon or net. The chaser can slowly and precisely place its gripper onto a solid site on the object that is unlikely to break off or become damaged. In addition, this solution leverages decades of robotics R&D in space and terrestrial sectors. Admittedly, gripper-based methods are operationally more complex than harpoon and net. A gripper-equipped chaser must come in close proximity to the object and delicately grasp it. If the object is spinning, the chaser must align its reach to the motion of the target, either with its manipulator or by synchronizing with the target. These are practical challenges for which one-size-fits-all solutions do not exist and need further developments leveraging today's technology. Synchronization has already been shown to work for debris that spin at 5deg/s [30], and it is worth noting that the spin of metallic debris in LEO can be damped to less than a degree per second within a few years [31]; synchronization is expected to apply to a large fraction if not most LEO objects. Electromagnets have been proposed as a solution to slow fast tumbles [32].

The autonomous robotic capture of an uncooperative tumbling target has a long history of research activities, as the review by [33] shows, and has not yet been openly demonstrated in orbit. The task of reaching out with a free-flying robot to grasp and stabilize an uncontrolled tumbling object requires the interplay of multiple onboard functionalities, including vision and controls. The computational cost of visual tracking limits the rate at which it operates, which motivated the development of state observers that include a dynamic model of the system, to provide adequate state feedback to the robot controller. A first step in this direction was made by [34], where the state of the target object was estimated. During capture, the robot controller had to account for multiple motion constraints and to provide sufficient compliance during contact with the target, to avoid high interaction forces. These features were demonstrated in [34], where the chaser was not actuated, i.e., in free-floating mode [33] and where the target was slowly tumbling and of small size. In this control architecture, a motion planner provides a feasible reference trajectory to account for the nominal motion constraints [35–38].

Further developments in feedback control have addressed the combined control task, e.g., free-flying or coordinated control modes [33]. The free-flying mode involves actuating the chaser, for example, synchronizing it with the grasping point's motion of a large target [30], while also actuating the arm to reach the grasping point [39–41], grasp, and rigidize the arm [42]. In these studies, full-state feedback was always assumed for the free-flying system. Task guidance is generally managed by an onboard skill engine that acts as an execution handler of the operational plan generated on ground by the mission control system. A task-oriented programming paradigm delivers the means of executing the operational plan on-board, without intervention from the ground [43, 44]. A critical aspect of on-orbit activities is the management of action sequences that lead to the accomplishment of the task [45]. In the case of simple missions, the sequence of states and tasks can be firmly defined, or dynamically adapted by a ground or on-board mission planner [46–48]. The concept of a Controlled Floating Space Robot (CSFR), in which the base is free to move with the robot arm but in a controlled manner, outperforms both free-flyers with controlled base and free-floaters with uncontrolled base [49]. CSFR dovetailed with robust pose controllers is an efficient methodology for rendezvous and synchronizing with tumbling targets [50–52].

## 2.2 Materials in space

Satellites are made of materials that resist, without failure or excessive distortion, the static, dynamic, and thermal stresses that occur during launch, deployment, and service [53–55]. Structurally a satellite can be divided mainly into two parts based on the material used and its functionalities. The primary structure comprises components designed to transmit loads through the satellite, attachment points for payloads and associated components. The secondary structure includes the rest of the parts, including solar panels, thermal blankets, and electronics. Aluminium and its alloys are the conventional primary structure material used for flight structures of all types. The main materials used are 2000/7000 series Aluminium for Tanks, Silicon, Lithium, Manganese, Magnesium, Aluminium Alloys, particularly Aluminium-coated polyimide and Kevlar for shielding. Conventionally, Aluminium is converted into alloys with other metals for increased strength and weight reduction; Aluminium is not strong on its own. Aluminium alloys reinforced with silicon carbide, alumina, or boron particulates or fibres offer increased stiffness and strength; however, these materials are more expensive than conventional alloys.

Satellites also use special materials for their various components [54]; for example, Aluminum-Lithium Alloys, Polymer-Matrix Composites, Carbon-Carbon Composites and Metal-Matrix Composites are popular. The Aluminum-Lithium alloys (WeldaliteTM, Alloy 2090, Alloy 8090) offer a weight reduction of 7 to 20 percent to the components manufactured in comparison with the conventional Aluminum alloys. These low-density alloys offer increased stiffness and higher strength and are used in liquid oxygen and liquid hydrogen fuel tanks. Polymer-matrix composites are another class of materials used in flat panel components, structural truss members and propellant tanks of spacecraft. Among the well-used polymer-matrix composite fibers, for example, glass, Kevlar$^{TM}$ and Graphite epoxy, the most commonly used polymer-matrix composite for primary spacecraft structures is Graphite epoxy. The polymer-matrix composites are subjected to environmental degradation effects, and the strength of the components is threatened by three to five years of exposure to the space environment. Carbon-carbon composites are another material used in satellite components that are exposed to extreme temperatures, typically up to 1650°C. These materials are used in the tails and wings of airframes, the leading edge of the nose, and over the parts of the fuselage along with titanium-matrix composite.

Chrome and nickel steel alloys have been widely used for building satellites and launchers for manned and unmanned missions. Their high resistance to extreme temperatures makes them ideal for spacecraft heatshields. The James Webb Space Telescope used steel molds to construct its 6.5m primary mirror containing pressed beryllium powder. Steel tubes are also used for building a telescope's cooling system. Likewise, solar sails use steel booms to ensure proper deployment. Various other sub-systems on board the International Space Station and other spacecraft are made of steel and other high-value materials. A detailed review of materials used onboard satellites and the application of steel and its unprecedented needs in the booming space industry can be found in [56].

## 2.3 Material characterization of space debris

The characteristics of materials used to manufacture a spacecraft vary under extreme environmental factors, but some parts might not degrade quicker even after end-of-service. There is a potential to reuse high-value parts before they become derelict. For capturing, disassembling, reassembling, and reusing debris, it is important to understand the science of materials used for construction [57], lifetime characteristics, and design constraints [58–60]. However, there is little research that dives deeper into the material science of space debris, the closest being [61–64]. In 2021, a study by Yalung et al. (2021) described a material classification methodology for In-Orbit Debris using ESA's DISCOS (Database and Information System Characterising Objects in Space) and other sources. Initially, a classification system based on the shape of objects was developed, and later material properties of each object category were added. However, none of this research covers the aging of systems and subsystems accounting for their physical morphologies, design constraints, and time-varying material properties.

## 2.4 In-space manufacturing

Additive manufacturing techniques are becoming more and more suitable for space applications driving the new era of in-space manufacturing. Additive manufacturing has the advantage of printing parts of various shapes and forms that conventional techniques could not produce. The three-dimensional printed parts accommodate complex designs and offer reduced mass, better performance, and reduced manufacturing time. There are diverse techniques available with different advantages and challenges for printing satellite parts [65, 66]. A few examples are: (a) cavity and flow path creation of EQUULEUS CubeSat thrusters from the Aluminium alloy AlSi10Mg (b) thermal management system for high power CubeSat (ALSat#1 mission) (c) powder-bed fusion of the metal alloy Inconel®718 for the redesign of NASA's thruster (d) stainless steel 316 L and CoCr for liquid rocket engine injector head (e) direct metal laser sintering of AlSi10Mg to prepare antenna feed arrays (f) selective laser melting of permalloy to prepare magnetic shields for fiber optic gyroscopes.

There is growing interest and possibilities in manufacturing materials in space and supporting advances from life sciences to materials, including semi-conductors, proteins, etc. The microgravity environment might simplify certain biological and physical properties and processes. This could offer new opportunities for manufacturing, pharmaceuticals, and other major industries [14]. Hence, there is the potential for discoveries that can both improve life on Earth and advance understanding of space. From more efficient therapies and better vaccines to stronger and more conductive materials, to developing new plant varieties, there are a range of end users and economic opportunities that can change our futures. Life science research on organ biomanufacturing could revolutionize organ transplants; novel materials investigations could transform the fiber optic and semiconductor industries; and plant varieties could be developed that are better adapted to extreme conditions.

## 2.5 Automated robotic disassembly and reuse techniques for low-gravity environments

The latest survey on robotic disassembly techniques in low-gravity environments showed few results. Most research focuses on docking, in-orbit servicing, and assembly rather than in-situ disassembly for reuse [67]. Robotic manipulation and automation are key enablers for in-orbit disassembly, repair and reuse of debris and components [33, 68, 69]. In the literature, orbital robotics focuses primarily on path planning and control of arms in low gravity [70], dynamical modeling of robotic manipulators [71], and capturing tumbling targets [41]. Capturing targets using robotic manipulators is widely studied [72, 73] and so are in-space robotic assembly operations [74]; however, there is limited research on automated robotic disassembly. In the terrestrial industry, automated disassembly of components is driven by the need to recover strategic materials. Dealing with unknown components is a key difficulty in robotic disassembly [75], slowing commercial uptake. Task planning for disassembly operations is in the early stages of implementation. It relies on a knowledge of the component, which is not readily available in the case of space debris [76]. Vision and sensor-guided techniques have been developed for disassembly operations such as fastener detection [77], removal [78], and cutting of components [79].

In-space automated assembly technologies [80], robotic manipulation and capture of objects in space [33] and robotic in-orbit servicing are well-researched topics [81]. Most in-orbit manipulators are designed for specific tasks [82], with contact dynamics and pose estimation studied extensively [83, 84]. Autonomous planning systems have been developed for the semi-autonomous robotic assembly of reconfigurable structures [85], and a concept for modular spacecraft assembly is being developed in Europe [86]. Grasp and path planning with robotics is well evidenced by most terrestrial demonstrations using a combination of vision and deep learning approaches [87]. Cost-benefit assessment is well understood and widely used across several domains [88], with the tool applied primarily in the literature for capture and removal [89]. For terrestrial applications, the design guidelines for disassembly have been widely documented in general design thinking [76, 90]. However, they have not been implemented on spacecraft, with modular design currently at the forefront [85].

Notably, no methodology for cost-benefit assessment has been identified for in-space disassembly and reassembly processes. Though there is some economic modeling of robotic disassembly of terrestrial products [91], there are no such cost-benefit or regulatory assessments for the disassembly and reassembly phases of debris disassembly and reuse in orbit. A recent NASA report [9] is an eye-opener revealing the massive problem caused by space debris and the pressing need for quicker remediation. The cost-benefit analysis published by NASA focuses primarily on remediating the top 50 objects identified by [92]. It estimates that in the absence of active debris remediation, over the next 25 years, the 50 largest debris alone will incur costs of over $1.2b to US satellite operators. Those costs primarily come from impacts from fragments that are expected to be generated from those 50 objects over the next 25 years. The costs associated with controlled re-entry, uncontrolled re-entry, and recycling are not explicitly addressed as they are too high using current space-proven technologies. The findings by NASA further reiterate the need for newer, efficient, scalable, and cost-effective solutions that will go beyond the top 50 objects.

### 2.6 Industry 5.0 and digital manufacturing

The fourth Industrial Revolution, also known as Industry 4.0, and associated technologies ignited disruptive innovation, bringing countless value-creation opportunities across all major market sectors. More specifically, it has enabled the interfacing of multiple elements comprising industrial systems with Internet communication technologies to form smart factories and manufacturing organizations of the future [93]. Industry 5.0 is a new and emerging phase of industrialization that complements the strength of Industry 4.0 while emphasizing the transition to a sustainable, human-centric and resilient industrial ecosystem [94–96].

Cloud-Based Design and Manufacturing (CBDM) refers to a new service-oriented product realization paradigm for the 21st century in the broader context of distributed and collaborative product development [97]. CBDM enables rapid product development efficiently by reducing costs through social networking and negotiating platforms between the service providers and consumers while fostering knowledge and resource sharing. A CBDM is a collaborative and distributed system comprising interconnected physical and virtualized service pools of design and manufacturing resources and associated search and retrieval capabilities. CBDM systems have the potential to become the backbone of future intelligent and semantics-based Web 3.0/4.0 applications. Industry 5.0 and CBDM have a huge potential to galvanize in-space manufacturing, but rigorous research and innovation are needed to advance the technology readiness levels across multi-disciplinary and cross-disciplinary areas.

## 3 Vision of upcycling and recycling of debris for in-space additive manufacturing

The space industry provides immense value to life on Earth by deploying satellite and space infrastructures facilitating communication, navigation, real-time global-scale monitoring of Earth and space, and supporting other technological developments. However, satellites reach end-of-service or become derelict in space due to end-of-lifespan or various technical malfunctions. Millions of space debris, large and small, orbiting Earth threaten the space ecosystem. There is a growing concern over the increasing number of space debris heavily affecting sustainable space operations. To address the alarming issue of space debris, many businesses, space agencies, regulators, investors, and insurers have stepped in to support ADR missions to clean up space strategically. Several upcoming ADR missions aim to de-orbit debris (targeting certain identified objects in various orbits) to a graveyard orbit or to demise upon re-entry. Consensus is being sought on even debris disposal in low-populated areas such as the South Pacific Ocean Uninhabited Area that could affect the marine ecosystem. However, the current business models are neither cost-effective nor environmentally friendly and do not consider the immense wealth of resources that some of this orbital debris offers. De-orbiting or graveyarding an object costs a substantial amount of fuel. De-orbiting some objects while more launches occur regularly is wasteful, even with sophisticated removal technology. Instead of deorbiting and graveyarding, space trash, an immense resource, should be reused and repurposed for manufacturing newer systems in orbit. A sustainable circular space economy appears difficult to develop without reusing orbiting parts and materials.

Due to the increasing awareness of space sustainability, the scientific community is eager to investigate reusing the parts and materials from derelict satellites in orbit as a step towards additive manufacturing in orbit. According to the study by Leonard and Williams [18], a total mass estimate of ~ 7000 tonnes is calculated for space debris having a net worth of ~$600 billion. These findings triggered the quest for harnessing high-value materials in orbit to establish a circular economy for space. However, understanding how much is potentially re-usable (whether materials and/or components) for future space initiatives is not wholly analyzed, and given the resources required for manufacturing and launching spacecraft on Earth, fully maximising their lifecycle in space needs to become an essential goal of the ISAM missions. This endeavor will be feasible if and only if there is a thorough understanding of the factors affecting space debris material properties. This is because the material characteristics change due to various extreme environmental factors once the spacecraft reaches its end-of-service or becomes derelict in space. However, to date, little is known about the ageing material properties of space debris, the potential for reusability of components of current spacecraft or how to design future spacecraft to facilitate remote reuse. These poor practices severely limit the human ability to plan and implement a circular space economy. Moreover, research on upcycling and recycling space debris and additive manufacturing in orbit is still in its infancy, hindering the goal of achieving an in-space circular economy. Although basic research has been carried out, as seen in [66, 98–100], currently, there is a lack of significant impact-based study which is practically viable.

The ability to evaluate and assess orbital debris and then categorise the potential for re-use (re-purpose and recycle, including remanufacture) is vital for establishing in-orbit manufacturing and a circular economy in space. Creating on-demand manufacturing capability in a zero-gravity or microgravity environment using robots and other onboard resources will enable long-duration exploration operations, for both manned and unmanned missions. The feedstock needed for on-demand manufacturing of new/replacement parts or components can be produced by repurposing, reusing, or recycling materials in space, including those previously used for packaging or current space debris. Undoubtedly, such innovations will expand the horizon of in-space operations, facilitating large-scale robotic construction and assembly of high-value infrastructure (e.g., Space-Based Solar Power and Large Aperture Space telescopes [74]) and carrying out repair and maintenance operations of satellites for life extension. In addition to significantly reducing launch costs, it will reduce carbon emissions by cutting down the number of launches and the need for ground-based fabrication. Moreover, it will also eliminate constraints on cargo imposed by the limited fairing capacity of launch vehicles. This will open a whole spectrum of new market opportunities for commercial removal and reuse of debris in orbit, promoting the added value of design for on-orbit reuse for a sustainable circular space economy.

Further, extending this concept to the manufacturing domain, and in step with the on-earth waste hierarchy, are the principles of circular manufacturing (manufacturing products that are long-lasting, easy to repair, refurbish, remanufactured, and recycled) and remanufacturing (where previously sold, worn, or non-functional products can be rebuilt and recovered through the disassembly, cleaning, repair and replacement of worn-out and obsolete components). To truly maximise the waste hierarchy for orbital debris and to regenerate high-value materials in orbit, these approaches must also be considered. Alongside conducting scientific investigations on the material properties of space debris, significant technological advancements in autonomous space robots are needed to undertake upcycling and recycling operations. This requires a change in design principles; future spacecraft should use a modular architecture so that they are designed to be serviced or decommissioned remotely in orbit. Further innovation in autonomous space robotics will unearth a new area of manufacturing new systems and components in orbit, facilitating the establishment of a circular space economy.

The ambitious prospects of using autonomous robots for a multitude of orbital missions, such as ADR, satellite servicing and refuelling, space-based solar power generation, assembly and manufacturing, is driving a new wave of innovation and increasing investments in the space sector. However, it also creates new challenges for the scientific community that need addressing. Validating an end-to-end robotic ADR mission in low-gravity experimental conditions

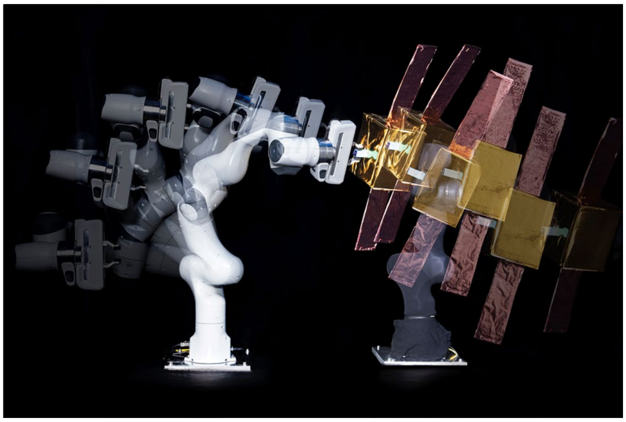

**Fig. 3** Demonstrating robotic ADR using an experimental testbed at the University of Lincoln, UK (Photography courtesy- Max Alexander) [101]

is not feasible, but some functionalities can be verified in earth-analogue setups. Such an experimental ADR testbed is shown in Fig. 3. This image illustrates the complex sequences involved in capturing uncooperative space debris (target on the right) using a spacecraft with a robotic manipulator (chaser on the left). This testbed is used for validating the close-proximity approach, safe capture, and controlling the worst-case tumbling behaviors of the debris for post-capture stabilization and subsequent deorbiting.

The GNC of the chaser spacecraft plays a crucial role in planning and executing debris capture and subsequent disassembly and reuse operations. A multi-layer planner is needed to schedule various processes from capture to reuse autonomously. The most challenging guidance phase is during the close-range operation (e.g., the last 20 m, depending on the target size, shape and rotation rate). As the perception system starts to sense the target pose, i.e. its position, attitude, and rotational velocity, the guidance system plans the course of actions depending on the nature of the target. For example, the target might be known but uncooperative, i.e., the shape and geometry of the target are available only to a certain extent but no information from the Guidance and Navigation System is available. However, the target might be out of control, thus no longer three-axis stabilized, but spinning or even tumbling. Once the chaser synchronizes its motion with the target and positions at a hold-point close to the target, the robotic arm will be deployed to capture the target. Whilst the planner executes the synchronization, capture and digitization, the perception function continues to estimate the pose and track the structure of the target but at a very close range (i.e., it can be down to a few centimeters). The next level of planning generates the post-capture stabilization and detumbling of the coupled system. Thereafter, the planner will schedule the disassembly and reassembly operations based on the sensor data.

Research on In-Situ Resource Utilization (ISRU) has focused primarily on planetary and lunar surface exploration missions. However, the domain of robotic ISRU for in-orbit missions, particularly harnessing resources through robotic disassembly and reuse of space debris, is not well explored. While assembly, disassembly, manufacturing and mining of new materials could arguably be cheaper on the Moon, transporting components to/from the Moon is not profitable. This will invariably require an orbital warehouse for storing objects between capture and reuse; however, there is limited understanding of storage requirements for different space debris. The trades one faces in designing an orbital warehouse depend substantially on understanding downstream disassembly and reuse. Conceptually, an orbital warehouse will house multiple object holders and dexterous robotic manipulators to undertake the (dis)assembly parallelly and collaboratively, thereby freeing up the chaser spacecraft to carry out more capture operations, maximizing its utility. If such an operational orbital warehouse becomes a reality, robotic (dis)assembly operation could commence upon successfully capturing and positioning the debris within the warehouse. Before executing any (dis)assembly or reuse techniques, it is highly important to have information on the debris' material characterization to avoid creating new debris. It is important to note that based on the material's durability, some debris can be repurposed, and others can be recycled to produce feedstock for on-demand manufacturing and re-manufacturing in orbit. The concept of bridging ADR with space debris upcycling and recycling for in-orbit manufacturing is depicted in Fig. 4. This illustration shows the sequence of operations involved, various interdependent and interconnected systems, and the system of systems constituting this complex orbital ecosystem. The vision for a circular economy in space will be facilitated by active debris removal, upcycling (disassembly, reassembly, reuse, or reshape), and recycling in orbit to harness feedstock for in-space manufacturing. It is envisaged that this coherent narrative will trigger discussions amongst scientists, engineers, and stakeholders to address the gaps in scientific understanding, technologies, regulations, and skills to make this vision a reality in the 21st century.

Engineering an orbital warehouse will be a massive undertaking that requires like-minded space agencies, businesses, end-users, policymakers, and investors to join forces. This vision is achievable by spinning cutting-edge terrestrial Industry 5.0 technologies into space, such as AI and

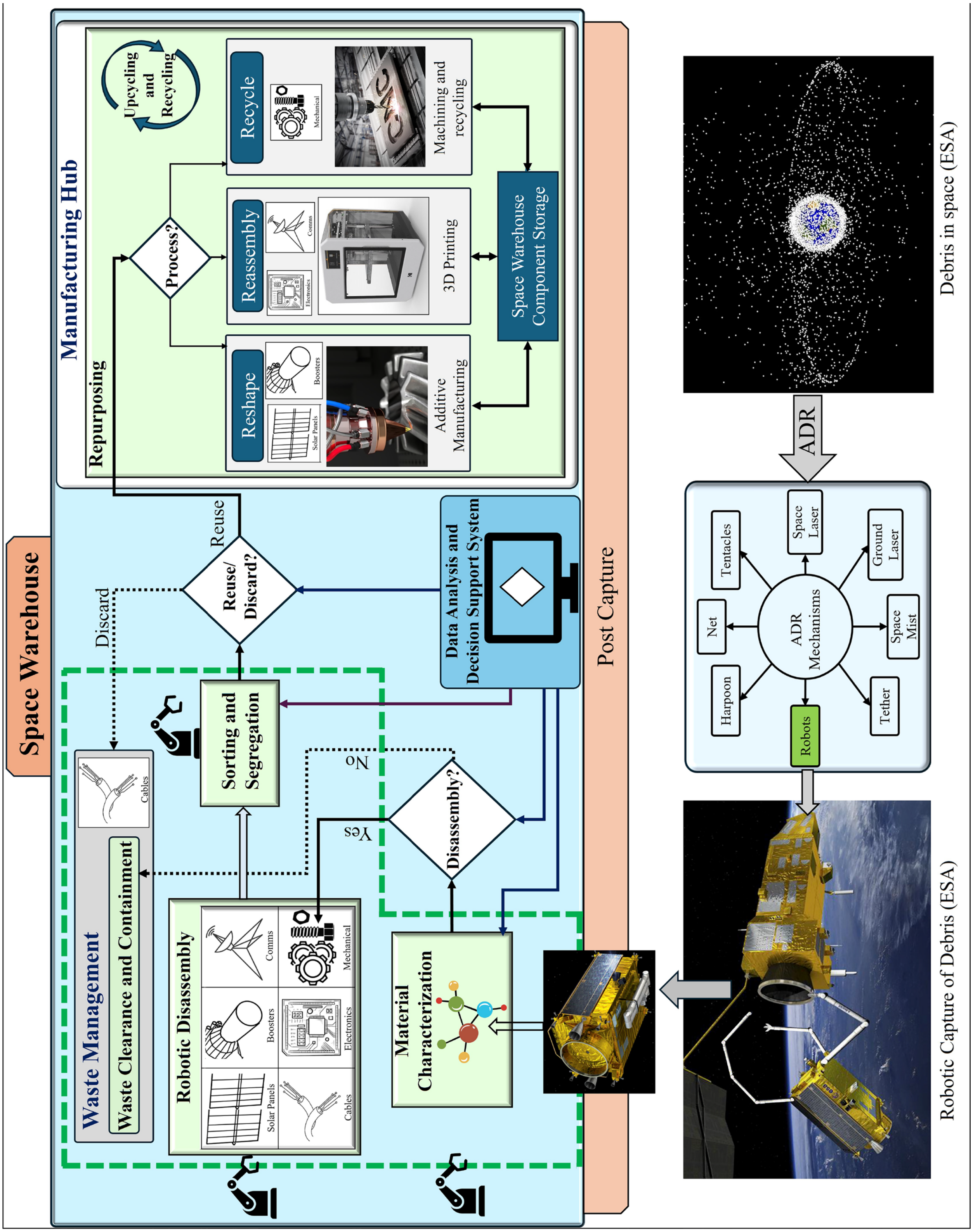

**Fig. 4** Artistic impression of sustainability beyond Earth: A holistic view of the new circular space ecosystem interfacing debris removal, upcycling, and recycling for in-orbit manufacturing

Machine Learning, Nanotechnology, Internet of Things, Human–Machine Collaboration and Biotechnology. These five pillars of the fifth industrial revolution have positively impacted the space industry by unlocking new business opportunities that will eventually change the economics of space. A suite of Industry 5.0 technologies and processes used to revolutionize digital manufacturing on Earth successfully can be applied to propel technological advancements in space to make space missions more accessible and sustainable. Adapting ever-evolving Space 5.0 solutions will enable the transition to a green economy that is more resilient and human-centric. However, the extremities of space and the high cost involved in building Earth analog test facilities at scale make this a difficult venture. Nevertheless, there is boundless potential to use digital technologies to design and validate advanced mission concepts virtually. Binding scaled-down Earth-analogue testbeds with Digital Twinning will help refine the design and evaluate system-level performance before scaling it up to create Digital Twins of a large-scale operational orbital warehouse. Moreover, dovetailing Cloud-Based Design and Manufacturing on Earth and orbital warehouse with other Space 5.0 solutions will catalyze in-space manufacturing. A novel concept of applying CBDM for digital manufacturing beyond Earth is presented in Fig. 5. Fusing disruptive ground-space technologies will facilitate the globalization of commercial in-space manufacturing and address the needs of diverse end-users (upstream and downstream applications) by democratizing the space sector. As Space 5.0 continues to evolve, there is much endurance in expanding the manufacturing horizon beyond Earth, fueling the swift expansion of a sustainable and greener space economy.

## 4 Conclusions

Space offers vital services that have a positive impact on our daily lives. It is envisaged that leveraging innovation in launchers and autonomous robots will create new avenues for a spectrum of in-orbit services, fostering sustainable economic growth and asset management. However, as global space activity booms, space debris proliferation has become a principal threat to satellites and the sustainability of the high-value space assets upon which society depends. Addressing space debris delivers benefits related to space sustainability and develops capabilities that open longer-term opportunities. A paradigm shift in two major areas is needed to address the growing challenges of space debris and increasing demand for manufacturing capability in orbit: (i) manufacturers should create new modular satellites designed to be serviced remotely in orbit for longer lifespans (ii) change the current business models aiming at deorbiting or graveyarding legacy space debris and instead, develop technological capabilities and reformed business models for upcycling and recycling space debris sustainably. The required change of policies should aim to increase the level of responsibility of space agencies, launch companies and satellite operators to take care of their debris and guarantee that at least no more debris is generated. In the best case, policies at the international and national levels should encourage the cleaning of existing debris and the cleaning of orbits, including actions such as upcycling and repurposing existing debris.

Robotic upcycling and recycling materials and digital warehouses in orbit are emerging fields with remarkable potential for changing the economics of space missions. This article provides an up-to-date overview and analysis of the great economic opportunities and technical challenges around scavenging failed satellites and their components to manufacture new parts in orbit. It addresses the benefits of in-orbit upcycling and recycling operations for implementing on-demand design and fabrication services. However, a major leap in technology readiness is needed to operate large-scale space junk sweeping missions as a commercial service. The visionary ideas on CBDM for space creates new business opportunities whilst addressing the scientific and technological barriers.

Comprehensive orbital in-situ resource utilization capabilities are pivotal for future space missions, like space tourism, assembling large-aperture space telescopes and space-based power generation, and setting up human habitats on the Moon and Mars. A suite of technological innovations driven by Robotics, Automation, AI, and Space 5.0 will enable adventurous missions in a shorter timeframe, efficiently and cost-effectively, and facilitate sustainable use of space resources to protect its ecosystem. Pushing the boundaries of in-space manufacturing aligns well with supporting next-generation downstream commercial services to Earth whilst achieving net zero on Earth and in space. It will also create the capability building blocks to enable longer-term commercial opportunities based on servicing, assembly, and manufacture. All these missions will be enabled by close-proximity robotic operations in orbit.

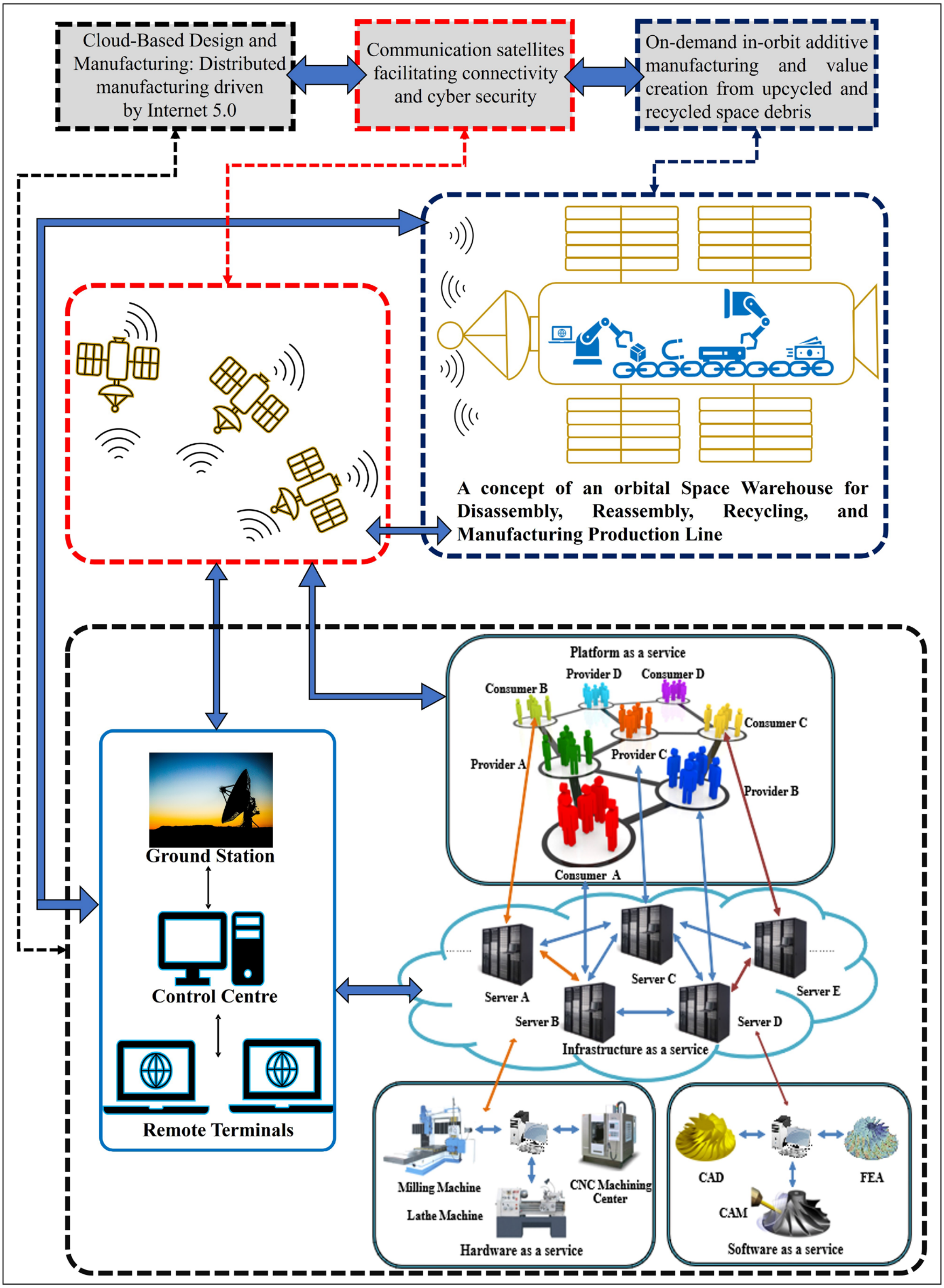

**Fig. 5** Illustration of a new Space 5.0 paradigm enabled by CBDM for distributed digital manufacturing and design innovation on Earth and in space

**Data availability** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

## References

1. International Banker - Brokerage, Space: Investing in the final frontier. https://internationalbanker.com/brokerage/space-investing-in-the-final-frontier/
2. ESA - Space debris by the numbers, https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers Accessed 20 July 2024
3. Space Environment Statistics, Space Debris User Portal, (2024). https://sdup.esoc.esa.int/discosweb/statistics/ Accessed 21 July 2024
4. Plantz, M.R.: Orbital debris: out of space. Ga. J. Int'l Comp. L. **40**, 585 (2011)
5. Banks, R., Auñón, S.M., Harding, R., Mumbower, A.: Spacecraft accident investigation. In: Principles of clinical medicine for space flight, 885–904 (2019)
6. Kelso, T., et al.: Analysis of the iridium 33-cosmos 2251 collision. Adv. Astronaut. Sci. **135**(2), 1099–1112 (2009)
7. Dennerley, J.A.: Managing the risks associated with space debris - risk management in outer space activities: An Australian and New Zealand perspective. In: Space law and policy, 107–149 (2022)
8. Kessler, D.J., Cour-Palais, B.G.: Collision frequency of artificial satellites: the creation of a debris belt. J. Geophys. Res. Space Physics **83**(A6), 2637–2646 (1978)
9. Colvin, T.J., Karcz, J., Wusk, G.: Cost and benefit analysis of orbital debris remediation (2023)
10. ESA - Space Safety: About space debris, https://www.esa.int/Space_Safety/Space_Debris/About_space_debris Accessed 21 July 2024
11. ESA - Space debris by the numbers, (2023). https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers Accessed 21 July 2024
12. NASA, LEGEND: 3D/OD Evolutionary Model, March 2023, [Online]. Available:. https://orbitaldebris.jsc.nasa.gov/modeling/legend.html [Last Accessed: 21st July 2024]
13. Liou, J.-C., Johnson, N.L.: Risks in space from orbiting debris. American Association for the Advancement of Science (2006)
14. Catapult, A \$1Bn UK opportunity for In-Orbit Services, (2021). https://sa.catapult.org.uk/news/in-orbit-servicing-capability/ Accessed 21 July 2024
15. Forbes, The global space debris monitoring and removal market is projected to grow from \$942.3 million in 2022 to \$1,527.7 million by 2029, at a CAGR of 7.15%, (2022). https://www.fortunebusinessinsights.com/space-debris-monitoring-and-removalmarket-104070 Accessed 21 July 2024
16. Morgan Stanley, The New Space Economy, (2022). https://www.morganstanley.com/Themes/global-space-economy Accessed 21 July 2024
17. ESA - The Zero Debris Charter, https://www.esa.int/Space_Safety/Clean_Space/The_Zero_Debris_Charter Accessed 20 July 2024
18. Leonard, R., Williams, I.D.: Viability of a circular economy for space debris. Waste Manage. **155**, 19–28 (2023)
19. Koch, F.: Orbit Recycling, (2024) https://orbitrecycling.space/ Accessed 21 July 2024
20. STARFAB - A space warehouse concept and ecosystem to energize European in-space assembly and manufacturing, (2024). https://www.horizon-starfab.com Accessed 21 July 2024
21. Liou, J.-C.: An active debris removal parametric study for LEO environment remediation. Adv. Space Res. **47**(11), 1865–1876 (2011)
22. Christiansen, E.: Micrometeoroid and orbital debris (MMOD) risk overview. In: NASA in-space inspection technology workshop (ISIW 2014) (2014)
23. Levin, E., Pearson, J., Carroll, J.: Wholesale debris removal from LEO. Acta Astronaut. **73**, 100–108 (2012)
24. Stuart, J., Howell, K., Wilson, R.: Application of multi-agent coordination methods to the design of space debris mitigation tours. Adv. Space Res. **57**(8), 1680–1697 (2016)
25. Shan, M., Guo, J., Gill, E.: Review and comparison of active space debris capturing and removal methods. Prog. Aerosp. Sci. **80**, 18–32 (2016)
26. Aglietti, G.S., Taylor, B., Fellowes, S., Salmon, T., Retat, I., Hall, A., Chabot, T., Pisseloup, A., Cox, C., Mafficini, A., et al.: The active space debris removal mission removedebris. Part 2: In orbit operations. Acta Astronautica **168**, 310–322 (2020)
27. Biesbroek, R., Aziz, S., Wolahan, A., Cipolla, S.-f., Richard-Noca, M., Piguet, L.: The Clearspace-1 mission: ESA and Clearspace team up to remove debris. In: Proc. 8th Eur. Conf. Sp. Debris, pp. 1– 3 ( 2021)
28. Blackerby, C., Okamoto, A., Fujimoto, K., Okada, N., Forshaw, J.L., Auburn, J.: ELSA-D: an in-orbit end-of-life demonstration mission. Proc. Int. Astronaut. Congr. IAC **6**, 43644 (2018)
29. Poozhiyil, M., Nair, M.H., Rai, M.C., Hall, A., Meringolo, C., Shilton, M., Kay, S., Forte, D., Sweeting, M., Antoniou, N., et al.: Active debris removal: a review and case study on LEOPARD Phase 0-A Mission. Adv. Space Res. (2023)
30. Jaekel, S., Lampariello, R., Rackl, W., De Stefano, M., Oumer, N., Giordano, A.M., Porges, O., Pietras, M., Brunner, B., Ratti, J., et al.: Design and operational elements of the robotic subsystem for the e deorbit debris removal mission. Front. Robot. AI **5**, 100 (2018)
31. Praly, N., Hillion, M., Bonnal, C., Laurent-Varin, J., Petit, N.: Study on the Eddy current damping of the spin dynamics of space debris from the Ariane launcher upper stages. Acta Astronaut. **76**, 145–153 (2012)
32. Yu, C., Gao, S.: Reducing collision checking for sampling-based motion planning using graph neural networks. Adv. Neural. Inf. Process. Syst. **34**, 4274–4289 (2021)
33. Papadopoulos, E., Aghili, F., Ma, O., Lampariello, R.: Robotic manipulation and capture in space: a survey. Front. Robot. AI, 228 (2021)

34. Lampariello, R., Mishra, H., Oumer, N., Schmidt, P., De Stefano, M., Albu-Schäffer, A.: Tracking control for the grasping of a tumbling satellite with a free-floating robot. IEEE Robot. Autom. Lett. **3**(4), 3638–3645 (2018)
35. Lampariello, R., Nguyen-Tuong, D., Castellini, C., Hirzinger, G., Peters, J.: Trajectory planning for optimal robot catching in real-time. In: IEEE international conference on robotics and automation, pp 3719– 3726 (2011)
36. Lampariello, R., Hirzinger, G.: Generating feasible trajectories for autonomous on-orbit grasping of spinning debris in a useful time. In: IEEE/RSJ international conference on intelligent robots and systems, pp 5652– 5659 (2013)
37. Virgili-Llop, J., Zagaris, C., Zappulla, R., Bradstreet, A., Romano, M.: A convex-programming-based guidance algorithm to capture a tumbling object on orbit using a spacecraft equipped with a robotic manipulator. Int. J. Robot. Res. **38**(1), 40–72 (2019)
38. Calzolari, D., Lampariello, R., Giordano, A.M.: Singularity maps of space robots and their application to gradient-based trajectory planning. Science and Systems (RSS), Robotics (2020)
39. De Stefano, M., Mishra, H., Balachandran, R., Lampariello, R., Ott, C., Secchi, C.: Multi-rate tracking control for a space robot on a controlled satellite: A passivity-based strategy. IEEE Robot. Autom. Lett. **4**(2), 1319–1326 (2019)
40. Giordano, A.M.: Whole-body control of orbital robots. PhD thesis, Technische Universität München (2020)
41. Mishra, H., De Stefano, M., Giordano, A.M., Lampariello, R., Ott, C.: A geometric controller for fully-actuated robotic capture of a tumbling target. In: American control conference (ACC), pp. 2150– 2157 ( 2020). IEEE
42. Vijayan, R., De Stefano, M., Ott, C.: A detumbling strategy for an orbital manipulator in the post-grasp phase. In: International conference on robotics and automation (ICRA), pp. 4080– 4086 ( 2022). IEEE
43. Jaekel, S., Brunner, B., Laroque, C., Flentge, F., Krueger, T., Schiele, A.: Robops-approaching a holistic and unified interface service definition for future robotic spacecraft. In: 13th symposium on advanced space technologies in robotics and automation (ASTRA) (2015)
44. Benninghoff, H., Rems, F., Risse, E., Brunner, B., Stelzer, M., Krenn, R., Reiner, M., Stangl, C., Gnat, M.: End-to-end simulation and verification of GNC and robotic systems considering both space segment and ground segment. CEAS Space J. **10**, 535–553 (2018)
45. Moghaddam, B.M., Chhabra, R.: On the guidance, navigation and control of in-orbit space robotic missions: A survey and prospective vision. Acta Astronaut. **184**, 70–100 (2021)
46. Tipaldi, M., Glielmo, L.: A survey on model-based mission planning and execution for autonomous spacecraft. IEEE Syst. J. **12**(4), 3893–3905 (2017)
47. Steel, R., Niézette, M., Cesta, A., Fratini, S., Oddi, A., Cortellessa, G., Rasconi, R., Verfaillie, G., Pralet, C., Lavagna, M., et al.: Advanced planning and scheduling initiative mrspock aims for xmas. Language. **1050** (3) (2009)
48. Peters, S., Pirzkall, C., Fiedler, H., Förstner, R.: Mission concept and autonomy considerations for active debris removal. Acta Astronaut. **129**, 410–418 (2016)
49. Seddaoui, A., Saaj, C.M., Nair, M.H.: Modeling a controlled-floating space robot for in-space services: a beginner's tutorial. Front. Robot. AI **8**, 725333 (2021)
50. Specht, C., Bishnoi, A., Lampariello, R.: Autonomous spacecraft rendezvous using tube-based model predictive control: design and application. J. Guidance Control Dyn., 1–19 (2023)
51. Zhao, X., Emami, M.R., Zhang, S.: Image-based control for rendezvous and synchronization with a tumbling space debris. Acta Astronaut. **179**, 56–68 (2021)
52. Zhao, X., Emami, M.R., Zhang, S.: Robust image-based control for spacecraft uncooperative rendezvous and synchronization using a zooming camera. Acta Astronaut. **184**, 128–141 (2021)
53. Kopacz, J.R., Herschitz, R., Roney, J.: Small satellites an overview and assessment. Acta Astronaut. **170**, 93–105 (2020)
54. National Research Council - Technology for Small Spacecraft, National Academies Press, (1994)
55. Weston, S., Miller, C.S., Ingersoll, J.E., Yost, B.D., Agasid, E., Burton, R., Carlino, R., Defouw, G., Perez, A.D., Karacalioglu, A.G., et al.: State of the art: Small spacecraft technology (2018)
56. Rai, M., Schaefer, D., Nair, M., Poozhiyil, M., Dulanty, S., et al.: Green steel: a new frontier for in-space manufacturing and circular economy (2023)
57. Finckenor, M.M.: Materials for spacecraft. Technical report, American Institute of Aeronautics and Astronautics (2018)
58. Gonzalo, J., Domínguez, D., López, D.: On the challenge of a century lifespan satellite. Prog. Aerosp. Sci. **70**, 28–41 (2014)
59. Abdelal, G.F., Atef, A.: Thermal fatigue analysis of solar panel structure for micro-satellite applications. Int. J. Mech. Mater. Des. **4**, 53–62 (2008)
60. Abulgasem, S., Tubbal, F., Raad, R., Theoharis, P.I., Lu, S., Iranmanesh, S.: Antenna designs for cubesats: A review. IEEE Access **9**, 45289–45324 (2021)
61. Toomer, C., Bolouri, A., Thompson, A., Yalung, F.: Modelling of the materials classification of in-orbit debris using discosweb and other sources (2021)
62. Mengqi, S., Xinqing, Y., Guiming, L., Zhongmin, H.: Fuzzy-based analysis of thermal effects on component failure for LEO satellites. In: IEEE 2nd international conference on big data, artificial intelligence and internet of things engineering (ICBAIE), pp. 933– 943 ( 2021)
63. Bock, F.E., Aydin, R.C., Cyron, C.J., Huber, N., Kalidindi, S.R., Klusemann, B.: A review of the application of machine learning and data mining approaches in continuum materials mechanics. Front. Mater. **6**, 110 (2019)
64. Plota, A., Masek, A.: Lifetime prediction methods for degradable polymeric materials–a short review. Materials **13**(20), 4507 (2020)
65. Blachowicz, T., Ehrmann, G., Ehrmann, A.: Metal additive manufacturing for satellites and rockets. Appl. Sci. **11**(24), 12036 (2021)
66. Sears, P.J., Ho, K.: Impact evaluation of in-space additive manufacturing and recycling technologies for on-orbit servicing. J. Spacecr. Rocket. **55**(6), 1498–1508 (2018)
67. Mitros, Z., Paraskevas, I.S., Papadopoulos, E.G.: On robotic impact docking for on orbit servicing. In: 24th IEEE mediterranean conference on control and automation (MED), pp. 1120–1125 ( 2016)
68. ESA - How many space debris objects are currently in orbit?, (2024). https://www.esa.int/Space_Safety/Clean_Space/How_many_space_debris_objects _are_currently_in_orbit Accessed 21 July 2024
69. ESA - Space Debris Mitigation, (2023). https://technology.esa.int/page/space-debris-mitigation (Accessed 21 July 2024)
70. Misra, G., Bai, X.: Optimal path planning for free-flying space manipulators via sequential convex programming. J. Guid. Control. Dyn. **40**(11), 3019–3026 (2017)
71. Nanos, K., Papadopoulos, E.G.: On the dynamics and control of flexible joint space manipulators. Control. Eng. Pract. **45**, 230–243 (2015)
72. Moosavian, S.A.A., Papadopoulos, E.: Cooperative object manipulation with contact impact using multiple impedance control. Int. J. Control Autom. Syst. **8**, 314–327 (2010)
73. Mou, F., Wu, S., Xiao, X., Zhang, T., Ma, O.: Control of a space manipulator capturing a rotating object in the three-dimensional

space. In: 15th IEEE international conference on ubiquitous robots (UR), pp. 763– 768 (2018)

74. Roa, M.A., Nottensteiner, K., Wedler, A., Grunwald, G.: Robotic technologies for in-space assembly operations. In: Proc. Symp. Adv. Space Technol. Robot. Automat. (ASTRA), pp. 5– 14 (2017)
75. Foo, G., Kara, S., Pagnucco, M.: Challenges of robotic disassembly in practice. Procedia CIRP **105**, 513–518 (2022)
76. Santochi, M., Dini, G., Failli, F.: Computer aided disassembly planning: state of the art and perspectives. CIRP Ann. **51**(2), 507–529 (2002)
77. Yildiz, E., Wörgötter, F.: Dcnn-based screw detection for automated disassembly processes. In: 15th IEEE international conference on signal-image technology and internet-based systems (SITIS), pp. 187– 192 (2019)
78. Li, R., Pham, D.T., Huang, J., Tan, Y., Qu, M., Wang, Y., Kerin, M., Jiang, K., Su, S., Ji, C., et al.: Unfastening of hexagonal headed screws by a collaborative robot. IEEE Trans. Autom. Sci. Eng. **17**(3), 1455–1468 (2020)
79. Chen, W.H., Foo, G., Kara, S., Pagnucco, M.: Automated generation and execution of disassembly actions. Robot. Comput. Integr. Manuf. **68**, 102056 (2021)
80. Zhihui, X., Jinguo, L., Chenchen, W., Yuchuang, T.: Review of in-space assembly technologies. Chin. J. Aeronaut. **34**(11), 21–47 (2021)
81. Ma, B., Jiang, Z., Liu, Y., Xie, Z.: Advances in space robots for on-orbit servicing: a comprehensive review. Adv. Intell. Syst., 2200397 (2023)
82. McBryan, K.: Comparing multi-arm robotics for in-space assembly. Front. Space Technol. **3**, 702614 (2022)
83. Aghili, F.: Modeling and analysis of multiple impacts in multibody systems under unilateral and bilateral constrains based on linear projection operators. Multibody Sys.Dyn. **46**(1), 41–62 (2019)
84. Agrawal, S.K., Pathak, K., Franch, J., Lampariello, R., Hirzinger, G.: A differentially flat open-chain space robot with arbitrarily oriented joint axes and two momentum wheels at the base. IEEE Trans. Autom. Control **54**(9), 2185–2191 (2009)
85. Rodríguez, I., Bauer, A.S., Nottensteiner, K., Leidner, D., Grunwald, G., Roa, M.A.: Autonomous robot planning system for in-space assembly of reconfigurable structures. In: IEEE aerospace conference (50100), pp. 1– 17 (2021)
86. Letier, P., Yan, X.T., Deremetz, M., Bianco, A., Grunwald, G., Roa, M., Krenn, R., Arancón, M.M., Dissaux, P., Casarrubios, J.S.G., et al.: MOSAR: modular spacecraft assembly and reconfiguration demonstrator. In: 15th symposium on advanced space technologies in robotics and automation (2019)
87. Duan, H., Wang, P., Huang, Y., Xu, G., Wei, W., Shen, X.: Robotics dexterous grasping: The methods based on point cloud and deep learning. Front. Neurorobot. **15**, 658280 (2021)
88. Griffin, R.C.: The fundamental principles of cost-benefit analysis. Water Resour. Res. **34**(8), 2063–2071 (1998)
89. Loughman, J.: Overview and analysis of the soldier satellite concept for removal of space debris. In: AIAA space conference and exposition, p. 8909 (2010)
90. Bogue, R.: Design for disassembly: a critical twenty-first century discipline. Assem. Autom. **27**(4), 285–289 (2007)
91. Ramírez, F.J., Aledo, J.A., Gamez, J.A., Pham, D.T.: Economic modelling of robotic disassembly in end-of-life product recovery for remanufacturing. Comput. Ind. Eng. **142**, 106339 (2020)
92. McKnight, D., Witner, R., Letizia, F., Lemmens, S., Anselmo, L., Pardini, C., Rossi, A., Kunstadter, C., Kawamoto, S., Aslanov, V., et al.: Identifying the 50 statistically-most-concerning derelict objects in LEO. Acta Astronaut. **181**, 282–291 (2021)
93. Thames, L., Schaefer, D.: Cybersecurity for industry 4.0 and advanced manufacturing environments with ensemble intelligence. Cybersecurity for Industry 4.0: Analysis for Design and Manufacturing, pp. 243–265 (2017)
94. European Commission - Research and innovation, Industry 5.0, (2024). https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/industry-50_en Accessed 21 July 2024
95. Barata, J., Kayser, I.: Industry 5.0–past, present, and near future. Proc. Comput Sci. **219**, 778–788 (2023)
96. Adel, A.: Future of industry 5.0 in society: Human-centric solutions, challenges and prospective research areas. J. Cloud Comput. **11**(1), 1–15 (2022)
97. Schaefer, D.: Cloud-based design and manufacturing (cbdm). A service-oriented product development paradigm for the 21st century 2014 (2014)
98. Fung, T.-Y., Roy, S.S., Shi, Q., DeLaurentis, D.A.: Space junk aggregation, neutralization, in-situ transformation, and orbital recycling. In: 17th IEEE annual system of systems engineering conference (SOSE), pp. 239– 245 (2022)
99. Matasa, I., Häuplik-Meusburgerb, S.: Order: Space station for orbital debris recycling population **4**, 8–10 (2018)
100. Linne, D.L., Palaszewski, B.A., Gokoglu, S.A., Balasubramaniam, B., Hegde, U.G., Gallo, C.: Waste management options for long-duration space missions: when to reject, reuse, or recycle. In: 7th symposium on space resource utilization, p. 0497 (2014)
101. Rai, M.C., Alexander, M.: Space debris: How the UK is tackling sustainability beyond the Earth. Science in Parliament, Winter Edition, All-Party Parliamentary Group's Journal of the Parliamentary and Scientific Committee (in press) (2024)

## Authors and Affiliations

**Mini C. Rai[1] · Manu H. Nair[1] · Dirk Schaefer[2] · Renaud Detry[3] · Mithun Poozhiyil[4] · Justyna Rybicka[4] · Shan Dulanty[4] · Josie Gotz[4] · Maximo A. Roa[5] · Roberto Lampariello[5] · Shashank Govindaraj[6] · Jeremi Gancet[6]**

✉ Manu H. Nair
mn1503mn@gmail.com

Mini C. Rai
dr_minicrai@orbitrise.co.uk

Dirk Schaefer
D.Schaefer@hull.ac.uk

Renaud Detry
Renaud.Detry@kuleuven.be

Mithun Poozhiyil
Mithun.Poozhiyil@the-mtc.org

Justyna Rybicka
Justyna.Rybicka@the-mtc.org

Shan Dulanty
Shan.Dulanty@the-mtc.org

Josie Gotz
Josie.Gotz@the-mtc.org

Maximo A. Roa
Maximo.Roa@dlr.de

Roberto Lampariello
Roberto.Lampariello@dlr.de

Shashank Govindaraj
Shashank.Govindaraj@spaceapplications.com

Jeremi Gancet
Jeremi.Gancet@spaceapplications.com

[1] Lincoln Centre for Autonomous Systems, School of Engineering, University of Lincoln, Lincoln LN6 7TS, UK

[2] Faculty of Science and Engineering, University of Hull, Cottingham Rd, Hull HU6 7RX, UK

[3] KU Leuven, Kasteelpark Arenberg 10 - box 2441, Leuven B-3001, Belgium

[4] Manufacturing Technology Centre, Coventry CV7 9JU, UK

[5] DLR German Aerospace Center, Muenchener Str. 20, Wessling 82234, Germany

[6] Space Applications Services NV/SA, Leuvensesteenweg 325, Sint-Stevens-Woluwe, Brussels 1932, Belgium