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The Making of the International Space Station (ISS): Implications for Construction Robotics and Automation

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ABSTRACT: The International Space Station (ISS) is a complex environment and the biggest human-made structure ever sent to the Earth's orbit. The ISS is an international collaboration involving five space agencies, including the United States, Russia, Japan, Canada, and European countries. The ISS is comprised of various components, including modular pressurized and non-pressurized spaces, trusses, solar panels, and several other elements, such as robotic arms. The ISS mission started in 1998, and it has since served as a human habitat in the extreme environment of outer space. The ISS prefabricated modular construction is an important example of a fully industrialized construction process built with modules that were shipped by more than 40 shuttle missions and then assembled in the Earth's orbit by astronauts and robotic technologies. The modular construction of the ISS has facilitated not only the assembly of interconnected components but also future expansions, periodic maintenance, flexible design, and zero fatality. The goal of this paper is to identify lessons learned from the ISS construction for its implications in construction automation in terrestrial environments. This paper provides a comprehensive case study review of the making of the ISS as it applies to the field of design and construction in the built environment, including modular design and construction, truss structure, energy systems, construction stages, assembly process, and construction robotic systems used during the ISS construction. The results identified opportunities for off-site fabrication, construction in extreme environments, sustainability, maintenance, safety, and robotics, as well as possible design and construction challenges.

1. INTRODUCTION

The International Space Station (ISS) is an exceptionally complex humanmade habitable satellite, that orbits the Earth at an altitude of over 254 mi (300 Km) enduring different conditions such as ultraviolet and ionizing radiation, space debris, Ionospheric plasma, high vacuum, extreme temperature, microgravity, and meteoroids (Damjanov and Crouch 2019; Thirsk et al. 2009). Humans have adapted to terrestrial circumstances over millennia, and life in space demands sophisticated interdisciplinary strategies to meet these challenges (Sarma and Shelhamer 2024). The ISS demonstrates international teamwork by uniting efforts from many space agencies (CSA 2024; ESA 2025; JAXA 2025; NASA 2025a). According to the National Aeronautics and Space Administration (NASA), the ISS has been in orbit for 25 years today, and more than 270 astronauts have visited this station (NASA 2025a). These missions have proved that the ISS structure is acceptable for long-term human settlement, and it will continue to serve in orbit until 2030 (Shen et al. 2024). The ISS comprises integrated truss structures merged with a modular design using a prefabrication approach (Bruner et al. 2004; Zipay et al. 2012). In prefabrication, components are produced offsite and transported to the site for assembly. Using modular design, the components of a system are assembled. The prefabrication and modular assembly of the ISS are ensured by several complex techniques, tasks, and scientific studies including the fabrication of components on Earth (Zipay et al. 2012), space transportation, and assembly in space using space walks, technologies like robotics and techniques such as docking and berthing (Arney et al. 2023; Zhihui et al. 2021). Despite operating in a highly hazardous environment with zero fatalities, the ISS showcases advanced planning and safety systems that surpass current Earth-based industrialized construction, which still struggles with manufacturing limitations and supply chain inefficiencies (Qi et al. 2020; Sanchez and Voss 2005). Studies have investigated the construction processes of the ISS with a focus on structural aspects, but there are limited studies on the ISS with a focus on construction engineering and management topics (Zipay et al. 2012). This paper examines the technologies and processes applied in the ISS construction, highlighting modular design, robotics, prefabrication, and planning to find lessons that can improve terrestrial construction practices, particularly in harsh and remote environments such as deserts, polar regions, and post-disaster zones.

2. BACKGROUND

Exploring and living in space was a persistent consideration of humans, and several theoretical attempts to live in space took place until the 1950s, when the concept of a space station emerged from the United States government (NASA 2024a). Consequently, NASA began to study the design of a space station in 1960 (Wensley 1984). Russia (formerly known as the Soviet Union), at the same time, started to focus on a smaller station after the unsuccessful launch of the N-1 Rocket (NASA 2024a). After an invitation from the U.S. President Ronald Reagan in 1984 to build the space station Freedom (Dupuis 2013), Canada, Japan, and eleven countries of Country (i.e., Belgium, Denmark, France, Germany, Italy, The Netherlands, Norway, Spain, Sweden, Switzerland, and The United Kingdom) agreed to collaborate with the U.S. in 1986 (Dupuis 2013). This collaboration began a new phase in space station design, setting the foundation for future modular and international projects. On the other hand, at the same time, the first space station, Mir, was launched by Russia into orbit around 248.5 mi (400 Km) from the Earth, and it operated for 15 years. The modular design of Mir and its operational technologies, including long-duration research and docking systems, laid the necessary groundwork for the development of the ISS (Luchinski et al. 2003; NASA 2025a). The design of the new space station, Freedom, started between 1984 and 1993, and the fabrication of its components started in the U.S. as well as the collaborating countries (NASA 2024a). The impending collapse of the Soviet Union and the end of the Cold War paved the path for international cooperation after 1990 (Pedersen 1992). In 1993, Russia joined the space station program, and ISS underwent a redesign. Mir space station was built up of 7 modules with a total mass of 285,900 lb (129,908 kg) and 12,400 SF (1,150.8 m²) of habitable volume and hosted 125 astronauts from 12 countries during its 13 years of human occupation. Advanced technologies like long-duration research and docking systems were later used in the ISS development (NASA 2024a). From 1994 to 1998, seven American astronauts lived with Russian astronauts on the Mir space station for 1000 days in orbit. This phase of cooperation between the U.S. and Russia prepared the programs for collaboration on the ISS (NASA 2023). Finally, in 2001, after six days of deorbiting, Mir crashed into the Southern Pacific Ocean, and the ISS remained the only habitable space satellite operated through international collaborations (Luchinski et al. 2003). This historical development underscores the importance of modularity, international cooperation, and adaptability in constructing space habitats, principles that hold valuable lessons for the construction industry on Earth.

3. RESEARCH METHOD

This paper provides a case study of the ISS construction by reviewing current literature and media sources. An in-depth analysis is performed by studying scholarly articles, historical data, and technical reports associated with the design of the ISS, modular assembly, and long-term operations. A media review includes relevant videos and documentaries demonstrating the ISS structure and construction processes. Additionally, websites and online resources from space agencies, including NASA, the European Space Agency (ESA), the Canadian Space Agency (CSA), and the Japan Aerospace Exploration Agency (JAXA), were reviewed to support the analysis with updated data of missions. Each source is critically evaluated to ensure the reliability and relevance of the findings. The methodology follows a multi-step analytical framework to achieve the paper's objective by collecting and reviewing technical and academic sources related to the design and assembly of the ISS. Categorizing processes and technologies involved in the operation of the ISS resulted in four main themes: modularity, prefabrication, robotics, and planning. A comparative analysis was performed to identify similarities between the ISS construction strategies and current terrestrial practices. Finally, the study assessed the opportunities for knowledge sharing by identifying lessons learned from the ISS and evaluating their feasibility and usability to terrestrial construction projects.

4. OVERVIEW OF THE ISS

Although certain modifications are still occurring in the ISS construction (NASA 2025a), the assembly was finished in 2010 at an orbital inclination of 51.6°, a velocity of 17,000-17,200 mph (27,360-27,720 km/h), and an altitude of 230-286 mi (370-460 km). The ISS assembly required control systems from international collaborators (NASA 2025b). The station's performance relies on specific modules, vehicles, and technologies like robotic arms given by JAXA, ESA, and CSA (Arney et al. 2023), while NASA coordinates utilization activities on the ISS to manage international partnerships (Ruttley et al. 2017). In order to provide habitation for crew members and as docking points for visiting spacecraft (Johnson Space Center 2015) life-support elements such as solar arrays, heat radiators, and external payloads are supported by the Integrated Truss Structure (ITS) with a length of 310 ft (94 m) and combination of 14 cylindrical pressurized modules with the length of 218 ft (67 m) including nodes, laboratories, airlocks and docking adapters (Johnson Space Center 2015; NASA 2025a). Moreover, its modularity facilitates not only the assembly of interconnected modules but also simple maintenance and flexible design (Post et al. 2021). The ISS has a pressurized volume of 35,491 CF (1,005 m^3) and a mass of 925,335 lb (419,725 kg). However, only 13,696 CF (388 m^3) of this pressurized volume is habitable, excluding visiting vehicles (NASA 2025a). The ISS is outfitted with solar panels to generate the required energy. As per NASA's webpage (NASA 2015) updated in 2015, the solar arrays aboard the ISS reach 240 ft (73 m), their total area is 27,000 SF (2,500 m^2), and their output ranges from 84 to 120 kilowatts. However, according to (Hyde et al. 2019), in 2019, the total surface area of solar arrays increased to 54,400 SF (5,053 m^2), with 12 solar array wings. Eight solar array wings span a total of 50,900 SF (4,725 m^2) on the U.S. Orbital Segment (USOS), and four smaller wings span a total of 3,500 SF (328 m^2) on the Russian Segment (RS), but the output range in kilowatts is unclear to the authors. According to the latest data from NASA, recently launched Roll-Out Solar Arrays (ROSA) increased the ISS's power output by 30%; each ROSA set generates more than 20 kilowatts. Today, the ISS comprises pressurized and non-pressurized modules (NASA 2025a) and trusses to facilitate its microgravity research and experiment objectives (Bruner et al. 2004).

5. MODULAR DESIGN

The ISS is the product of the connection and integration of trusses, modules, solar arrays, radiators, and other elements, such as robotics (NASA 2025a). Figure 1 shows connectivity details among the ISS trusses, modular parts, and units. It highlighted the layout into two sections, Russia (yellow) and the U.S. (remaining layout). 12 "Truss" sections labeled as S6, S5, S3/S4, S1, S0, P1, P3/P4, P5, P6, and Z1 are named according to their position, P for port (right), S for starboard (left), and Z for zenith (top center); and supports solar systems, radiators and external storage platforms (Johnson Space Center 2015). "Solar arrays," including ROSA and Photovoltaic Arrays (PVR), convert sunlight to electrical power to support ISS operations (NASA 2025a). "Radiators" labeled as Starboard and Port Heat Resistant Subsystem Radiators regulate the thermal environment of the ISS by dissipating excess heat (NASA 2025a). "Pressurized Modules" are designed as linked capsules that provide habitable areas for astronauts to live and work (Bruner et al. 2004), and "Units" are like robotic arms for assembly and maintenance (NASA 2025a).

Key modules on the U.S. section of the ISS include the Quest airlock for spacewalks, Unity, Harmony, and Tranquility nodes, and the Destiny laboratory as well as Bigelow Expanded Activity Module (BEAM), which is an expandable module. The scientific capability of the U.S. sector is further enhanced with the integration of (a) the Japanese Kibo by JAXA that consists of the pressurized module, the experiment logistics module, and the exposed facility and is equipped with a 32.9 ft (10 m) Remote Manipulator System (RMS) (JAXA 2025; NASA 2025a), and (b) Columbus by the ESA which supports research in fluid physics, materials science, and life sciences, and the Automated Transfer Vehicle (ATV) (ESA 2025). The ESA modules include Tranquility which provides additional crew space (NASA 2025a), Harmony node as a critical hub connecting international science labs and cargo spacecraft (NASA 2025b), Columbus Laboratory with research capabilities for various scientific experiments (NASA 2025b), Cupola for observing external operations on the ISS that also houses the workstation for controlling Canadarm 2 (NASA 2025b), and Permanent Multipurpose Module (PMM) used for a variety of storage and utility needs, including food, equipment, and trash (Walsh et al. 2024). Jointly, these components enable the space station to conduct research, maintain life support systems, and facilitate space exploration (NASA 2025b).

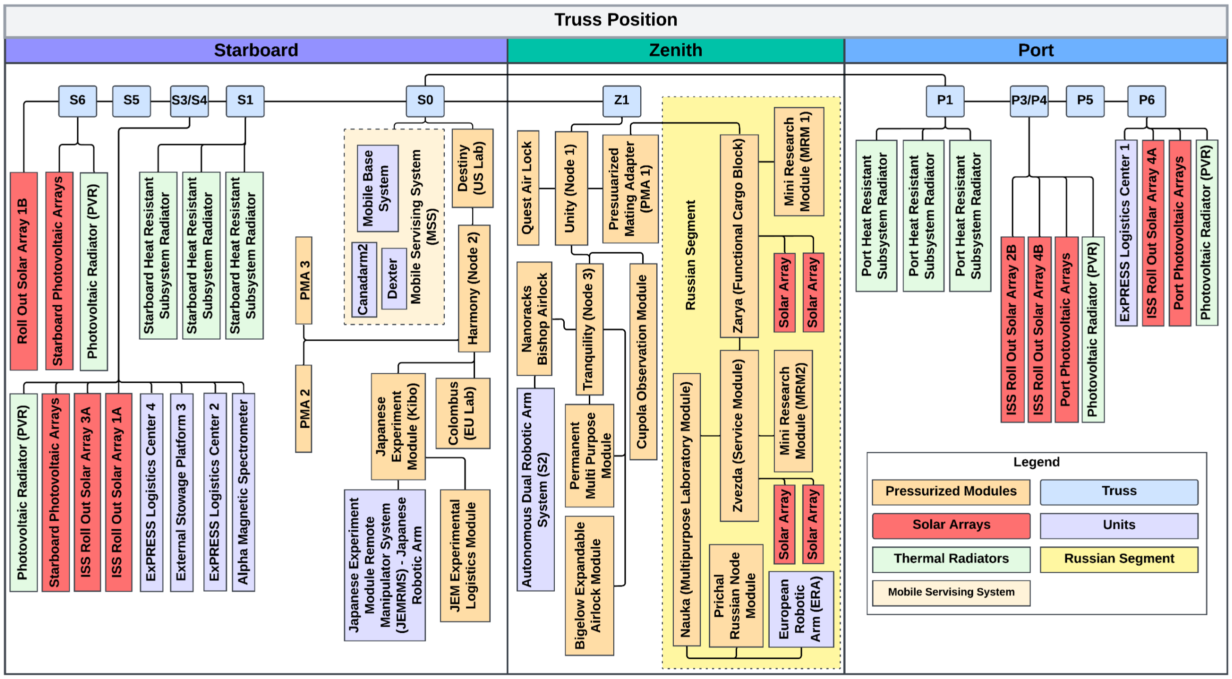

Figure 1: Integration and connectivity of the ISS truss and modular system

By the end of 2021, six modules were forming the ISS Russian segment (Shown in Figure 1) (Sorokin et al. 2022). Russian modules include Zarya module known as the functional cargo block which was the first component to be launched for the ISS, Nauka Multi-Purpose Laboratory module (MML) as the largest laboratory module of the Russian segment (NASA 2025b), Zvezda that provides propulsion and supervises flight operations (NASA 2025b), Poisk docking module for crew access (NASA 2025b), Rassvet a.k.a. the Mini-Research Module (MRM-1) that adds a fourth docking port for Russian space crafts (NASA 2025a), and Prichal module the latest module connected to Nauka MML (NASA 2025b). While the modular design of ISS demonstrates efficiency, safety, and interoperability, it is also influenced by unique economic and regulatory frameworks (Farand 2001). Unlike terrestrial construction, which is driven by cost-efficiency, real estate markets, or client needs (Walacik and Chmielewska 2024), space-based infrastructure is typically funded through multinational governmental agreements (NASA 2025a), and cost–benefit analysis focused on scientific return and geopolitical collaboration, rather than financial profit (Ruttley et al. 2017).

6. CONSTRUCTION AND FABRICATION PROCESS OF THE ISS

6.1 Fabrication on Earth

All components of the ISS are fabricated on Earth and transferred to orbit for assembly during missions involving astronauts and robotics (Zhihui et al. 2021; Zipay et al. 2012). According to (Lim et al. 2017) extraterrestrial spaces are categorized into three types based on their fabrication and assembly process:

Type I or prefabricated hard-shell units, such as most of the ISS modules like Destiny, Unity, and Zarya, which are categorized as non-expandable modules. Type II structures are manufactured on Earth and set up on-site, such as expandable structures, and Type III structures originate from In-Situ Resource Utilization (ISRU), which could be a mix of type I and II to create an enhanced ecosystem (Lim et al. 2017). The BEAM module aboard the ISS is an example of a Type II structure initially fabricated on Earth in compact form and launched as a part of the SpaceX Commercial Resupply Mission. After it docked to the port of node 3 (tranquility module) of the ISS, it started expansion on-site (Taylor et al. 2020). Modules like Unity Node, Destiny Laboratory, and Quest Airlock were built by the Boeing Company in cooperation with McDonnel-Douglas, Grumman Aerospace, and Corning in Huntsville, Alabama. The pressure shells of the Modules were created from Aluminium 2219 material and welded using Electron Beam Welding and Variable Plasma Arc Welding, which come with their distinct challenges. For example, a welding mismatch problem occurred during Unity manufacturing due to heat input from the Variable Polarity Plasma Arc (VPPA) process. This problem led to a welding schedule redesign and improved the manufacturing tools' robustness. The truss segments for the ISS were pre-integrated and fabricated on Earth, undergoing complete testing and structural verification to confirm safety during launch and orbit operation. These segments were assembled and verified by a group of structural engineers from space agencies before their launch to space.

6.2 Logistics and Transport to Space

The Earth-based tasks that ensured ISS components' structural integrity and longevity from transport to orbit through assembly and operations have not been thoroughly documented (Zipay et al. 2012). The ISS was assembled over multiple flights, utilizing the U.S. vehicles named Shuttle and Russian launch vehicles such as the Soyuz, and Proton, with contributions of spacecraft like Dragon and Cygnus to deliver dry cargo, propellant, eater, atmospheric gas, and other standard logistical supplies (Arney et al. 2023; Johnson Space Center 2015). Assembly occurred in low-Earth orbit (LEO) at 200 mi (322 km) above Earth, posing challenges like extreme temperatures and a near vacuum (Foster et al. 2004a). The U.S. used three space shuttles, Discovery, Atlantis, and Endeavour, capable of delivering 14 ft (4.27 m) diameter by 50 ft (15.24 m) long structures with a cargo capacity of 35,000 lb (16,000 kg) (Galvez et al. 2010). Shuttle preparation involved a strict "flow" process of pre-checking the shuttle, payloads, Solid Rocket Boosters (SRBs), and External Tank (ET), requiring NASA and Boeing engineers to create critical mission guidelines, manuals, software, and plans for each mission, taking four to five months of work. The flight sequence involved ten steps, including liftoff, solid rocket booster separation, main engine cutoff, external tank separation, orbital maneuvering, and on-orbit operations to connect the transported module to the ISS using robotic arms. Canadarm2 helped attach modules, and the Orbital Maneuvering System initiated deorbit before landing, with the “flow” process restarting afterward (Galvez et al. 2010; Johnson Space Center 2015).

6.3 Assembly in Space

The ISS assembly required interagency collaboration and unique assembly techniques after launching and transferring the ISS elements to space using the modular approach (Foster et al. 2004a). The assembly process demanded astronaut training, broad flight mission planning, and robotic support (Rembala and Ower 2009). Microgravity was one of the important challenges of the ISS assembly, which even required specific tools for simple tasks like securing bolts (Foster et al. 2004a). Several assembly techniques have been used in the ISS to ensure safety, efficiency, and structural integrity. The modular construction approach enabled flexibility and expansion during its 13-year assembly period (Arney et al. 2023; NASA 2025a) by using mechanisms like the Common Berthing Mechanism (CBM) and Androgynous Peripheral Attach System (APAS) to connect habitable and pressurized ducts for transferring crew (Arney et al. 2023; Foster et al. 2004b). Additionally, assembling unpressurized components on the ISS employs specialized structural connection mechanisms, such as the Segment-to-Segment Attachment System (SSAS). This automated system facilitates the precise alignment, capture, and bolting of inboard truss segments, including P1-S0, S1-S0, P3-P1, and S3-S1 (as illustrated in Figure 1), to ensure mechanical stability and load transfer across the integrated truss structure. Rocketdyne Truss Attachment System (RTAS) is the manual version of SSAS, which assembles outboard truss elements using man operation bolts and Common Attachments system (CAS) for attaching payloads such as experiment and logistics cargo support structures to the P3 and S3 trusses (Foster et al. 2004b). In the ISS assembly, four essential processes were involved: Rendezvous and Proximity Operations (RPO), docking, capture, and mating, relying on manual and automated docking procedures (Arney et al. 2023). These techniques enabled the interaction between spacecraft. RPO refers to the maneuvers of a satellite while considering the movement and position of another satellite. Docking is the process where a satellite moves into position to mate with another spacecraft. These two technologies were crucial in merging modular units of the ISS. Capture refers to when a larger satellite grabs a smaller one to connect with it. Finally, mating is the operation that uses two spacecraft to join each other. After delivering modules and supplies by spacecraft, standardized docking systems enhanced optimization in attaching components and maintaining space structures. Astronauts performed Extravehicular Activities (EVAs), commonly called spacewalks, to install structural hardware manually, establish electrical and data connections, and conduct maintenance operations on the ISS. These operations are planned precisely to ensure astronauts' safety during manual assembly or repairs when operations are not completed only by robotic systems (Arney et al. 2023).

7. UTILIZING ROBOTIC TECHNOLOGIES

There are many roles that robotics can perform in the field of extraterrestrial construction, such as assembly and maintenance for mega structures in space like space stations, telescopes, and solar power stations (Jiang et al. 2022; Zhihui et al. 2021). Robots are suitable for long-term and extravehicular missions due to their unlimited physical potential, and these aspects lead to their performance in harsh environments that impact astronauts' health and safety risks (Jiang et al. 2022). Robots can also operate continuously and be controlled remotely, facilitating optimal separation of crew members and Earth-based functions to save time and increase efficiency (Rembala and Ower 2009). Some robots can perform tasks precisely, such as dexterous manipulators and high-precision sensors (Jiang et al. 2022), and can reduce the need for humans by long-distance operations and working autonomously (Post et al. 2021; Rembala and Ower 2009). Robots in the ISS can be categorized into two types, as specified below.

7.1 Construction and Maintenance Robots

In ISS construction, Canadarm2 and the European Robotic Arm (ERA) are utilized in deploying, capturing, and moving payloads. They also assisted in docking spacecraft and completing several missions (Jiang et al. 2022). Space Station Remote Manipulator System (SSRMS), known as Canadarm2, is part of CSA participation in ISS with the 57.7 ft (17 m) long robotic arm that played a significant role in ISS assembly. Each end of Canadarm2 is created as an identical hand, famous as the Latching End Effect (LEE). The LEEs are made of cables that can be tight and allow the robotic arm to grasp objects or latch itself to the station (CSA 2024; NASA 2025a). ERA is a robotic arm that walks through the Russian segment of the ISS to install, remove, and replace payloads and transport crew members. It can operate autonomously or execute astronaut’s commands. The arm's seven Degrees of Freedom (DoF) and flexibility make it useful for maintaining and operating tasks of the ISS (ESA 2025). The Kibo Remote Manipulator System (KiboRMS) is a robotic arm on the ISS’s Japanese Experiment Module, designed for moving payloads and replacing Orbital Replacement Units on the Exposed Facility. It consists of a 32.8 ft (10 m) main arm and a 4.9 ft (1.5 m) fine arm, both with six DoF, allowing precise manipulation like a human arm (JAXA 2025; NASA 2025a). Special Purpose Dexterous Manipulator (SPDM), known as Dextre, with a 3,664 lb (1,662 kg) weight and 11.4 ft (3.5 m) length, is a robotic system operated remotely by NASA and CSA that provides maintenance services like changing batteries and cameras. It features dual arms, precision tools, and video equipment, reducing the need for spacewalk missions by astronauts. Mobile Base System (MBS), which has 3,196 lb (1450kg) and 18.5 ft (5.6m) length, provides a movable platform for Canadarm2 and Dextre. It can access eight workstations with power connections to complete several tasks (NASA 2025a). Canadarm2, Dextre, and MBS all form the Mobile Servicing System (MSS) (Aziz and Chappell 2004). In 2024, an autonomous S2 dual robotic arm with a 4.92 ft (1.5m) length was transported to the ISS aboard SpaceX’s Falcon 9. It is mounted on Nanoracks Bishop Airlock and performs in-space servicing, maintenance, and assembly tasks in EVA activities (GITAI 2024).

7.2 Non-Construction Robots

In the ISS, other robots help the crew perform tasks. Robonaut 2 (R2) is a humanoid robot developed by NASA and boarded in 2011 is designed to represent human movements to assist and replace astronauts.

R2 has 42 DoF and over 350 sensors to complete tasks precisely (Jiang et al. 2022). Astrobee is another NASA robot designed as a free-flying robot to assist astronauts' regular tasks on the ISS. Astrobee includes three cube-shaped robots, Honey, Queen, and Bumble, that move using electric fans and cameras. Launched in 2018 and 2019, it assisted in developing robotics for future missions like lunar and Mars explorations (NASA 2024b). Multiple unmanned missions have played a crucial role during the construction of the ISS, including autonomous systems, remote operations, and health monitoring. Autonomous systems allow robots to perform tasks with minimal human interaction by combining high and low-level commands. Remote operations were conducted from Earth to monitor and control robots, which helped reduce the crew time and did not require real-time in-person human work (Rembala and Ower 2009; Zhihui et al. 2021).

8. DISCUSSION: OPPORTUNITIES FOR CONSTRUCTION AUTOMATION

Lessons from the ISS assembly continue to affect space construction projects and provide opportunities for terrestrial construction projects. The main lessons learned from the ISS include construction management, safety, methods of recycling, and renewable energy systems.

8.1 Construction Management

During the ISS assembly, scheduling and planning procedures were complex and divided into distinct stages to ensure effective management. These stages included strategic planning, tactical planning, pre-increment planning, and increment execution (Popov 2003). Strategic planning refers to a five-year timeframe prioritizing the establishment of long-term goals and estimating resource needs like crew time and logistics (Leuttgens and Volpp 1998). Tactical planning takes one year to develop increment definition and requirements documents (IDRDs), which assign resources and define the priorities of each mission for each increment. Pre-increment planning is long-term planning that starts between 1 and 18 months before launch with the delivery of Baseline and extends until the increment's launch when flight and increment products are developed. Increment execution looks at short-term detailed operations such as short-term plans (STP) and onboard short-term plans (OSTP), which focus on daily and weekly activities (Leuttgens and Volpp 1998; Popov 2003). According to (Popov 2003) a key process is integrating the planning of devices for the management of resources, robotics planning, and flight dynamics. The Integrated Planning System (IPS) helped solve restrictions like resource supply and operational challenges. It further assists robotic operations such as the MSS. This unified structure helps the ISS respond to progressive needs while enhancing operations among international collaborations (Leuttgens and Volpp 1998; Popov 2003). Although terrestrial construction already utilizes phases planning, the ISS emphasizes the need for organized phases, which includes long-term, short-term, and detailed planning. Implementing a comprehensive system like IPS in construction could improve and streamline operations and resource management, reduce delays, and enhance communication.

Lessons from the ISS's modular design can reduce waste and assembly time. In the construction sector, prefabricated modules can help with faster production and less waste. An expandable module like BEAM (Taylor et al. 2020) is another lesson for the construction industry and for instances when there is an urgent need for shelter in post-disaster areas (Lines et al. 2022). Similar robotic technologies used in the ISS construction are being applied in Earth-based projects. For example, SAM (Semi-Automated Mason) automates bricklaying, improving efficiency, and automated rebar tying robots like Advanced Construction Robotics streamline repetitive tasks. 3D printing technologies also print homes and components on-site, showcasing parallels to modular assembly techniques used in the ISS (Gharbia et al. 2020).

8.2 Safety

Since the ISS was successful in terms of safety, with zero fatalities (Freiberg and Zhou 2020), these insights can benefit terrestrial construction projects. One of the critical challenges in space is the exposure to the extreme environment. Temperature regulation on the ISS EVAs relies on active heating, passive heating, and active cooling systems provided by extravehicular mobility units or space suits. Similar approaches can be used in terrestrial construction sites for workers in extremely hot or cold environments. Noise exposure is another challenge in space that the ISS overcomes with crew noise monitoring using acoustic monitor hardware (Limardo et al. 2021), acoustic insulation, and hearing protection. These methods can be utilized in construction sites to protect workers from the intense sounds of machinery and tools. Astronauts face risks from micrometeoroid strikes and unexpected punctures during space walks. To reduce this risk, a space suit with 14 Kevlar layers has been produced to minimize penetration risks (Thirsk et al. 2009). This holistic approach to safety clothing can be helpful for construction workers to keep them safe against sharp debris or falling objects. In the ISS, wearable biosensors, such as BioHarness and Astroskin, are used by astronauts to track their heart rate, movement, sleep patterns, and hydration level (Belobrajdic et al. 2021). These technologies and implantable biomarker monitoring like blood glucose can be adapted for construction workers, especially those working in remote locations. Also, Prognostics and Health Management (PHM) systems on the ISS allow for early medical diagnosis and prevention of health risks (Popov et al. 2016). Implementing these approaches in construction will help prevent accidents related to fatigue, dehydration, and other health conditions. Furthermore, robotics helps with ISS tasks by reducing the need for high-risk spacewalks (Ticker and Callen 2012). In terrestrial construction, robotic systems similar to those used in the ISS can potentially help perform hazardous tasks such as inspections at height and working in harsh environments to improve workers' safety.

8.3 Recycling and Renewable Energy

The efficient use of available resources is essential for providing a consistent life support system on the ISS. Water is a critical need supplied by several systems and technologies in the ISS (Grigoriev et al. 2011). The Environmental Control and Life Support System (ECLSS) produces potable water for drinking, hygiene, and oxygen generation from sources such as humidity condensate, urine, and sweat (Damjanov and Crouch 2019). Sorption-catalytic purification and vacuum distillation are crucial technologies of this process to supply water with persistent quality (Grigoriev et al. 2011). The water recovery system (WRS) significantly reduces the supply needed from the Earth by recycling water from waste liquid. Thus, the recycling water system of the ISS supports consistent sustainability (Grigoriev et al. 2011). The closed-loop system and recycling technologies prove an effective model for water supply in arid or hard-to-access locations and in construction tasks that need water supply, such as concrete work. The ISS solar arrays are designed to automatically track the sun as the station orbits the Earth (Reddy et al. 2011). ROSA uses a flexible photovoltaic surface supported by storable cylindrical extendible members (STEM booms) developed by Deployable Space Systems (DSS), which eliminates the need for motors in deployment to have structural stability (Chamberlain et al. 2021). Lightweight and flexible ROSA (Spence et al. 2018) substrates can inspire the construction industry by utilizing lightweight and portable photovoltaic surfaces. Rosas scalable design (Spence et al. 2018) supports prefabricated building elements for flexible and fast construction.

9. CONCLUSION

Industrialized construction and prefabrication are growing fields in the construction industry. By examining the ISS's modular design, prefabrication, phased planning, and robotics, this study identified key strategies that can enhance terrestrial industrialized construction. Notable lessons include using comprehensive planning systems like IPS to streamline project phases, applying modular and robotic technologies to improve efficiency and safety, and integrating advanced wearable and environmental monitoring systems to protect workers. Additionally, the closed-loop water recycling and solar technologies used in the ISS offer models for sustainable use of natural resources. These insights highlight the value of adapting space-based innovations to Earth-based projects. Future research can explore robotic systems and in-situ resource utilization to support fully automated, sustainable construction on Earth and in extraterrestrial environments.

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