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Review of In-Space Assembly Technologies

Qaveem Idrees
Centre for Precision Manufacturing,
DMEM, Glasgow, UK
Univeristy of Strathcylde
Glasgow, UK
qaveem.idrees@strath.ac.uk

Xichun Luo
Centre for Precision Manufacturing,
DMEM, Glasgow, UK
Univeristy of Strathcylde
Glasgow, UK

Wenkun Xie
Centre for Precision Manufacturing,
DMEM, Glasgow, UK
Univeristy of Strathcylde
Glasgow, UK

Dorothy Evans
National Manufacting Insitute Scotland
(NMIS)
Glasgow, UK

Abstract*—In-Space Assembly (ISA) refers to assembly processes which occur above the Karmen Line. It is a novel method of assembling structures in space as an alternative to traditional terrestrial based assembly methods. ISA technologies are some of the most advanced and innovative, combing powerful software with robotics and high-level machinery. There are many advantages of using ISA, but there are also a number of challenges, such as human-robot coordination, precision and efficiency and large-scale assembly. This paper reviews these challenges and discusses how they can be overcome with the use of autonomous robotics as well as digital twin technology with AI integration and use of predictive maintenance.

***Keywords*—In-Space Assembly, In-Orbit, On-orbit, Space Manufacturing, Digital Twin**

I. Introduction

The current model for manufacturing or assembling spacecraft and satellites is to first manufacture them on Earth, using sophisticated and high precision machinery, integrate them into a launch vehicle and then deploy the spacecraft into orbit with a single launch. Other than the International Space Station (ISS), this is how spacecraft have been deployed into orbit since Sputnik 1 was launched in 1957. This model is limited to the capabilities of the launch vehicle, mainly size, shape, and mass, resulting in complex mechanisms to fold and stow antennas, solar panels and other appendages, and unappealing "box" designs. The extreme vibrations and stress of a launch also requires for additional structural support and redundancy for electrical components. Simply put, spacecraft are designed to survive the launch rather than for maximum performance. Due to this, In-Space assembly (ISA), becomes an attractive alternative, as ISA allows for the assembly of larger structures with lower mass for cheaper costs and with greater efficiency [1].

In-space assembly can be split into two components, "in-space" and "assembly". Space is defined as the region beyond the Earth's atmosphere [2]. The internationally agreed upon boundary between the Earth's atmosphere and Space is the Karman line, 100km (62 miles) above mean sea level [3]. Assembly can be defined as putting parts or components together to make a machine or other products [4]. In-space assembly can therefore be defined as the construction of spacecraft, -systems, and -structures above the von Kármán line, using prefabricated elements, components, or modules.

The advantages of ISA are regarded as:

- Deploy structures which due to launch vehicle constraints such as fairing, shape and size cannot be launched from Earth,
- Increase the flexibility and resilience of spacecraft and their assets with payload additions, replacements and updates,
- Cost savings due to less "packaging" material and more useful mass such as components and sensors,
- Number of and the intensity of ground testing is reduced, leading to further cost savings,
- Terrestrial gravitational constraints are minimised [1].

These advantages lead to scientific and commercial space advancements allowing of the development of new structures and architectures which do not fall under the constraints of gravity, current manufacturing processes and launch vehicle limitations [1]. Figure 1 shows the development of ISAM technologies which have or are being demonstrated and established over time. Starting in 1969 with Soyuz 6 cosmonauts demonstrating welding in orbit, the first-time vacuum welding was done. Cosmonaut Valeri Kubasov used Vulkan to test three different methods of welding; plasma arc, electron beam and gas metal arc [5] [6]. In 1990 the Hubble Telescope was launched and demonstrated in-space servicing. Missions included repairing existing instruments, installation of new instruments and replacement of critical hardware [7]. In 1998 the modular assembly of International Space Station (ISS), the largest humanmade object to orbit Earth, begun. Using the Remote Manipulator System, the modules of the ISS were connected to one another to form complete the space station. Through to 2020 with PULSAR, the robotic assembly

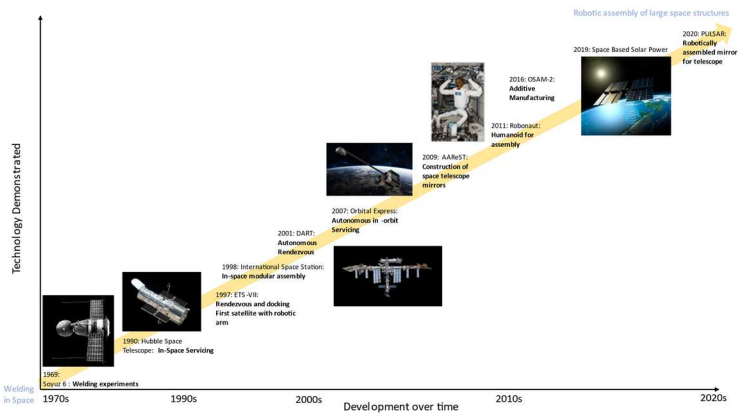

Fig 1: Graph showing the Development of ISAM technologies over time

of large mirrors in space for a space-based telescope. Research is ongoing on modular assembly techniques as well as autonomous assembly [8]. ISA is a new technology and current knowledge is dispersed. This paper aims to classify current research and to provide a structured review, whilst exploring what future developments can be made in ISA. The rest of this paper discusses technologies that enable ISA, the challenges faced by ISA, and how these challenges can be overcome, ending with concluding remarks.

This paper is part of larger literature review, in which roughly 273 papers, books and reports were read and analysed. For this paper 38 were chosen to provide a high-level review in-space assembly technology. The search criteria used "in-space assembly", "in-space manufacturing", and "in-space robotics". The reason being the overlap between the topics, resulting in a larger data set. Other in-space activities such as serving were also looked at, however we stayed focused on in-space assembly as that is the scope of this review and project.

II. Classification of In-Space Assembly

Based upon the complexity of the assembly task, ISA can be classified into four different levels. Level 1 is mating between elements. This is where two or more independent spacecraft are assembled into a larger structure. This level is the least complex. Level 2 is modular assembly. This involves the docking and assembly of cabins and modules to either create a spacecraft or to expand and rebuild one. Level 3 is the complex assembly of components. This involves an assembly sequence linking operation and interactions, for the assembly to connect. Level 4 is assembly from parts. This involves multiple stages of assembly, where individual parts are assembled to create components, which are then assembled to create the spacecraft [9].

A. Level 1 Assembly- Mating between Elements

Level 1 Assembly is the least complex assembly procedure. Two or more existing spacecraft are joined together to form a larger single spacecraft/structure. Most common examples are resupply missions, where the independent capsule docks with another spacecraft and forms part of a larger space structure. Although this process is known as rendezvous and docking, the technological process is mating between two elements. There are examples of Level 1 assembly for ISA, one such example is iBOSS. The Intelligent Building blocks for on-orbit satellite servicing and assembly (iBOSS), was launched in 2010 in Germany. This is an in-space manufacturing program designed for a reconfigurable spacecraft which uses standardised interfaces and modular design for on-orbit assembly and service. Using a "building block" design, the satellite is constructed of 40cm individual cubes, each containing different subsystems and sub-components. The cubes are joined together via multi-function interfaces. By using standardisation and modulization, iBOSS aims to reduce the cost of satellite maintenance whilst simultaneously studying the technologies for smart intelligent subs to reconfigure spacecraft [10] [9].

B. Level 2 Assembly -Modular

Level 2 assembly is the most common and well-known assembly process in space. This is where space modules are docked and assembled together in order to form an independent large structure. The International Space Station took 10 years and over 30 missions to be fully assembled. It is the largest structure ever assembled in orbit, approximately the size of a football field and weighing 460 tonnes [11]. The assembly began in 1998, with the launch of Zarya, a Russian module. The Russian modules were launched and docked robotically, whilst the other modules were delivered by the Space Shuttle and were installed by crewmembers with the assistance of the Canadaram2 [12].

C. Level 3 Assembly – Complex Assembly of Components

On-orbit Servicing, Assembly and Manufacturing 1, OSAM-1, is a robotic spacecraft designed as a servicing robot, to expand the lifespans of satellites. During the mission, OSAM-1 will rendezvous, attach, refuel, and then redeploy a satellite. OSAM-1 would also include a payload called Space Infrastructure Dexterous Robot (SPIDER). Previously known as Dragonfly, SPIDER will assemble 3-meter communications antennas out of seven elements, to communicate with a ground station on Earth in Ka-band [13].

D. Level 4 – Assembly from Parts

Level 4 is the most complex assembly on terrestrial applications and becomes far more complex when you move to space applications. This assembly requires the use of both in-space manufacturing, as launching individual parts into space would not be cost efficient, and in-space assembly. In-space manufacturing (ISM) is its own detailed subject area, and is not within the scope of this paper, however there are some overlapping shared technologies between ISM and ISA. OSAM-2 is one such example. OSAM-2 is a partnership between NASA and Redwire to demonstrate the deployment of a solar array, whilst using additive manufacturing to print one of the structural beams. The technology demonstration would include the construction of two beams and then the deployment of a surrogate solar array using robotic manipulation [14].

E. Summary:

Figure 2 shows the various levels of assembly, organised by complexity with examples of each assembly level given.

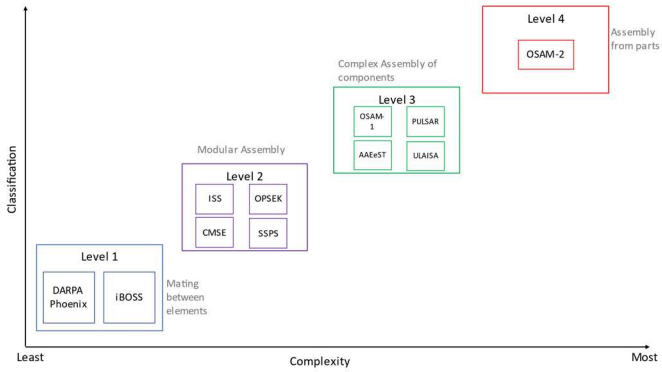

Fig 2: Graph showing the increasing complexity of ISA technologies

There are of course many other examples of ISA research, which have been summarised in Table 1, showing the technology demonstrated, its limitations and future direction.

TABLE I. TABLE SHOWING ISA TECHNOLOGIES AND THEIR LIMATIONS

Project/Program	Technology	Limitations	Future Direction
International Space Station	Modular Assembly	Alignment precision Manual & Robotic labour Standardisation and Integration challenges Testing and Validation Constraints	ISS being retired, but modular assembly is a stalwart in ISA and will be used for future missions.
The Demonstration for Autonomous Rendezvous Technology, DART	Autonomous rendezvous using laser based optical sensor	Sensor Errors and failures Faulty control software logic Sensor logic faults	GNC Software development Development of better sensor logic
Spacecraft for the Universal Modification of Orbits, or SUMO	Autonomous rendezvous for servicing using algorithms	Docking precision Autonomous operation challenges Standardisation issues	Autonomous capabilities and technology Improving robotic precision Industry-wide standard interfaces
Orbital Express	Rendezvous proximity sensors	Autonomous operation challenges Standardisation issues	Autonomous capabilities and technology Improving robotic precision Industry-wide standard interfaces
DARPA Phoenix	Modular Assembly via Satlets POD for delivering components	Complex robot operations in harsh space environment Satlet integration due to not being designed for modular assembly	Robotic operations in space environment Design for modular assemble
Robonaut	Robotic assembly on ground	Electronic issues Limited autonomy and processing power	Electrical system design Autonomous capability improvement CPU design for Space
OSAM-1	Rendezvous and servicing Assembly of antenna array from elements	Precise control, integration and coordination Autonomous control algorithms	Technical, financial and strategic challenges lead to its cancellation, however lessons on autonomous control are useful going forward
OSAM-2	Additive Manufacturing Robotic Manipulation	AM in space and material property reactions to microgravity Robotic precision and autonomy Integration with existing spacecraft	No flight demonstration took place
Dextre	Robotic Manipulation Servicing	Limited autonomy, required human controls Power supply issues	Robot autonomy System integration
Intelligent Building blocks for on-orbit satellite servicing and assembly (iBOSS)	Modular Assembly	Complexity in physical structures and control systems Structural integrity and reliability Autonomous Assembly and Servicing	Standardisation in interfaces Structural engineering for space Autonomous systems Co-design methodologies
Prototype of an Ultra Large Structure Assembly Robot (PULSAR)	Robotic assembly Robotic Manipulation	Precision in autonomous robotic assembly Coordination of multiple robotic systems Autonomy and fault tolerance	Autonomous capabilities and software Fault detection systems and corrective actions
Autonomous Assembly of the Reconfigurable Space Telescope (AAEeST)	Rendezvous Assembly from components	Precision in autonomous robotic assembly Coordination of multiple robotic systems Autonomy and fault tolerance	Autonomous capabilities and software Fault detection systems and corrective actions
Space Solar Power Station (SSPS)	Modular Assembly Robotic Assembly	Energy transmission challenges Space environmental hazards	Still in development, so the limitations are all being worked upon

III. ISA TECHNOLOGIES

A. Artifical Intelligence and Machine Learning:

A multitude of technical advances in the areas of machine learning, path planning and compliance control are required to enable autonomous grappling for ISA. Robust image processing algorithms must locate the target spacecraft, identify key features, perform pose estimation and identify obstacles. Efficient motion planning algorithms allow the manipulators to operate in real time while avoiding collisions [15]. Machine vision is the enabling technology, as it provides the underlaying data for navigation, collision avoidance and fine motion control of any end effectors. The machine vision system is comprised of the individual cameras, illuminators, image processing algorithms for range and additional image processing to generate target pose from the range images [15]. The combination of computer vision and sensor fusion allows for real-time perception leading to the system being able to interpret its environment. Visual Simultaneous Localisation and Mapping (SLAM) techniques use input from cameras to identify features in the environment and track movement over time. Some the key techniques used include feature extraction, where key points within images are identified via algorithms such as SIFT or ORB, pose estimation which determines the robot's orientation and position and then mapping data. Sensor fusion is also used in ISA. This is where data from multiple sensors such as cameras, LiDAR, IMUs are combined to form an inclusive understanding of the working environment. There are 3 levels to sensor fusion; data level fusion, in which raw data is combined from multiple sensors, feature level where features extracted from sensor data are merged together, and decision level where the decisions made independently by the sensors are integrated [37] [38].

MOSAR, or Modular Satellite Assembly and Reconfiguration is a space robotics SRC project, developing modular satellites systems for in-space servicing. A set of re-useable heterogenous spacecraft modules are aimed at being an ecosystem of interoperable components, such as control, power and thermal management [16].There are Common Building Blocks (CBBs) used in the MOSAR project. The first is the European Space Robotics Control and Operating System (ESROCOS), a model-based framework for the development of space robotics applications. It will be used to model the system components and their interfaces. The second block is the European Robotic Goal-Oriented Autonomous Controller (ERGO). This is a framework for the development of autonomous capabilities in robotic applications [17]. Another CBB is the Integrated 3D Sensors (I3DS). This CBB comprises of an Instrument Control Unit (ICU) and a suite of sensors to assist autonomous navigation in space robotic missions. This includes cameras (stereo, TIR, Hi-Res), LIDAR, RADAR, Force/Torque sensors and a Star Tracker [17].

B. Robotics:

Robotic construction capabilities can be applied to create space infrastructure, standing structures such as refuelling depots, in-space manufacturing facilities, space tourism complexes and asteroid mining stations. Robot based assembly in micro and zero gravity environments does pose its own challenges. The robot is mounted on an actively regulated platform, and its motion has dynamic effects on the platform itself. The dynamic effects depend on the mass of the objects and the velocity of motion [18].

The Robonaut project had been conducting research on board the ISS since 2011. It is the first humanoid robot in space, designed with advanced sensors, mechanical control, and dual arm dexterity [19]. NASA developed Robonaut 1 (R1) to assist crew with servicing tasks. R1 demonstrated its ability to work with existing EVA tools and interfaces. Being an anthropomorphic robot, R1 is well suited for applications in less structured environments and are expected to reduce the

workload by carrying out routine maintenance etc [20]. In order to achieve the desired performance results, Robonaut 2 (R2) required a number of significant advancements over R1, including electromechanical design, sensing integration, controls strategy, and user interface. R2 has 42 independent DOFs and over 350 sensors. It is composed of two 7-DOF arms, two 12-DOF hands, a 3-DOF neck and a single DOF waist. The system includes 50 actuators with low level joint controllers embedded throughout. The controllers perform motor commutation and current control, serialisation and de-serialisation of joint data and commands, sensor processing and control of the arm's elastic actuators [20]. Figure 3 summarises this in a simple infographic.

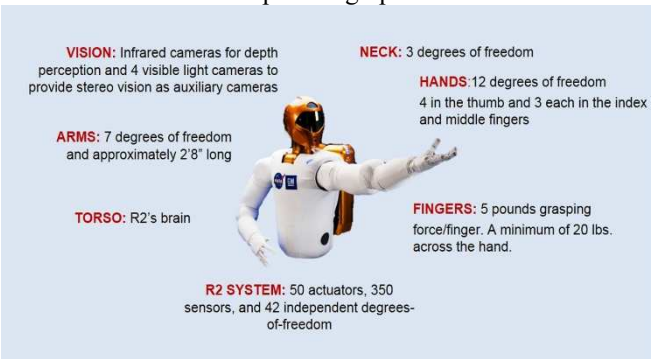

Fig 3: Robonaut 2 infographic [20]

IV. Challenges and Potential Solutions

A. Challenges Facing ISA

ISA faces the following challenges:

1) Assembly Constraints

- For modular assembly, the costs of developing modules are high even before launch.
- Assembling structures of different materials. Light weight, high strength, high stiffness, materials with high dimensional stability, structures with micro-stable joints.

2) Human- Robot Coordination

- On-orbit assembly requires a robotic system with high reliability and high levels of trust between human and machine.
- Multimodal interaction. Effective use of multiple sensory, display and communications to enhance situational awareness and achieve efficient interactions
- Distributed collaboration and coordination. Using an interactive architecture to support human-system coordination, communication and collaboration
- Collaborative operation. Large degree of freedom system coordination. Force control, multi-point contact problems, superimposed human-robot interaction modes on robust systems.

3) Precision and Effeciency

- Achieving the required precision demanded by geometrically complex shape such as antenna and precise instruments is difficult. Antennas need to be very smooth which requires high accuracy metrology techniques.
- High-precision sensing and multi-pattern recognition technology. 3D sensing, state estimation, force and tactile sensing, target identification and measurement.
- Fault detection and safe behaviour mode
- Automatic decision making and data analysis
- Dexterity. Control a large number of degrees of freedom, advanced multi-modal control system, real-time external force response, high resolution sensor array to sense contact.

4) Space Environment

- Lack of gravitational acceleration
- Presence of atomic oxygen
- Exposure to radiation
- Orbital debris
- Variations in thermal environment for LEO
- Variations of lighting in LEO makes it difficult for visual-based alignment.
- Communication latencies for deep space means docking and rendezvous must be automated

B. Autonomous Robotics:

A space robot system is a complex system involving various technologies, such as mechanics, optics, electronics, communications and software. The main functional requirements of spaces robots include motion functions, load handling functions, perception and measurement function, decision making and planning functions, fault detection functions, and repair and upgrade functions [21].

Teleoperating a robotic assembly system in space, from Earth, involves a number of challenges, including time delays, communication losses, and limited control modalities. The time delay results in operators applying a move-and-wait strategy, with delays up to 0.3s for operations in GEO. Communication constraints such as packet loss, loss of signal and jitter also affect teleoperations [22]. An increase in autonomy of robots in space could improve the efficiency of operations. Moving away from a dependence on human-in-the-loop robotic systems would extend the usable reach of robots for space applications. There are a number of different approaches of closed-loop feedback for robotic systems. The majority include visual feedback in order to verify the relative position of the robot. Two examples which have been researched extensively for terrestrial based uses are eye-in-hand visual servoing and model-based trajectory planning. Current research explores using these approaches separately, but not together. By utilising two approaches or even three, the robotic system will be able to assemble spacecraft in a dynamic environment safely and efficiently [23].

C. Digital Twins:

Digital assembly technology is the combination of digital technology and traditional assembly technology, including computer-aided assembly process planning (CAAPP) virtual assembly and assembly accuracy analysis. Measuring and testing is a measure to assure the quality of a product. Currently, intelligent detection has become an important part of quality control for complex product assembly. The current development priorities for the intelligent detection are: 1) research on intelligent measuring equipment and micro

sensors, 2) development of intelligent measurement, recognition and assessment algorithm, and 3) implementing artificial intelligence to realise measurement data [24]. When developing a digital twin for space applications, the main consideration is the seamless integration of robotics. This concept revolves around creating a simulated digital environment that mirrors the space environment, facilitating the on-orbit manufacturing, servicing, and assembly of robotic end-effectors with precision and adaptability. The centrality of robotics integration within the digital twin framework lies in its impact on robotic operations' efficiency, reliability, and autonomy in space. Digital twin serves as a critical platform for rigorously testing and optimizing the functionality of space robots before their deployment in the space environment. This virtual emulation environment enables stakeholders to fine-tune robotic operations, pre-emptively address challenges, and refine control strategies, significantly reducing the risks and costs associated with on-orbit missions [25].

Digital twins enable continuous real-time monitoring and control of in-orbit assembly processes by establishing a seamless data exchange between the physical spacecraft and its digital counterpart [26]. ISA faces constraints such as delayed communication due to latency, autonomy requirements for deep space missions and limited situational awareness. DT can help minimise these with capabilities such as state estimation, in which real time telemetry from spacecraft updates the DT, allowing for precise virtual reflection; anomaly detection, in which any changes in the system behaviour is flagged instantly with the DT, resulting in an alert or automated response; autonomous adjustments which integrated with AI, DT would be able to modify robotic paths or assembly processes in response to any issues that may appear [27]. In the harsh and inaccessible environment of space, predictive maintenance is crucial. Digital twins assist in early fault detection and predictive maintenance by analysing sensor data to anticipate potential failures. This proactive approach minimizes unexpected downtimes and extends the operational lifespan of space assets [28]. The AI-enabled Cyber-Physical In-Orbit Factory project demonstrates this by integrating digital twins with artificial intelligence to enhance fault detection and improve the robustness of satellite production processes in space [28]. DT cans be used with AI to provide predictive diagnostics via a number of ways including Sensor fusion, where the combination of thermal, mechanical and electrical data can detect deviations; Failure Mode Simulation, where the DT would simulate the assembly process's failure points to see its impact on the system; and Fault Recovery Planning where the DT can simulate and work on alternative assembly process in case of failure with the main process [28].

D. Software:

ROS or Robot Operating System, is an open-source robotics middleware suite. It is a set of software frameworks for robot software development. Used extensively by industry across the planet, there are various packages and tools for ROS, designed for a wide range of capabilities [29]. In 2020, NASA announced that Blue Origin would co-develop the Space Robot Operating System (Space ROS) with three NASA centres [30] [31]. The purpose of Space ROS is to provide reusable modular software frameworks for robotic and anonymous space systems [32]. Another space-based ROS framework is OnOrbitROS. Developed by the Human Robotics (HURO) group at the University of Alicante, in collaboration with Cranfield University. The framework is designed for the application of robot and autonomous systems for operations within a space environment, investigating the development of robotic systems and control for performing tasks in space [33].

Opteran in partnership with Airbus, ESA and UKSA, will test its software, Opteran Mind, in the Airbus built space rovers. Using extensive research in animal and insect vision, the company says that they have "reversed engineered natural brain algorithms", enabling autonomous systems to move efficiently, using its visual and perception systems, in challenging environments constructed upon the topology of the Martian surface [34].

V. Conclusion

In-space assembly is the next step in our quest for space exploration. The skills and technologies that are being developed and researched are of great importance to the success of ISA, and in turn future space missions. Projects such as space based solar power systems, large space telescope and even habits on other planets all require the technology and knowhow of ISA techniques and processes. However, in-space assembly faces some challenges, such as human-robot coordination, precision and efficiently of the system, as well as the space environment itself. The use of autonomous systems and digital twins can help mitigate these challenges. By using autonomous systems, we can remove the need for any human interaction, resulting in robots and robotic systems being capable of assembling and manufacturing structures in space, and in turn on other planets such as Mars. With the integration of Artificial intelligence and Digital Twins, autonomous systems will then be able to "think" for themselves, allowing for fully autonomous systems capable of predictive maintenance, path planning and corrective actions. This could mean that these systems would be sent to the surface of distant planets and moons to build infrastructure ahead of any human arrival or in place of humans, furthering the exploration of the Solar System.

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