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ROBOTIC SYSTEMS FOR ADVANCED ADDITIVE MANUFACTURING

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Abstract

Additive manufacturing (AM) has revolutionized the way we layout and manufacture products. The inception of complicated geometries immediately from virtual models gives more freedom and flexibility. However, AM systems have boundaries in terms of building volume, space, and the capability to manufacture multi-material and multi-practical items. A mixture of robotics and AM has emerged as a promising solution. The robotic tool of AM expands its capabilities via the growing toolpath strategies and robotic trajectories, paving the way for the advent of large, more complicated, and functionally included factors. This review paper explores the current-day robotic structures of AM, outlining advantages and challenges, and highlighting studies' achievements.

Keywords: *additive manufacturing, robotics, 3D printing*

1. Introduction

The robotic systems of Additive Manufacturing (AM), additionally called robotic-assisted additive manufacturing, are a rising manufacturing approach that mixes the use of robotics with additive production tactics (Urhal et al., 2019; Barjuei et al., 2024; Obuz, Tatlicioglu and Zergeroglu, 2024). This innovative approach permits the introduction of complex and customizable objects with more accuracy, flexibility, and performance (Bhatt et al., 2020; Zhang et al., 2022). By leveraging the precision and flexibility of robots, additive manufacturing can be taken to new heights, eliminating the need for traditional manufacturing methods such as cutting and shaping (Kanayo Alaneme and Apata Olubambi, 2013; Sustarevas, Kanoulas and Julier, 2022). This no longer simply reduces material waste but additionally permits the advent of complicated geometries and specific designs that could be difficult or not possible to acquire through traditional method (Despeisse and Ford, 2015; Ozkan et al., 2024). It has revolutionized numerous industries, such as automobiles, aerospace, healthcare, and construction (Ashour Pour and Johansen, 2022; Ozkan et al., 2024). In addition, the ability to work with an extensive range of substances, such as metals, plastics, and composites, makes robotic systems of additive manufacturing suitable for numerous sets of applications (Keating and Oxman, 2013; Bhole and Kale, 2022). Furthermore, these systems can convert industries by permitting the manufacturing of custom-designed and customized products on call (Dai et al., 2020; Mohanavel and Ravichandran, 2022).

AM has been a famous challenge matter on account of the fast-prototyping structures of invention in the late Nineteen Eighties (Kocovic, 2017; Lengua, 2017). Rapid prototypes are models created using AM and different approaches to get a visualization of the final product (Despeisse and Ford, 2015). In the Nineties, hybrid manufacturing structures emerged, combining AM with subtractive techniques along with milling, which showed how robots must enhance detail for first-class and overall performance (Ho, Ng and Yoon, 2015). The 2000s saw the introduction of multi-axis AM structures based mostly on robotic end effectors, which enabled the fabrication of complicated geometries without help structures (Despeisse and Ford, 2015; Kocovic, 2017) (Ford and Despeisse, 2016). In the 2010s, researchers targeted cooperative printing structures associated with a couple of robots. Several studies have found superior additive manufacturing in the use of robotic systems (Kocovic, 2017; Ozkan et al., 2024). Examples include Keating and Oxman who developed a multi-purpose robot platform capable of additive, subtractive, and formative fabrication (Keating and Oxman, 2013). Dai et al. introduced a multi-axis printing method using robot hands, permitting the guide-unfastened fabrication of complicated geometries (Dai et al., 2020). Then Bhatt et al. presented a comprehensive survey of the robotic structures of additive production. demonstrated the first bodily implementation of large-scale concurrent 3D printing using a team of mobile robots (Bhatt et al., 2020). Currently, researchers are trying to cope with disturbing situations along with robot localization, route planning, and collision avoidance (Zhang et al., 2022).

2. Robotic systems of Additive Manufacturing

2.1. Types of Robotic Systems Used

Robotic structures used in AM strategies provide more flexibility, large construct volumes, and advanced component complexity in comparison to traditional systems with limited degrees of freedom freedom (DOF) (Jones and Straub, 2017) (Cabibihan et al., 2023).

2.1.1. Cartesian Robots

These robots make use of linear motion along X, Y, and Z axes, making them high-quality for layer-with the resource of-layer additive tactics (Obuz, Tatlicioglu and Zergeroglu, 2024). They offer excessive accuracy and pressure, making them appropriate for massive-scale AM with materials like concrete or metals. It can be utilized in Large-scale 3D printing (Buchanan and Gardner, 2019), concrete printing (Singh et al., 2021), metal 3D printing (e.g., Directed Energy Deposition) (Liu et al., 2020). Greer et al. Created Metal Big Area Additive Manufacturing (mBAAM), which makes use of an articulated robot arm with Gas Metal Arc Weld to increase assemble amount and deposition fee over powder bed techniques shown in *Figure 1*. MBAAM has a low decision, so components made the usage of it require machining for abilities. (Greer et al., 2019).

Figure 1. *(left)3-d metallic published arm and its deployment* (Greer et al., 2019), *(middle)The MX3D bridge at Dutch Design Week 2018* (Buchanan and Gardner, 2019). *(right) Side view of Office of the Future in Dubai* (Sakin and Kiroglu, 2017).

2.1.2. Articulated Robots/Robot Arm

Robot Arms have rotary joints that provide more than one range of freedom, those robots offer flexibility and dexterity for complicated geometries. They are often used for duties past material deposition, collectively with pre- and put up-processing (Barjuei et al., 2024) It is used within the domains of Polymer 3D printing (Bedarf et al., 2021), multi-axis deposition (Lublasser et al., 2018), hybrid manufacturing, material handling, finishing operations (Keating and Oxman, 2013). An Additive Robot Manufacturing System (ARMS) become successfully superior and commissioned related to the software program solutions for 6-DOF printing by Schwicker et al. (Schwicker and Nikolov, 2022) in Figure 2.

Figure 2. *(left) present day view of Commissioned ARMS* (Schwicker and Nikolov, 2022), *(middle) 3DP of inorganic foams revealed onto walls* (Lublasser et al., 2018), *(right) a robotic arm construction 3D* (Barjuei et al., 2024).

2.1.3. SCARA Robots

Selective Compliance Assembly Robot Arm (SCARA) robots excel at immoderate-pace, repetitive obligations inside a horizontal aircraft (Okabe and Masarati, 2016; Al Mashhadany, 2012). They are nicely desirable for pick-and-region operations and small-issue AM (Poudel, Zhou and Sha, 2021; Öğülmüş and Tinkir, 2023). It's in the main packages in Desktop 3-D printing (Hyden, n.d.), fabric handeling, assembly (Hyden, n.d.), (Haq et al., n.d.). Podel et al. Created a completely covered C3DP platform with new chunking strategies, a scalable scheduler for multi-robot printing, a SCARA-based printing robot, a cellular platform, modular ground tiles, and a charging station as it shown in Figure 3. The mission of Koo et al. Uses a 3D published SCARA robotic with one actuator riding a two-diploma-of-freedom planar arm. A non-collocated linearization manipulate approach is used to cope with the underactuated state of affairs and layout the ideal controller (Koo et al., n.d.).

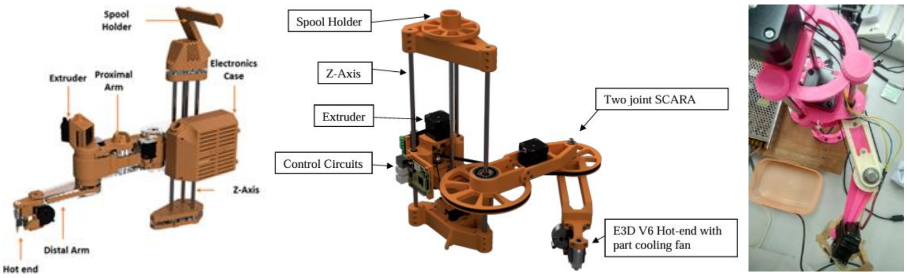

Figure 3. *(left) The updated 3D printer, equipped with SCARA arm* (Poudel, Zhou and Sha, 2021), *(middle) Mobile Printing Platform and SCARA Breakdown* (Hyden, n.d.), *(right) Assembled SCARA Robot Prototype* (Koo et al., n.d)

2.1.4. Delta Robots

Delta robots are confined to planar layers because of their three levels of freedom (Rodriguez et al., 2019). Moreover, their big footprint makes them much less portable and may require assist structures for complex geometry (Vasques and Figueiredo, 2021). Delta robots use 3 arms associated with a base, with every arm controlling the motion of the print head through a chain of parallelograms (Carabin et al., 2021). This format allows for fast and unique moves internal a smaller working area, ensuing in immoderate pace and acceleration (Zrazhevskiy et al., 2021; Wang et al., 2023). This tool as in in *Figure 4* gives immoderate precision and repeatability, together with a compact footprint (Wang et al., 2023). is required for complicated geometries (Hsieh, 2017; Wang et al., 2023), and suitable for Pick-and-area, small-component 3-D printing (Keating and Oxman, 2013), and food printing.

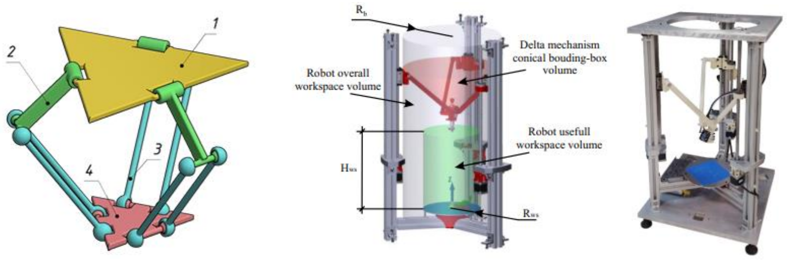

Figure 4. *(left) Delta robot design, 1-base; 2-lever; 3-drive; 4-platform.* (Zrazhevskiy et al., 2021), *(right) Prototype of the Linear Delta robot for AM with aluminum base structure* (Rodriguez et al., 2019)

2.1.5. Collaborative Robots (Cobots)

Designed for safe human-robotic interaction, cobots are more and more used in AM for tasks like loading/unloading materials, running 3D printers, and performing extremely good checks (Pollák and Kočiško, 2021). It is useful in helping human operators in several AM obligations, small-scale 3D printing (Velazquez, Palardy and Barbalata, 2021; Poor, Broum and Basl, 2019). For example,A modeling, cooperative planning and compliant manipulate method is supplied for multi-arm area non-stop robots in goal manipulation with the research of peng et al. As shown in *Figure 5*. Nine, is the coordinate dating of the i-th wellknown joint on the Arm-h, which decomposes the output torque on orthogonal shafts (Peng et al., 2023).

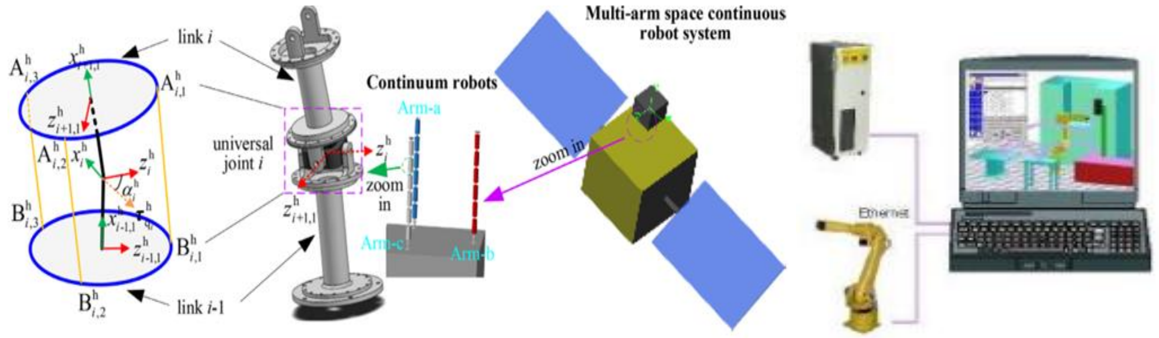

***Figure 5**. (left) Coordinate diagram of the i-th universal joint of Arm-h.* (Peng et al., 2023), *(right) Collaborative Robot Environment* (Poor, Broum and Basl, 2019)

2.1.6.Additional Considerations

- **Mobile Robots:** Integrating robotic arms with mobile platforms (e.g., wheeled or tracked) as in *Figure 6* can significantly increase the build volume and enable on-site printing for large structures (Zhang et al., 2018; Sustarevas, Kanoulas and Julier, 2022). However, this introduces challenges in localization, navigation, and maintaining print quality due to potential vibrations (Tiryaki, Zhang and Pham, 2019).

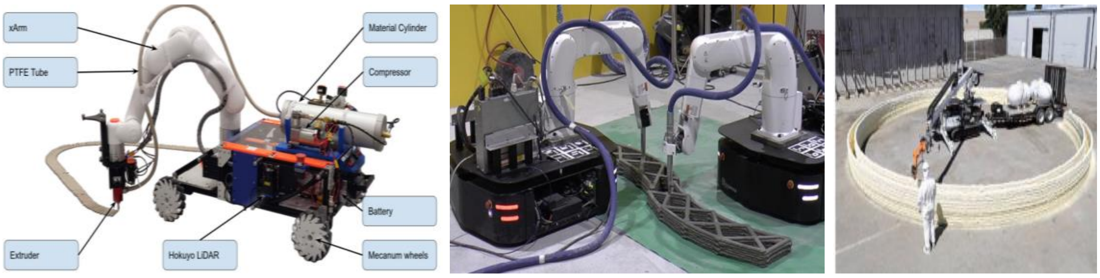

Figure 6. *(left) Armstone robot's major components (two Intel Nuc computers and the xArm DC control box)* (Sustarevas, Kanoulas and Julier, 2022), *(middle) a large, single-piece, concrete structure by two mobile robot printers* (Zhang et al., 2018), *(right) Digital Construction Platform by a robots with a wide-range reach* (Keating et al., 2017)

- **Multi-Robot Systems:** Using multiple robots collaboratively in a multi-robot system can further improve efficiency and build volume (Arbogast et al., 2024). Sophisticated path planning and coordination algorithms are necessary to avoid collisions and ensure synchronized material deposition in additive manufacturing (Zhang et al., 2018) a novel discrete multi-objective cross-entropy optimization (CrMOCEO) algorithm is proposed by tang at al. to solve the path planning problem of dual-robot cooperative arc welding (Tang et al., 2024). Gang et al. Alleviate the influence of those constraints on a multi-robot cooperative delivery device (MRCTS), a six degree-of-freedom connector capable of sensing 3-axial displacements, 3-axial forces, and 3-axial angular displacements is designed and hired shown in *Figure 7*. Based at the local displacements derived from every connector (Gong et al., 2023).

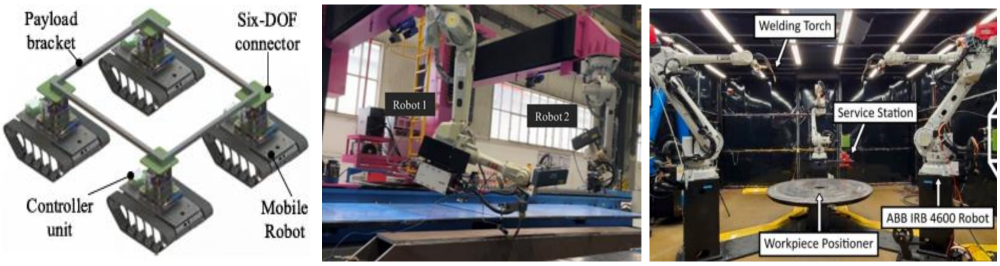

Figure 7. *Structure of MRCTS*(Gong et al., 2023), *Workshop on-site experimental platform* (Tang et al., 2024), *MedUSA – Multi-robot coordinated motion deposition system* (Arbogast et al., 2024)

2.2. Integration Mechanisms, Hardware, and software Considerations

There are several methods to mix robots into AM strategies, depending at the particular AM technology and favored functionalities. Some commonplace hardware integration mechanisms consist of:

2.2.1. Hardware Considerations

- **Robotic arm with mounted extruder/deposition head:** This configuration is widely utilized in extrusion and directed deposition techniques (Pollák and Kočiško, 2021). The robot arm offers multi-axis motion, allowing non-planar and conformal deposition (Deng, Zhang and Fu, 2023). Fused Filament Fabrication (FFF) equipment can simply deposit substances in a single tiny lines, proscribing the energy and getting more accurate result (Yao et al., 2021). This technique as shown in *Figure 8* increases the tensile strength by 22-167% in assessment to standard flat slicing method for curved-surface part (Yao et al., 2021). Rau et al. Combine the pneumatic extruder onto a robot arm with six levels of freedom, allowing particular, multi-axis fabrication deposition on complicated geometries (Rauch, Hascoet and Querard, 2021).
- **Robotic arm controlling the build platform:** In this setup, the print head is stationary, and the robot arm manipulates the build platform, allowing for multi-directional printing and support-free fabrication of complex geometries (Dai et al., 2020). For fused deposition modelling, the robot FDM platform effectively demonstrated and explored multi-plane and 3D lattice structure printing, validating its capabilities (Shah, 2022). Ishak et al. successfully developed a six degrees of freedom robot arm integrated with a fused deposition modelling extrusion system for 3D printing applications as it shown in *Figure 9* (Ishak and Larochelle, 2019).

Figure 8. *(left) Multi-DOF FFF printing platform for multi-axis continuous path printing* (Yao et al., 2021), *(middle) Realization of 3D printing by robot UR5* (Pollák and Kočiško, 2021), *(right) A six degree of freedom robotic arm enables multi-axis conformal deposition* (Rauch, Hascoet and Querard, 2021)

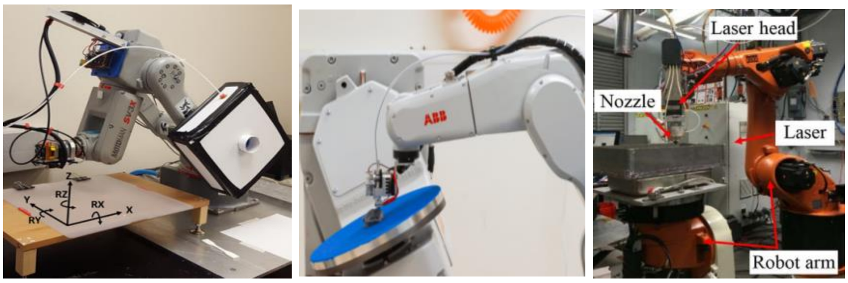

Figure 9. *(left) representative set-up of multi-directional FDM platform* (Ishak and Larochelle, 2019), *(middle): 8-DOFs robot-assisted 3D printing system consisting of a 6-DOF ABB IRB1200-7/0.7 robotic arm and a 2-DOF IRBP A-250 tilting table* (Dai et al., 2020), *(right) Setup of the LBDMD system (Laser-based direct metal deposition)* (Ding, Dwivedi and Kovacevic, 2017)

- **Robotic arm controlling the construct platform:** In this setup, the print head is desk bound, and the robotic arm manipulates the assemble platform, bearing in mind multi-directional printing and help-loose fabrication of complicated geometries (Dai et al., 2020). For fused deposition modelling, the robot FDM platform correctly verified and explored multi-plane and 3D lattice form printing, validating its talents (Shah, 2022). Ishak et al. Efficiently advanced a six ranges of freedom robot arm included with a fused deposition modelling extrusion tool for 3-D printing programs (Ishak and Larochelle, 2019).
- **Multiple cooperative robots:** Using multiple robots strolling together to print huge parts or more than one elements simultaneously in the Cooperative 3-D printing (C3DP) (Poudel et al., 2019), significantly reducing fabrication time and improving workspace utilization (Elagandula et al., 2020; Wang et al., 2024). This study in *Figure 10* proposes two methods: Dynamic Dependency List Algorithm (DDLA) and Modified Genetic Algorithm (GA). Both methods effectively generate a print schedule with equal print time and valid print schedules using a specific number of robots, while minimizing the make-span (Poudel et al., 2021).

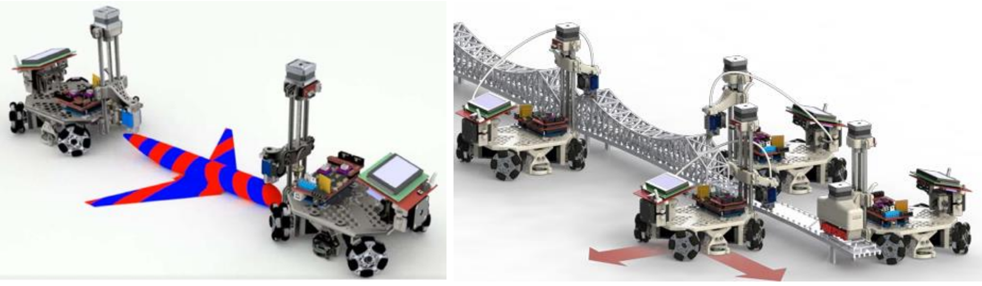

Figure 10. *(left) Demonstration of C3DP: two mobile printers running cooperatively* (Poudel, Zhou and Sha, 2021), *(right) Illustration of ADAM* (Marques, Williams and Zhou, no date)

- **Assistive robots:** Robots can be used to carry out auxiliary responsibilities in the AM method (Keating and Oxman, 2013), along with fabrication managing, factor manipulation, and in-situ tracking, similarly improving the performance and versatility of the tool. Felsch et al. Broaden a "authentic" 3-dimensional additive robotic gadget that cost successfully builds huge models and from any thermoplastic fabrication with volumes of one.000x1.000x1.000 mm³ (Felsch et al., 2017). The production device *(Figure 11)* consists of an commercial robotic: (1) with a construct platform, (2) for insert positioning, a base frame (three), 3 extruder gadgets (4) with needle nozzles, a scanner (five) to degree temperatures and a manipulate unit with a collision detector.

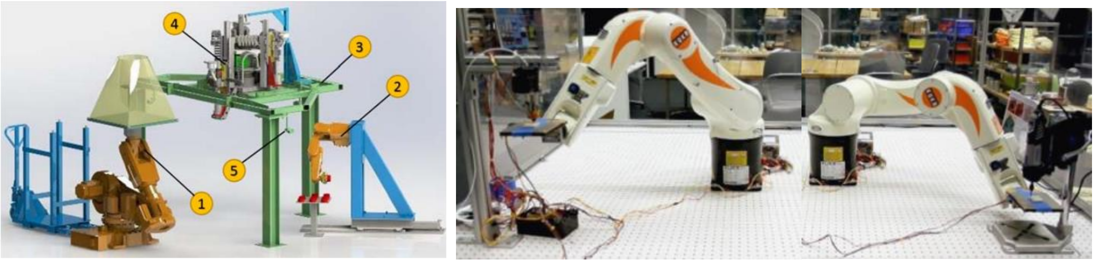

Figure 11. *(left) CAD layout of the genuine manufacturing system* (Felsch et al., 2017), *(right) an ABS part being 3D printed and subsequently undergoing surface milling in the bottom image to achieve a better finish* (Keating and Oxman, 2013).

The choice of the appropriate hardware integration mechanism depends on factors such as the desired build volume, part complexity, material properties, and budget constraints.

2.2.2. Software Considerations

The development of dedicated software program solutions tailored to the right the robot structures of AM setup and application is critical for accomplishing most useful general overall performance and unlocking the overall functionality of the robot structures of additive manufacturing:

- **Slicing algorithms:** this generate toolpaths for the robotic primarily based absolutely at the digital version (Cheibas et al., 2023). For the robot systems of AM, specialized multi stages algorithms are had to account for multi-axis and multi-fabric deposition (Arbogast et al., 2024). Armstrong et al. Makes use of a six-axis robotic arm and a custom set of rules to print right away onto complex, unstructured surfaces. The functionality to manufacture practical systems with conductive paths for in situable deformation monitoring *(Figure 12)* is increasing capability programs to repair, reinforcement, and customization of cutting-edge structures (Armstrong et al., 2024). Yang et al. use adaptive cutting of Moving Least Squares surfaces (MLS) to create a modern-day approach for at-once manufacturing factor-set surfaces. it is strong for noisy or sparse factors and allows for upsampling and downsampling (Yang and Qian, 2008). The figures display yellow planes as reducing planes, pink dots as output 2D contours, and green crosses as enter element factors. The intensity of inexperienced crosses fades away as they flow far from the slicing plane.

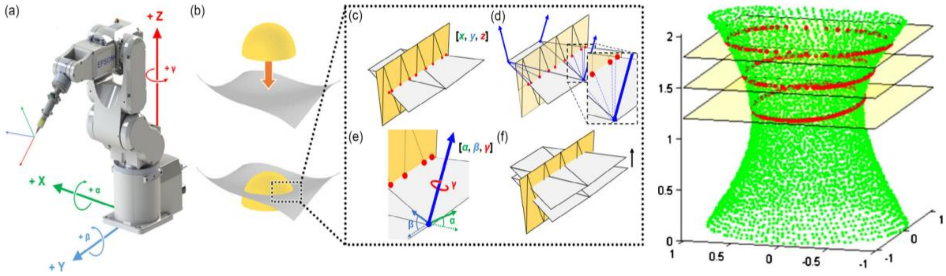

Figure 12. *(left) Graphical depiction of the slicing procedure. a) The robotic arm and tool coordinate systems. b) Defining placement of the triangulated model (yellow) substrate surface model (gray). c) spatial intersection. d) vectors (blue) of substrate faces e) rotation angles. f) subsequent layers.* (Armstrong et al., 2024), *(right) Slicing of the can data with three horizontal planes* (Yang and Qian, 2008)

- **Path planning algorithms:** These algorithms decide the maximum suitable collection of actions for the robotic to execute the toolpaths on equal time as warding off collisions with the surroundings, and one-of-a-kind robots in the tool (Tang et al., 2024). Rauch et al. Introduces a novel multi-axis tool direction era approach this is specifically designed for Wire Arc Additive Manufacturing (WAAM), with a focal point on growing thin wall structures. It successfully addresses the key integration demanding situations amongst CAD/CAM/CNC information for WAAM through progressive strategies, with non-planar non-parallel slicing and optimizing part orientation. (Rauch et al., 2021).
- **Control systems:** Robust control systems are needed to synchronize the robot's motion with the material deposition process, ensuring accurate and high-quality printing (Yao et al., 2021). This is particularly challenging for robots with multiple DOFs. Marzi et al. combine extrusion and

photopolymerization processes to create complex lattice structures using a 6-axis robotic arm with superior strength-to-weight ratios. The process in *Figure 13* includes a custom graphical user interface (GUI) and control over printing head orientation, which guarantees accurate replication of digital models and enhances the mechanical properties of the printed parts (De Marzi et al., 2023). Felbrich et al. studied computational design and robotic fabrication (CDRF) and deep reinforcement learning (DRL). They trained a robotic agent to plan and build structures using two DRL algorithms, TD3 and SAC, in two case studies: robotic block stacking and sensor-adaptive 3D printing. The study utilized highly efficient geometry manage based on CAE and SDF, real-time physics simulation in CAD, industry-grade hardware control, and outstanding motion complementation through geometric scripting. (Felbrich, Schork and Menges, 2022)

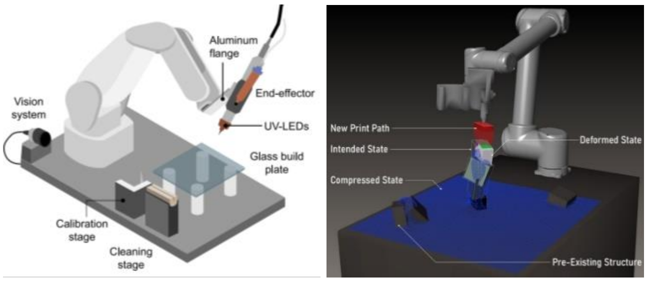

Figure 13. *(left) graphical representation of the robot hybrid UV-DIW setup* (De Marzi et al., 2023), *(right) Virtual print environment of the sensor-adaptive 3D printing* (Felbrich, Schork and Menges, 2022)

- **Middleware and simulators:** Middleware enables communique between the robotic controller and the AM device. As a simulator, it allows the sorting out and optimisation of the robotic's motion in a virtual environment before actual printing. Mitropoulou et al created single-shell bifurcating systems as shown in *Figure 14*. The technique allows the multi-axis robotic arm to print easily on quite curved surfaces without causing the staircase impact or collisions (Mitropoulou, Bernhard and Dillenburger, 2022). Finite Element Analysis (FEA) for thermal simulation is used to address common failure models located in massive-scale AM of polymer and composite elements via Akbari et al. The development of a correct simulation model that could count on temperature distribution and probably strain distribution in the found-out item is a big achievement (Akbari et al., 2022).

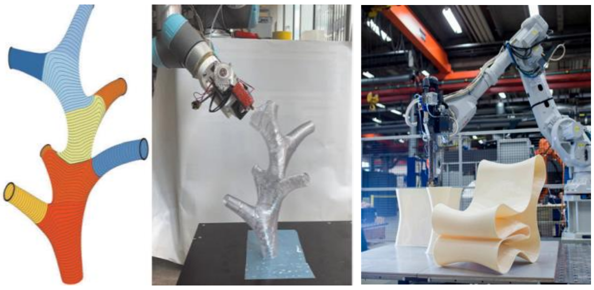

Figure 14. *The approach for the fabrication of a bifurcating shapes* (Mitropoulou, Bernhard and Dillenburger, 2022), *(C) IRBAM system of the printed chair* (Akbari et al., 2022)

Considering both hardware and software integration mechanisms, the robotic systems of additive manufacturing can significantly enhance the capabilities of AM processes, paving the way for the creation of innovative and high-performance products across various industries.

3. Discussion

3.1. Advantages of robotic System of Additive Manugacturing

Recent studies on additive manufacturing indicate that robotics plays a crucial role in this area for various reasons (Urhal et al., 2019; Bhatt et al., 2020). The primary reason is to automate the entire AM process from start to finish. Currently, most of the AM process is handled manually, which limits the full potential of AM. The whole process should be automated to overcome this limitation, including part handling, post-processing, inspection, and testing. Robotic systems offer the best solution to achieve this level of automation at a high production rate and with the wide capabilities of various additive manufacturing processes over traditional AM systems (Peppler et al., 2020).

- Increased build volume: Robots' extended reach and flexibility permit the advent of large parts, overcoming the limitations of conventional AM techniques. Robotic AM allows for multi-directional fabrication, conformal deposition, assembling prefabricated components, supportless AM, and large-scale AM, increasing the useful capabilities of AM processes (Brandstötter, Petersmann and Bosch, 2023).
- Enhanced dexterity: Robots'multi-degree-of-freedom (DOF) allows for multi-directional fabrication and conformal deposition, improving part quality and extending into complex geometries (Shah, 2022; Schwicker and Nikolov, 2022).
- Multi-material and multi-technique fabrication**:** Robotic systems of AM facilitates the mixing of multiple materials and AM techniques within a single system, main to greater flexible and practical products (Bhatt et al., 2020; Munguia-Galeano et al., 2023).
- Improved automation and efficiency Robots can automate various tasks in the AM manner, such as material handling, part manipulation, and in-situ monitoring, leading to extended efficiency and reduced production time. (Felsch et al., 2017; Shah, 2022).
- Innovative manufacturing techniques: New techniques such as multi-axis printing, in-situ manipulation and embedding of components, and hybrid manufacturing processes are further improving the skills and versatility of the robotic acting of AM systems (Zhang et al., 2018; Felbrich, Schork and Menges, 2022).
- AI integration: Artificial intelligence (AI) is being included in the robotic structures of AM structures to optimize method parameters, predict, and save failures, and enhance robotic coordination and manipulation (Barjuei et al., 2024).
- Customization and Reduced Costs: AM technology capacitate the layout of customized products without fee consequences, reducing the need for molds, shapes, Material Waste and assembly work, in the long term lowering prices for consumers (Ford and Despeisse, 2016; Routray and Saha, 2024).
- Large-Scale Production: Robotic-assisted AM facilitates the cost-effective production of huge fashion and moulds, combining the flexibility of industrial robots with revolutionary additive manufacturing (Felsch et al., 2017; Urhal et al., 2019).
- Resource Efficiency and Sustainability: AM, when combined with robotics, contributes to improved useful resource efficiency and sustainability in industrial systems (Singh et al., 2021; Brandstötter, Petersmann and Bosch, 2023).

- Efficient Manufacturing: The use of robots in additive manufacturing can lead to shorter lead times and a higher level of demand, increasing manufacturing efficiency and generating enhanced customer value (Marques, Williams and Zhou, 2017; Zander et al., 2016).

3.2. Current challenges

Additive Manufacturing, encompassing cooperative printing structures with a couple of robots, assistive robots for stronger capability, and statistics waft issues for seamless integration of robots into the AM workflow. Additionally, the paper addresses key demanding situations and studies gaps inside the field, consisting of:

- Limited kinematic configurations of gantry systems: Current gantry structures restriction printhead movement, hindering the entire ability of cooperative printing.
- Mobile robot layout demanding situations: While mobile robots offer expanded workspace, their positioning accuracy and energy consumption require further optimization.
- High computation time for path making plans: Collision avoidance and synchronization complexities in multi-robotic systems cause multiplied computational demands.
- Uncertainty and calibration: Precise calibration and error compensation are vital for multi-robotic systems to make certain accurate and reliable printing.
- Lack of standardized software and tracking systems: The improvement of devoted software and monitoring answers is critical for the broader adoption of the robot systems of additive manufacturing.

3.3. Future trends and developments

As technology continues to advance, robotic additive manufacturing will play an increasingly important role in reshaping the manufacturing landscape. Ongoing innovation in the field has the potential to drive further advancements in product design, production processes, and the overall capabilities of additive manufacturing. With its ability to create customized and personalized products on demand, robotic additive manufacturing is poised to revolutionize industries and pave the way for a new era of manufacturing excellence.

3.3.1.Emerging technologies:

- Advanced materials: Development of new materials with improved printability, mechanical properties, and functionalities will expand the application space of the robotic systems of additive manufacturing. This includes materials with self-healing, shape-memory, and conductive properties. (Munguia-Galeano et al., 2023)
- Sensor integration and closed-loop control: Real-time monitoring and feedback control can improve the accuracy and reliability of the robotic systems of additive manufacturing processes. (Arbogast et al., 2024)
- Swarm printing: Research into swarm printing with multiple autonomous robots has the potentia l to revolutionize large -scale construction and fabrication.
- Standardization of software and hardware: The development of standardized software and hardware platforms for the robotic systems of additive manufacturing can facilitate wider adoption and interoperability.

3.3.2. Potential new applications:

- On-site construction and repair: Robotic systems of additive manufacturing can be used to print and repair structures directly on-site, reducing the need for transportation and assembly. This is particularly beneficial for large or complex structures and for repairs in hazardous or hard-to-reach locations.
- Space exploration: robotic systems of additive manufacturing systems can be used to build structures on the Moon and Mars using in-situ resources, reducing the need to transport materials from Earth.

3.3.3. Strategies for overcoming existing challenges:

- Developing more efficient path planning and collision avoidance algorithms: This can be achieved through improved search strategies, utilization of machine learning, and development of dedicated hardware architectures for the robotic systems of additive manufacturing (Shah, 2022).
- Improving robot accuracy and repeatability: This can be achieved through advanced calibration techniques, sensor integration, and closed-loop control systems.
- Exploring new robotic configurations: This includes investigating the use of mobile manipulators, cable-driven robots, and swarm printing. also, the development of toolpath strategies, robot trajectory, robotic-assisted hybrid manufacturing, and various applications (Munguia-Galeano et al., 2023).

4. Conclusions

Through an in-depth assessment of the combination of robotics and AM, it explores how robotic structures overcome the inherent limitations of conventional AM. The paper evaluates the functionality benefits, collectively with extended flexibility and scalability, at the side of the demanding conditions, technical complexities, and integration hurdles. Furthermore, it outlines promising directions for future research, emphasizing the need for persevering innovation in the transformative capacity of robot additive production and supplying a paradigm shift closer to extra efficient, bendy, and complex production answers.

5. Acknowledgements

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