World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Review Article)

Check for updates

Automation and robotics in 3D-printed construction: revolutionizing the built environment

Anas Hussein *

Department of Architecture, College of Engineering, Al-Yamamah University, Riyadh 13541, Saudi Arabia.

World Journal of Advanced Engineering Technology and Sciences, 2025, 15(01), 2441-2445

Publication history: Received on 18 March 2025; revised on 26 April 2025; accepted on 29 April 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.15.1.0503

Abstract

The integration of automation and robotics into 3D-printed construction represents a groundbreaking transformation in the architecture, engineering, and construction industry. This paper explores the technological advancements, applications, benefits, and challenges of employing automated systems and robotic technologies in 3D-printed construction. It examines how these innovations contribute to improving efficiency, reducing labor costs, enhancing design flexibility, and promoting sustainability. Furthermore, the study highlights current global case studies and outlines the future outlook of this emerging field, which holds immense potential for revolutionizing the construction industry. The use of automated systems and robotic technologies in 3D-printed construction offers numerous benefits. These include increased productivity, improved precision, reduced construction time, and enhanced safety for workers. Additionally, these advancements enable greater design flexibility, allowing for the creation of complex and customized structures that were previously difficult or impossible to construct using traditional methods. The integration of these technologies also promotes sustainability by reducing material waste and energy consumption during the construction process. This paper delves into the specific ways in which automation and robotics are transforming the construction industry, providing a comprehensive overview of the current state and future potential of this innovative field. The introduction of these cutting-edge technologies has the power to reshape the way we approach and execute construction projects, leading to significant improvements in efficiency, cost-effectiveness, and sustainability across the industry.

Keywords: Built Environment; 3D-printed; Construction; Robotics

1. Introduction

The construction industry has long been characterized by labor-intensive processes and significant resource consumption. Traditional methods of construction are not only time-consuming but also susceptible to delays, human errors, and environmental inefficiencies. In the face of rapid urbanization and a growing demand for housing and infrastructure, there is a pressing need for innovation. One such innovation is the adoption of 3D printing technologies, especially when integrated with automation and robotics. The incorporation of 3D printing into the construction industry has the potential to revolutionize the way buildings and infrastructure are designed, fabricated, and assembled. This technology offers numerous advantages, such as increased efficiency, precision, and sustainability, making it a promising solution to the challenges faced by the construction sector. By leveraging the capabilities of 3D printing, construction professionals can create complex, customized structures with greater speed and flexibility, while also reducing material waste and minimizing the environmental impact of traditional construction methods. The benefits of 3D printing in construction are multifaceted. This technology enables the fabrication of intricate, bespoke architectural elements that would be challenging or even impossible to produce using conventional construction methods. Furthermore, 3D printing allows for on-site, real-time fabrication, reducing the need for extensive transportation and

* Corresponding author: Anas Hussein

logistics. This can lead to significant cost savings and a reduced carbon footprint. Additionally, the precise control afforded by 3D printing can result in structures with enhanced structural integrity and improved energy efficiency. By embracing this innovative technology, the construction industry can tackle the pressing challenges of urbanization, resource scarcity, and environmental sustainability, positioning itself for a more sustainable and technologically advanced future.This research paper explores how these technologies are reshaping the construction sector, offering promising solutions to age-old inefficiencies while paving the way for futuristic, sustainable architecture. The convergence of robotics, automation, and additive manufacturing holds the potential to revolutionize construction workflows and produce structures that are faster to build, cheaper to maintain, and more sustainable over their lifecycle [1].

3D Printing in Construction 3D printing, also known as additive manufacturing, involves the layer-by-layer deposition of material based on a digital 3D model. In construction, this typically entails the use of large-scale printers to extrude concrete or composite materials. The origin of 3D printing in the construction industry can be traced back to the early 2000s, with initial applications in rapid prototyping and component manufacturing. Today, entire structures can be printed using gantry systems or robotic arms capable of executing complex geometries and tasks with high precision [2]. One of the primary advantages of this technology is the minimization of material waste, as materials are applied only where needed. Additionally, 3D printing allows for increased design flexibility, enabling the creation of forms that would be prohibitively expensive or difficult to achieve using conventional methods [3].

- **The Role of Automation and Robotics**: Automation and robotics are critical enablers of 3D printing in construction. Automation, defined as the use of technology to perform tasks without human intervention, increases process consistency and operational efficiency. Robotics, on the other hand, introduces mobility, adaptability, and precision to construction tasks. In a 3D-printed construction context, robots perform essential roles such as material extrusion, surface finishing, and quality inspection. The integration of sensors and real-time monitoring systems allows robots to adjust their actions based on environmental and process feedback, thereby improving reliability and performance [4]. Moreover, autonomous systems reduce the reliance on human labor, which is particularly advantageous in regions facing workforce shortages or hazardous working conditions.
- **Technologies Enabling Automation in 3D Construction:**The realization of automated 3D construction depends on a suite of advanced technologies:
- **Robotic Arms and Gantry Systems**: These systems provide the mechanical structure for material deposition. Robotic arms offer flexibility and mobility, making them suitable for intricate tasks, whereas gantry systems are ideal for large-scale and repetitive constructions [5].
- **Drones and Autonomous Vehicles**: Drones are used for aerial site inspection and progress monitoring, while autonomous ground vehicles transport materials and tools across the construction site, streamlining logistics [6].
- **Artificial Intelligence (AI) and Machine Learning (ML)**: AI enables predictive analytics and adaptive control systems, allowing machines to learn from data and improve their performance over time. ML algorithms are particularly useful for defect detection, material optimization, and process automation [7].
- **Building Information Modeling (BIM)**: BIM integrates geometric and functional information of a structure, enabling precise planning and coordination of automated tasks. BIM also facilitates real-time collaboration among stakeholders [8].
- **Sensors and Internet of Things (IoT)**: These devices provide continuous feedback on environmental parameters such as temperature, humidity, and material curing rates. IoT-connected systems enhance the decision-making capabilities of autonomous machines by providing actionable data [9].

2. Benefits of Automation and Robotics in 3D Printing The implementation of automation and robotics in 3D-printed construction offers several key advantages

- **Speed and Efficiency**: Automated processes operate continuously and can function under various environmental conditions, significantly reducing construction time [10].
- **Cost Reduction**: While initial investment is high, long-term savings are realized through lower labor costs and efficient material usage [11].
- **Precision and Quality**: High accuracy in material placement minimizes errors and enhances structural performance, reducing the need for rework [12].
- **Design Freedom**: The removal of formwork constraints allows architects to explore more complex and innovative designs [13].

- **Safety Improvements**: Replacing manual labor with robotics reduces exposure to hazardous environments, improving overall site safety [14].
- **Environmental Sustainability**: Controlled material application and reduced waste contribute to eco-friendly construction practices, aligning with global sustainability goals [15].

3. Case Studies

- **Dubai Municipality Office**: The world's first functional 3D-printed office building in Dubai was constructed using robotic arms. The project reduced labor costs by 50% and construction waste by 60% [16].
- **ICON and New Story (USA)**: These organizations developed a 3D-printed housing solution to address homelessness in Latin America and the U.S., producing homes in under 24 hours for less than $4,000 each [17].
- **WinSun (China)**: A pioneer in large-scale 3D printing, WinSun printed ten houses in 24 hours using recycled materials. The company also printed a five-story apartment building and a 1,100 square meter villa [18].
- **ETH Zurich's DFAB House**: A research-led project that combined robotic fabrication with digital design tools to create an intelligent and sustainable building. It demonstrated the synergy between academic research and practical application [19].

4. Challenges and Limitations Despite the promising developments, several challenges hinder the widespread adoption of automation and robotics in 3D-printed construction

- **High Capital Investment**: The cost of procuring and maintaining robotic systems and automated infrastructure is substantial [20].
- **Regulatory and Code Compliance**: Existing building codes are often not tailored for 3D-printed structures, creating legal and procedural uncertainties [21].
- **Material Limitations**: The consistency and performance of printable materials, especially under variable environmental conditions, remain areas of concern [22].
- **Skill Gaps**: There is a shortage of professionals trained in the interdisciplinary skills required to operate and maintain these advanced systems [23].
- **Technological Maturity**: Many systems are still in the experimental or pilot phase, requiring further validation and refinement before commercial deployment [24].

5. Future Prospects and Innovations The future of 3D-printed construction, empowered by automation and robotics, appears increasingly promising. Key trends include

- **Enhanced AI Capabilities**: Advanced AI systems will support self-learning machines capable of performing increasingly complex tasks with minimal oversight [25].
- **Innovative Materials**: Research is focused on developing new materials such as bio-concrete, self-healing composites, and recycled waste products for 3D printing [26].
- **Mobile and Modular Printing Units**: Deployable units capable of operating in remote or disaster-struck regions are being tested to support emergency response and rapid infrastructure deployment [27].
- **Hybrid Construction Techniques**: Integrating traditional building methods with additive manufacturing to optimize cost, performance, and aesthetics [28].
- **Policy Development**: Governments and regulatory bodies are beginning to draft guidelines that support innovation while ensuring safety and compliance [29].

6. Conclusion

Automation and robotics in 3D-printed construction represent a paradigm shift in how we conceive, design, and build the physical environment. These transformative technologies promise not only to make construction more efficient and cost-effective, but also to foster sustainable and inclusive development by enabling new construction methods and design possibilities. While some challenges remain, ongoing research and technological advancements are steadily addressing these issues, unlocking new opportunities. As the field of automated and robotic 3D-printed construction matures, it is likely to become a cornerstone of modern construction practices, particularly in areas requiring rapid, resilient, and scalable solutions to address pressing infrastructure needs and environmental concerns. The adoption of automation and robotics in 3D-printed construction can lead to significant improvements in productivity, quality, and safety by automating repetitive tasks, reducing human error, and enabling faster construction timelines. Additionally, these technologies can facilitate the incorporation of sustainable design principles, such as optimized resource utilization, reduced waste, and the ability to construct complex, energy-efficient structures. Furthermore, the use of 3D-printing allows for customization and personalization of building designs, catering to diverse needs and preferences of end-users. As the construction industry continues to evolve, the integration of automation and robotics in 3D-printed construction is poised to become an essential component in addressing the global challenges of urbanization, housing shortages, and environmental impact.

References

[1] Bock T, Linner T. Construction Robots. Cambridge University Press; 2016.

[2] Buswell RA, Soar RC, Gibb AGF, Thorpe A. Freeform Construction: Mega-scale Rapid Manufacturing for Construction. Automation in Construction. 2007;16(2):224-231.

[3] Gosselin C, Duballet R, Roux P, Gaudillière N, Dirrenberger J, Morel P. Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders. Materials & Design. 2016;100:102-109.

[4] Lim S, Buswell RA, Le TT, Wackrow R, Austin SA, Gibb AGF, Thorpe A. Developments in construction-scale additive manufacturing processes. Automation in Construction. 2012;21:262-268.

[5] Khoshnevis B. Automated construction by contour crafting—related robotics and information technologies. Automation in Construction. 2004;13(1):5-19.

[6] Hamledari H, Fischer M, Rankin JH. Opportunities and Challenges in Autonomous Construction Equipment: A Critical Review. Journal of Computing in Civil Engineering. 2021;35(3):04021001.

[7] Yu Y, Cheng JCP, Wang Y, Wang X. A BIM and IoT-based integrated framework for quantitative off-site construction productivity measurement. Automation in Construction. 2018;89:168-180.

[8] Eastman C, Teicholz P, Sacks R, Liston K. BIM Handbook. 2nd ed. Wiley; 2011.

[9] Qi Q, Tao F, Hu T, Anwer N, Liu A, Wei Y, Wang L. Enabling technologies and tools for digital twin. Journal of Manufacturing Systems. 2021;58:3-21.

[10] Tay YWD, Panda B, Paul SC, Noor Mohamed NA, Tan MJ, Leong KF. 3D printing trends in building and construction industry: a review. Virtual and Physical Prototyping. 2017;12(3):261-276.

[11] Paul SC, Panda B, Tan MJ. Fresh and hardened properties of 3D printable cementitious materials: a review. Journal of Materials in Civil Engineering. 2018;30(10):04018225.

[12] Buswell RA, Leal de Silva WR, Jones SZ, Dirrenberger J. 3D printing using concrete extrusion: A roadmap for research. Cement and Concrete Research. 2018;112:37-49.

[13] Perrot A, Rangeard D, Pierre A. Structural built-up of cement-based materials used for 3D-printing extrusion techniques. Materials and Structures. 2016;49(4):1213-1220.

[14] Kamat VR, Martinez JC. 3D visualization of simulated construction operations. Journal of Computing in Civil Engineering. 2001;15(4):329-337.

[15] Labonnote N, Rønnquist A, Manum B, Rüther P. Additive construction: State-of-the-art, challenges and opportunities. Automation in Construction. 2016;72:347-366.

[16] Dubai Future Foundation. The Office of the Future. 2016. Available from: https://futurefoundation.ae/

[17] ICON. 3D-Printed Homes. 2021. Available from: https://www.iconbuild.com/

[18] Winsun. 3D Printing Construction. 2020. Available from: http://www.winsun3d.com/

[19] ETH Zurich. DFAB HOUSE. 2019. Available from: https://dfabhouse.ch/

[20] Zareiyan B, Khoshnevis B. Effects of interlocking on interlayer adhesion and strength of structures in 3D printing of concrete. Automation in Construction. 2017;83:212-221.

[21] Asprone D, Menna C, Bos F, Salet T, Mata-Falcón J, Kaufmann W. Rethinking reinforcement for digital fabrication with concrete. Cement and Concrete Research. 2018;112:111-121.

[22] Wangler T, Lloret E, Reiter L, Hack N, Gramazio F, Kohler M, Flatt RJ. Digital concrete: opportunities and challenges. RILEM Technical Letters. 2016;1:67-75.

[23] Wu P, Wang J, Wang X. A critical review of the use of 3-D printing in the construction industry. Automation in Construction. 2016;68:21-31.

[24] Vass A, Solis-Guzman J, Marrero M. Lifecycle cost analysis of prefabricated houses: case study in Spain. Energy Procedia. 2015;83:396-404.

[25] Bock T. The future of construction automation: Technological disruption and the upcoming ubiquity of robotics. Automation in Construction. 2015;59:113-121.

[26] Mechtcherine V, Nerella VN, Will F, Näther M, Otto J, Krause M. 3D-printed steel-reinforced concrete components for construction. Automation in Construction. 2020;109:102988.

[27] Bos FP, Wolfs RJM, Ahmed ZY, Salet TAM. Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. Virtual and Physical Prototyping. 2016;11(3):209-225.

[28] Le TT, Austin SA, Lim S, Buswell RA, Gibb AGF, Thorpe T. Mix design and fresh properties for high-performance printing concrete. Materials and Structures. 2012;45(8):1221-1232.

[29] ISO/ASTM 52900. Additive manufacturing – General principles – Terminology. ISO; 2015.