Towards to the Hyperautomation

An integrated framework for Construction 4.0: a case of Hookbot as a distributed reconfigurable robotic assembly system

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Almost every technological and industrial concept changes the built environment around us and our understanding of the architectural practice. Recently, Hyperautomation, an all-encompassing digital transformation with the help of advanced techniques, has been presented as a game-changing concept that can affect any industry. Despite this promising concept, the Architecture, Engineering, and Construction (AEC) industry seems far behind the latest technological breakthroughs and automation of processes compared to other industries. Therefore, this study provides a better understanding of adopting the novel Hyperautomation paradigm in the AEC industry by focusing on Industry 4.0. In this context, the first section introduces the Construction 4.0 concept, its counterpart in the AEC industry, briefly mentions fundamental approaches and indicates the need for a framework. The second section introduces an integrated framework throughout the entire building life-cycle for design and construction processes and exemplifies the stages in an autonomous system and their interrelationships. The third section presents a hypothetical case, a distributed reconfigurable robotic assembly system, and the assembler 'HookBot' to understand the relationships in an autonomous system better. The last section discusses the place of the Hyperautomation paradigm in architecture.

Keywords: *Autonomy, Autonomous Systems, Construction 4.0, Assembly Robotics.*

INTRODUCTION

With the recent studies of Hyperautomation and Artificial Intelligence (AI), almost every industry and practice are preparing for an enormous shift in automation and digitization (Haleem et al., 2021; Soni et al., 2020), and this shift, the Fourth Industrial Revolution, arouses serious attention (Schwab, 2017). Similarly, there has been a shift in architecture that focuses on applications of concepts (da Costa et al., 2019) such as AI, Machine Learning (ML), Cyber-Physical Systems (CPS), Internet of Things (IoT), Robotic Process Automation (RPA), Multi Agent-based Simulation (MABS) and Digital Twin (DT) into design practice (Sawhney, Riley and Irizarry, 2020), and also, there are pioneers such as some research institutes, initiatives, and multiple studies that can be examples of this new trend in architecture (Figliola and Battisti, 2020). Despite these promising studies, the AEC industry seems far behind the latest technological breakthroughs and automation of processes compared to other industries (Davila Delgado et al., 2019).

Hyperautomation is an all-encompassing digital transformation with the help of advanced techniques such as RPA, ML, and AI (Haleem et al., 2021). In other words, hyperautomation represents a layer of advanced technology added to the changing traditional automation. It also aims to provide a more accurate adaptation and more optimized processes to changing situations. In a nutshell, hyperautomation represents a transformation that automates as many processes and tasks as possible.

Meanwhile, Industry 4.0, which includes the mentioned technologies and approaches, is a new paradigm that proposes automation, digitalization, and sensorization to improve processes. In this context, the concept of ‘Construction 4.0’, which manipulates these technologies, is proposed as its counterpart in the AEC industry (Bolpagni, Gavina and Ribeiro, 2021; Sawhney, Riley and Irizarry, 2020). In addition, thanks to a continuous and accurate monitoring process of digitization and automation, Construction 4.0 facilitates a better diagnosis and prediction for the whole process. Therefore, these technologies and approaches can advance the AEC industry towards higher levels of freedom and control in construction and save time, material, labor, and costs. However, ambiguity about the appropriate adoption of automation technologies in the AEC industry is confusing. Therefore, an integrated framework for Construction 4.0 that explains the interrelationships of technologies and systems is necessary to understand the Hyperautomation paradigm's adoption better (Muñoz-La Rivera et al., 2020).

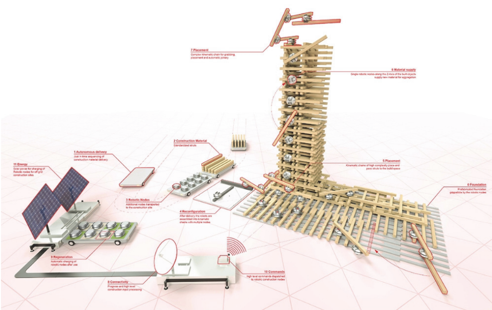

Figure 1
Distributed robotic assembly system for in-situ timber construction (Leder et al., 2019).

Besides, Construction 4.0 “proposes to automate and digitize the design and construction processes, with a strong component of real-time data capture and the incorporation of sensors in the on-site construction processes, to optimize time and costs, quality control and worker safety.” (Muñoz-La Rivera et al., 2020, p. 690). In order to provide this definition and achieve autonomous design and construction processes throughout the entire building life-cycle, the focus should be on the integration of DT and CPS concepts in architectural practice. DT is a virtual representation of a system that works with real-time data throughout its life-cycle and uses AI, ML and MABS to aid decision making (VanDerHorn and Mahadevan, 2021). Accordingly, DT would be a tool to accomplish all non-physical tasks such as management, design, and monitoring in autonomous architectural processes. Also, CPS “are enabling technologies that bring the virtual and physical worlds together to create a truly networked world in which intelligent objects communicate and interact with each other.” (Casini, 2021, p. 46). Thus, CPS would be a tool to perform all physical tasks such as logistics, building, and manufacturing in autonomous architectural processes. With proper integration of these two concepts under the AEC industry, a framework throughout the entire building life-cycle would explain the sub-concepts of these technologies and their relationship.

In this context, this paper aims to introduce an integrated framework throughout the entire building life-cycle for design and construction processes, relates architecture and technology concepts associated with the framework, and exemplifies the stages in autonomous systems and their interrelationships. We will present a hypothetical case, a distributed reconfigurable robotic assembly system (like shown in Fig 1.) with the reconfigurable robotic assembler (RRA), the ‘HookBot’, and also explains the processes and mechanism to understand the relationships in an autonomous system better, and discusses the place of the Hyperautomation paradigm and the shift of building materials and the AEC industry with autonomous processes.

AN INTEGRATED FRAMEWORK FOR CONSTRUCTION 4.0

Since the Enlightenment, academics and practitioners have been fragmenting problems to make them more manageable, determined, and understandable. Architecture, like many practices, has fragmented sub-problems and disciplines such as all of the AEC industry. Despite many benefits, this specialization and sophistication cause circumstances that waste time, material, labor, and money (Mohd Nawi, Baluch, and Bahauddin, 2014). Nevertheless, with the innovations of ICT technologies, more challenging issues can be solved, and their relationships become more integrated. Over the last two decades, the AEC industry has accelerated the implementation of some significant innovations for design, management, and construction processes. These developing approaches such as Lean Construction, which proposes continuous improvement and waste reduction processes (Tauriainen et al., 2016), Integrated Project Delivery for contractual integration between all project participants, and Building Information Modeling (BIM) for the generation and management of multidimensional parametric models (Succar, 2009), are integrating industry and increasing efficiency with more automated processes (Muñoz-La Rivera et al., 2020).

The most comprehensive and promising of these three approaches is BIM, which can be defined as "a digital representation of physical and functional characteristics of a facility and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle defined as existing from earliest conception to demolition" or "the development and use of a multi-faceted computer software data model to not only document a building design but to simulate the construction and operation of a new capital facility or a modernized facility" (da Silva Lopes Vieira and Jens-Uwe, 2019). These foundational definitions include Building Life-cycle Management (BLM), a state-of-the-art approach that covers all processes of architecture (Meng et al., 2020). With the recent Hyperautomation and Industry 4.0 studies, there has been an improvement in BIM and AEC relations that focuses on applying concepts such as AI, IoT, CPS and DT (da Costa et al., 2019) into research and practice. Among these approaches that stand out for the higher level of flexibility, adaptability, predictability, and efficiency in production, DT has developed at the core of Industry 4.0, which aims to achieve deep cyber-physical integration (VanDerHorn and Mahadevan, 2021). Zhang, Luo and Xu (2022) identified "BIM is currently developing towards DT to support the booming building automation and robotics" in the BIM-enabled building automation review. A cloud computing-based and BIM-enabled DT model, a decision-maker that can connect and operate the entire BLM process, could be a unifying factor for AEC Industry 4.0 (Stjepandić, Sommer and Denkena, 2021).

In addition, the other most prominent element for the operability of this DT model is CPS. The increase in communication, monitoring and sensing capabilities of manufacturing machines and robots enables new CPS that connect physical production processes with cloud computing and IoT (Menges, 2015). Interaction with the physical world can occur with CPS in an integrated framework for Construction 4.0 (as proposed in Fig. 2), where design, management and operation are carried out entirely digitally with cloud computing. All CPS in the system can transfer behavior data, self-positioning and scheduling to the DT model with (IoS) Internet of Services. This relationship establishes the feedback and control mechanism of the system. In addition, the decentralization of the system can be achieved by the IoT relationships between CPS and Cloud Computing. Moreover, a Cognitive Digital Twin (CDT) model that integrates with a learning algorithm can improve itself and adapt to other systems. The processes of the Integrated Framework for Construction 4.0 are described in three sub-stages as follows: Planning and Designing, Manufacturing and Logistics, Construction and Assembling.

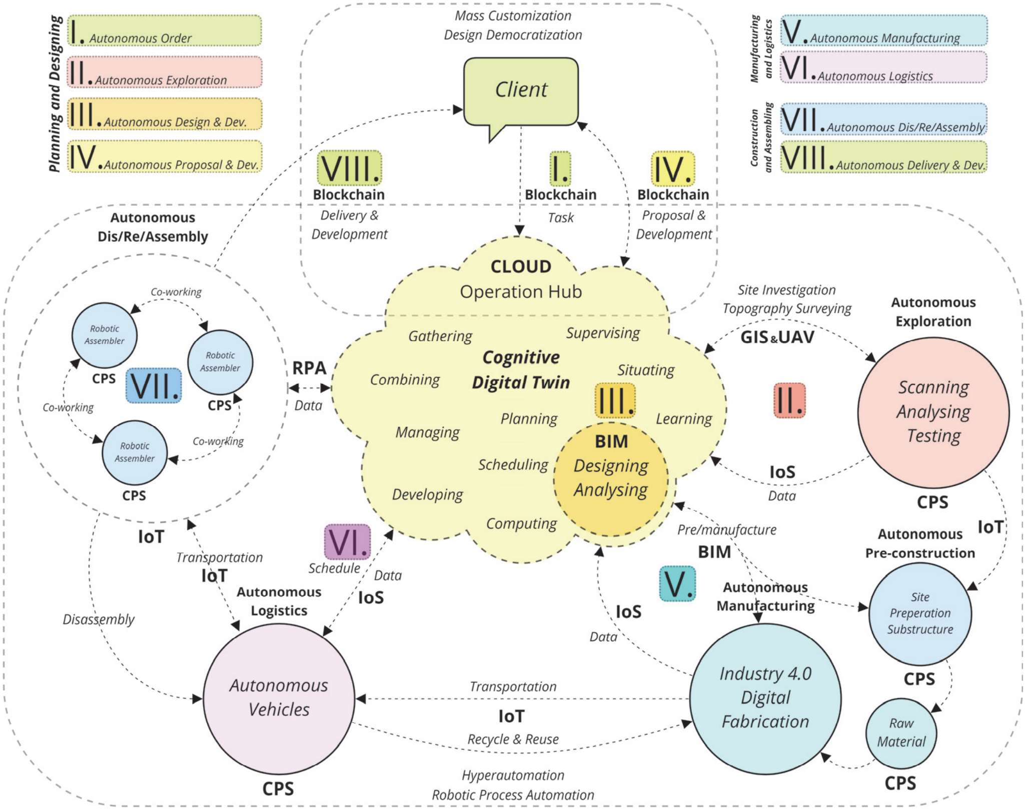

Figure 2
An Integrated Framework for Construction 4.0.

Planning and designing

The aim of Construction 4.0 is to maintain all processes and tasks in the system autonomously by using automation and robotic technologies (Muñoz-La Rivera et al., 2020). Robotic and cybernetic stimulations can replace the relationships of the client, contractor, and stakeholders in the traditional AEC industry. The client is the agent that stimulates the Operation Hub in this autonomous system. Stage [I] is where the design task is defined in detail (illustrated in Fig.2) using natural language processing and quantitative data collection. At this stage, the detailed information about the design task can be defined on the cloud with the help of promising Neural Networks and AI studies (Ilmudeen, 2022), which is of great importance in processing qualitative data. Furthermore, the agreement between the client and the system can be guaranteed by Blockchain-based smart contracts (Dounas, Lombardi and Jabi, 2020; Sigalov et al., 2021). These integrations in the system would include concepts such as mass customization, design democratization and decentralization.

As parallel, the Stages [I] and [II] would continue to execute by launching the first stimulation. BIM and Geographic Information System (GIS) integration represent the most current approach at Stage [II] (Karimi and Iordanova, 2021). Computer systems that analyze and display geographically referenced information can automate processes in integrating data. Furthermore, this data can be supported by Unmanned Aerial Vehicles (UAV) that can collect the data autonomously and the GIS integration (Hognogi et al., 2021). This system is a proposal of the CPS that can work as an [Autonomous Exploration] module. The system components are connected to IoT through IoS with the Operation Hub. After the system has collected enough data, the CPS goes to standby mode or the next task.

Consequently, combining all the data necessary for the design and development stimulates Stage [III]. This stage is a module integrated into the Operation Hub with cloud computing, including BLM processes such as architectural and structural design, development, and design analysis. The [Autonomous Design and Development] module would integrate with learning systems, cognitive models, Neural Networks and AI studies. As with integrating Generative Design approaches with BIM (Ma et al., 2021), these studies are open to development. The most beneficial approach that stands out in this integration is Parametric Design (Dautremont et al., 2019), which also contributes to the re-interpretation of the produced knowledge for adapting new CPS. A production-ready project stimulates Stage [IV], and during this [Proposal & Development] module, a series of cycles occur between the design module and the client. The client's project approval with a Blockchain-based smart contract stimulates Stage [V].

Manufacturing and logistics

Stage [V] consists of autonomous CPS modules that maintain pre-construction and pre/manufacturing processes. When the design is finalized, BIM documents are transferred to the production facility and site preparation robots (Melenbrink, Werfel and Menges, 2020). Raw materials excavated from the construction site can be converted into building materials or stored. Besides, the autonomous manufacturing CPS is stimulated by the transfer of the raw materials to the Industry 4.0 facility. Robotic technologies are widely used to produce standardized building materials (Chea et al., 2020), and pioneering digital fabrication studies are carried out for customized building materials (Figliola and Battisti, 2020). Meanwhile, sensor-based in-line quality control draws attention to customized building materials (Garms et al., 2019).

The completion of construction site preparation and building materials production starts the autonomous transportation process as Stage [VI]. This stage is maintained with the coordinated combination of autonomous rail, ship, road, and air transportation vehicles that interact with each other. Cloud computing determines shipment routes, and available vehicles can be positioned between the production facility and the construction site. Besides, autonomous on-site and off-site transportation initiatives are gradually progressing (Chea et al., 2020), and also, innovative studies (Romanishin et al., 2015) show that we may encounter self-transportation discrete building materials in the future.

Construction and assembling

Traditional construction processes typically involve site preparation, substructure, and superstructure phases. The [Autonomous Pre-construction] CPS performs tasks such as earthmoving, leveling for the Site preparation and anchoring, and laying the foundations for the substructure phase. Afterwards, the completion signal of the Autonomous Pre-construction and Transportation CPS stimulates the [Autonomous Dis/Re/Assembly] CPS, which is Stage [VII]. There are two approaches for superstructure construction automation: off-site (Gusmao Brissi et al., 2021) and on-site (Melenbrink, Werfel and Menges, 2020). Off-site construction automation focuses on modular building processes in which some or all of the building components are prefabricated or preassembled. These modular or specialized prefabricated components are assembled on-site, and also, there is an “Automated Building Construction System” approach to converting construction sites into conventional production facilities (Ikeda and Harada, 2006).

On the other hand, on-site construction automation focuses on discrete automation of tasks in the traditional processes of raw material procurement, manufacturing, and construction. Autonomous Construction and Dis/Re/Assembly would be achieved by manipulating and automating working relations in these processes. Automation studies in these processes are generally related to additive manufacturing or component assembly. There are additive manufacturing studies at different scales and techniques, such as building scale (D-Shape) and small-scale mobile (Minibuilders) 3D printers at building scale, Gas Metal Arc Welding robots (MX3D), adaptive formwork technologies (VoxelCrete). Besides, there are building scale gantry systems, brick-laying robots (Hadrian X), and innovative technologies such as aerial, terrestrial, and climbing robots that can change the relationship between components and assemblers (Melenbrink et al., 2020). These examples introduce emerging technologies and draw attention to the communication protocols of these technologies and the importance of standardization so that they can become widespread.

Stage [VII] can be completed using the mentioned approaches, and the project can be delivered to the client by the Blockchain-based smart contract. In addition, Stage [VIII] includes a detailed feedback process, and the system can be reactivated in case of possible changes in the project. Furthermore, the project would be re/dis-assembled for recycling or reusing at the end of the building's lifespan.

HOOKBOT: A DISTRIBUTED RECONFIGURABLE ROBOTIC ASSEMBLY SYSTEM

Based on the framework (Fig.2), we present a hypothetical case as an example of such a system, the HookBot, mentioning the phases of the system and focusing on the [Autonomous Dis/Re/Assembly] stage. Since the construction phase is a combination of physical and digital processes, it can be a useful tool for understanding autonomy. The Hookbot aims to use integrated and autonomous processes in truss structures for design and construction tasks such as semi-open spaces, temporary or permanent pavilions, and logistic bridges. The system would provide benefits in design and construction processes such as time, material, labor, cost savings, site safety, accident prevention, mass customization, design democratization, and automation in organizational process management.

As proposed in the framework above, the client orders the design task to the assembly system using a mobile application. With the application and AR integration, design visualizations would be experienced in cyberspace. Meanwhile, UAVs transmit live construction site data such as wind, insolation, and scanning to the Operation Hub with GIS and various sensors. With the analysis of all data, the client can approve or renovate the project. The approved component information is sent to different facilities and then autonomously transported to the site. With the preparation of the construction site and the substructure, the HookBot RRA can erect the structure.

The Assembly System

Truss structures are often used to achieve long spans, minimize the weight, and support heavy loads, and also, they consist of struts and joints arranged to form one or more triangles since the joints are fixed and cannot transmit moments. Space trusses vary from plane trusses with their geometric possibilities. Even if the struts and joints dimensions differ, there is no substantial variance in assembly techniques. Two solutions differ for increasing automation in truss assembly: one of them is gantry systems (Rhodes, Will and Quach, 1995), which generally work with a robot arm that can move in X and Y directions through a frame larger than the structure, and the other is mobile or climbing robots (Hjelle and Lipson, 2009) that can easily move and locomote on or around the structure. Mobile or climbing robots are promising research due to their degree of freedom and size advantages (Melenbrink, et al.; Jenett and Cheung, 2017).

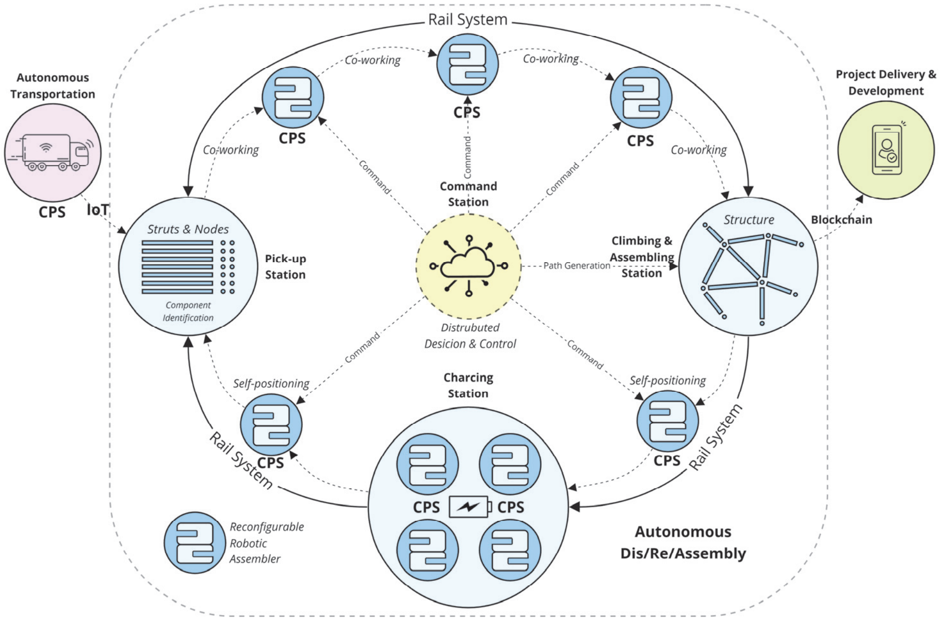

Figure 3
A framework for distributed reconfigurable robotic assembly system

Initially, the [Charging Station] containing the reconfigurable robotic assemblers (RRA) and the [Pick-up Station] with marked components such as struts and nodes are dropped off at the construction site. Each of the RRAs in this system works as a CPS with distributed decision and control. Distributed operations, widely used in autonomous control systems in the aviation industry, provide collaborative swarm control to the system (Chen et al., 2021). So, the [Command Station] assigns tasks to RRAs in standby mode at the charging station. RRAs begin to assemble a specialized rail system that enables locomotion between stations. RRAs move on the specialized rail system and work together to transfer the components of the truss structure to the [Climbing and Assembling Station]. At this station, they erect the structure by climbing and assembling it. RRAs with low batteries head to the charging station and are replaced by new ones. After the structure's assembly, the RRPs get together and pick up from the construction site at the charging station (as illustrated in Fig3).

The HookBot RRA

Climbing robots, specialized mobile robots, are robotic systems used to move over walls, ceilings, roofs, and geometric structures and perform various tasks (Chu et al., 2010). Besides, relative robots, which are climbing robots with different classes according to locomotion and adhesion mechanisms, can locomote on the structure they assemble (Carney & Jenett, 2016). There are many experimental studies on the construction, assembly, and reconfiguration of structures with different materials by these robots, which emphasize building material design and robotic concepts (Nigl et al., 2013; Petersen et al., 2019). Unlike these examples, Leder et al. (2019) conceptualized a system that stands out by lightening, simplifying, and minimizing features. However, the single-axis design of the assembly robots in the system reduces the degree of freedom and creates new complexities. This single-axis design, which limits its mobility, can be overcome with a reconfiguration mechanism applied in pipe climbing robots (Sattar et al., 2008).

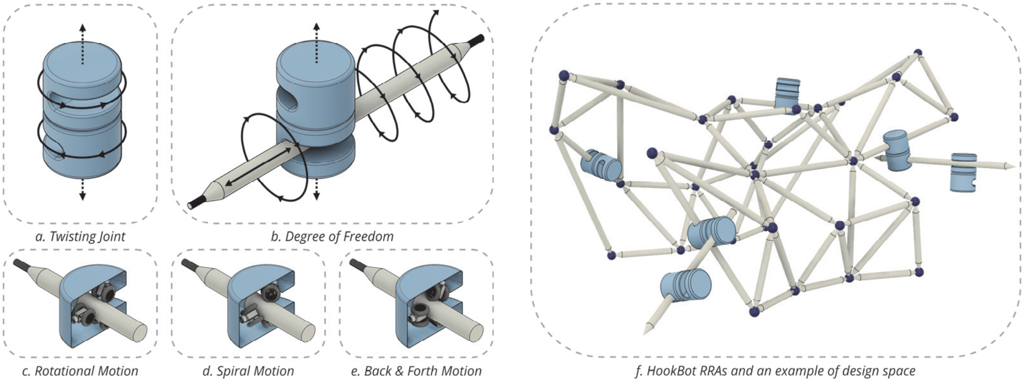

Figure 4
HookBot RRA concept and an example of design space

The proposed system consists of multiple collaborative RRAs designed to use the truss system for its locomotion. The HookBot RRA, a climbing robot that can dis/re/assemble in truss systems, differs from the literature regarding its reconfiguration system and degree of freedom. It can grab and release struts thanks to the gripper mechanism and rotate the trusses or itself thanks to the twisting joint (as illustrated in Fig.4a). Due to the reconfiguration of the six-wheel gripper mechanism, it can move rotational, spiral, back and forth on the truss system (as illustrated in Fig.4b-c-d-e). The collaboration of two RRAs can move and assemble struts and joints on each axis within the system. It shows that the six degrees of freedom emerging from the collaboration in this system can enrich the resulting geometries (as illustrated in Fig.4f).

CONCLUSIONS

This paper highlights the possibilities of robotic shift that may emerge with the hyperautomation paradigm with an integrated framework such as mass customization, design democratization, and high efficiency. It also presents a path for Construction 4.0 by embracing emerging technologies and linking potential applications throughout the building life-cycle. Consequently, DT integration with BIM may become the most efficient way for managing, monitoring, and communicating directly with robots for the AEC industry. However, the AEC industry seems distant from such an integration. The most obvious reason for this might be workflows that focus on human relations. Digitizing these workflows with BIM and finding new intersections with AI-based Hyperautomation is a excellent opportunity to increase efficiency for the industry. On the other hand, the studies proposing to design robot-friendly building materials such as Robot-oriented Design (ROD) are gaining significance. Besides, there is a transformation from assembler-constructor robots that imitate human actions to robots that can develop, generate, and adjust as an integral part of architectural systems. The changing relationship between building materials and constructor-assembler robots may have introduced a new robot classification. Therefore, the presented robotic assembly system exemplifies such a classification. The system's high degree of freedom is an advantage for the dimensions of the design space. However, the possible problems of the conceptualized RRA, such as payload, remote and distributed control complexities, inverse kinematics, and self-positioning, are disadvantages. This hypothetical system proposal can serve as base research for future studies. Also, a digital simulation of collaborating and assembling robots will be made to eliminate these uncertainties for future work. In addition, with a functioning prototype as a proof of concept, a small-scale space truss structure will be assembled with cardboard tubes or PE pipes.

REFERENCES

Bolpagni, M., Gavina, R., & Ribeiro, D. (2021). Industry 4.0 for the Built Environment: Methodologies, Technologies and Skills (Structural Integrity Book 20). Springer.

Carney, M., & Jenett, B. (2016, June). Relative Robots: Scaling Automated Assembly of Discrete Cellular Lattices. Volume 2: Materials; Biomanufacturing; Properties, Applications and Systems; Sustainable Manufacturing.

Casini, M. (2021). Construction 4.0: Advanced Technology, Tools and Materials for the Digital Transformation of the Construction Industry. Woodhead Publishing.

Chea, C. P., Bai, Y., Pan, X., Arashpour, M., & Xie, Y. (2020). An integrated review of automation and robotic technologies for structural prefabrication and construction. Transportation Safety and Environment, 2(2), 81–96.

Chen, H., Wen, Y., Zhu, M., Huang, & et. al. (2021). From Automation System to Autonomous System: An Architecture Perspective. Journal of Marine Science and Engineering, 9(6), 645.

Chu, B., Jung, K., Han, C. S., & Hong, D. (2010, August). A survey of climbing robots: Locomotion and adhesion. International Journal of Precision Engineering and Manufacturing, 633–647.

da Costa, M. B., dos Santos, L. M. A. L., Schaefer, J. L., Baierle, I. C., & Nara, E. O. B. (2019). Industry 4.0 technologies basic network identification. Scientometrics, 121(2), 977–994.

da Silva Lopes Vieira, T., & Jens-Uwe, S. (2019). Design Method Aided by MABS and Cloud Computing-Framework integrating: construction techniques, materials, and fabrication.

Dautremont, C., Jancart, S., Dagnelie, C., & Stals, A. (2019). Parametric design and BIM, systemic tools for circular architecture.

Davila Delgado, J. M., Oyedele, L., Ajayi, et al. (2019). Robotics and automated systems in construction: Understanding industry-specific challenges for adoption. Journal of Building Engineering, 26.

Dounas, T., Lombardi, D., & Jabi, W. (2020). Framework for decentralised architectural design BIM and Blockchain integration. International Journal of Architectural Computing, 147807712096337.

Figliola, A., & Battisti, A. (2020). Post-industrial Robotics: Exploring Informed Architecture. (1st ed. 2021 ed.). Springer.

Garms, F., Jansen, C., Schmitz, C., Hallerstede, S., & Tschiesner, A. (2019). Capturing value at scale in discrete manufacturing with Industry 4.0. McKinsey & Company.

Gusmao Brissi, S., Wong Chong, O., Debs, L., & Zhang, J. (2021). A review on the interactions of robotic systems and lean principles in offsite construction. Engineering, Construction and Architectural Management, 29(1), 383–406.

Haleem, A., Javaid, M., Singh, R. P., Rab, S., & Suman, R. (2021). Hyperautomation for the enhancement of automation in industries. Sensors International, 2, 100124.

Hjelle, D., & Lipson, H. (2009). A robotically reconfigurable truss. 2009 ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots, 73–78.

Hognogi, G. G., Pop, A. M., Marian-Potra, A. C., & Someșfălean, T. (2021). The Role of UAS–GIS in Digital Era Governance. A Systematic Literature Review. Sustainability, 13(19), 11097.

Ikeda, Y., & Harada, T. (2006, October). Application of the Automated Building Construction System Using the Conventional Construction Method Together. Automation and Robotics in Construction (IAARC), 722–727.

Ilmudeen, A. (2022). Artificial Intelligence, Big Data Analytics and Big Data Processing for IoT-Based Sensing Data. Transforming Management with AI, Big-Data, and IoT, 247–259.

Jenett, B., & Cheung, K. (2017). BILL-E: Robotic Platform for Locomotion and Manipulation of Lightweight Space Structures.

Karimi, S., & Iordanova, I. (2021). Integration of BIM and GIS for Construction Automation, a Systematic Literature Review (SLR) Combining Bibliometric and Qualitative Analysis. Archives of Computational Methods in Engineering, 28(7), 4573–4594.
Leder, S., Weber, R., Wood, D., Bucklin, O., & Menges, A. (2019). Distributed Robotic Timber Construction. Proceedings of the 39th ACADIA.
Ma, W., Wang, X., Wang, J., Xiang, X., & Sun, J. (2021). Generative Design in Building Information Modelling (BIM): Approaches and Requirements. Sensors, 21(16), 5439.
Melenbrink, N., Kassabian, P., Menges, A., & Werfel, J. (2017). Towards force-aware robot collectives for on-site construction. 382–391.
Melenbrink, N., Werfel, J., & Menges, A. (2020). On-site autonomous construction robots: Towards unsupervised building. Automation in Construction, 119, 103312.
Meng, Q., Zhang, Y., Li, Z., Shi, W., et. al. (2020). A review of integrated applications of BIM and related technologies in whole building life cycle. Engineering, Construction and Architectural Management, 27(8), 1647–1677.
Menges, A. (2015). The New Cyber-Physical Making in Architecture: Computational Construction. Architectural Design, 85(5), 28–33.
Mohd Nawi, M. N., Baluch, N., & Bahauddin, A. Y. (2014). Impact of Fragmentation Issue in Construction Industry: An Overview.
Muñoz-La Rivera, F., Mora-Serrano, J., Valero, I., & Oñate, E. (2020). Methodological-Technological Framework for Construction 4.0. Computational Methods in Engineering, 28(2), 689–711.
Nigl, F., Shuguang Li, Blum, J. E., & Lipson, H. (2013). Structure-Reconfiguring Robots: Autonomous Truss Reconfiguration and Manipulation. IEEE Robotics & Automation Magazine, 20(3), 60–71.
Petersen, K. H., Napp, N., Stuart-Smith, R., Rus, D., & Kovac, M. (2019). A review of collective robotic construction. Science Robotics, 4(28).
Rhodes, M. D., Will, R. W., & Quach, C. C. (1995). Verification tests of automated robotic assembly of space truss structures. Journal of Spacecraft and Rockets, 32(4), 686–696.
Romanishin, J. W., Gilpin, K., Claici, S., & Rus, D. (2015). 3D M-Blocks: Self-reconfiguring robots capable of locomotion via pivoting in three dimensions.
Sattar, T., Leon-Rodriguez, H. E., Shang, J., Mondal, & et. al. (2008). Mobile wall climbing and swimming robots to inspect aircraft, storage tanks, pressure vessels and large infrastructure.
Sawhney, A., Riley, M., & Irizarry, J. (2020). Construction 4.0: An Innovation Platform for the Built Environment (1st ed.). Routledge.
Schwab, K. (2017). The Fourth Industrial Revolution.
Sigalov, K., Ye, X., König, M., Hagedorn, P., & et. al. (2021). Automated Payment and Contract Management in the Construction Industry by Integrating Building Information Modeling and Blockchain-Based Smart Contracts. Applied Sciences, 11(16), 7653.
Soni, N., Sharma, E. K., Singh, N., & Kapoor, A. (2020). Artificial Intelligence in Business: From Research and Innovation to Market Deployment. Procedia Computer Science, 167, 2200–2210.
Stjepandić, J., Sommer, M., & Denkena, B. (2021). DigiTwin: An Approach for Production Process Optimization in a Built Environment, Springer.
Succar, B. (2009). Building information modelling framework: A research and delivery foundation for industry stakeholders. Automation in Construction, 18(3), 357–375.
Tauriainen, M., Marttinen, P., Dave, B., & Koskela, L. (2016). The Effects of BIM and Lean Construction on Design Management Practices. Procedia Engineering, 164, 567–574.
VanDerHorn, E., & Mahadevan, S. (2021). Digital Twin: Generalization, characterization and implementation. Decision Support Systems, 145, 113524.
Zhang, J., Luo, H., & Xu, J. (2022). Towards fully BIM-enabled building automation and robotics: A perspective of lifecycle information flow. Computers in Industry, 135, 103570.