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The Current State and Future Directions of Industrial Robotic Arms in Modular Construction

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Abstract: Industrial robotic arms are widely adopted in numerous industries for manufacturing automation under factory settings, which eliminates the limitations of manual labor and provides significant productivity and quality benefits. The U.S. modular construction industry, despite having similar controlled factory environments, still heavily relies on manual labor. Thus, this study investigates the U.S., Canada, and Europe-based leading modular construction companies and research labs implementing industrial robotic arms for manufacturing automation. The investigation mainly considered the current research scope, industry state, and constraints, as well as identifying the types and specifications of the robotic arms in use. First, the study investigated well-recognized modular building associations, the Modular Building Institute (MBI), and renowned architecture design magazine, *Dezeen* to gather industry updates. The authors discovered one university lab and a few companies that adopted Switzerland-based robotic arms, ABB. Researching ABB robotics led to the discovery of ABB's competitor, Germany-based KUKA robotic arms. Consequently, research extended to the companies and labs adopting KUKA models. In total, this study has identified seven modular companies and four research labs. All companies employed robotic arms and gantry robot combinations in a production-line-like system for partial automation, and some adopted design standardization for optimization. The common goal among the labs was to achieve greater flexibility and full automation with robotic arms. This study will help companies better implement robotic arm automation by providing recommendations from investigating its current industry status.

Key words: Industrialized construction, Modularization, Standardization, Automation, Offsite Construction

1. INTRODUCTION

The traditional stick-built method strictly utilizes the on-site-based workspace for all construction activities from foundation to erecting the buildings [1]. Modular construction is a combination of several techniques that export the portion of site-based construction activities to a faster, more efficient, and predictable factory or locations other than the final installation site [2],

[3]. Moreover, the modular construction essentially eliminates any schedule delays and costly on-site variables, such as daily work hour limitation, higher worker number demand, site-based work permit requirements, and extreme weather conditions that are inevitable when adopting the stick-built method [2]. As a result, modular construction enables significant project schedules and cost benefits.

Many countries have long been adopting modular construction and successfully addressed construction project-related issues such as skilled labor shortage, higher environmental restrictions, higher schedule, safety, and cost savings demand [2], [4]. In the U.S., Canada, and Europe, the modular construction industry has developed rapidly in recent years to respond to these issues, otherwise known as modularization drivers [4]. Modular construction processes under its fabrication shop resemble other manufacturing industries. They both adopt similar factory environments. But there lies a significant difference in the degree to which they utilize such similarity. The manufacturing industries such as airplane, car, and shipbuilding industries achieved, at a large scale, manufacturing automation by adopting industrial robotic arms with significant productivity, schedule, and cost benefits [5], [6]. Whereas the modular construction processes widely remain manual despite recent developments, leaving room for drastic efficiency and productivity improvements through automation [7].

This study aims to provide several recommendations to help the industry recognize the benefits of automated module fabrication and further implement module fabrication automation via industrial robotic arms. Consequently, this study investigates those leading modular construction companies and research labs in the U.S. and Europe that utilize industrial robotic arms to automate modular construction processes for better interpretation of the current research scope, industry state, and constraints, as well as identify the types and specifications of the robotic arms in use.

2. METHODOLOGY

This study uses the 'snowballing' search method [8] and identifies leading U.S. and European companies and research labs leading module fabrication automation via industrial robotic arms. First, the authors investigated Modular Building Institute (MBI), a reputable international non-profit trade association dedicated to modular construction. The authors discovered three relevant companies (Brave Control Solutions, Autovol, and Z Modular) from their latest article, 'MODULAR ADVANTAGE (2021 INNOVATION EDITION) [9].' The companies were adopting Switzerland-based ABB's [10] robotic arms, and while investigating ABB robotics, the authors discovered a German-based automation company, KUKA [11], as ABB's competitor. Second, the investigation continued with ABB and KUKA as the new keywords, and, as a result, authors discovered four ((House of Design [12] (ABB value provider), Randek Robotics [13] (ABB System Integrator), Intelligent City [14] (ABB partnership), and Mighty Buildings [15] (KUKA user)) more companies. Third, *Dezeen* [16], a world-renowned architecture, interiors, and design magazine, was investigated, and the authors identified a university research lab at ETH. Last, the authors investigated other well-known research labs and university labs and discovered Autodesk robotics lab [17] and two university labs (U-M [18] and IRIM [19]).

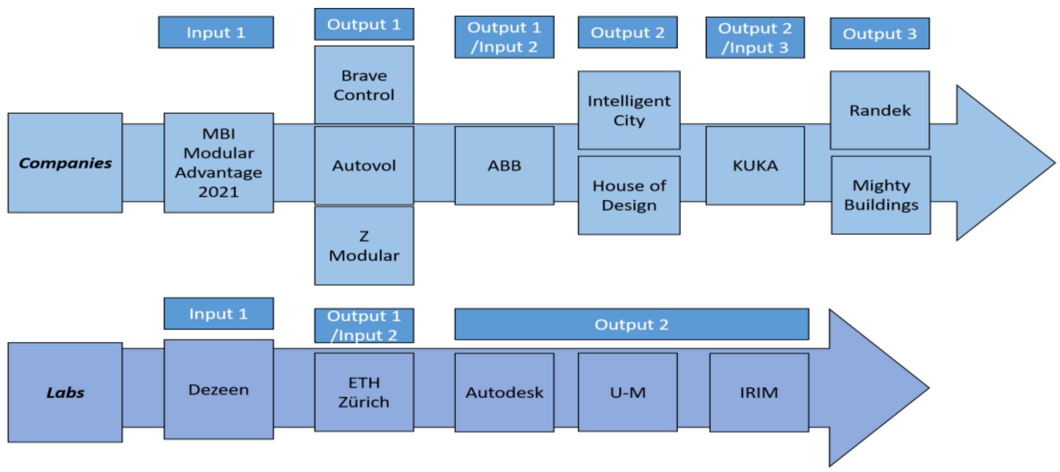

Figure 1. Snowballing search method diagram

3. RESULTS

Through investigation, authors identified seven modular construction companies and four research labs throughout the U.S., Europe, and Canada that implement robotic arm automation processes.

3.1. Companies

The seven industrial robotic arms implementing modular companies are as follows:
1. Brave Control Solutions – U.S.;**2.** House of Design – U.S.; **3.** Mighty Buildings – U.S.
4. Z Modular – U.S.; **5.** Autovol – U.S.; **6.** Intelligent City – Canada; **7.** Randek Robotics – Sweden

Table 1. Industry Robotic Arms Specifications

No.	Name	Robotic Arm Type	Model	Payload (kg)	Reach (m)	Axes	Material
1	Brave Control Solutions	ABB	IRB 6650, 8700, etc.	200~800	2.75~4.20	6	Steel
2	House of Design	ABB	IRB 7600, 6650, 4400, etc.	60~500	2.55~2.75	6	Timber
3	Mighty Buildings	KUKA	N/A	N/A	N/A	N/A	Timber
4	Z Modular	ABB	IRB 4400, IRB 6790, etc.	60~235	1.95~2.80	6	Steel
5	Autovol	ABB	IRB 6790, etc.	~235	~2.80	6	Timber
6	Intelligent City	ABB	IRB 6790, etc.	~235	~2.80	6	Steel
7	Randek Robotics	KUKA, ABB	KR QUANTEC, etc.	~120	~3.50	6	Steel/Timber

Out of seven companies, five are based in the U.S., one is in Sweden, and one is in Canada. Five (1,2,4,5 and 6) utilize robotics arms made by ABB robotics, a Switzerland-based automation company that manufactures industrial robotic arms with payloads up to 800 kg and a maximum reach up to 4.20 meters. One (3) uses Germany's KUKA robotics arms that have a payload up to 500kg and a maximum reach up to 3.50 meters, and one (7) uses both KUKA and ABB robotic arms. Table 1 includes more detailed specifications of the robotic arms in use. The labor shortage is a common issue among companies, and they are aiming to help meet the ever-rising market demands on housing with automated modular construction. All companies are utilizing a streamlined line-like production system, which implements robotic arms for partial or full automation of timber or steel modular building components. In each production line, the robotic arms are mounted on top of gantry robots to minimize the reach limitations. No companies have fully automated the volumetric module manufacturing processes at this stage. One (7) uses timber and light gauge steel for wall, floor, and roof manufacturing systems. Two (1,4) are using steel systems, and robotic arms mainly undertake material welding, variable fixturing, mechanical fastening, dispensing, and handling activities. Others adopt timber/mass-timber systems. For timber systems, dedicated production lines can fully automate non-volumetric building components such as a wall, floor, ceiling, and roof truss manufacturing processes. Five (2,3,4,5 and 7) are extensively implementing a design standardization that ranges from a simple timber product design standardization to module design standardizations to reach maximum efficiency and cost benefits. All identified robotic arms from the companies have 6-axes, regardless of the type. Two engineering consultant companies (1,2) higher-capacity models such as IRB 7600 and IRB 8700 to be adequately equipped to handle diverse automation projects from other companies.

3.2. Research Labs

The four industrial robotic arms implementing research labs are as follows: **1.** Autodesk Robotics Lab – U.S.; **2.** U-M Research – U.S.; **3.** Institute for Robotics and Intelligent Machines (IRIM) – U.S.; **4.** ETH Zurich – Switzerland

Out of four research labs, three (2~4) are university labs, and one (1) is a lab owned by a publicly owned company. Three (1~3) are based in the U.S., and one (4) is in Switzerland. Moreover, three (1~3) are using KUKA robotic arms, and only one (4) is using ABB robotic arms. Table 2 includes the detailed specifications of the ABB and KUKA robotics arms the four research labs use. A common goal among the four research labs is to significantly increase the level of automation by developing a technique or an algorithm to help robotic arms to understand each construction activity and adjust it accordingly to any changes that might occur.

Autodesk Robotics Lab

Kerrick and her team have developed a CAD-Informed Robotic Assembly (CIRA) tool, which enables the robots to assemble products from exploded 3D models. However, extensive manual calibrations are required to help robotic arms to identify exact places to carry out the assembly operations. Kerrick's research team is currently working on implementing A.I. technology in CIRA 2.0 to make robots recognize each component of a building within the work frame and carry out the entire assembly/construction processes by simply receiving a higher-level command. The team has tested CIRA 2.0 using LEGO blocks. However, it has not been tested using real-life scale building components yet.

U-M Research

Dr. Kamat and his team at Michigan Engineering have developed a modeling technique called 'Dynamic Manipulation' that enables the robotic arms to program their motions by examining the surrounding work environments. Dynamic Manipulation allows the robotic arms to adjust to the changes and plan their activities accordingly without extra programming by utilizing the 3-D model of the work environment in real-time. The robotic arm recognized the cavity pattern through 3-D modeling and carried out a filling activity adequately. The U-M research team has not experimented with automation using Dynamic Manipulation on any other construction activities yet.

IRIM

The IRIM research team is aiming to achieve flexible automation. The team's main modular construction-related topics are specialized in external sensing and feedback control methods and data driven-method for accurate industrial robotics automation and modeling of robot behaviors. At this moment, they have enabled accurate robotic milling by utilizing a closed-loop wireless force feedback control of a KUKA industrial robotic arm.

ETH Zurich

The ETH Zurich research teams and Switzerland construction industry experts have collaborated on a multi-story residential project called the 'DFAB House' project. Initially, eight research teams broke the DFAB House project into several smaller projects. Spatial Timber Assemblies, as one such smaller project, implemented two ceiling-mounted ABB robotic arms/gantry robot systems controlled by a computer algorithm that recalculates their plan of movement in real-time. As a result, the robots cut timber beams into sizes, drill holes for installing the beams, and located the beams to designated positions to be bolted and secured. Furthermore, the robot's movements adjust accordingly to any changes made via an updated computer model. However, the systems are not fully automated as they require manual labor of bolting in the wooden beams after the robots place them in their positions.

Table 2. Research Labs Robotic Arms Specifications

No.	Name	Robotic Arm Type	Model	Payload (kg)	Reach (m)	Axes
1	Autodesk	KUKA	KR QUANTEC	120	3.50	6
2	U-M Research	KUKA	KR QUANTEC	120	3.50	6
3	IRIM	KUKA	KR 500 FORTEC, KR 210	210~500	2.50~3.30	6
4	ETH Zurich	ABB	N/A	N/A	N/A	N/A

The main tasks assigned to robotic arms were material welding, variable fixturing, mechanical fastening, dispensing, and handling activities. Some achieved full automation of timber wall, floor, ceiling, and roof truss manufacturing processes with dedicated production lines. Information regarding models, notable features, and applications of each robotic arm adopted by the seven companies and four research labs are shown in Table 3.

Table 3. Features and Applications

Robotic Arm Type	Model	In use by	Features	Applications

ABB	IRB 4400	Companies	Fast/Compact (handling two parts at a time)	Cutting/Deburring Grinding/Polishing Measuring
ABB	IRB 6650	Companies	High production up-time/short cycle times	Material Handling Spot Welding Die Casting
ABB	IRB 6790	Companies	Designed for harsh industrial uses in two variants: 205 kg, 2.80 m 235kg, 2.65m	High-Pressure Deburring
ABB	IRB 7600	Companies	Heavy applications	Heavy fixtures/parts Handling Loading/Unloading Machine Cells
ABB	IRB 8700	Companies	Robust design elements w/ simpler parts (high up-time)	Heavy fixtures/parts Handling in production lines
KUKA	KR QUANTEC	Both	Best reach/payload in this category	Handling Welding/Cutting Assembly
KUKA	KR 500 FORTEC	Labs	Machine Tool predestined for milling Foundry variant for heavy tasks	Handling Welding/Cutting Assembly
KUKA	KR 210	Labs	Ideal for foundry setting	Handling Assembly

3.3. Future Directions

The qualities of industrial robotic arms are drastically improving, and the new methods, computer algorithms, and techniques are becoming more and more applicable in a real-life modular construction setting. Fully automated modular construction will be an inevitable next step in the industry as the industrial robotic arms improve and become more versatile. Currently, it is demanding to have several production-line-like systems to partially automate the manufacturing processes of a few modular components that are not volumetric. However, when effective communication with industrial robotic arms is achieved through technological improvements, the authors expect there will be a drastic shift in the designing process of the production-line-like systems. Instead of having multiple systems, there will be much fewer systems capable of automating the volumetric modular construction processes, if not fully automating them. As a result, the efficiency potential of modular construction will be fully utilized, just like the other mass-production industries that have already fully automated their manufacturing processes in a similar factory environment.

4. CONCLUSION

The need for robotic arm automation in the modular construction industry is rising due to the increasing demands for housing and the skilled labor shortage. However, the current level of robotic arm technologies is insufficient for the full automation of volumetric construction processes. Therefore, the companies are utilizing a production line-like system to let robotic arms undertake non-volumetric construction tasks. Some are extensively implementing design standardization in the process, which helps them gain additional schedule and cost benefits by making many tasks repeatable for robotic arms. The focus of the research labs was to develop a more efficient and effective way to communicate with robotic arms to let them understand each component of construction in real-time and undertake more complex volumetric construction tasks.

However, the conclusions made from this study do not reflect the worldwide status of robotic arm automation in modular construction. The research scope is limited to the companies and research labs that are based in the U.S., Canada, and Europe. Also, this study only investigates the information that has already been made public, and it is plausible that the information accessed does not precisely represent the latest industry status.

Nonetheless, this study has identified an effective robotic arm automation trend in the modular construction industry that mitigates limitations regarding the level of robotic arm technology. Firstly, for the aspiring modular construction company planning to implement automation with industrial robotic arms, using either KUKA's KR QUANTEC or ABB's IRB 6750 or 6790 will suffice in most cases. If the company aims to serve as an engineering service consulting firm that imports numerous projects at a varying scale from different companies, adopting more robust models such as ABB's IRB 7600 or 8700 or KUKA's KR 500 FORTEC or KR 1000 Titan might be necessary. Secondly, it seems highly desirable to implement design standardization to make tasks as repeatable and optimizable as possible to minimize the coding work needed to make robots undertake various tasks. Lastly, a production line-like system with gantry robot paired robotic arms seems to be the most efficient way of automating the manufacturing processes in factory environments. For research labs, robotic arm and user-friendly algorithms, software, and techniques have been developed and tested with promising results. However, some need small improvements like bolting operation automation to rid the necessity of manual labor, and others need more experiments in general on real-life scale scenarios.

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