Design and Prototype of a Multi-Functional Robotic Cell for the Fabrication of Exterior Retrofit Panels

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***Abstract*— This paper presents an ongoing project of designing and prototyping a multi-functional robotic cell for the fabrication of exterior retrofit panels. To address the cost and labor-intensive challenges in producing customized retrofit panels, we first conduct a simulation-based study to evaluate the feasibility of introducing robotic technologies into the fabrication process. Then, we design and propose a robotic cell that can fabricate these retrofit panels based on their specifications. The simulation results suggested that the robotics method can increase fabrication productivity by 60%. A prototype of this robotic cell has been established as a case study in Edmonton, Alberta, enabling the research team to perform further sim-to-real tests and conduct productivity analyses of the robotic fabrication process.**

I. Research Background

The global labor shortage trend is driving the construction industry to seek innovative solutions to reduce the labor requirements within the construction process. Utilizing robotic technologies to replace some human-oriented tasks that are repetitive and physically demanding has recently raised significant attention from both academia and industry. This also has the potential to reduce safety hazards in construction and improve the productivity of the project [1].

Although applying robotics to the construction process is a promising direction, it still requires significant research effort to develop corresponding processes, algorithms, tools, and knowledge. Over the past few years, the University of Alberta (UA) has worked closely with local industrial partners to develop new methods to improve construction productivity and reduce labor requirements using robotics and automation technologies. One of UA's industrial partners, RoBIM Technologies Inc. (RoBIM), has identified the fabrication of exterior retrofit panels as a strong use case for introducing robotic technologies. This is because exterior retrofit panels are typically highly customized, involving many tailor-made components based on on-site measurements. Such characteristics result in high costs when utilizing existing labor-based methods for the fabrication of these panels.

The objective of this research is to evaluate the robotic fabrication for exterior retrofit panels and prototype a robotic cell that allows the team to implement designed fabrication processes. This research first considers the specifications of existing industrial robot models and the characteristics of the target products to design a multi-functional robotic cell. Then, a simulation of the retrofit panel robotic fabrication is conducted to analyze the performance. Finally, a prototype of the robotic cell is built according to the design and simulation as a case study. Challenges and future research directions are also identified and discussed.

II. Literature Review

A. Robotics in Building Prefabrication

As the price of robotics' falls and its capabilities advance, utilizing robotic technologies to replace some human labor components in construction processes has raised great attention in recent years. Studies have also been conducted to develop knowledge and evaluate the feasibility of introducing such technologies into the industry. Popular applications include but are not limited to additive manufacturing (e.g., 3D concrete printing) [2], on-site installation (e.g., interior finishes installation) [3-5], and off-site prefabrication (e.g., wall framing, modular homes, etc.) [6].

Building prefabrication is an off-site construction approach that fabricates building components in a factory and transports them to the site for installation. Through moving parts of the on-site process into a controllable structured environment, the method has been validated to increase the overall construction productivity and reduce the project costs [7]. Transferring on-site assemblies into manufacturing processes also brings new opportunities to introduce robotic technologies [8]. New robotic systems have been developed in previous studies to prefabricate both structural and non-structural components. For instance, [9] utilized two industrial robot arms to assemble timber-based large-scale spatial components. [10] discussed the effectiveness of using robotics for the joining of steel parts and its influence on architectural design. [11] developed a collision avoidance method for the industrial robot arm to conduct tasks of timber framing.

Although robotic technologies have found extensive applications in various fields, especially in the manufacturing industry, their adoption in the construction industry still requires substantial research and development efforts [12]. The non-standardized products, complex ecosystems, and a shortage of interdisciplinary engineers make it challenging for the construction industry to directly transfer successful experience from other industries regarding the introduction of robotics. Moreover, the high initial cost of establishing a robotic cell and the subsequent research and development

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investments significantly reduce stakeholders' willingness to adopt this technology [12].

B. Panelized Exterior Building Retrofit

Building retrofits is considered one of the most critical means to reduce building energy consumption and carbon emissions [13]. In developed countries, approximately 20% to 40% of total energy consumption comes from buildings [14]. In Canada, 14.5 million buildings account for more than one-sixth of national energy usage and close to 14 percent of its energy-related Green House Gas (GHG) emissions. Eliminating GHG emissions from existing buildings is critical to Canada meeting its climate commitments [15].

Using insulated panels to retrofit buildings from the exterior is one of the common approaches to enhance a building's sustainability and energy efficiency. However, the current manual fabrication process of a wall panel is labor-intensive and time-consuming. Additionally, the need for mass-customized panel sizes based on on-site measurements results in high production costs when using a labor-based manufacturing process. Robotics technologies, which can be programmed to assemble various types of components with proper end-effectors, could play a key role in speeding up the prefabrication process and reducing overall panel manufacturing costs.

III. Robotic Cell Design

For the robotic cell design, this research first defines the target product and its specifications by interviewing RoBIM's partners who have conducted retrofit projects previously. Based on the target product, this research identifies hardware requirements for the robotic cell. Then, a survey of industrial robot arms provided by different manufacturers in the existing market is conducted to list potential robot models. Last, a robotic cell layout with the required hardware list is proposed.

A. Target Product and Hardware Requirement

When selecting the industrial robot arm model, the size and weight of the target product are the two dominant factors, as these could directly impact the robot arm's payload and reach requirements. The target panel is 2.14 m by 3.05 m with a weight of approximately 272 kg. The panel will be constructed using lightweight steel studs and insulated with mineral wool. Metal sheets are used to cover the entire panel. In addition to the sizes of the target panel, the flipping of the 272-kg panel is necessary during the assembly process. Based on discussions with local general contractors and specifications of the target product, four hardware requirements are concluded:

- A robotic cell with one industrial robot arm that can conduct multiple tasks, such as pick and place, screwing, drilling, etc., is preferred.
- The industrial robot arm should have at least a reach of 3 meters to access most parts of the panel. Since all individual parts would be less than 20 kg, the industrial robot arm having a payload capacity of more than 60 kg is preferred.
- A tilting material positioner will be required to flip the panel during the fabrication process. The payload of the positioner should be at least 455 kg.
- An assembly jig that can be mounted on the positioner and allows the robot arm to conduct assembly tasks on both sides of the panel is required.

B. Industrial Robot Arm Identification

To identify the potential robot arm model that can be utilized in the robotic cell, this research reviews five leading manufacturers' existing robot arm solutions, including ABB, Yaskawa, KUKA, Fanuc, and Kawasaki. This research uses 3-m reach as the factor to select robot models provided by the five manufacturers. Then, the 60 kg payload requirement is used to filter the robot model that can be potentially utilized in the robotic cell. There are 278 industrial robot arm models reviewed in this research, including 26 from ABB, 31 from Kawasaki, 60 from Yaskawa, 94 from KUKA, and 67 from Fanuc. Among these 278 models, 12 models are selected based on the 3-m reach and 60 kg payload factors (TABLE I.).

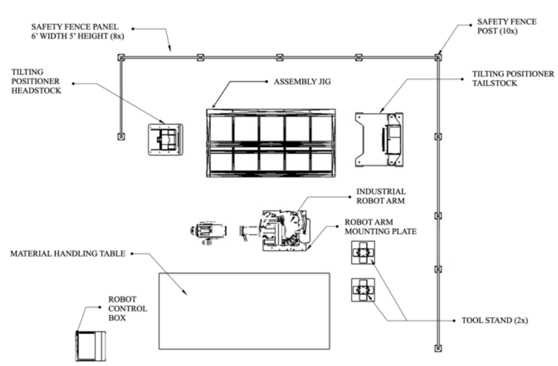
TABLE I. TWELVE IDENTIFIED ROBOT ARM MODELS

Brand	Model	Reach (m)	Payload (kg)
ABB	IRB 660	3.15	180
	IRB 6650S	3.5	125
	IRB 6700	3.2	150
Kawasaki	BX130X	2.991	130
	BX200X	3.412	200
Yaskawa	GP180-120	3.058	120
	GP200R	3.140	200
	MH180-120	3.058	120
KUKA	KR120R3100	3.100	120
	KR150R3100	3.100	150
Fanuc	R2000ic/125L	3.100	125
	R2000ic/165R	3.095	165

C. Multi-Functional Robotic Cell Design

We propose a robotic cell that can be utilized to fabricate the target retrofit panels. Figure 1 illustrates the layout of the robotic cell design. The cell size is approximately 7.52 m by 7.52. The robotic cell is surrounded by a wired fence to ensure the operator's safety during the development stage.

Figure 1. Layout of the proposed robotic cell design



An industrial robot arm is positioned at the center of the cell as a stationary robot. A tilting positioner is placed in front of the robot arm for panel-flipping tasks. The robot arm will pick materials from the material handling table and place them on an assembly jig, which is mounted on the positioner. The cell includes two tool stands capable of holding at least six different end-effectors, allowing the robot to switch between different tools for various tasks. The primary structure of the jig comprises four aluminum T-slotted rails with a cross-sectional area of 160 mm by 80 mm. Two 2.75-m rails are directly mounted to the positioner, while two 4.57-m rails are horizontally mounted between the two 2.75-m rails. This configuration results in a maximum working area of approximately 2.13 m by 3.66 m. Additionally, three pneumatic cylinders, controllable via digital signals, are installed on top of the jig. These pneumatic cylinders are used to temporarily secure the panel, allowing the positioner to flip the entire frame, thereby enabling the robot to perform tasks on both sides.

IV. SIMULATION

To evaluate the possibilities and effectiveness of applying robotics to the exterior wall panel prefabrication, RoBIM and their strategic partners have conducted a preliminary study with a finished retrofit project in Edmonton using robot simulation (Figure 2). The project uses insulated steel panels to retrofit a commercial building. Approximately 85% of the panels are 2.13 m by 6.1 m and fabricated using steel studs. The fabrication process consists of studs and end caps assembly, insulation, metal sheets placement, membrane seal, C-channels assembly, angle supports assembly, Z-bar assembly, and screw process. During the process, the panel needs to be flipped twice in order to fabricate both sides. According to the general contractor, it requires two workers and 96 minutes to fabricate one panel.

Figure 2. Robotic fabrication simulation

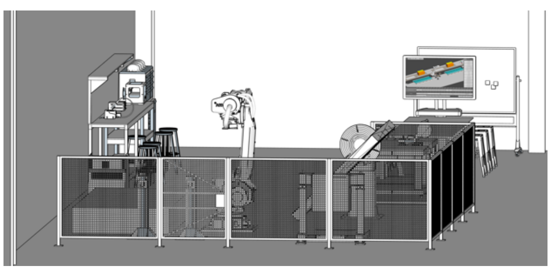


TABLE II. ROBOTIC FABRICATION SIMULATION RESULTS

Step	Manual/ Robotic	Simulated Time (sec)
Track placement	Manual	60.0
Vertical studs and end caps	Robotic	249.1
Screw the panel	Robotic	140.4
Flip the panel	Manual	300.0
Insulate and seal frames	Manual	131.0
Metal sheets placement	Robotic	82.7
Screw metal sheets	Robotic	133.1
Seal joints with membrane	Manual	100.0
Primer around the perimeter	Robotic	95.9
Wrap Soprema membrane	Manual	100.0
Place and screw C-channels	Robotic	85.8
Drill holes on C-channels	Robotic	44.1
Place and screw angle supports	Robotic	77.1
Flip the panel	Manual	300.0
Insulation for stud cavities	Robotic	180.6
Place the Z-bar	Manual	30.0
Screw the Z-bar	Robotic	37.9
Insulations within the Z-bar	Robotic	224.0
Simulated fabrication time (min)		36.79
Total robot process time (min)		17.02 (43%)
Total manual process time (min)		22.7 (57%)

We simulate the robot fabrication process in the RoBIM simulator and measure the process time, as shown in Table II. The fabrication process is hybrid, i.e., the combination of robotic and manual work. The robotic work includes pick-and-place, screw, and tool switching time. The manual work time is estimated by the general contractor with two workers in the process. Based on the simulation result, it took 36.79 minutes to fabricate a 2.13 m by 3.05 m panel and 70 minutes to fabricate two panels in order to obtain the same size of panel as the manual work. The results indicated that utilizing an industrial robot arm in the fabrication process can reduce the fabrication time by 40% and worker requirement by 43%.

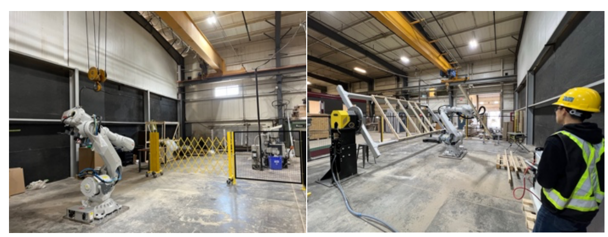
V. CASE STUDY

Based on the simulation results and design, we prototyped the robot fabrication system in Edmonton.

A. Robotic cell prototype setup

The robotic cell is situated inside a factory environment (Figure 3). The cell is positioned against the wall, with two sides enclosed by wired safety fences. A safety barricade gate is installed on the left-hand side of the cell to facilitate the entry and exit of materials and finished products. Following the design, the tilting positioner is placed in front of the robot arm (ABB IRB 6700 with 3.2 m reach and 150 kg payload). A jig is assembled using four T-slotting rails and mounted on the positioner, enabling the robot arm to perform assembly tasks on both sides of a panel. To temporarily secure the panel when rotating the positioner, pneumatic cylinders are used to clamp the materials placed on the jig. A test was conducted to determine the clamping force required to hold the panel, and the results indicated that a minimum of five pneumatic cylinders are needed to secure the 272-kg retrofit panel.

Figure 3. Prototype of the designed robotic cell



A tool stand was also prototyped using T-slotting rails and 3D-printed parts, as shown in Figure 4. The system utilizes the Schunk SWS pneumatic tool changing system with an auto-locking mechanism, allowing the robot arm to switch between different end-effectors. This system consists of one master unit, mounted at the end of the robot arm, and multiple adapters that can be installed on various end-effectors. The master unit can connect and disconnect with the adapters using compressed air.

Figure 4. The tool stand and pneumatic tool changing system

B. Discussion

This research designed, simulated, and prototyped a multi-functional robotic cell for the fabrication of exterior retrofit panels, successfully establishing it in Edmonton. Future research directions for this project include:

- **Integration of different end-effectors**: End-effector is a specialized tool or device attached to the end of a robot arm. It plays a critical role that determines what kinds of tasks the robot arm is capable of. In the current prototype, gripper, vacuum gripper, and nail gun are three available end-effectors. This research will design new or integrate existing end-effectors that can be applied to the panel fabrication process, such as needle grippers for insulation.
- **Design of a material handling table**: This research will also focus on designing a material handling table for the supply of raw materials for the retrofit panel. The table should have a mechanism or sensors to help the robot arm to localize positions of different raw materials on it.
- **Fabrication test and productivity analysis**: The last step of this research is to conduct a sim-to-real test for the fabrication of the retrofit panel. This research will use the results of the simulation to conduct a full-scale panel fabrication. Then, the productivity of the robotic process will be analyzed and compared with the manual approach.

VI. Conclusion

This paper shared an ongoing project of designing, simulating, and prototyping a robotic cell for the fabrication of exterior retrofit panels. This research proposed a design of a multi-functional robotic cell with a stationary robot arm and tilting positioner. The cell design also encompasses safety features, assembly jig, and tool stands for automatic tool changing, making it a production cell for panel fabrication. A simulation was analyzed to evaluate the robotic fabrication process. Based on the proposed design, a robotic cell prototype was established in the Edmonton area, equipped with an ABB IRB 6700 robot arm and a 1,361-kg payload capacity tilting positioner. Future research directions will include end-effector integration, material handling table design, and a sim-to-real test for productivity analysis, marking the next steps in robotic technologies for construction efficiency and sustainability.

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References

[1] C.-J. Liang, T.-H. Le, Y. Ham, B. R. K. Mantha, M. H. Cheng, and J. J. Lin, "Ethics of artificial intelligence and robotics in the architecture, engineering, and construction industry," *Automation in Construction,* vol. 162, p. 105369, 2024/06/01/ 2024, doi: 10.1016/j.autcon.2024.105369.

[2] B. Panda, S. C. Paul, L. J. Hui, Y. W. D. Tay, and M. J. Tan, "Additive manufacturing of geopolymer for sustainable built environment," *Journal of Cleaner Production,* vol. 167, pp. 281-288, 2017/11/20/ 2017, doi: 10.1016/j.jclepro.2017.08.165.

[3] E. Asadi, B. Li, and I. M. Chen, "Pictobot: A Cooperative Painting Robot for Interior Finishing of Industrial Developments," *IEEE Robotics & Automation Magazine,* vol. 25, no. 2, pp. 82-94, 2018, doi: 10.1109/mra.2018.2816972.

[4] C.-J. Liang, V. R. Kamat, and C. C. Menassa, "Teaching robots to perform quasi-repetitive construction tasks through human demonstration," *Automation in Construction,* vol. 120, p. 103370, 2020/12/01/ 2020, doi: 10.1016/j.autcon.2020.103370.

[5] S. N. Yu, S. Y. Lee, C. S. Han, K. Y. Lee, and S. H. Lee, "Development of the curtain wall installation robot: Performance and efficiency tests at a construction site," *Autonomous Robots,* vol. 22, no. 3, pp. 281-291, 2007/04/01 2006, doi: 10.1007/s10514-006-9019-2.

[6] K. Iturralde and T. Bock, "Integrated, Automated and Robotic Process for Building Upgrading with Prefabricated Modules," presented at the Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC), 2018/07/22, 2018.

[7] V. W. Y. Tam, C. M. Tam, S. X. Zeng, and W. C. Y. Ng, "Towards adoption of prefabrication in construction," *Building and Environment,* vol. 42, no. 10, pp. 3642-3654, 2007/10/01/ 2007, doi: 10.1016/j.buildenv.2006.10.003.

[8] C.-H. Yang, T.-H. Wu, B. Xiao, and S.-C. Kang, "Design of a Robotic Software Package for Modular Home Builder," presented at the Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC), 2019/05/24, 2019.

[9] P. Eversmann, F. Gramazio, and M. Kohler, "Robotic prefabrication of timber structures: towards automated large-scale spatial assembly," *Construction Robotics,* vol. 1, no. 1-4, pp. 49-60, 2017/12/01 2017, doi: 10.1007/s41693-017-0006-2.

[10] T. Heimig, E. Kerber, S. Stumm, S. Mann, U. Reisgen, and S. Brell-Cokcan, "Towards robotic steel construction through adaptive incremental point welding," *Construction Robotics,* vol. 4, no. 1-2, pp. 49-60, 2020/06/01 2020, doi: 10.1007/s41693-019-00026-4.

[11] C.-H. Yang and S.-C. Kang, "Collision avoidance method for robotic modular home prefabrication," *Automation in Construction,* vol. 130, p. 103853, 2021/10/01/ 2021, doi: 10.1016/j.autcon.2021.103853.

[12] C.-J. Liang, X. Wang, V. R. Kamat, and C. C. Menassa, "Human–Robot Collaboration in Construction: Classification and Research Trends," *Journal of Construction Engineering and Management,* vol. 147, no. 10, p. 03121006, 2021/10/01 2021, doi: 10.1061/(asce)co.1943-7862.0002154.

[13] A. L. Webb, "Energy retrofits in historic and traditional buildings: A review of problems and methods," *Renewable and Sustainable Energy Reviews,* vol. 77, pp. 748-759, 2017/09/01/ 2017, doi: 10.1016/j.rser.2017.01.145.

[14] L. Pérez-Lombard, J. Ortiz, and C. Pout, "A review on buildings energy consumption information," *Energy and Buildings,* vol. 40, no. 3, pp. 394-398, 2008/01/01/ 2008, doi: 10.1016/j.enbuild.2007.03.007.

[15] T.-P. Frappé-Sénéclauze. (2020) A deep retrofit of homes and buildings is the megaproject Canada needs. *Policy Options*. Available: https://policyoptions.irpp.org/magazines/may-2020/a-deep-retrofit-of-homes-and-buildings-is-the-megaproject-canada-needs/