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Evaluating a BIM-Driven Robotic Manufacturing Framework for Off-Site LGS Wall-Frame Assembly: A Virtual Design and Construction Approach

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ABSTRACT: The construction industry's labor shortages and the growing complexity of off-site manufacturing have intensified the need for integrated robotic solutions. This study evaluates a BIM-driven robotic manufacturing (BIM-RM) framework designed for the automated assembly of light gauge steel (LGS) wall frames using a Virtual Design and Construction (VDC) approach. By facilitating seamless data exchange between Autodesk Revit (BIM) and ABB RobotStudio, the framework enables robotic simulation of distinct wall-frame designs. Key performance aspects, including data translation accuracy, collision avoidance, and assembly efficiency, are assessed through the RobotStudio simulations, the primary VDC platform used. The results demonstrate that the framework can automatically translate BIM models into executable robot programs, accommodating design variations with minimal manual intervention. Furthermore, RobotStudio proves to be a robust VDC tool, offering built-in capabilities such as collision detection, offline programming, and immersive virtual reality visualization, which enhance simulation fidelity and streamline evaluation. Although minor discrepancies, such as occasional misplacements, were observed, these primarily stem from kinematic constraints or algorithmic immaturity rather than fundamental flaws in the workflow. Overall, this research provides an empirically validated example of BIM-enabled robotic assembly and underscores its potential to improve prefabrication productivity. Future work should extend the framework to more complex structural components and include real-world implementation trials, advancing more efficient, adaptive, and resilient construction practices.

1. INTRODUCTION

The construction industry faces a well-documented workforce shortage, worsened by an aging labor force, leading to productivity challenges and project delays (Sokas et al. 2019, Won et al. 2021). Automation and robotics are increasingly seen as viable solutions, particularly in off-site construction (OSC) factories where controlled environments favor repetitive, high-precision tasks (Chen et al. 2018, Gharbia et al. 2020). In this context, industrial robots can enhance safety by performing demanding activities and boost productivity, consistency, and the scalability of mass-customized component assembly (Ng et al. 2022, Anane et al. 2023a, Metvaei et al. 2024). Previous studies on the robotic fabrication of timber modules have demonstrated feasibility in principle (Thoma et al. 2019), suggesting similar methods could be extended to other components, such as Light Gauge Steel (LGS) wall frames, offering potential gains in accuracy and efficiency. Yet, despite these benefits, the pace of adoption remains slow, impeded by high setup costs, fragmented project structures, and poor compatibility with traditional workflows (Buchli et al. 2018, Davila Delgado et al. 2019).

A key barrier lies in the need for structured, machine-readable data to direct robotic operations (Kim et al. 2021), which most construction workflows are not designed to produce. This underscores the importance

of design-to-manufacturing (DtM) processes, which aim to automatically extract, refine, and convert digital design data into robotic instructions, minimizing manual programming efforts (Fardhosseini et al. 2019, Anane et al. 2023b). In practice, however, many current OSC workflows lack such integration.

Building Information Modeling (BIM) offers a promising foundation for automation. As a centralized digital platform for design and coordination, BIM provides the structured data needed to fabricate customizable and dynamically evolving building components (Chen et al. 2020, Kamal et al. 2022, Aghajamali et al. 2024, Fu et al. 2024). Yet, while BIM is essential for supplying data to robotic systems (Hamid et al. 2018), it often lacks built-in capabilities for robotic automation planning (Meschini et al. 2016, Zhu et al. 2024), and simulation integration (Kim et al. 2021). Additionally, limited interoperability between design and robotic platforms necessitates manual data exchange, which is time-consuming, error-prone, and labor-intensive. In response, researchers have begun developing BIM-integrated robotic fabrication workflows. For example, Metvaei et al. (2025) introduced a BIM-RM integration framework to streamline information flow from BIM to robotic systems, addressing key scalability and operational efficiency challenges. Nonetheless, further validation is needed to assess how effectively such systems translate complex digital designs into executable robotic instructions.

Building on this prior work (Metvaei et al. 2025), the present study evaluates the framework's performance in simulating robotic assembly operations in response to wall framing design changes. To facilitate this, Virtual Design and Construction (VDC) approach is adopted, which has proven effective in analyzing the benefits and limitations of robotics in construction (Wong Chong et al. 2022). VDC environments support robotic simulation and iterative testing of control algorithms, focusing on efficiency, safety, and reliability. For instance, Kim et al. (2021) developed a BIM prototype for planning interior wall painting and validated it using Gazebo, an open-source 3D robotics simulator. Similarly, Wong Chong (2022) employed Webots, another simulation platform, to model robotic wood-frame assembly. These studies underscore the value of VDC for optimizing robotic workflows and proactively identifying implementation challenges under realistic conditions.

Leveraging VDC-based simulations, this study evaluates the framework across three wall designs of varying complexity. The assessment focuses on (i) adaptability to design variations (in geometry and sequencing), (ii) precision and efficiency in simulated robotic tasks (e.g., placement, collision detection), and (iii) identification of failure points that may impact real-world deployment. The evaluation utilizes key features of ABB RobotStudio, including offline programming, collision detection, and VR visualization, to demonstrate the platform's potential as a robust VDC tool. The remainder of this paper provides a brief overview of the prior research, outlines the evaluation methodology, discusses key findings, and concludes with implications for automation in off-site construction.

2. BIM-RM FRAMEWORK OVERVIEW

In their previous work, Metvaei et al. (2025) introduced a BIM-enabled robotic manufacturing (BIM-RM) framework aimed at improving interoperability between BIM and off-site robotic manufacturing processes. The framework automates the DtM workflow by extracting data from BIM models and translating it into executable robotic instructions, thereby eliminating manual data exchange and reducing design rework. This approach addresses the complexities of mass customization by enabling a seamless flow of information from digital design to industrial robots, supporting flexible manufacturing that can adapt to customized design requirements. The system integrates custom-developed APIs for Autodesk Revit and ABB RobotStudio (RS), allowing for automated data extraction, transformation, and robotic programming. The Revit API retrieves geometric information and assembly-related details, including manufacturing sequences not explicitly modeled in BIM, and stores them in a structured database. The RS API then generates 3D representations of the BIM models for simulation purposes and produces robotic commands and toolpaths for assembly.

A key feature of this setup is its ability to convert Revit's global coordinate system to RobotStudio's local workspace, ensuring that vertically oriented wall frames in Revit (typically aligned along the X-Z or Y-Z planes) are accurately repositioned for horizontal table assembly on RobotStudio. In addition, the RS API manages communication across the virtual workstation, synchronizing the operation of robotic arms, end-effectors, conveyors, and other automated systems. Figure 1 illustrates the complete workflow developed for this framework.
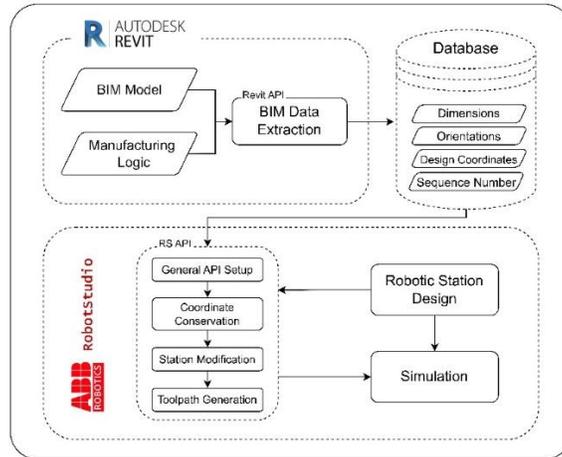
Figure 1. BIM-Driven Robotic Manufacturing Workflow

By combining automated data processing with robotic programming, the BIM-RM framework streamlines the transition from parametric BIM models to robotic fabrication, improving data flow efficiency, minimizing data loss, and enhancing scalability. Furthermore, through streamlined user interfaces in both Revit and RobotStudio, the framework delivers a no-code solution, making it accessible to users without advanced programming skills. Nevertheless, while the framework establishes interoperability, further validation is needed to assess its adaptability to real-time design changes and more complex robotic tasks. Accordingly, the current study investigates how effectively the BIM-RM framework accommodates design modifications and whether the automated workflow accurately reflects these updates in robotic operations.

3. FRAMEWORK EVALUATION METHOD

The evaluation of the developed BIM-RM framework focuses on assessing the accuracy, efficiency, and reliability of the simulation in replicating real-world robotic assembly processes. This methodology is adapted from Wong Chong et al. (2022), which originally targeted wood-frame assembly but provides a solid foundation for BIM-based robotic systems. Specifically, the three core evaluation criteria from their approach—BIM-simulator integration, manufacturing process simulation, and collision detection—have been adopted and customized to meet the distinct requirements of light gauge steel (LGS) framing.

The first criterion, BIM-simulator integration, examines how effectively data is exchanged and synchronized between the BIM environment and the robotic simulator. In this study, it focuses on verifying whether the LGS stud profiles generated in RobotStudio match their counterparts in the BIM model, ensuring consistency between digital design and robotic execution. The second criterion, manufacturing process simulation, evaluates robotic operations programmed through the RobotStudio API. This includes assessing the framing process and auxiliary systems, such as the end-effector tool and conveyor belt. The primary aim is to verify whether the robotic system can adapt to variations in BIM inputs, such as different wall-frame configurations, without manual reprogramming. This evaluation identifies potential discrepancies, including spatial or temporal errors, between the intended and actual performance of the robotic components.

The third criterion, collision detection, ensures that robotic operations are executed safely and within a controlled, collision-free environment. To enhance this aspect of the evaluation and better investigate RobotStudio's potential as a VDC tool, this research incorporates the software's built-in capabilities, such as Virtual Reality (VR) integration, for collision detection. Immersive environments like RobotStudio's VR are essential components of modern VDC practices (Aslam et al. 2021), and provide realistic visualizations of the assembly process, improving users' ability to detect, analyze, and understand potential safety or spatial issues during simulation (Holubek et al. 2021).

While all three evaluation criteria are derived from Wong Chong et al. (2022), significant modifications were necessary to accommodate the unique requirements of LGS framing. Unlike standard wood studs with simple rectangular cross-sections, LGS members often feature more intricate geometries, such as C-shaped profiles with lips, sloped flanges, or other non-rectilinear attributes. As a result, the BIM-simulator

integration criterion in this study includes additional cross-sectional validation, confirming that the geometry of each steel member generated in RobotStudio precisely matches the design specifications in the BIM model. Additionally, due to the need for precise orientation of LGS members, specifically aligning the open side of channels, the manufacturing process simulation criterion has been expanded to confirm proper stud orientation, an aspect not typically relevant in wood framing. Another modification was the use of a third-party application, Autodesk Fusion 360, to compare geometries from both Revit and RobotStudio; this neutral platform ensures accurate dimensional analysis across tools that use different modeling kernels and coordinate systems. Ultimately, these evaluations determine how accurately the BIM data is translated into robotic operations and validate the reliability of the integrated robotic system for assembly tasks.

4. EXPERIMENT

4.1 System Setup

The robotic setup and implementation process used in this evaluation follow the configuration established in the previous work (Metvaei et al., 2025). The system consists of an ABB IRB7600 industrial robot arm mounted on a linear motion track, integrated with a conveyor system for automated material feeding. The entire assembly environment is modeled and managed within RobotStudio, which enables the coordinated operation of robotic tasks and material handling through virtual simulation. To support this setup, all data translation processes, including BIM data extraction, transformation, and simulation setup, were executed using custom-developed APIs for Revit and RobotStudio. The Revit API, developed in VB.NET and operated within the Visual Studio environment, enables automated retrieval of geometric data, assembly sequences, and orientation logic from Revit models. These outputs were structured into a Microsoft Access database and consumed by the RS API, developed using ABB's PC SDK, to generate 3D component representations, define toolpaths, and produce RAPID code for robotic execution. All development and simulation processes are conducted on Windows-based systems that exceed Autodesk Revit and RobotStudio's hardware requirements. For immersive simulation, RobotStudio's built-in VR capabilities are employed via a Meta Quest 3 headset connected through a Link cable, providing immersive visualization and accurate collision detection within the virtual assembly environment.

4.2 Test Cases

To assess the BIM-RM framework under typical LGS framing configurations, this study used a cottage model designed in Autodesk Revit. The building is intended for off-site manufacturing in a panelized format, with LGS wall frames modeled using MWF Pro Metal, a widely adopted Revit add-in for steel-framing projects. Figure 2 illustrates the BIM model of the cottage, framed using this plugin in Revit. Using MWF's pre-loaded libraries (based on standard LGS profiles from industry-leading manufacturers) and customizable settings like stud spacing, this study ensures that the proposed robotic system aligns with common industry practices and supports a wide range of real-world steel-framed construction scenarios.

From this cottage model, three distinct wall-frame designs were selected to evaluate the system's adaptability to varied framing layouts and its ability to generate robotic operation codes without manual intervention. Although the selection was not based on a systematic sampling process, the frames were chosen to represent a broad spectrum of typical framing conditions, including interior vs. exterior walls, bearing vs. non-bearing configurations, the presence or absence of openings, varied stud spacing, and orientation along the X or Y axis in the Revit coordinate system. These variations challenge the system's logic by requiring it to process different opening types and positions, adapt to changes in stud spacing, and apply appropriate coordinate conversion algorithms based on wall orientation. Figure 3 illustrates the dimensions and characteristics of each test frame, providing a comprehensive overview of the scenarios used to validate both the data transfer workflow and the robotic operations.

Figure 2. Cottage BIM model with LGS wall frames in Revit

Test Case 1   **Test Case 2**   **Test Case 3**
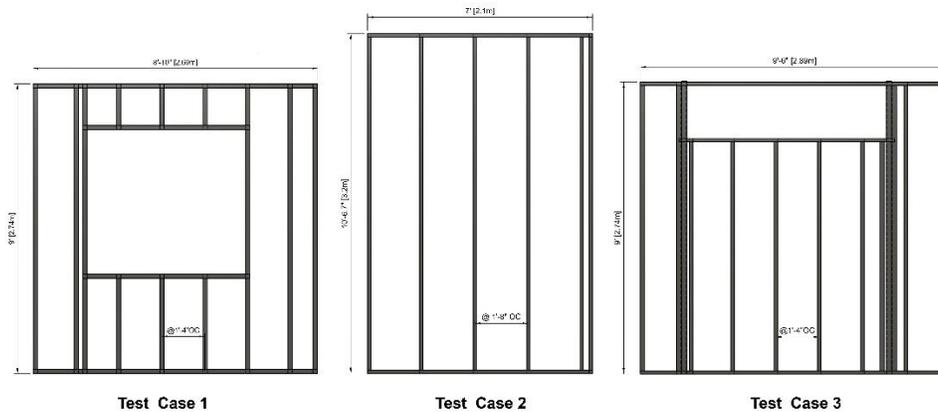
Figure 3. Characteristics of the experiment's test cases: (Test Case 1) Exterior non-bearing wall frame (16-inch standard spacing, X-axis), (Test Case 2) Interior non-bearing wall frame (20-inch custom spacing, Y-axis), (Test Case 3) Exterior bearing wall frame (16-inch standard spacing, Y-axis).

4.3   Evaluation

The selected test frames were fed into the BIM-RM framework, which automatically generated 3D representations of the BIM elements and corresponding robotic instructions within the RobotStudio for assembly simulation. To assess simulation performance across the categories defined in Section 3 (BIM-simulator integration, manufacturing process simulation, and collision detection), the geometry from both the original BIM models and those generated in RobotStudio was compared using Autodesk Fusion 360. As noted earlier, this neutral platform enables precise and consistent evaluation of cross-sections, dimensions, and spatial positioning between the design and fabricated models, helping to detect and quantify geometric discrepancies that may arise from modeling or coordinate mismatches.

For the first two evaluation categories, any deviations observed in Fusion 360, such as differences in stud spacing, cross-sectional geometry, or angular alignment, were documented. Additionally, any manual adjustments required in RobotStudio for a successful simulation were recorded to evaluate the system's performance and identify areas requiring refinement. Collision detection was subsequently evaluated using RobotStudio's built-in features and immersive VR simulations, allowing the team to identify potential collisions and verify clearances before finalizing the manufacturing process.

4.4   Results and Discussions

4.4.1   BIM-simulator integration

BIM data were successfully integrated into RobotStudio across all test models, enabling the automated generation of 3D objects that represent individual stud profiles. As illustrated in Figure 4, the proposed robotic framework uses key geometric parameters from BIM, such as profile length, web height, flange width, thickness, and lip size, to create simulation objects. In cases involving more complex cross-sections (e.g., the C-channel Sloped Flange), the system applies a simplified 3D representation derived from these fundamental parameters.
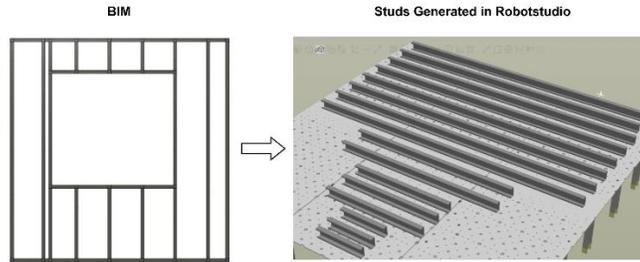
Figure 4. Integration of test frame 1 and RobotStudio.

Figure 5 compares the cross-sections generated in RobotStudio with their BIM counterparts for three representative profile types. The results indicate that standard C-channel profiles and those with lips closely match their BIM equivalents. Minor discrepancies appear only in more intricate sections, such as the sloped-flange variant, which is less prevalent in panelized construction. Overall, the automated creation of these 3D elements is rapid and precise, eliminating the need for manual file transfers or user-generated profile objects, which would be a time-consuming and error-prone task.
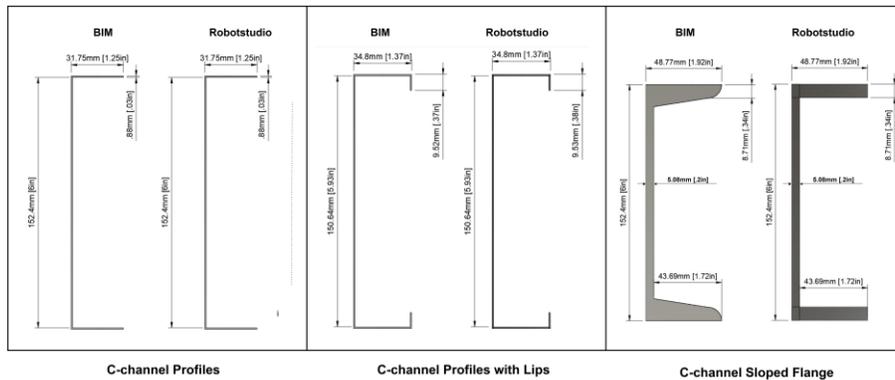

Figure 5. Cross-sectional comparison of BIM-derived and RobotStudio-generated C-channel profiles.

4.4.2 Robotic Manufacturing Process

The proposed methodology was validated by simulating the robotic assembly of LGS wall frames, with all toolpaths automatically generated through the framework. In each test case, the robot picked and positioned studs according to the BIM-derived geometries, placing them onto a worktable at specified targets. Nearly all of the generated toolpaths were executed without issue, except in Test Case 3, where the "set" target for the opening's footer was unreachable. Specifically, the framework initially programmed the robot's tool to approach and pick the stud perpendicularly, resulting in an end-effector angle beyond the robot's kinematic limits at the set point (see Figure 6, API generated targets). To resolve this, the pick and set targets for the affected stud were adjusted by ±90 degrees, allowing the tool to be aligned with the stud profile instead of perpendicular, and successfully place the channel (see Figure 6, modified targets). This orientation constraint is particularly important in LGS assembly, where each stud's face side must be aligned correctly, an issue less pronounced in wood framing. Figure 7 illustrates the successful simulation results for all test cases, confirming the framework's capability to define and manage the initial position and orientation of construction materials in the virtual environment.

In assessing material handling precision and overall robotic operational accuracy during the simulation, Figure 8 compares the RobotStudio-assembled frame in Test Case 1 with its corresponding BIM model, revealing discrepancies of less than 0.07 inches. These minor discrepancies primarily result from differences in geometric kernel precision between Revit and RobotStudio, as well as small inconsistencies in unit conversion. Additional deviations stem from sensor response delays, where a plane sensor at the end of the conveyor belt is meant to halt stud movement at a precise pick point, predefined at half the stud's length from the sensor, but minor timing lags can cause the stud to overshoot. As a result, the end-effector's

actual pick location shifts, leading to a slight misalignment in the final placement. Slowing the conveyor belt helps mitigate this issue by reducing overshoot and improving assembly accuracy. The level of error observed in this study aligns with observations by Wong Chong et al. (2022), who reported average deviations under one centimeter, with a few outliers reaching up to 10 cm.
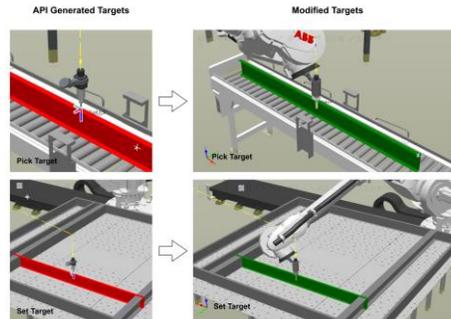

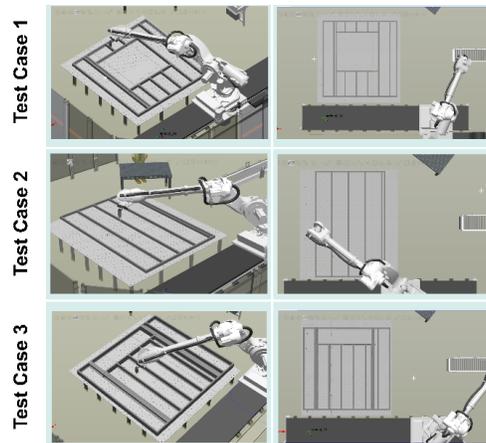*Figure 6. API-generated and manually modified targets for resolving kinematic limitations in Test Case 3.*

Figure 7. Simulation results for test frames 1, 2, and 3.
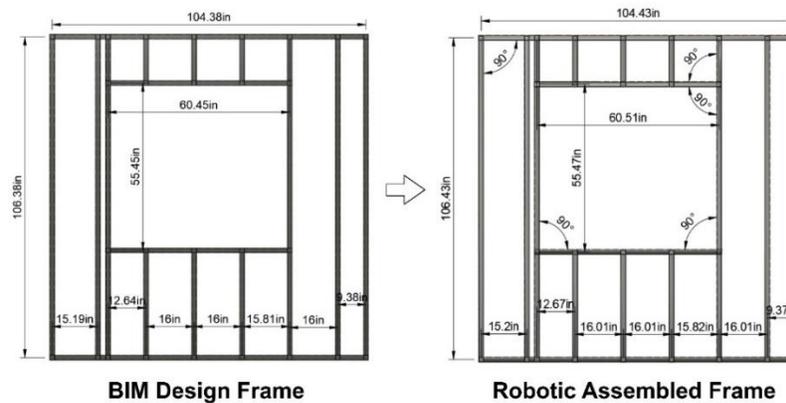

Figure 8. Verification of simulation results by comparing models from BIM and RobotStudio in Test Case 1

Another factor influencing accuracy and throughput involves the robot's motion parameters, namely Speed and Zone (also referred to as blending). Speed defines the travel velocity of the tool center point (TCP), whereas Zone determines whether the robot smoothly transitions between move instructions or comes to a complete stop at each target. In this simulation, setting the Zone to "Fine" improved positional precision by enforcing a complete stop at each waypoint, at the expense of total cycle time. Operating at 500 mm/s,

the robot assembled the three test frames in approximately 6.6, 4.3, and 8 minutes, respectively. These values exceed those reported by Wong Chong (2022) for wood frames, likely due to the simpler vertical placement procedure and shorter travel paths employed in their study. Overall, the findings of these simulations confirm that the proposed framework accurately handles a variety of LGS wall-frame configurations, validating its precision, adaptability, and potential for real-world scalability.

4.4.3   Collision detection

Collision detection was evaluated using RobotStudio's built-in features, which monitor and report contacts between any two objects in the virtual environment. As illustrated in Figure 9, RobotStudio not only identifies the colliding objects (in this case, a stud and the workstation table) but also provides the precise collision location. To reduce the likelihood of these incidents, the framework applies a 0.5 m offset above the pick and set elevations. Specifically, the robot lifts the stud clear of its initial position, travels horizontally across the workspace, and then lowers it onto the assembly table before adjusting it to its final location. This approach mitigates collisions with surrounding objects (e.g., the conveyor belt, workstation table, or robot components) while maintaining a relatively efficient path.

Figure 9. Collision detection capability in RobotStudio

Across the three test cases, four collisions were recorded, each involving a stud contacting the conveyor belt. In contrast, Wong Chong et al. (2022) reported only one collision, which occurred between the robot and the tool table, an issue that was resolved through physical adjustments to the workstation objects. Although the collisions observed in this study could likewise have been avoided by raising the pick offset, doing so would have extended travel distances and reduced overall operational efficiency. Future iterations of the framework may integrate RobotStudio's more advanced collision-free path-planning features to optimize traversal. Notably, collisions between the studs themselves were not registered. Although the system provides basic handling of the intricate assembly paths needed for interlocking C-shaped LGS members, further refinement is required to fully eliminate these interactions until more sophisticated logic is developed.

In addition, RobotStudio's virtual reality (VR) environment can provide a more immersive platform for identifying and mitigating potential collisions. By visualizing the robot's trajectory in real time, users can promptly detect high-risk movements and refine the end-effector's path before physical implementation. Figure 10 illustrates how VR-based simulations highlight actual or potential collisions in various scenarios, thereby improving safety considerations. This immersive approach also creates opportunities for broader research in human-robot interaction and operator training, as it allows engineers, technicians, and other stakeholders to gain hands-on familiarity with automated processes without incurring real-world risks.
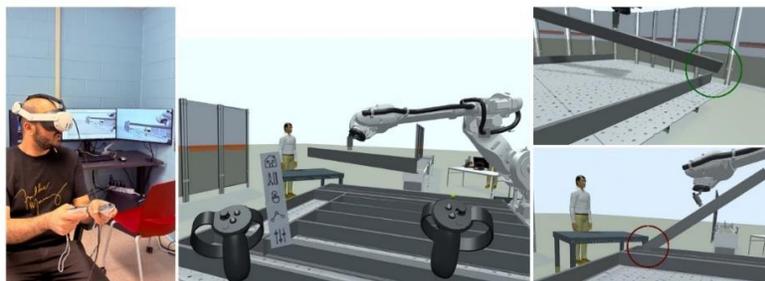

Figure 10. Immersive visualization of assembly simulations in RobotStudio's VR environment

5. CONCLUSIONS

The findings of this study confirm that the proposed BIM-RM framework can effectively convert digital design data into executable instructions for off-site construction, particularly in the context of LGS wall framing. Through the simulation of three test wall frames of varying complexity in RobotStudio, the framework demonstrated its ability to accommodate diverse BIM inputs with minimal manual intervention. Minor discrepancies, such as occasional stud misplacements or collisions, were primarily attributed to kinematic constraints and potentially immature algorithms rather than any fundamental flaw in the workflow. Throughout the evaluation, VDC tools, including VR visualizations, played a critical role in verifying geometric fidelity, detecting potential collisions, and refining robot motion strategies. This research further highlights RobotStudio's value as a comprehensive VDC platform. Its built-in capabilities, such as collision detection, offline programming, dynamic simulation, VR integration, and API-based automation, enable streamlined data translation, accurate simulation of complex assembly tasks, early hazard identification, and robot path optimization, ultimately reducing manual effort and human error.

These results underscore the framework's potential to support wider robotic adoption in the AEC sector by addressing persistent challenges such as skilled labor shortages, productivity inefficiencies, cost overruns, and fragmented digital workflows. By automating data exchange and tightly integrating BIM environments with robotic platforms, the system enhances flexibility and efficiency, paving the way for scalable deployment in off-site manufacturing. VR-based simulation adds a critical safety layer, allowing operators and engineers to test, analyze, and refine robotic operations in a risk-free environment.

To accelerate industry adoption, we recommend using this evaluation framework as a foundation for broader techno-economic studies, including assessments of energy consumption, sustainability, and life-cycle cost analysis comparing robotic investment with long-term labor and productivity gains. Furthermore, addressing current interoperability barriers will require the development of industry-wide standards for BIM-to-robot data exchange, including the definition of neutral data formats that enable seamless integration across diverse robotic systems and software platforms.

Nevertheless, the study has a few limitations. First, the evaluation could be expanded to include a broader set of performance metrics, such as joint efficiency, energy consumption, and toolpath accuracy. Second, while simulation in RobotStudio offers valuable insights, it does not fully capture real-world conditions such as material tolerances, sensor noise, or actuator delays. The absence of physical testing limits the ability to assess the framework's performance under actual assembly constraints. Future research should include real-world trials, explore more complex structural elements, and validate the system's effectiveness across diverse production environments.

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