Advancing Robotic Assembly with BIM and Mixed Reality Integration

An integration of computational and visual experience

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Since the last century, the evolution of digital tools and automation has witnessed great development in the construction industry. As the industry faces the challenges of labor shortages and increased demand for precision, advancements in robotic technology have strengthened the digital workflow and fostered creativity (Claypool and Retsin, 2025). While robots do offer precision and advancement, their usage still faces challenges like safety and adaptability (Walker et al., 2023). These challenges can be addressed by combining Building Information Modelling (BIM) and Mixed Reality (MR) with robotic automation (Morse et al., 2020). Thus, the paper presents an approach for integrating BIM, MR, and Robotics as a transformative approach to enhance collaborative human-robot interaction. This research focuses on assembling prefabricated wall panels using a robotic arm. BIM serves as a central interface for managing real-time data, with MR facilitating safe, visual interaction between humans and robots on-site. Developed in collaboration with Blufab, an offsite/prefabrication construction unit of the Casais Group, the proposed framework aims to create more efficient, less resource-intensive construction solutions. With the use of MR interfaces, professionals can issue commands, monitor progress, provide real-time feedback to robotic systems, and conduct structural analysis of the material and its assembly in a controlled environment (Bahri et al., 2019). The studies will be further enhanced by providing an optimal layout for the configuration of the assembly system to develop the environment for the Human-Robot collaboration system (Fu, Chen and Lu, 2024).

Keywords: *BIM, Mixed Reality, Robotic Assembly, Human-Machine Interaction, Automation in Construction.*

INTRODUCTION AND MOTIVATION

In the digital era, with technological advancements, the need to work remotely yet collaboratively arose. The utilization of robotic arms in the AEC industry has been a subject of intense research, spurred by the pioneering work of (“Pike Loop by Gramazio and Kohler,” 2009) in applying industrial robotic arms for constructing building systems, as well as Mark Burry's involvement in the construction of the Sagrada Família since 1992 (Burry, 2016). This heightened flexibility exponentially increases creative freedom but also introduces complexities in programming and associated safety risks, contributing to their later adoption in architecture compared to other technologies (Burry, 2016). Virtual, Augmented, and Mixed Reality (MR) are the core pillars of the construction 4.0 platform that help in increasing the level of digitalization and collaboration in a world with non-human actors.

While various studies have explored MR and automation separately, research on their integration, specifically in data storage and on-site implementation, remains limited.

Therefore, the research bridges this gap and worked towards creating a methodology where the tasks at a construction site were automated with the robots working side-by-side with human workers in a safe environment, and all the data was stored in digital BIM models. The work focused on a single-building element and then further developed modular construction for an automated production line and auxiliary on-site assembly. The research considered safety regulations and standards for human-robot interaction. The experiments were done in a controlled environment, focusing primarily on technological integration.

The paper is structured into three main sections, each aligned with the research objectives. The Literature Review offers a comprehensive overview of BIM and MR integration, highlighting existing gaps in collaborative workflows. Building on this foundation, the Methodology section outlines the approach developed to address these gaps. Finally, the Implementation section presents a case study that tests the proposed workflow under real-world conditions, followed by a discussion of the Results and the Conclusion.

LITERATURE REVIEW

Over the last decades, as technology has developed, the adoption of BIM in modular construction, a process of off-site prefabrication of building components in a controlled environment, has continuously increased. These modules are then transported to the construction site for assembly. BIM Models generate detailed shop drawings, detect clashes, and enhance coordination.

BIM and Robotic Fabrication

Robotic fabrication involves using robots to automate tasks and improve the efficiency of manufacturing processes.

BIM models facilitate the programming of robotic systems, enabling them to perform tasks such as cutting, welding, and assembling components. This automation reduces fabrication time and improves the overall quality of the constructed elements (Tavares et al., 2019). By storing geometry, task execution, and sequence data in the BIM model, the robot can use this data for performing assembly tasks and locating the placements of the building and its components (Kim and Peavy, 2022). Kim and Peavy, (2022) provides a framework where the BIM model is converted to a format that supports integration with the robotic program.

As it is difficult to work with a text-based environment, further research was done around computational design, where the environment of Rhino-Grasshopper was explored. This simulation software works on visual-based language and was, therefore, easy to learn and comprehend.

Mixed Reality Integration in AEC

“MR merges real and virtual environments to create an interactive space where physical and digital objects coexist and can influence each other in real time”. The technology of MR allows architects and engineers to visualize and interact with the 3d models in real time, providing dynamic interaction and allowing them to adjust and immediately see the impact of changes (Follini et al., 2021).

MR is a step further from AR, which only superimposes digital objects over the physical world without allowing interaction with physical objects. AR tools may be extended with sensors, spatial mapping, and tracking. With the use of MR interfaces, such as Microsoft HoloLens, users can visualize complex structures in their real-world context, enhancing design accuracy and therefore reducing errors (Bahri et al., 2019).

Similarly, developers have introduced a range of applications in the AEC industry that facilitate user interaction with geometric models. These applications provide hands-on experience that can be simulated in a controlled environment. With the use of mobile Augmented Reality (AR) devices, the complete process is monitored, and with the assembly sequence provided, the user can follow step-by-step commands (Atanasova et al., 2020) . The author develops a workspace where an AR device superimposes the video to assist the builders with geometry information, and, simultaneously, precision is achieved for the timber framework (Atanasova et al., 2020).

Therefore, by defining the tasks and sequence of tasks for completing the workflow, MR bridges the gap between the actual and virtual world and offers greater precision and control over the environment.

Combined Synergy of BIM, Robotics, and Mixed Reality

The research project, entitled AR Digi-Component, attempts to digitalize traditional architectural components and combines AR technologies to explore new possibilities for design and assembly (Song, Koeck and Luo, 2021). In the paper, the author, with the help of the MR tool Fologram, incorporates hand tracking, gesture identification, and device location recognition methods to provide users with a more realistic and immersive design experience, as shown in Figure 1. By visualizing the complete step using HoloLens, the spaces and conditions required for setting up robotic assembly in the factory can be studied and implemented.

Thus, a review of the current state of the art highlighted that the integration between BIM, MR, and Robotics remains underdeveloped. The next section discusses the methodology developed for addressing the gap.

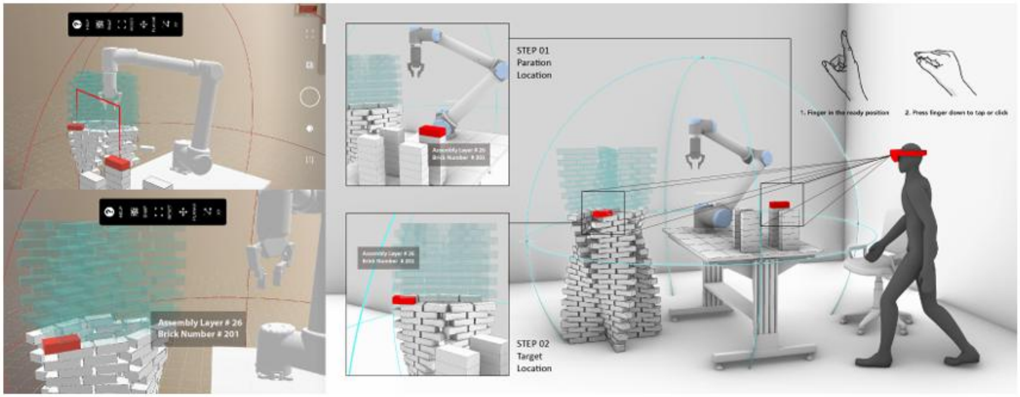

Figure 1
AR Robotic Assembly process and robotic operation trajectory (Song et al., 2021).

METHODOLOGY

From the research papers read during the research process, it was observed that various tools are used by the industry for MR and Virtual Reality visualizations. After analyzing the tools, on parameters like file support, interoperability with BIM, and Robotic fabrication, it was observed that:

- The Unity platform had much wider experience and tools, yet the adoption effort was limited. Considering the time frame of the thesis research, this tool will be utilized for future work.
- Shapediver was best for users who were looking for web-based parametric design, as it easily integrates with Rhino-Grasshopper. However, it provides limited direct support for robotic fabrication and can integrate through some Rhino plugins.
- Fologram, on the other hand, had strong integration for MR collaboration with the Rhino-Grasshopper interface. The app was useful for hands-on robotic fabrication and was easy to use.

Therefore, for this research, the Fologram as an MR tool was used. The tool creates a real-time experience and was easy to integrate with the Grasshopper interface, with the option to scale the geometry.

Design of Workflow

The proposed workflow, as described in Figure 2, for the research implementation focused on integrating robotic assembly tasks with human monitoring and visualization using advanced computational tools and augmented reality technologies. The process began with the BIM model provided by the Blufab company in an Autodesk Revit file, encompassing all essential architectural elements.

This model was the foundation, providing comprehensive information on materials, dimensions, and structural specifics necessary for subsequent stages. Once the BIM model was established, it was exported to Rhino/Grasshopper using the interoperability tool IFC and imported into the Rhino environment using the Geometrygym plugin, ensuring the geometry was maintained during the transition. It is important to note that the IFC file is not directly openable in the Rhino software, and therefore, the plugin Geometrygym was used.

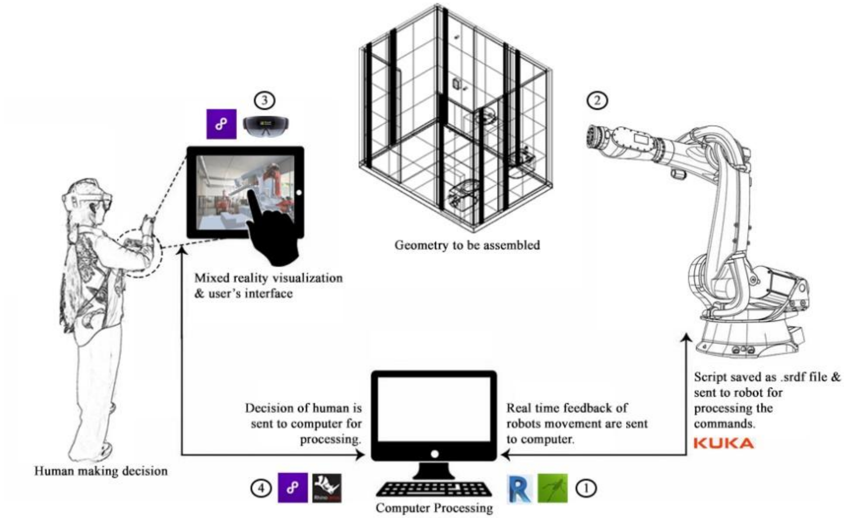

Figure 2
The workflow of the script for the robot and its visualization.

The setup of the robotic fabrication involves:

- Calibrating the Tool Center Point (TCP) of the KUKA robotic arm to ensure precise control and operation.
- When the robotic arm is properly configured and equipped with the necessary tools, the developed scripts from Grasshopper are transmitted to the robotic system, initiating the on-site assembly tasks. The robotic arm executes these tasks, assembling modules with accuracy as dictated by the predefined tool paths.
- With the HoloLens, the human monitors the tasks performed by the robotic arm and guides the path for assembly. This MR collaboration is visualized on the Fologram plugin, which enables users to enhance the visualization process and play with the geometry placements and scale.
- With the option of uploading the models on the website in Fologram, regardless of the location, any user can visualize, change, and update the model, providing a real sense of control and efficient working in case of deviations.

IMPLEMENTATION

The model was implemented to study the workflow, considering the environmental restrictions and available tools and materials. To initiate the process, the project was set by defining Rhino environment variables. The position was reviewed and checked to define the script for Grasshopper.

The data from the BIM file initiated the visualization process and requested Revit drawings to create the 'as-built' BIM model. From the library provided by the Blufab company, one of the toilet unit pods was selected for execution; see Figure 3. The size of the unit selected was 2846 by 1946 mm. The toilet pod consisted of a shower and a WC area. The panels were prefabricated on-site and then assembled. The dimensions of the panels were 1200*2100, 900*2100, and 600*2100 mm.

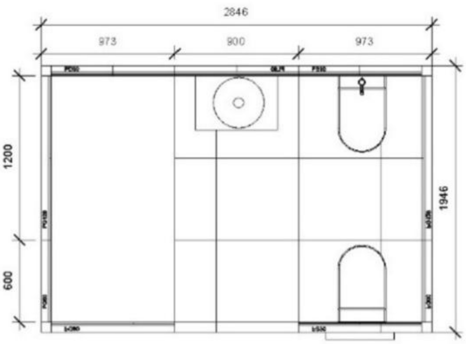

Figure 3
Toilet pod plan

The BIM model contains data like the dimensions of the panel, its material, and the sequence of the panel assembly. The model was imported into Rhino 8.0 software, where the geometry was set. Using the Grasshopper program, the file's geometry was taken as a reference, and this was the starting point for the code. As the IFC file was not directly interoperable with the Rhino/Grasshopper software, therefore a plugin, Geometrygym, was installed. The plugin was open-source and works on the principles of buildingsmart and ISO standards. With the use of this plugin, the IFC file geometry was used as the base for the Rhino script execution.

The Arena lab of the School of Architecture, Art and Design of the University of Minho was used for the implementation, where the KUKA KR120-R2700-2 F Robotic arm was installed. The robotic arm was set on a table height of 800 mm, providing a greater coverage area. The robotic arm had a 6-axis and was equipped with a vacuum gripper as an end effector. The Kuka robotic arm had a reach of approximately 2700 mm; therefore, to execute the script in real-time, the dimensions of the panels and pod were reduced to half of the actual dimensions. The KR 120 R2700-2 F was designed for a rated payload of 120 kg to optimize the dynamic performance of the robot.

Process of Prototype Assembly Testing

The process was initiated with the pick-up commands, which involved the definition of geometry and the plane of picking up for the robotic arm. The command also contained the robotic arm to use the coordinates of the end effector, in this case, the vacuum gripper. After that, the robotic arm went to the transition area and then placed the panel. The whole process was visualized through the Fologram app. This definition presents an overall picture of how the script was designed to understand the workings of the prototype testing.

The entire process was documented in the form of steps that were required for the implementation of the script's 'as-built' BIM project plan and execution work, as detailed in Figure 4. These steps ensured that all the work was documented in the BIM execution plan and followed in sequence.

After the geometry was calibrated, markers were placed in the Rhino environment to scan the model at the same place. The grasshopper script was more refined, and an attempt was made to visualize the picking and placing geometry.

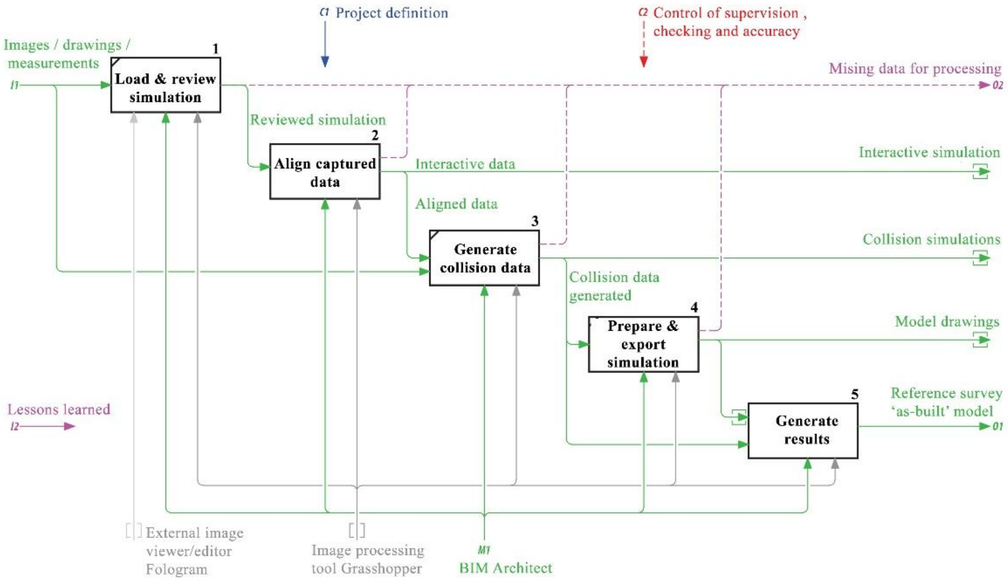

Figure 4
Diagram presenting the captured data.

Here was the second key step that was learned during the implantation. To pick the geometry, it was important to define the approach plane for it, where the robotic arm goes to the approach plane and then to the pickup plane.

The markers were placed around the setup; therefore, with the help of HoloLens, the assembly of robotic arm commands was visualized, and the panels were held up together by humans. This was where MR had an important role.

The markers, as shown in Figure 5, helped in locating the position of the panels and generated commands for the humans to work with the robotic arm.

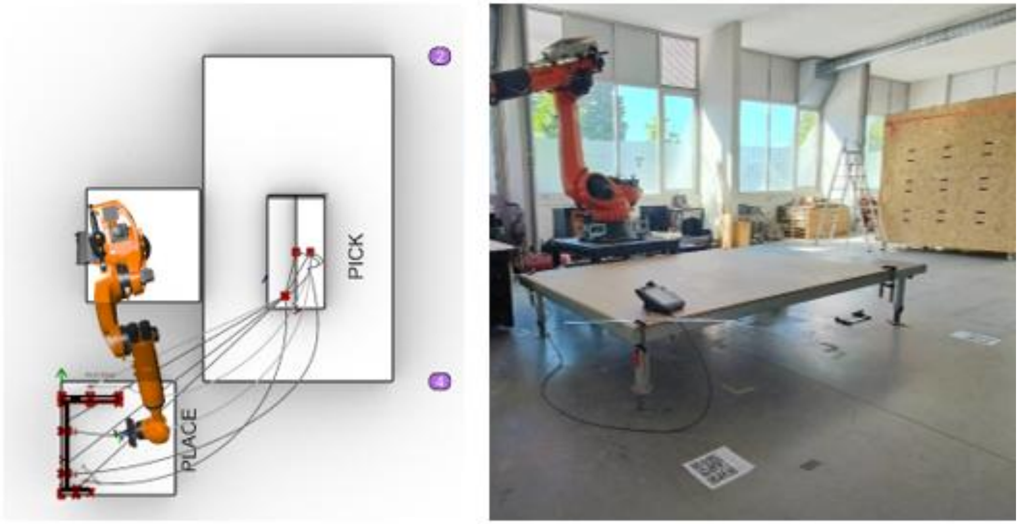

Figure 5
Markers in the rhino interface and placed in the lab.

RESULTS

The human wore the HoloLens, as shown in Figure 6, where the path taken by the robotic arm was visualized. That also prepared the human to work within the safety net and collaborate with the robot.

Figure 6
A human wearing HoloLens.

As the visualization guided the human to know the location of the panel, the task of holding and binding the panels together was performed by him. With the text inserted in the Grasshopper script, of “Hold here” and “Screw here”, the same was visualized through the Fologram plugin, and the human visualized where to hold and screw the panels.
This completed the implementation process for the testing of the framework developed for the research. Various problems that were encountered were tested, reviewed, and changed accordingly.
A major use of MR and BIM integration was that during the whole process, every detail was visualized, and a collaborative environment was achieved, as shown in Figure 7. The human interaction with the robotic arm was safely monitored, increasing the efficiency of the work. The integration of BIM in the robotic fabrication process helped in controlling the parameters and environment of the geometry.

Figure 7
A robotic arm picks up the panel and places it on the table, and a human visualizes it through HoloLens and the Fologram app.

CONCLUSION

Through this research, a framework was developed and evaluated to increase human-robot collaboration within the AEC industry. With the engagement of MR with the robotic fabrication workflow, various small deviations were studied beforehand, and much of the capital was saved. Compared with automated fabrication processes, the advantage of this process is flexibility. There is a margin for correcting errors and allowing users to interact with the robotic processes, which would otherwise have to be automated. This reduces the upfront engineering work to automate production, while also enabling precision and enforcing safety.

During prototype testing, the involvement of MR with robots was a major step towards the upcoming technological developments. With HoloLens, the human workers on-site could visualize the robots' movements and work accordingly, as shown in Figure 8. The safety around the robot was also enhanced, reducing the likelihood of accidents when the robot is in operation.

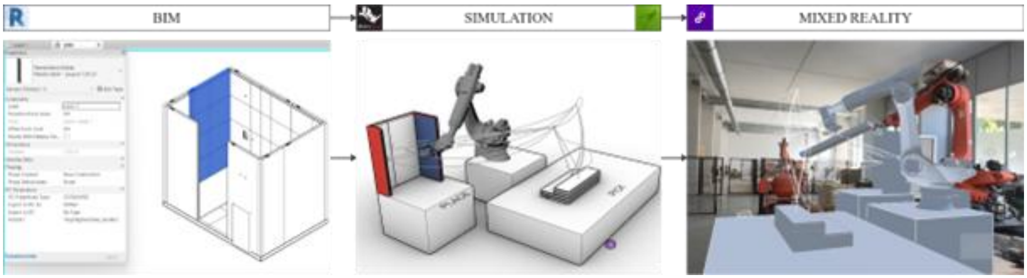

Figure 8
Simultaneous visualization of geometry in Revit, Rhino-Grasshopper, and MR.

With the MR, it was also possible to capture all the data and visuals and use them for further checking later. This was useful in the sense that sometimes the problems were seen later after the process had happened. The other stakeholders involved in the project were also able to check the model and specify if any errors were seen, resulting in saving time and capital before execution.

The stakeholders were provided with documentation of how the process would be executed in the form of a BIM Execution Plan (BEP), which describes the step-by-step method of execution, the necessary precautions to consider, and the way the script is to be used for sequential placement of panels. With the use of BEP, the client or the users were able to gain the knowledge required for the working of the framework. The use of BIM in automation enhances the documentation process, with the model being built up with all the parameters, making it easy to change the geometry and provide diverse options for execution. The data in the form of an IFC file was updated timely manner and provided to the user.

During the research work, observed and learned about various software that were being used by the industry. The framework also defined which software was good to use for the various stages of the project. BIM interoperable software enhances the productivity of the work provided, and it is easy to update the model with changes happening. The HoloLens is a strong visualization tool that will help the user understand the workflow in a more real sense, being able to fully immerse themselves in the experience of the construction.

In the case of the working of the Kuka plugin commands in the Grasshopper environment, a new plugin is being developed. With the new plugin, a user can remotely access the robotic arm and provide commands for its movement. This will be collaborated by the Fologram app. As for now, only the geometry can be changed, and the path of robotic movement can be visualized with the use of mixed reality. This upcoming development will take a step up and will allow users even more control of the robotic arm with MR.

Thus, this research field is evolving constantly, and various tools and functions are being studied and evaluated. Concerning the computational model script developed during the research work, the code can be further refined, and multiple tasks like 3d printing, cutting, painting, etc., can be included in the workspace so that the human-robot collaboration is not just limited to the assembly tasks.

The MR tool gestures can be further developed by including sensor-based recognition of tasks and machine learning-based systems. BIM interoperable software still does not have direct approachability with computational tools like Rhino; this field of work can be advanced by using high-end computational frameworks like Unity, Robotic programming like ROS, and Compass XR. With these tools, the script could be used for large-scale industrial automation applications.

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