AR-Assisted Assembly in Self-Build Construction with Discrete Components

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Abstract. The prevailing issue of low housing supply is caused in part by a lack of skilled construction workers. If unskilled residents were adequately equipped, they could potentially address this issue, expanding and adapting their homes without professional builders and designers. This research proposes the use of discrete components to build on unused community lands using augmented reality (AR) assisted assembly. Enfield, a low-density community in London, was chosen as the case study location. Modular components, pre-assembled off-site by robots, were designed to form a set of interlocking structures making them easy to install and dismantle. AR-assisted construction integrates design and construction processes, helping to resolve sequencing and flow issues during assembly. A robotic simulator was used to visualise the robotic assembly process and an AR programming was used to guide self-builders with no building experience through assembly. An experiment was set up, where AR-assisted non-professionals use modular components to assemble a 1:2 scale pavilion model. This workflow could encourage individual and community-led building expansions and could be effective in reducing pressure on the construction industry and providing more housing.

1. Introduction

Driven by urbanisation, fluctuating economic dynamics, and market conditions, there has been a surge in population, employment, and economic growth in urban space. However, urban infrastructure and housing supply are limited and cannot keep up with growing housing and market demand. In the United Kingdom, inadequate housing supply, unaffordability, and low spatial standards are well beyond the control of the City of London Council. The government has yet to deliver decent housing to all residents, despite its plans to introduce affordable housing and a new housing market system (Department for Levelling Up, Housing and Communities 2022). Increases in land prices, housing prices, and rents have ensured that the ‘housing issue’ has consistently remained on the formal political agenda (Edwards, 2016). In the United Nations vision for sustainable development, Goal 11 states that by 2030 everyone should have access to affordable housing (Goodier, 2007). The lack of innovation in construction technology in the building and manufacturing industries is a major reason for the shortage of housing supply (Goodier, 2007). Through improvements in design and technology, flexible structures, modular construction, and ease of construction and demolition, the problems of high raw material consumption, low productivity, and low return on human resources in the traditional construction industry initially seemed have been overcome (Linner, 2013; Wasim, 2020). These avenues of development present potential solutions to increase productivity, reduce production costs and improve safety in construction, which could contribute to environmental, social, and economic sustainability (Vinuesa, 2020). Although modular construction transfers off-site work to indoor environments, standardised construction production can limit the flexibility of building design and still requires a large amount of labour during construction (Diekmann, 2003). Parametric design and automated robotics can increase flexibility and reduce labour in modular prefabrication processes, addressing the problems inherent in standardised manufacturing (Yang, 2021). In recent years, digital tools and robotic fabrication have gained popularity in the construction sector, and the use of digital tools for design and fabrication in construction projects has become increasingly popular, including Artificial Intelligence (AI) -assisted design, robotic fabrication, and Augmented Reality (AR) -assisted construction (Claypool, 2019). The use of robotic arms in prefabrication is increasing in popularity, as these machines can perform various precise tasks with advanced control to assemble components independently in unilluminated environments (Yang, 2021). AR-assisted construction can be used for participatory decision-making (Potseluyko, 2022), combining digital information with third-party surveying tools and depth scanners to visualise digital information and provide clear feedback to users about construction accuracy and sequencing.

The objective of this research is to propose a building construction method by providing a complete technical workflow from design, to fabrication, to assembly. This research focuses on how to use robotic and AR processes to guide self-builders with no construction experience in construction and assembly. This responds to the housing problem caused by a shortage of skilled construction workers. The approach can effectively reduce pressure on the local infrastructure and provide more self-build housing. The specific process is divided into three parts; 1) component design and application, 2) robotic factory prefabrication, and 3) AR on-site assembly.

2. Literature Review

2.1 Self-Build Housing in the UK

The inadequate supply of housing stock and the environmental sustainability of housing is an issue that is consistently reported by the UK housing department (Heffernan, 2020). The current demand for self-build housing appears to be driven by the housing crisis (Ehwi, 2022). Many architects in the UK are attempting to break the shackles of the traditional building market using self-build housing to address the severe housing crisis facing most UK cities and to create sustainable community environments (Gyger, 2019). Collective self-builds can be used to meet individual spatial needs while at the same time regulating the integration of communal spaces to create a community environment that is characterised by both individual use and the collective memory of its inhabitants. Self-builds provide a way for residents to build or extend their own homes according to their personal preferences and to participate in design, cost management, and construction process (Goossen, 2022). In the context of zero-carbon housing construction, self-built housing has advantages over speculative construction in terms of energy efficiency, affordability, quality, and innovation. It is well-suited as a model for sustainable community and zero-carbon housing-oriented development (Bramley, 2016; Heffernan, 2020). The problem for self-build is ultimately about scaling up, technological innovation will effectively improve the feasibility of self-construction (Newberry, 2021).

2.2 **Modular Construction**

According to a 2019 McKinsey study, modular construction methods will effectively reduce construction costs (Bertram, 2019), provides an effective and appropriate way for self-built houses. Modular construction breaks structures down into constituent parts that can be manufactured, including roofs, walls, and floors. These parts are assembled in a factory and then transported to the site for on-site assembly. To produce building components efficiently, modular prefabrication plants use the industrialised manufacturing production chains (Grills, 2013). Unlike traditional manufacturing, modular construction is limited by the size of the site for both production and transportation, as large components must be transported to sites using truck trailers (Chen, 2018). Having an off-site factory that can accommodate all modular components is a necessity for modular construction. As thousands of different building components must be manufactured on a limited production line, personnel and machine scheduling and the planning of modular production are important (Ding, 2023). Although moving component fabrication from the construction site to an indoor factory reduces the labour required for building projects, a high degree of human-machine interaction is required in the modular production process. On average, each building module takes 208 hours to assemble and transport in the USA, and this process is still heavily dependent on labour (Mullens, 2011). Also, modular production occurs in a human-machine working environment, workers are at increased risk of injury during this part of the production process (Yang, 2021). If labour is robotically automated, this could reduce labour and worker safety issues.

Timber is an ideal material for prefabricated and modular structures. This is primarily because of its low weight compared to other building materials, ease of transport, and ease of installation. Its machinability allows for the efficient pre-cutting and milling of various features off-site (Bhandari, 2022). Design for disassembly (DfD) aims to reduce material consumption, costs, and waste during construction, renovation, and demolition. Material recycling aims to maximise economic value and minimise environmental impact through subsequent reuse, restoration, remanufacturing, and recycling of construction materials (Heinlein, 2019; Guy, 2005; Mule, 2012).

2.3 Robotic Assembly

The construction industry faces labour costs and safety challenges as global ageing reduces the proportion of workers who can participate in construction (Hwang, 2022). As the complexity and costs of robotic automation decreases, many industries are turning to robots to automate repetitive, high-volume production activities (Tilley, 2017). Modular construction can be effective in reducing construction uncertainty and project costs, but there are still several limitations including sufficiently large factory spaces and large workforces (Innella, 2019). Robotic automation can be applied to the construction of modular houses to solve these problems (Yang, 2021). Automation and robotics are now promising directions for the construction industry's future (Bock, 2015). The unilluminated manufacturing is gradually becoming a common feature of modern manufacturing, with completely automated handling of all manufacturing processes and materials (Jia, 2022). Robotic automation technology can replace increasingly expensive labour costs, whilst reducing the risk of failure, hazards, and variability in the workplace (Tilley, 2017).

2.4 AR-assisted Construction

AR technology emerges in the 1990s (Rosenberg, 1992), as researchers explored the shared 3D visual information digitally (Steuer, 1995). Today, AR technology is constantly growing in sophistication. The use of AR is becoming more widespread and normalized, AR and digital tools are increasingly being combined in new ways. AR technology is already being used as an interface between digital information and the real world, facilitating human access to information and providing visual aids and manufacturing guidance for existing 3D modelling schemes (Song, 2021). In traditional building construction, forms of buildings are as 2D drawings are unable to convey the same degree of complexity as a 3D visualisation can, whereas AR technology can effectively visualise 3D designs (Dunston, 2008). The superimposition of computerised 3D model information and structural drawings onto real-time scenarios in construction facilitates human-computer interaction in digital construction through real-time shared information and assistance (Song, 2021). In digital fabrication projects for architectural design, many architects use AR to visualise the construction process (Song, 2021). In recent years, several experiments and studies on AR-assisted digital construction have emerged to guide construction workers to understand the site and construction process more quickly. For example, GAMMA can visualise models before construction and can overlay 3D Building Information Model (BIM) models onto the building site (using a camera and a screen), displaying and sharing construction models with multiple parties. It allows builders or architects to identify problems before construction, avoiding errors during construction, and enabling efficient communication (Mirshokraei, 2019).

3. Methods

This paper proposes an efficient self-build-friendly construction process based on the Design for Manufacturing and Assembly (DFMA) modular system. The methodology introduces a workflow to develop and build a modular system of self-build-friendly buildings which residents can use from design to construction. In this workflow, the construction is performed using the design and development of discrete timber modular elements, off-site automated robotic manufacturing and assembly, and AR-assisted on-site self-building (Figure 1).

To achieve the objectives of this research, easy-to-install modules were designed. These were then simulated using a robot simulator, to create an application for use in robotic manufacturing without the need for a physical machine. This application can be used to control physical machines as well. The sequence of the AR-assisted installation was developed using Unity 3D. The user is given an overview of the construction using an AR handheld or wearable device. The program can adjust the self-built assembly sequence in real-time according to the position of the user. The stability of the structure was also inspected in the Unity 3D program using Rigidbody to ensure that the structure always remains stable during the self-build assembly process.

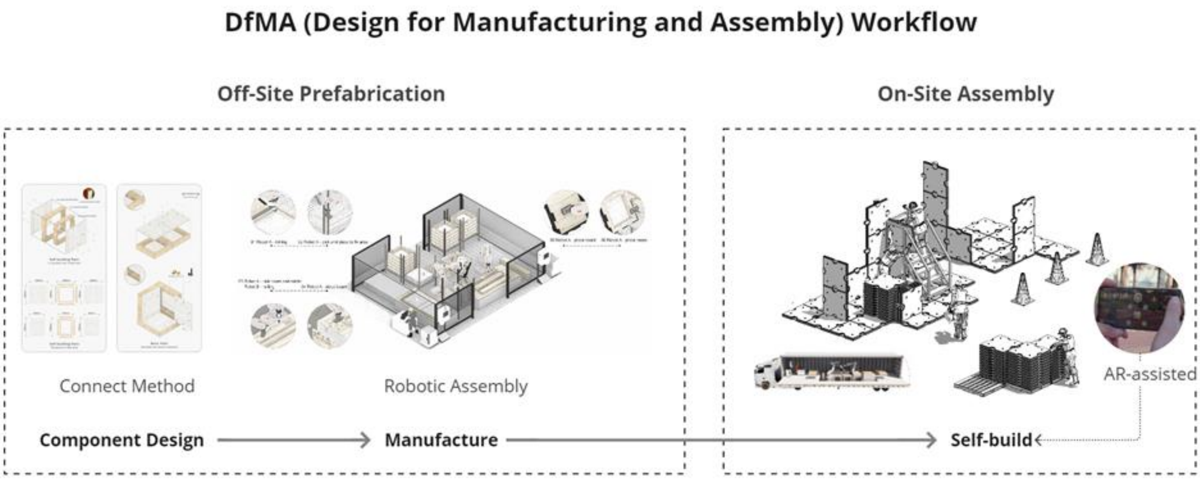

Figure 1. Design for Manufacturing and Assembly Workflow

4. Result

4.1 Component Design

This research combined digital models and high-precision manufacturing to develop a set of prefabricated structures that can easily be assembled and replaced, disassembled, and recycled (Figure 2). The material of choice for the modularisation was timber, a renewable and easily processed building material (Figure 3). The modules were connected both horizontally and vertically using post-tensioning screws which allow each module to be combined freely.

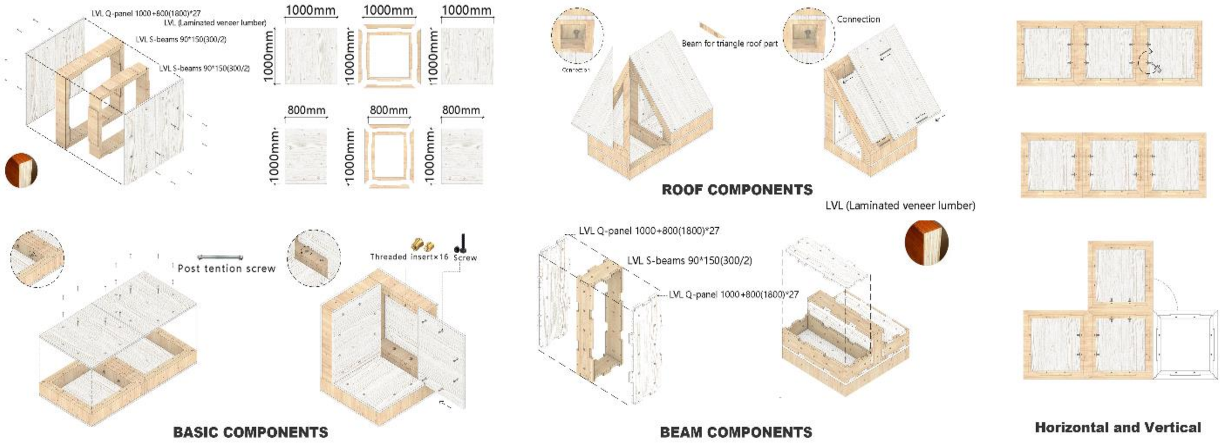

Figure 2. Discrete Module Component Design

The modules were designed in three separate sizes, length 100mm * width 100mm * thickness 20mm, length 100mm * width 80mm * thickness 20mm, and length 100mm * width 40mm * thickness 20mm. These correspond to the timber sections of the roof, the walls (generally), the beams, as well as the ground piles.

Figure 3. Modular Prefabrication

The foundation comprised of a strip foundation and U-shaped fixed support with spiral ground piles instead of traditional reinforced concrete poured foundations. This made the building foundation more flexible and faster to assemble. It furthermore eliminated the need for ground levels, waste disposal, and excavation, which can be costly. Spiral piles are typically driven into the ground in a gyratory manner. They have good tensile strength and insertion grip so that the soil is not easily loosened and the soil itself can be used strategically. The U-shaped fixed supports allow the centre and height of the timber structure to be adjusted in its horizontal and vertical position, making it easy to install (Figure 4).

Figure 4. Structure & Process of Self-Build

4.2 Robotic Assembly

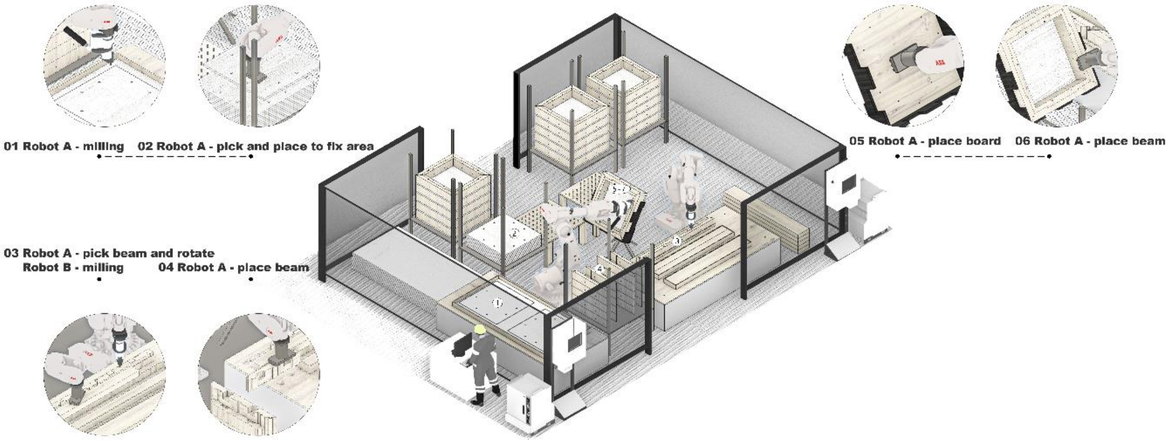

Figure 5. Two Industrial Robots Collaborate on Assembly

The modular prefabrication used robots to cut and assemble the modules, controlling the materials and the robotic arm within the scope of the buildable structure. The visualise robotic manufacturing process and the control files were integrated into the computational design process. The assembly process was collaborative, using two industrial robots which worked in a controlled environment to assemble the modules appropriate to their scope (Figure 5). The boards were first cut to modular application sizes using precision CNC milling and were pre-drilled for screw holes. After the template cutting and drilling was complete the objects were placed precisely wherever they were needed. Finally, the screws were placed in the prefabricated hollows to complete the assembly. Only the end effector of the multi-axis robot arm required changing to enable different functions throughout the process. This provided a more efficient and precise process for prefabrication and eliminated the need for manual movement of parts and the need for measuring. This increases to productivity of prefabrication on-site assembly.

4.3 AR-Assisted Self-Build

The assembly sequence of a building is the most crucial aspect of AR-guided construction. Two guidelines were created for the setting of the component assembly sequence. The first ensured that the structure always remained stable during construction, ensuring the safety of the builders. The second ensured that the components that were ready to be installed were closer to the builder, thus facilitating more efficient construction. To confirm the usability of the AR program, three non-professionals assembled a 1:2 scale pavilion by using modular components (Figure 5), without the use of architectural 2D drawings and instead using only an augmented reality application customized for mobile devices.

Figure 6. AR-Assisted Construction Test

Regarding the first guideline, the pairwise distances between each building component and the agent were calculated in Unity3D and ordered according to world coordinates using appropriate code. 2D coordinates consisting of the x-axis and z-axis were prioritized, and the y-axis coordinates (which were vertically oriented to the ground) were given second priority. By approximately setting the two levels, it was possible to ensure that the building was assembled generally from the bottom upward, and broadly ensured that the structure remained stable. In Figure 6, the cylinder is the agent, and each cube is a building component. Bright yellow to pale yellow represents the order in which the components were installed. By controlling the agent movement, the assembly order could be adjusted in real-time.

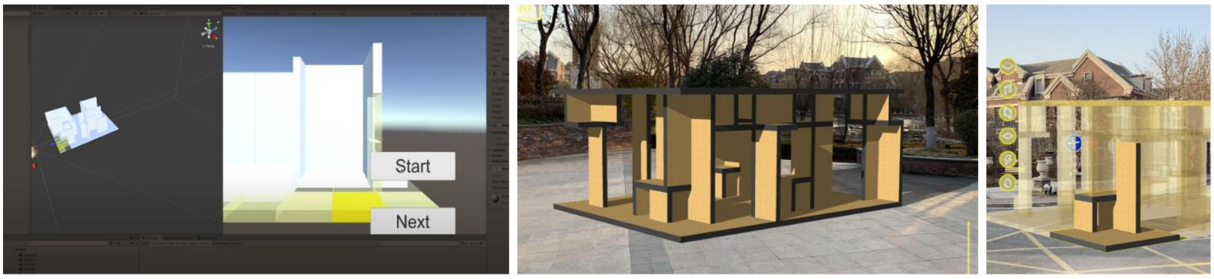

Figure 7. AR Assembly Sequence

Regarding the second guideline, the stability of the building structure was monitored using the Rigidbody plugin in Unity 3D. After the previous step had roughly ensured the stability of the building structure, the Rigidbody review was refined to ensure that the structure always remained stable during the assembly process. If the structure of the building was not stable enough, the program adjusted the existing assembly sequence until the structure was stable. After the success of the first experiment, the project improved the AR program for more complex discrete buildings consisting of multiple components.

Further experiments were conducted on a larger scale to explore the potential of the AR program by using HoloLens for larger-scale building construction. In terms of AR-assisted construction technologies, the AR construction devices used were a mobile terminal-phone and a tablet. To a certain extent, this was inconvenient during assembly and position calibration. This was due to the inaccurate measurements of the gyroscope and other azimuths. This caused a degree of error which demonstrated the necessity for accurate and repeated calibration. Therefore, a new collaborative work method is proposed using a HoloLens wearable device, to realize the assembly process in real-time and with greater efficiency. The current AR-assisted assembly system of the terminal is not open source, and there are issues such as unstable signal transmission in the practice area. Regardless of the potential improvements, the current system enables real-time visualisation and manipulation of the assembly process, improving the potential working methods of architects and engineers.

5. Discussion

In terms of reconfiguration; planning, design, production, construction, maintenance, disassembly, and reuse should all be considered in the original design of modular buildings. Standardized modules used in various building structures become the foundation of design conditions when they are later repurposed. Modularisation eliminates the production complexity of established products and makes self-build processes more practical for residents (Bakhshi et al. 2022).

In terms of BIM, collaboration using integrated BIM and DfMA parametric and algorithmic design software optimized the design process. It also facilitated the information transmission, technical coordination, and resource allocation during the construction process. It furthermore enables customers to participate in the construction configuration process and allows collaboration between different teams to achieve integrated design and customisation strategies.

In the design phase, customers can be in direct contact with the design process. This forms a closed-loop feedback system and optimizes collaboration in the existing BIM workflow (Alfieri et al. 2020; Bakhshi et al. 2022). Improving precision and efficiency through automated manufacturing and AR-assisted construction methods reduces the amount of waste generated during the construction process and reduces the risk of potential repeated work. In large-scale production processes, the three stages of "supply chain management", "product architecture and modularisation", and "customer preference and customization" are completed in an orderly and systematic manner. This enables the completion of prefabrication and production, realising commercial and productive ends. The current typology test validates the proposed module prefabrication workflow for AR-assisted fabrication. Future research should fully automate module manufacturing and assembly to reduce the demand on already scarce labour resources, such as in Tesla factories where unilluminated manufacturing occurs.

This robot study is limited by time and equipment issues, thus only the whole process of robot assembly is visualised. Future research will use the control files from this experiment and the UR10robot, mechanical gripper, and other end-effectors mentioned above to assemble the modular components.

6. Conclusion

This research demonstrates that combining modular components, robotic off-site prefabrication, and AR-assisted self-building is a feasible approach to rapidly increasing housing stock. During the off-site assembly process, two robots will complete the assembly of the generic wooden components. The AR-assisted construction program subsequently helped people to build discrete prefabricated structures on-site without technical expertise.

This research envisages self-construction using prefabricated discrete structures as a response to the housing supply problems caused by the lack of skilled construction workers in the construction industry. Emerging innovations in AR technology and robotic manufacturing could thus bring about transformative and sustainable changes to construction practices while increasing productivity on site. This research leverages knowledge of AR-assisted self-building and robotic assembly of prefabricated components, to create a continuous digital workflow that seamlessly connects the design, manufacture, and construction of a project. It also illustrates the potential of using robotic fabrication and AR-assisted installation in prefabricated building applications, providing a systematic technical construction approach and a theoretical contribution to modular self-build construction research.

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