AR-enabled human-robot collaboration for exploratory design-fabrication

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With the rapid advancement of augmented reality (AR) technologies, architectural designers can now easily visualise and interact with digital data in a real-world setting. AR technologies lend themselves well to bolstering human capability in non-standard, implicit fabrication tasks in the context of architecture, engineering and construction (AEC). Research has demonstrated that these interfaces have allowed materials and designs to be flexible, adaptable and non-uniform. It has been established that augmented fabrication environments can assist with the manual fabrication and assembly of linear timber pieces, bamboo, bricks, irregular foam blocks, and bending steel. Nonetheless, there is also an opportunity to explore AR in human-robot collaboration (HRC) in these non-standard fabrication scenarios, allowing the design to be altered during the fabrication procedures. This research area would enable a hybrid approach that leverages the strength of the robotic system to support human designer(s). In this position paper explores the possibilities of integrating collaborative robots in exploratory design-fabrication scenarios via AR interfaces to lend a helping-hand to the human designer(s).

CCS CONCEPTS • Human-robotic collaboration (HRC) • Human-centered computing → Augmented reality (AR) • Interactive Design

Additional Keywords and Phrases: creative architectural exploration, interactive fabrication, digital fabrication, human-robot collaboration (HRC), augmented reality (AR) interface.

1 INTRODUCTION

The introduction of augmented reality (AR) technology has significantly impacted the nature of the architectural design process, especially in how architectural designers interact with digital data. The concept of complementing the real world with digital data that otherwise is not visible has offered a great variety of opportunities for the architectural design industry. For example, AR has been used to enhance design communication and collaboration (Alonso-Martin et al., 2015) through shared model visualisation, facilitate complex onsite manual construction tasks, enable complex site inspection (Jahn & Newnham, 2022) and extend craft-based fabrication procedures (Goepel & Crolla, 2020).

Despite AR capabilities in enhancing the architectural design process, the adoption of AR technology within the architecture, engineering and construction (AEC) industry remains low. The low adoption rate is largely contributed by the affordability and maturity of the technology at the time. According to Cheng et al. (2020), the authors also pointed out several contributing factors that limit the integration of AR technology in the current AEC landscape, namely issues with regards to spatial registration, data transfer and storage management, user design interfaces as well as the limited capability to allow for multiuser collaboration.

With the increasing maturity of AR technology and commercially affordable mixed-reality (MR) products becoming more accessible in recent years, research surrounding augmented reality (AR) yet again garnered much attention within architectural design practices (Rankohi & Waugh, 2013; Wang, 2009; Wang et al., 2013). This has created an opportunity for the integration of human-robot collaboration (HRC) with augmented reality (AR) in architectural design practice. This is further enabled by recent developments of AR software applications such as *Fologram*, *MRTK*, and *URDF*, which create an opportunity for researchers to explore more possibilities — for instance, integrating collaborative robots in complex non-standard fabrication scenarios to support human designer(s).

1.1 AR-ASSISTED DESIGN-FABRICATION PROCESS

From the significant body of research in AR-assisted fabrication, AR has shown promising results in enabling human augmentation for constructing geometrically complex structures, a task formerly designated for computer-numerically-controlled (CNC) machines. This research area is primarily driven by the need to upskill onsite human workers and reduce the dependency on digital fabrication tools. In addition, applications such as *Fologram*; an experimental mixed-reality (MR) platform for *Rhinoceros 3D*, *Vuforia*; an AR-enabled platform for *Unity* and *MRTK*; a mixed-reality toolkit developed by *Unity*, also have allowed AR devices to superimpose three-dimensional feedback directly on the real-world environment.

Many architectural experimental projects have demonstrated that AR-assisted fabrication can support unskilled workers in assembling complex structures with high precision in a short timeframe. The AR-assisted assembly process proposed by Fazel & Izadi (2018) is one of the early examples in architectural design that explored AR capability as a visual guide for the manual assembly of complex freeform brickwork. This AR approach is further explored in an unstructured environment by the research team from the University of Tasmania and Fologram (Stinson, 2019). Both studies showcased AR’s ability in human augmentation through the direct visual overlay of specific holographic instructions into sequential manual actions. By overlaying construction information directly within the wearer's field of vision, AR technology improves users' spatial understanding and reduces the need to switch between cognitive tasks.

The assembly of ARgan (Goepel & Crolla, 2020), a geometrically complex bamboo sculpture, is another remarkable example that exemplifies AR's ability to enhance the manual fabrication process. The design workshop demonstrated how AR technology could be utilised in a collaborative fabrication scenario, enabling multiple users to work off a single digital-based model simultaneously. The virtual model was superimposed onto the field of view of the users. However, the purpose of the holographic overlay was only to guide the users through the crucial steps of the production process (Goepel & Crolla, 2020). This fabrication setup offers users the flexibility and opportunity to deviate from the initial design intent and have a greater agency in the final design-fabrication output. In other words, this project highlights AR technology's ability to stimulate dialogue and collaboration in a fabrication process, augment craftsmanship, and allow for a more diverse design output.

Fologram and Soomeen Hahm Design's Steampunk pavilion is another astonishing example demonstrating how AR holographic guidance could enable fabricators to quickly produce highly intricate objects with primitive analogue tools (Jahn & Newnham, 2022). The holographic models serve as direct visual feedback regarding the accuracy of the fabricated components and allow the users to modify their fabrication techniques intuitively to produce fabricated pieces that fit within the acceptable tolerance. These fabricated components are then digitised and fed into the digital environment to allow the computer-generated design to make any necessary adaptations (Jahn & Newnham, 2022). This feedback loop symbolised the direct collaboration between the design and fabrication process and enabled the bi-directional flow of information between the physical and virtual realms.

In summary, AR technology can assist human designers in completing complex fabrication structures. AR technology also allows designers to have a greater agency and achieve more diverse designs by stimulating dialogues and collaboration in the design-production process. However, these examples would require extensive cooperation and coordination between multiple installers, fabricators and human workers, potentially resulting in onsite accidents.

1.2 AR-ENABLED HUMAN-ROBOT COLLABORATION

While investigating the field of augmented fabrication, it would be remiss to overlook the potential of the robotic system within the context of AEC. Robotic technology has advanced greatly from the research realm to become a viable solution for delivering complex fabrication geometries. However, despite the apparent advantages, robotic technology does have its limitations. For instance, the technology offers little flexibility in a dynamic situation, thus preventing itself from performing well in an unstructured environment. As a result, in-situ construction still relies significantly on human workers to respond dynamically to the changing onsite conditions.

In recent years, there has been a growing interest in human-robot collaboration (HRC) research surrounding the AEC sector. The research aims to develop an intuitive, flexible solution that combines human operators' dexterity with robots' strengths in a collaborative work environment. Furthermore, as affordable AR headsets have become more accessible, AR-based HRC research is also focused on this research area. AR technologies have shown promise in increasing communication between robots and designers by fusing optical flow data into the real-world environment via AR displays (Alonso-Martín et al., 2015). For context, this position paper uses the model framework (Amtsberg et al., 2021) developed to study AR-based HRC development in the AEC context.

1.2.1 *Human designer(s) as instructor(s), whereas robots as an augmenting tool.*

The collaboration between human designers and robots could be achieved by integrating multiple sensors and emitters (Amtsberg et al., 2021). In this scenario, human designers could easily interact with robots through gestural instructions, which will then translate to physical actions performed by the robot machines. One of the earlier adoptions of this model framework is ROMA, a novel robotic modelling assistant system developed by Peng et al. (2018). The study investigated how an AR interface could enable human-robot collaboration in 3D printing. The method proposed by Peng et al. (2018) leveraged a turn-taking approach to allow human designers to express their design forms in a mixed-reality (MR) environment. The robotic arm subsequently materialises the described geometry.

The interactive robotic plastering system (IRoP) established by Mitterberger and her research team is another notable example that implements a similar model framework (Mitterberger et al., 2022). This human-guided robotic fabrication process utilises hand-held devices to facilitate the motion-capture process; the gestural instructions are captured and interpreted. These digital designs are then projected to the wall surface alongside other vital information, such as the number of sprayed layers. The projected graphics enable designers to visualise and refine the design shapes. The robot machine will only initiate the plastering process once the design has been finalised. Both examples enable the human-in-the-loop approach, which allows designers to visualise and manipulate their initial design in a mixed-reality (MR) environment before the robot machines execute it.

1.2.2 *Human and robot as a collaborative unit.*

Adopting a fully automated workflow in an unstructured building construction setting is highly complex since it frequently involves processes requiring tremendous knowledge and craftsmanship. However, an AR-HRC could address this issue by allowing robots and human operators to work together to achieve a common goal (Amtsberg et al., 2021). For example, CROW, a collaborative robotic workbench introduced at the 2018 Hannover Messe, has achieved collaborative task sharing between a robot and non-expert users in the cooperative fabrication of a complex timber structure (Kyjanek et al., 2019). The workbench improved users' capabilities by providing direct access to robotic control and superimposing digital information via an AR interface, allowing for an interactive, collaborative robotic building process.

2 CONCLUSION AND OUTLOOK

Augmented reality (AR) technologies have shown to be an intuitive interface that could facilitate human-robot collaboration and enable human augmentation in complex architectural design-fabrication tasks. A significant portion of this research will contribute to architectural robotics, mainly on how these robots could be utilised as active agents in an exploratory design-fabrication process. This research also attempts to establish a more unified and accessible digital design-fabrication process, blurring the line between the physical and the virtual worlds.

The main objective of this position paper is to provide a contextual framework that illustrates how collaborative robotics could be integrated into these flexible design-fabrication scenarios to aid human designers. The aim of this paper is not to develop an entirely new approach to human robotic collaboration (HRC), but rather to explore the synergy between AR and HRC's synergy and how it can be implemented in the architectural design industry.

3 ACKNOWLEDGMENTS

This research has been supported by the Queensland University of Technology (QUT). In addition, I would like to acknowledge all the help and support from my supervisors, Jared Donovan, Markus Rittenbruch and Muge Fialho Leandro Alves Teixeira. Lastly, I would like to thank Noel Lavery for his helpful comments on this paper.

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