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Design Considerations for AR-Enabled Human-Robot Collaboration in Fabrication-Centric Architectural Design Process: A Co-design Approach.

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Abstract. The emergence of collaborative robotics presents an opportunity for architectural designers to safely engage in design and fabrication through human-robot collaboration (HRC). By leveraging the adaptability, creativity, and design judgement of designers with the strength, repeatability, and design precision of robotic assistance, HRC has the potential to create a unified design-fabrication workflow. Recent advancements in augmented reality (AR) technology further enhance these prospects by enabling users to superimpose context-sensitive, computer-generated information in the real world. AR technology also provides situational awareness, which proves beneficial in the context of HRC. The maturation of AR technologies offers new possibilities for developing HRC systems tailored to architectural design-fabrication needs. Recognizing the pivotal role of human factors in HRC development process, this paper aims to explore the architectural designers' needs to develop an AR-enabled HRC system that better supports the fabrication-centric design process, such as exploratory collaborative assembly tasks. Key findings highlight the necessity for a unified design-fabrication workflow, a clearer allocation of tasks between designers and robotic arms, an intuitive user interface, a streamlined interaction process, a better understanding of robot intentions and movements, intuitive procedures for error avoidance and correction, and enhanced user safety in HRC scenarios.

Keywords: Augmented Reality (AR), Human Robot Collaboration (HRC), Human Robot Interaction (HRI), Architectural Design, Fabrication-centric Design Process, User Interface / User Experience (UI/UX), Co-design, User Centered Design (UCD).

1 Introduction

Collaborative robots, commonly known as cobots, are specialized robots designed to operate alongside humans in a shared workspace [1], [2], [3], [4]. In contrast to traditional industrial robots, typically confined to cages for safety reasons, cobots are intended to interact with humans collaboratively. The introduction of collaborative robotics creates an opportunity for architectural designers to design and fabricate safely and accurately through human-robot collaboration (HRC). Combining the adaptability, creativity, and design judgement of designers with the strength, repeatability, and precision of robotic assistance, HRC has the potential to create a unified design-fabrication workflow. Despite all the benefits of HRC, its adoption within the architectural, engineering and construction (AEC) industries remains low, partly due to the challenges associated with robot interfaces [5].

With the maturation of augmented reality (AR) technologies, new possibilities emerge for developing HRC systems tailored to architectural design-fabrication needs. AR technologies introduce a novel approach to how architectural designers perceive and interact with the physical environment, blending digital data within the physical space [2], [3]. When coupled with collaborative robots, AR could enable architectural designers to engage with robotic assistants more intuitively and efficiently [5]. Furthermore, the integration of AR and HRC holds the potential to streamline the architectural design-fabrication workflow and enhance the user experience.

Realizing the full benefits of AR-enabled HRC in architectural design requires a focus on user interface/user experience (UI/UX) design. It is crucial to establish a framework that fosters effective communication, interaction, and cooperation between human designers and collaborative robots. The design of the AR interface, the human-robot interaction (HRI) protocols, and the overall collaborative workflow will significantly influence the success and usability of such systems in architectural design practices. As a step towards this goal, this study aimed to gather insights into what architectural practitioners consider necessary when introducing an AR-enabled HRC solution in architectural design-fabrication tasks, such as exploratory collaborative assembly tasks and to identify future applications on other fabrication-centric design tasks of such technology.

The paper is organized into the following sections: section 1: a review of existing related work surrounding AR-enabled HRC system within the context of architectural design-fabrication workflows and discuss the research approach taken towards HRC research; section 2: our research methodology and the supporting features; outlining the research findings and highlights, relevant insights that informs the development of an AR-enabled HRC system for the architectural design tasks, such as collaborative assembly tasks; and finally, the summary of the study findings, and design strategies that could be implemented in the AR-enabled HRC system on other architectural design tasks.

2 Related Work / Background

The sections below illustrate how our study contributes to the existing research on robotic fabrication process in architectural design. The section then delves into several case studies that utilized AR application to support robotic fabrication, and the exploration of the research approach adopted by previous studies. Furthermore, we suggest the potential benefits of adopting a user-centric perspective to investigate this emerging research area.

2.1 Collaborative Robotics in Architectural Design-Fabrication Process

Over the past decade, robotic fabrication has brought significant advancements to the field of architecture, engineering, and construction (AEC). It offers benefits such as customized construction parts, speed, precision, and new design possibilities [6]. However, there are still challenges while utilizing robotic fabrication, especially in non-linear fabrication processes. Non-linear fabrication processes involve a dynamic approach where the design and making process can occur simultaneously [7]. Moreover, the final design often emerges throughout the fabrication process rather than being predetermined. Such exploratory design-fabrication tasks play a vital role in fostering creative ideation and cross-disciplinary learning in the design field. Robots often struggle in these situations as they lack predictable and stable conditions necessary for the conventional robot operation.

Conventional robotic fabrication processes excel in handling specific tasks and workflows, but as we navigate increasingly intricate settings, the collaboration between human operators and robots becomes paramount [7]. Collaboration becomes particularly crucial in non-linear fabrication processes. The dynamic and ever-changing nature of these conditions poses challenges for robots, which are typically programmed to follow predetermined actions [8]. The predetermined action approach has inherent limitations, including inflexibility in adapting to environmental changes, as well as imprecision in complex tasks [9]. Furthermore, these robotic machines also operate within a graphical user interface (GUI), impeding a seamless design fabrication workflow [10], [11].

Emerging technologies like AR interfaces show promise in addressing the challenges and increase the potential of HRC in architectural design. AR interfaces offer custom user interfaces that enable seamless human-in-the-loop fabrication processes [7], [8], [9]. Moreover, these interfaces provide a unique blend of the physical and virtual worlds, tightly coupling the physical interaction space with visual feedback [14]. The integration between AR and collaborative robots not only alleviates user's cognitive workload [15] by facilitating a clear understanding of the intricacies inherent within the robotic system but also enabling the users to directly and physically engaged in design-fabrication processes, where the utilization of a separate screen-based interface would be impractical and cumbersome [10], [11].

The integration of robotic fabrication and AR interfaces introduces a new paradigm where humans and robots work collaboratively through HRC process. This approach allows a strategic allocation of design and fabrication tasks, leveraging the distinct strengths of each party [5], [16]. Architectural designers are adept at tasks demanding higher flexibility, nuanced interaction, and subjective decision-making, due to their cognitive abilities. Conversely, collaborative robots excel in executing precision-oriented, repetitive actions, and tasks that are labor-intensive. This synergistic allocation of tasks not only optimize the overall efficiency of the workflow, but also mitigates the risk of injuries associated with labor-intensive activities [17].

This paradigm shift is necessary in the context of architectural creative exploration, primarily due to the limitations of conventional digital design-to-fabrication workflow, which heavily relies on linear data communication [5], [10]. The prevalent unidirectional nature of these workflows stems from the explicit nature of the machine instruction. In contrast, in a HRC scenario, there is a demand for bidirectional communication channels between designers and collaborative robots. This setup enables architectural designers' creativity and engagement throughout the design-fabrication process, as it does not strictly prescribe the path of execution [10].

To fully utilize the potential of HRC in the architectural design process, it is essential to incorporate new interaction approaches such as intuitive AR interfaces. These interactive modes of communication enable seamless communication, efficient task allocation, and synchronized decision-making between humans and robots throughout the design and fabrication processes. This shift towards more interactive and dynamic communication channels not only allows for creative input from designers but also optimizes the overall efficiency of the design-fabrication processes.

2.2 AR-enabled HRC in Architectural Design-Fabrication Process

In recent years, various case studies have demonstrated the utilization of HRC systems in non-linear design-fabrication processes. These research studies stem from the concept of Interactive Fabrication, initially proposed in the article "Interactive fabrication: new interfaces for digital fabrication" [18]. According to the authors, interactive fabrication empowers users to exercise complete control over the digital fabrication of a physical form using real-time input devices. This approach aims to bridge the gap between design and fabrication, emphasizing the importance of a human-in-the-loop approach throughout the design fabrication workflow.

In the realm of architectural design, several works surrounding AR-enabled HRC have emerged in recent years. RoMA is an interactive fabrication system, offering an in-situ modelling experience [10]. As the designer creates and refines a model using RoMA's CAD editor in AR, a 3D printing robotic arm, operating within the same design volume, concurrently constructs the designed features. Another example is IRoP [13], an interactive robotic plaster spraying process employing a projected AR interface. Or CROW, a collaborative robotic workbench, demonstrated collaborative task sharing between a robot and non-expert users in the cooperative fabrication of a complex timber structure [19]. The workbench enhanced user capabilities by granting direct access to robotic control and overlaying digital information via an AR interface, facilitating an interactive, collaborative robotic building process.

These examples exemplify the human-in-the-loop approach, allowing designers to visualize and manipulate their initial designs in an AR environment before the robot executes them. AR technologies prove to be an intuitive interface that facilitates HRC and enables human augmentation in complex architectural design-fabrication tasks.

2.3 Research Approaches in Human-Robot Collaboration Research

As previously discussed, integrating AR into HRC processes offers significant potential for enhancing architectural designers' capabilities in creative design-fabrication endeavours. However, the adoption of AR-enabled HRC processes remains predominantly confined to research institutions. Furthermore, the current research in HRI and HRC is strongly “robot-centred” or “techno-centric”, focusing mainly on the technological solutions, without exploring how human-factors could contribute to the effectiveness of the HRC systems [20]. Recognizing that robots are designed to support humans, regardless of the specific task performed, is crucial. Therefore, discussing robots without considering their relationship with humans is incomplete. Design consideration from the user perspective must be integrated into the development of AR-enabled HRC processes. This research adopts a human-centric approach to identify and explore these design considerations.

3 Methodology

The following sections discuss the research method implemented in this study before explaining the research participants, design setup, data collection methods, and analysis procedure. Each component plays a pivotal role in uncovering user needs and preferences for an AR-enabled HRC system in architectural design-fabrication process.

3.1. Research Method – Co-design Study

This research study employed a co-design approach to understand the design requirements necessary for developing an effective AR-enabled HRC system for the fabrication-centric design process, such as a collaborative assembly task. Three research team members were responsible for facilitating the co-design workshop, one serving as the workshop moderator and the others as the note-keeper and observer. The activities were designed to engage research participants as active participants, engaging in conversations, fabrication activities and group discussions. Furthermore, the participants proactively contributed suggestions to enhance the presented proof-of-concept prototypes, discussed how the HRC system and AR interface could be further improved, as well as proposed alternative methods that would be more suitable for supporting architectural practitioners. Through active participation in workshop activities, the participants played a crucial role in assisting the research team in gaining insights into the user needs, preferences and challenges that architectural designers might face during the fabrication-centric architectural design process. These insights were instrumental in refining the proposed prototypes and allowing the research team to make informed decisions about the features that would be most beneficial for the users. It is important to note that this research study took an exploratory research approach to understand how AR could be used to facilitate human-robot collaboration in architectural design-fabrication setting. The overarching objective of this research study is to uncover the design requirements necessary for developing an AR-enabled HRC system that could support architectural designers in collaborative assembly tasks.

3.2. Research Participants

Five research participants with diverse backgrounds in architectural design were recruited for the co-design workshops, irrespective of their prior experience with AR technology or collaborative robotics. The participants included architectural design students, PhD students with a background in architectural design, and architectural designers from local architectural practices. The recruitment process employed various methods, such as distributing flyers, utilizing email bulletin boards, and making general announcements through the university webpage, ensuring a diverse and representative participant pool. All participants provided written informed consent, acknowledging their rights, anonymity, and the purpose of the research. Participant details are summarized in **Table 1**, providing an overview of their roles and backgrounds.

Table 1: Summary of the total participants in the study, including their job titles, years of experience in the architectural design field, and prior experience with either augmented reality or collaborative robots.

Participant ID	Job Role	Years of Experience in Architectural Design field	Prior Experience with AR or Collaborative Robots (Yes/No)
P1	Senior Architectural Graduate	5-10	No
P2	Junior Architectural Graduate	1-5	No
P3	Architectural Student	1-5	Yes
P4	Architect	10-15	No
P5	PhD Student	1-5	Yes

3.3. Data Collection Methods

Given the multifaceted nature of the research topic, two data collection methods were used to capture the nuances that could facilitate effective HRC: (i) observations and (ii) semi-structured interviews.

3.3.1. Observations. According to Kawulich, an observational study allows researchers to capture participants' physical and non-verbal expressions, offering crucial contextual information for qualitative research [21]. Therefore, an observational study was chosen due to its ability to facilitate a deeper understanding of participants' interactions during collaborative assembly tasks and their engagement with the collaborative robot through the AR interface. The majority of the observational study occurred during activities I and II. To complement the observational study, additional video recordings were captured to document participants' actions, gestural motions, and perceived emotions for further analysis. These recordings corroborated the data collected from workshop discussions, adopting a triangulation approach to enhance the overall robustness of the findings.

3.3.2. Semi-Structured Interview. The co-design workshop consistently utilized a semi-structured interview approach to enable a free-flowing conversational interviewing style. This method allowed researchers to introduce and explore new ideas based on the interviewee’s responses [22]. It encouraged in-depth discussions and enabled participants to express their opinions and thoughts. The semi-structured interview format also enabled the exploration of knowledge avenues that may not materialize within preliminary surveys/questionnaires or formal interviews [23]. This method is particularly beneficial for understanding the multifaceted requirements involved in creating a HRC system for creative design exploration activities.

3.4. Data Analysis Methods

Due to the qualitative nature of the research data, inductive thematic analysis was employed for analysing and interpreting the patterns within the dataset. According to Braun and Clarke, this approach involves examining the data without predetermined themes or theoretical frameworks [24]. The themes were developed through a systematic and inductive coding, and analysis process.

The data analysis process for this study involved deriving themes by analyzing audio-recorded transcripts and video data. Initial open codes were documented in Microsoft Word, and subsequent refinement phases involved an iterative process leading to the visual clustering of higher-order themes via affinity mapping. In the study results section, the paper presents the key findings derived from the thematic analysis. These insights are reinforced by incorporating relevant quotes from participants around significant themes, providing a nuanced understanding of the research outcomes.

3.5. Design Setup

The co-design workshop was conducted at Advanced Robotics for Manufacturing Hub (ARM Hub), Northgate a research and development organization that Queensland University of Technology (QUT) co-founded. The workshop's primary objective was to gain insights into the design requirements and user preferences to develop an effective AR-enabled HRC system tailored for the fabrication-centric design process.

The co-design workshop focused on the collaborative assembly of a lightweight structure, as an effective and practical demonstration of the benefits of HRC in architectural design. The collaborative assembly tasks showcased how the combined efforts of human dexterity, creativity, robotic strength, and precision can lead to more efficient design exploration processes.

The co-design workshop comprised three key activities, each tailored to address different aspects of the research inquiry. An overview of the main research activities can be seen in

Fig. 1, illustrating the key stages of the co-design workshop.

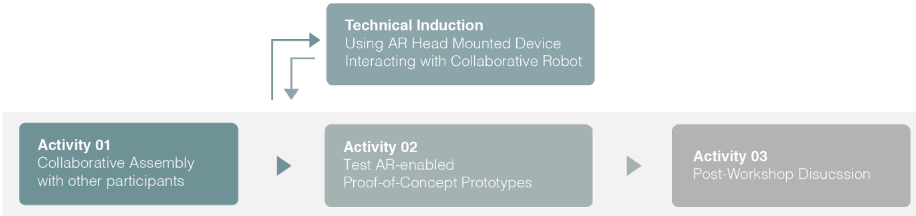

Fig. 1: 4 key stages of the co-design workshop. (1) Activity 01: Collaborative Assembly with other participants; (2) Technical induction; (3) Activity 02: Test AR-enabled Proof-of-Concept; (4) Activity 03: Post-workshop discussion

Fig. 2 illustrates the carefully curated layout setup of the co-design workshop, designed to accommodate different activity needs. The first and last workshop activities were held around a table, fostering a communal atmosphere. On the other hand, the technical induction and activity 2 took place near a workstation and a UR10 collaborative robot.

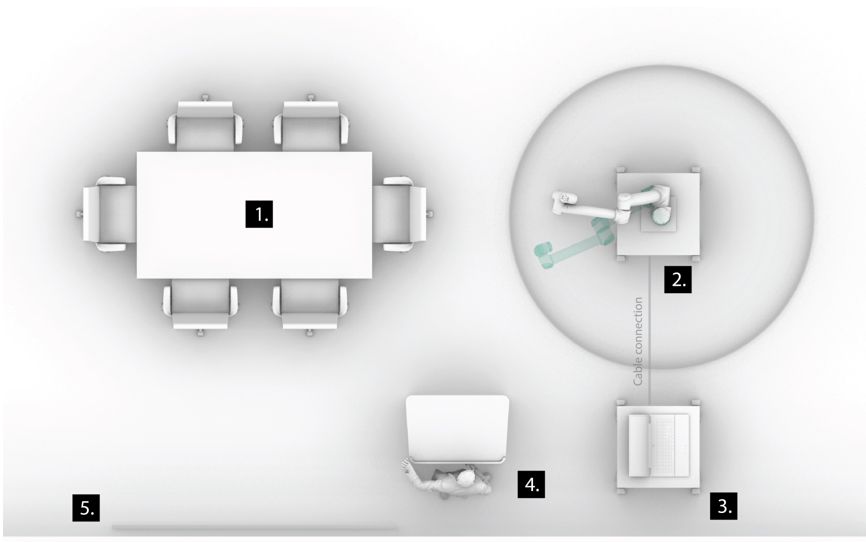

Fig. 2: Co-design workshop – floor plan layout setup. (1) Table for activity 1 and 3. (2) UR10 hosted on aluminum table. (3) Workstation. (4) Podium for project briefing. (5) Project screen.

During activity 2, participants took turns interacting with the UR10 collaborative robot, while the other participants were asked to maintain approximately 1.5 meters from the robot (depicted in Fig. **3**). An additional facilitator managed UR10's controller; teach pendant, throughout the activity to ensure participant safety. The teach pendant featured a red button that allowed the facilitator to terminate the robot movement in case of potential collisions or incidents.

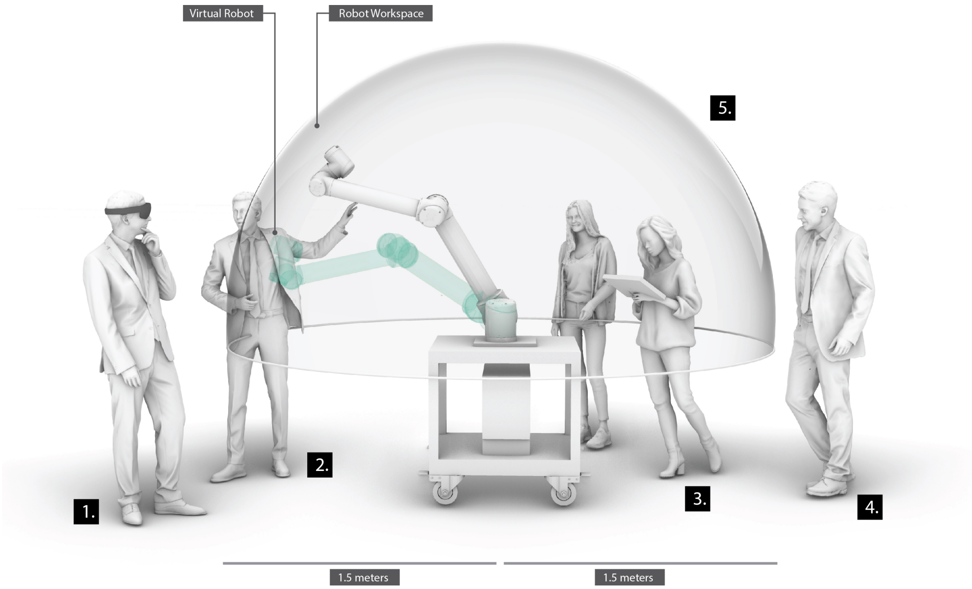

Fig. 3: Physical spatial setup for Activity II. (1) Participant with AR head-mounted display; (2) Workshop facilitator guided participant; (3) Workshop facilitator managed teach pendant; (4) Other participants; (5) Robot workspace

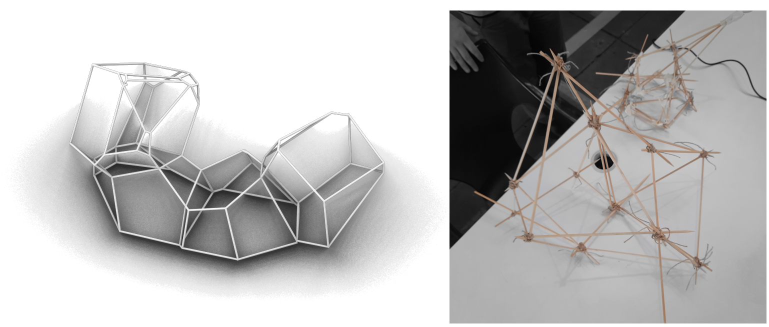

Fig. 4: A reference photograph of a Voronoi structure (left); constructed structure (right).

3.2.1. Activity I. The primary objective of Activity 1 was to stimulate discussions on the significance of physical fabrication in the creative architectural design process through a hands-on activity. The research participants engaged in a collaborative assembly activity, constructing a Voronoi structure (an open-cell lattice structure) using wooden skewers and strings. Although reference photographs were available (refer to

Fig. **4**); participants were encouraged to exercise creativity and were free to deviate from the images provided.

Moreover, the hands-on activity allowed researchers to observe the challenges encountered and strategies employed by architectural designers, offering valuable input for the design of the HRC platform. The artefacts produced during this activity were instrumental in further analysis, allowing for an in-depth investigation into the strategies employed by the designers during collaborative assembly tasks.

3.2.2. Activity II. In the second phase of the research activity, participants took turns testing two proof-of-concept prototypes developed by the research team (shown in

Fig. **5**). The first prototype, "Robot or Puppy Dog", allowed participants to interact with the collaborative robot, UR10, through an AR head-mounted device. The aim was to encourage a positive and cooperative attitude towards collaborative robots, highlighting their potential as helpful partners in various tasks. Inspired by the dynamics of a relationship between a domesticated dog and its owners, this prototype showcased playful interactions, with the UR10 robot following the participant's position in three-dimensional space, like a faithful puppy dog following its owner. Participants could switch between head tracking and hand tracking, enhancing the playful nature of the activity.

Fig. 5: The participants interacted with the "robot or puppy dog" demo with the intention to get acquainted with AR-HRI interfaces.

The second prototype enabled participants to control the configuration of a collaborative robot using simple pinching gestures through an AR interface (illustrated in

Fig. 6). Subsequently, participants used the AR interface to direct the robot to pick up a wooden dowel from their hands and drop it into a basket. This hands-on task provided participants with firsthand experience of controlling and collaborating with the robot through an AR interface, which was particularly valuable for those with limited to no experience with either AR or collaborative robots.

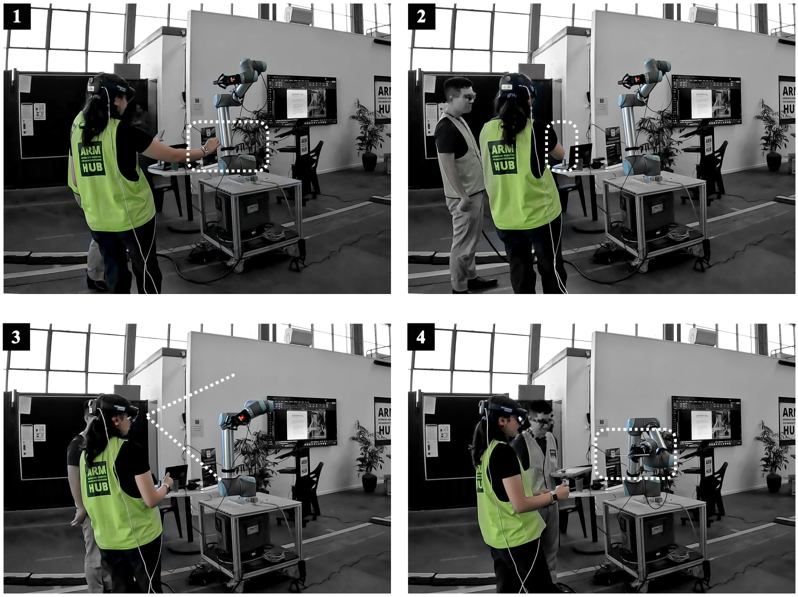

Fig. 6: The participant used the AR interface to direct the robot to the desired location. (1) User established robot waypoint; (2) User used the virtual menu to send robot command; (3) User observed the robot in motion; (4) User confirmed the robot reached the desired robot waypoint.

It's important to note that these prototypes were not final designs but served as a basic proof-of-concept, showcasing potential interactions and visualizations for the eventual design. Throughout this activity, participants explored available interactions, considering how they could be improved or expanded to support exploratory design-fabrication tasks, such as collaborative assembly tasks. The primary goal was to identify usability issues that might arise during participants' interactions with the collaborative robot.

3.2.3. Activity III. After interacting with the proof-of-concept prototypes, participants engaged in a 20-minute guided group discussion to refine the presented interaction methods. This activity allowed the research team to capture participants' initial impressions and usability concerns. In addition, the participants explored ways to enhance the interaction methods demonstrated in the proof-of-concept prototypes. Some participants also used physical reenactment of the interactions to articulate their thought processes. This collaborative effort allowed researchers to glean into the usability of the presented AR-enabled system and identify areas for improvement. Furthermore, it also fostered a deeper understanding of user preferences, and some key considered need to be addressed in order to create an effective AR-enabled HRC system.

During the group discussion, participants were also prompted to discuss the potential implementation of such an HRC system in architectural design processes. The group considered alternative fabrication-centric design tasks that could benefit from the AR-enabled HRC platform. This exploration broadened the scope of potential applications and highlighted the system's versatility in the architectural design field. In addition to envisioning possibilities, the group also examined the challenges associated with integrating such a platform within the current landscape of architectural practice. Addressing these challenges could facilitate an effective integration of AR-enabled HRC systems into real-world architectural workflow.

4 Study Results

The following section summarizes the main findings surrounding design considerations that needed to be considered while developing an AR-enabled HRC system for collaborative assembly tasks. However, some of these design principles can be applied to other fabrication-centric design tasks. The key findings include the need for a unified design-fabrication workflow, a clearer allocation of tasks between designers and robotic arms, the necessity of an intuitive user interface, a streamlined interaction process, a better understanding of robot intention and movement, intuitive procedures for error avoidance and correction, and the need to enhance user safety in HRC scenarios.

4.1 The Need for Unified Design-Fabrication Workflow.

HRC presents an exciting opportunity for architectural designers to construct large-scale physical exploratory models safely with collaborative robots. Despite the evident benefits of HRC, the participating architectural designers think many practices will be hesitant to embrace this approach within the current architectural landscape due to various legitimate challenges.

During the co-design workshop, the participants identified two primary obstacles. Firstly, there were concerns about cost efficiency. Secondly, labor-intensive processes were a significant challenge. **P1** and **P4** highlighted the significant investment in cost and human resources required for physical prototyping throughout the design exploration process. **P1** also explained that the digitization of physical prototypes resulted in additional labor and substantial costs. This process often resulted in an extended design process, creating a bottleneck. Architectural designers found themselves juggling the demands of physical prototyping alongside the imperative task of translating tangible forms into digital representations, a process that requires considerable time and effort. The inherent disconnect between the physical and digital realms often leads to a fragmented workflow, hampering the seamless integration of physical prototyping into the broader architectural design process.

As the workshop participants delved deeper into this issue, the need for a streamlined solution that bridges the gap between physical and digital realms emerged as a critical focal point. The proposition emerged where AR could facilitate the digitization of physical forms while architectural designers explored physical forms with collaborative robotic arms. Such an integrated workflow would not only enhance the overall efficiency of the design process but also alleviate the labor-intensive burden associated with documentation and digitization.

HRC allows architectural designers to design and prototype near collaborative robots safely. The seamless integration of digital capture technology within the HRC process would relieve the staff from manual digitization tasks and enable them to focus on more critical aspects of architectural design. Moreover, this hybrid data capturing approach could also improve the accuracy of the built structure's data capture.

4.2 The Need for a Clearer Allocation of Tasks between Designers and Robotic Arms.

This research aims to explore the dynamics of human-robot teams working towards shared objectives. To understand how to establish an effective human-robot partnership within a collaborative assembly process, the research team conducted a detailed analysis of video footage documenting interactions between participants. By scrutinizing these interactions, the team identified specific behaviors and coordination patterns crucial for successful collaboration.

From the video footage (Fig. 7), it was observed that typically, one participant adopted the role of ‘designer’, tasked with exploring various design options. Meanwhile, the other participants played supporting roles, securing, and holding the wooden dowels together. This division of tasks highlighted a clear distinction of roles that facilitated an efficient workflow.

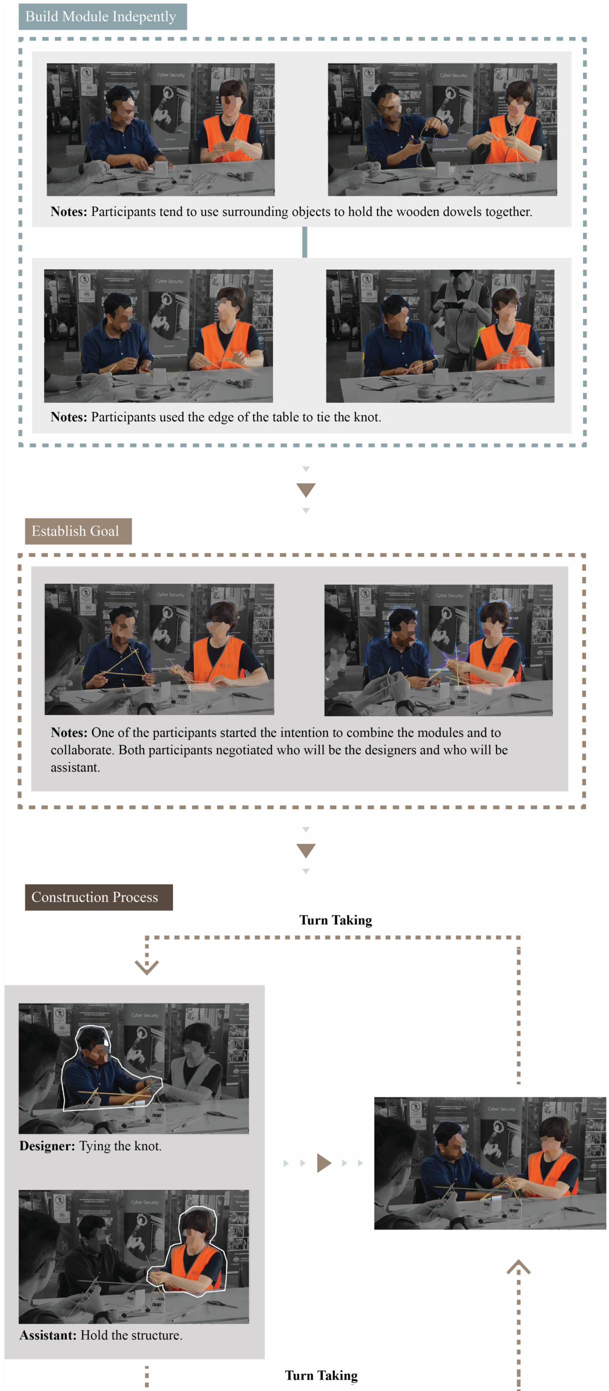

Fig. 7: Video analysis from collaborative assembly exercise.

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Applying these observations to a HRC scenario, the study proposes that robotic arms be tasked with labor-intensive activities. Such a role is well-suited to robotic arms, given their capabilities for endurance and precision in repetitive tasks. On the other hand, designers could focus on tasks requiring dexterity, problem-solving and creative input.

This strategic task allocation not only accentuates the distinct strengths of humans and collaborative robotic arms but also aims to reduce physical strain on designers. By offloading physically demanding tasks to robotic machines, this arrangement reduces the risk of injuries, such as muscle strain, among designers.

4.3 The Necessity of an intuitive User Interface.

As AR remains an emerging research field, it is crucial to investigate how the design of the user interface (UI) affects users' engagement with and perception of the AR environment. Additionally, it is important to further our understanding of UI design, particularly in supporting effective collaboration scenarios between humans and robots.

The presented proof-of-concept prototype employed a menu-based approach, which proved problematic in HRC scenarios, as highlighted during the co-design workshop. The participating architectural designers reported usability challenges, notably the need to frequently open and close the AR menu while moving around within the robot's workspace. The repetitive task was seen as cumbersome, underscoring the need for a more intuitive user interface.

The research team proposed a redesign of the interface to address the concerns. One of the key improvements is to anchor the interface to the user's field of view (FOV), which aims to eliminate the need for frequent adjustments, making the interface more intuitive. In addition, P1 suggested integrating audio feedback to enhance the user experience, making it more immersive and engaging, "the audio cues could confirm interactions, such as button presses, which would improve user confidence and interaction efficiency" (P1).

Another notable issue was the proximity of the buttons within the menu, which led to frequent accidental presses. P2 suggested increasing the spacing between these buttons. Reflecting on this incident, the following UI design iteration will incorporate principles from Fitts's Law to reduce the likelihood of user errors and enhance overall usability.

4.4 The Need for a Streamlined Interaction Process

User cognitive workload emerged as one of the critical factors in the design of HRC systems. A streamlined interaction process not only enhances the system's overall efficiency but also supports effective collaboration between designers and collaborative robots. The proof-of-concept prototype 2 presented during the co-design workshop employed a multi-step approach to manage interactions with the collaborative robotic arms, which participants found mentally demanding. During the guided group discussion, one recurring theme was the need to consolidate this multi-step approach into a single, more intuitive action. **P4** elaborated, "it would be great if there was a way to combine the steps needed to control the robot's grip on the wooden dowels into a single step". **P3** also added that simplifying the interaction reduced the cognitive load on designers and facilitated a more intuitive interaction system.

Additionally, while hand gestures initially dictated the orientation of the gripper, the architectural designers expressed a desire for more precise control over the robot's tool flange. **P2** recommended "incorporating a slider to adjust the rotation of the [mechanical] gripper". Meanwhile, **P1** proposed employing "a machine-learning algorithm to autonomously calculate the rotation value based on the position the [wooden dowels]". These enhancements aimed to provide the designers with finer control over the robotic system, allowing for more precise and efficient collaboration.

4.5 The Need to Better Understand Robot Intention and Movement

Another recurring theme was the need for users to understand the robot's intention and limitations in order to foster an effective HRC. The proof-of-concept prototypes have incorporated several features aimed at assisting architectural designers in comprehending the robot's intention.

One particularly well-received feature was the ability to visualize the robotic arm's path within the AR environment before it performs movements has been proven to be crucial. This functionality allows users to understand the robot's intended actions and movements. Such transparency fosters better coordination and builds trust between architectural designers and robotic arms. P3 also reported that “a clear understanding of the robot's actions would make architectural designers more comfortable and confident in their interactions (P3)”, thus enhancing the collaborative process.

P4 also underscored an additional benefit of visualizing the robot's trajectories: improving situational awareness. By visualizing the robot's potential trajectories, users could better anticipate the robot's movements and identify any potential collisions. P4 added, "This capability can be valuable in scenarios like on-the-fly design-fabrication process, where it could prevent collisions with models" and assist designers in making informed adjustments to the robot's position to mitigate such incidents.

4.6 The Need for Intuitive Procedures in Error Avoidance and Error Correction.

Despite the advantages of collaborative robotics arms, it is vital to understand the limitations inherent within the robotic system. The research team implemented several design strategies to assist participants in comprehending these limitations. Using a virtual dome to represent the shared workspace garnered positive feedback from the participants, successfully allowing them to grasp the robot's operational range. The virtual dome is depicted in
Fig. **8**.

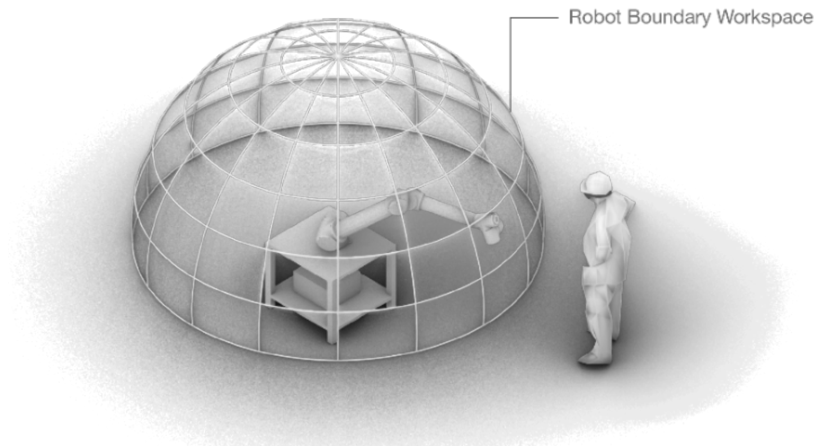

Fig. 8: Virtual dome represented the robot's operational range within the AR environment.

On the other hand, the research team also explored utilizing the AR environment as a notice board to convey essential information, such as robot joints' angles. P1 and P2 expressed although the notification system (seen in
Fig. 9) is well-intentioned, "it lacked clarity in guiding users through mitigating these issues" (P2), such as avoiding robot joint limitations. P1 suggested incorporating visually intuitive error correction elements, such as "directional arrows around the robot's joints, could better inform users about how to correct the robotic error" (P1).

A similar issue arose with the use of colored mesh (seen in
Fig. 9). While effective in creating a sense of urgency, P1, P2, P4, and P5 found the colored mesh is inadequate in communicating specific details that required user attention. This deficiency can be seen in the figure below, where the part of the robot that is about to reach its angular limitation was shown in orange in the AR environment. However, there were "insufficient details to guide users on how to mitigate such issues" (P4). Integrating directional arrows to guide users in error

avoidance would be necessary in assisting architectural designers in making informed decisions in real-time.

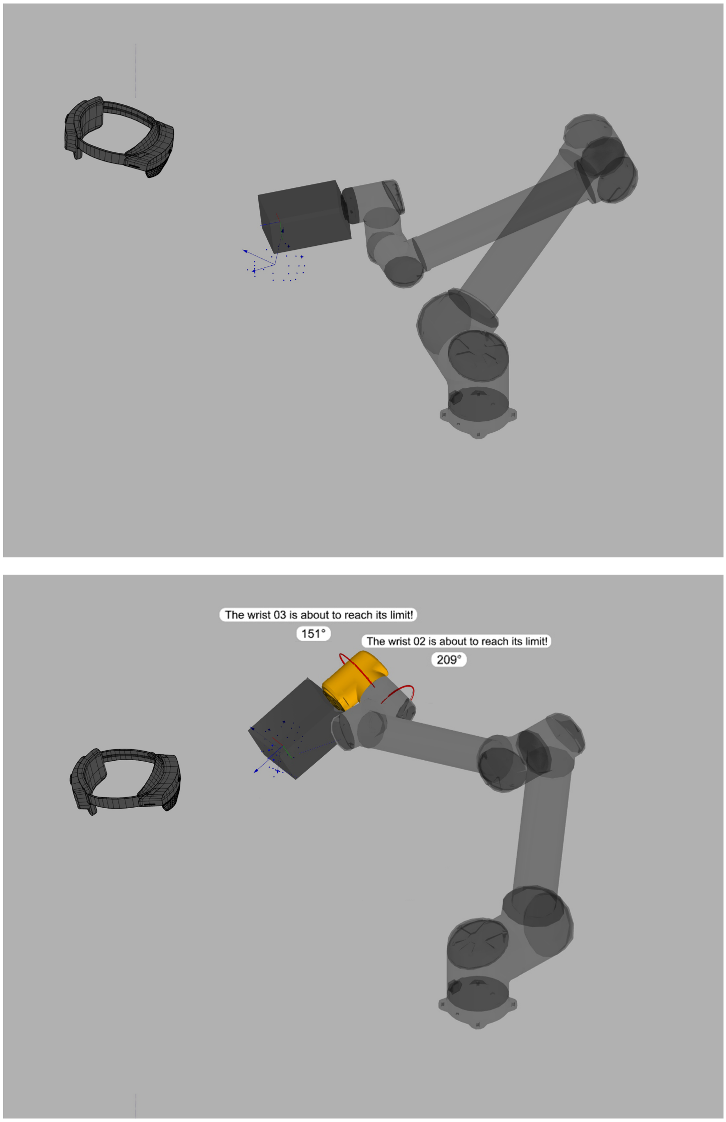

Fig. 9: The screenshots of the program interface during the co-design workshop. (Top) This screenshot shows if the robot doesn't encounter any internal robot limitation. (Bottom) This screenshot shows the robot mesh changed into orange and accompanied text was being used to inform the user the robot joint is about to reach its limitation.

In conclusion, to foster an effective HRC system, it is essential to integrate intuitive procedures for error correction and avoidance. These techniques help users understand how to address potential problems and provide users with critical information that can assist in making informed decisions and minimizing the risk of errors.

4.7 The Need to Enhance User Safety in Human-Robot Collaboration (HRC)

Safety hazards must be considered when working alongside robots, even those designed to work closely with humans. A detailed analysis of user interactions with a robotic arm revealed multiple potential risks. One major concern identified is the risk associated with mechanical gripper, as illustrated in
Fig. 10. The proximity of the mechanical grippers to the participant's fingers greatly increases the risk of accidentally pinching users' fingers during interactions. Thus, it is essential to alert users about this potential hazard and take measures to mitigate the risk. One viable solution is to integrate a notification system within the AR interface to inform users about the status of the gripper.

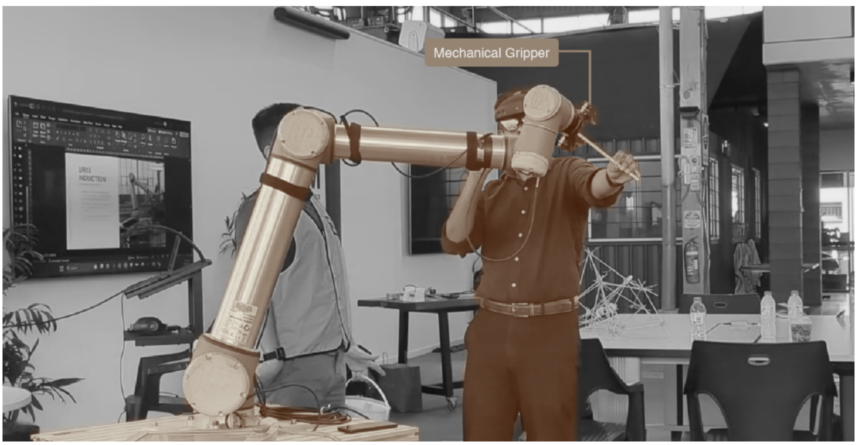

Fig. 10: Video clips of users participated in a "grab and release" procedure using the proof-of-concept 2.

It has been observed that there is specific safety hazards associated with users' behavior when interacting with robots, particularly those without an AR head-mounted display (HMD). These participants exhibited signs of unease and often retreated from the robotic arm, as captured in the video analysis (seen in
Fig. 10). This behavior aligns with findings from Sauppe & Multu [25] and Wurhofer et al. [26], which suggest that human operators rely on visual or audio cues to understand a robot's actions. These cues are essential for ensuring users' safety while they are in close proximity to these robotic machines.

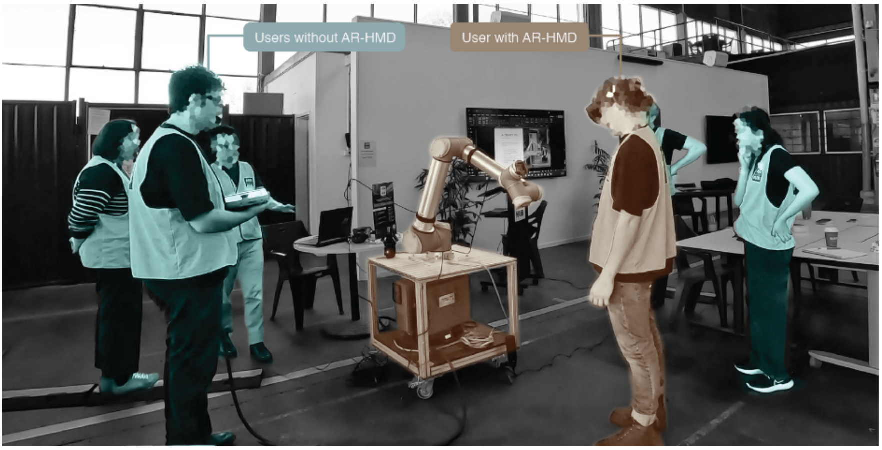

Fig. 11: Users' behavior during interaction with proof-of-concept prototypes. Users with AR-HMD are colored brown; and users without the AR-HMD are colored in teal.

Given that the AR-enabled HRC system will be deployed in a multi-user scenario, it is vital to extend safety measures to those not equipped with the AR devices. One practical approach could be to install programmable LED lights on the robotic arm. These lights can be programmed to change color to indicate different states of the robotic arm, with a green light indicating that the robot is online and red light indicating robot movement. Furthermore, audio cues can be integrated into the system to alert all users in the vicinity when the robot is about to move. Alternatively, those who do not have AR head-mounted displays can use their AR-supported mobile devices to participate in the AR sessions. In summary, establishing a comprehensive safety protocol is needed in order to safeguard users in environments where human-robot interactions occur.

5 Discussion

Based on the literature review, it has been observed that the majority of research on human-robot interaction (HRI) in architectural design fabrication focuses on how robots can be used in customized fabrication [10], [27], [28] However, there are limited publications investigating human-in-the-loop approaches in robotic operations [9], [29]. To continue the investigation of human-in-the-loop approaches in a robotic fabrication setting, this research study adopts a human-centered approach. Specifically, it explores the design requirements that needed to be considered while developing augmented reality (AR)-enabled human-robot collaboration (HRC) for exploratory architectural design-fabrication tasks, such as collaborative assembly tasks.

It is important to highlight that there are some challenges that need to be addressed when studying the potential of these new technologies in facilitating the architectural design-fabrication process. Specifically, there may not be enough design practitioners with the necessary domain expertise and familiarity with the capabilities and limitations of these technologies. To address this challenge, the paper proposes a method involving creating mini mock-up applications with partial functionality to serve as proof-of-concept prototypes. These prototypes not only provide a research context for the participants but also foster discussions on beneficial types of robots or AR interfaces for supporting design practices. It is also important to note that research such as this presents a significant challenge for the research team, because it requires familiarity with the robotic application within architectural design domain, the technology used (collaborative robotic arm and AR), and expertise in interface design and interaction design.

The co-design workshop proved to be an insightful platform for architectural designers to share their ideas and insights about the potential of AR-enabled HRC systems in architectural design practices. The participants pinpointed several design-fabrication processes that could be gained from AR technology, including form-finding with tensile fabric structures, brick layering, and exploring façade designs on a 1:1 scale. However, the current system still requires further development to optimize its functionality and usability. While AR is an emerging technology with significant potential, the UX/UI design in three-dimensional space poses its own set of challenges. Despite these challenges, AR-enabled HRC systems could hold the potential to enhance architectural design practices.

One crucial point that emerged during the co-design study was that there is no one-size-fits-all solution when it comes to designing a solution that supports different architectural design fabrication processes. It is important to identify which architectural design-fabrication tasks can benefit from HRC systems. Identifying these tasks will help researchers develop HRC platforms tailored to the user's needs.

This study points to a number of new research directions. For example, we can utilize the insights from this research to develop a functional AR-enabled HRC platform that could support architectural designers in collaborative assembly procedures. Alternatively, we could conduct similar user-centered design research study to gain a comprehensive understanding regarding how AR could be leveraged to support HRC processes.

6 Conclusion

This paper explored the potential of using collaborative robots and AR technologies to enhance architectural design-fabrication workflows through HRC. Collaborative robots offer a unique opportunity for architectural designers to work collaboratively alongside robots. However, challenges still need to be addressed, particularly in the realm of intuitive interfaces. The development of AR technologies holds great promise for addressing these challenges. AR can blend digital data with the physical environment and holds great potential when coupled with collaborative robots. This setup can enable architectural designers to interact more intuitively and efficiently with robotic assistants.

To fully benefit from AR-enabled HRC in architectural design, meticulous user interface/user experience (UI/UX) design is crucial. The design of the AR interface, human-robot interaction (HRI) protocols and collaborative workflows have significant influence on the success and usability of such systems in architectural design practices. This study takes a significant step toward this goal by gathering insights from architectural practitioners through a co-design approach. It provides a foundation to inform the development of AR-enabled HRC systems for architectural design tasks, outline key design strategies, and suggest directions for future research. Overall, the convergence of collaborative robotics and AR presents a promising trajectory for the future of architectural design, with the potential to influence the way architectural designers work.

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Data Availability. The data that support the findings of this study are available from the corresponding author upon reasonable request. Due to privacy and ethical restrictions, raw data cannot be shared publicly, but anonymized data may be provided under certain conditions.

CRediT author statement. Wei Win Loy: Conceptualization, Methodology, Software, Formal analysis, Investigating, Data curation, Writing – original draft preparation. **Anthony Franze**: Investigating, Writing – review and editing. **Jared Donovan**: Conceptualization, Data curation, Writing – review and editing, Supervision. **Muge Fialho Leandro Alves Teixeira:** Conceptualization, Resources, Writing – review and editing, Supervision. **Matt Adcock:** Conceptualization, Writing – review and editing, Supervision. **Markus Rittenbruch:**

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