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INVESTIGATING THE ROLE OF INTERFACE IN ENHANCING HUMAN-ROBOT COLLABORATION IN DIGITAL FABRICATION FOR ARCHITECTURE

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Abstract

The construction industry is rapidly integrating robotics and digital fabrication into architecture. Incorporating these human-robot collaboration (HRC) systems can improve workflow efficiency and precision. However, challenges remain in task allocation, worker acceptance, and regulatory frameworks. Through a comparative case study, this paper explores the role of the interface between human and machine in shaping the workflow and engagement during an open-ended design processes. The findings identify strategies for implementation during advanced construction techniques, enabling a socially sustainable approach for more efficient and inclusive HRC in construction.

Introduction

In recent years, significant advancements have been made in the field of traditional industrial robots, which have primarily been characterized by pre-programmed, repetitive tasks commonly found in controlled settings. In the construction sector, the integration of human-robot collaboration (HRC) has focused on enhancing productivity, precision, and safety during the fabrication phase but also on adaptability in performing complex construction activities in unstructured environments (Zhang et al., 2023). In the context of human–robot interaction (HRI), the concepts of collaboration and cooperation are differentiated based on the temporal and spatial proximity of humans and robots.

Interfaces are the central element of this evolution. An interface is the primary medium for communication between human operators and robotic systems. In HRC these systems enable coordination and allocation of tasks among different stakeholders and provide a stable exchange of information and perception on the fabrication process. This can be achieved by integrated hardware or software components, such as sensors, controllers, and other additional devices, that convey visual, gestural or voice commands. Given the potential range of opinions on automation and robotics, it is important to emphasize the social acceptability and benefits of these technologies in the built environment. Several studies highlight the importance of interfaces in HRC for construction and digital fabrication in optimizing workflow, logistics, and efficiency while ensuring the well-being of human workers.

However, there are still many open questions regarding the role of interfaces in HRC in construction context. It is not yet clear how interfaces impact workflow efficiency in open-ended design processes and whether certain types of communication systems are more effective than others in supporting interaction methods. Additionally, questions remain about how interfaces influence the levels of agents' engagement and task distribution and to what extent do they facilitate balanced participation of human operators and diverse robotic systems?

To address these gaps, this study aims to evaluate new patterns in HRC for construction purposes, contributing to a deeper understanding of the influence of different modes of communication on the digital fabrication workflow. The study expects that appropriate selection of feedback delivery systems foster more nuanced communication, enabling smoother and more effective interactions between human and robotic agents. User-centric interfaces are likely to foster iterative and exploratory design processes, enabling more flexible and creative approaches to problem-solving. This study anticipates that intuitive interfaces will promote balanced participation by directly impacting engagement levels and task distribution, ensuring that both human and robotic agents can contribute effectively to shared tasks.

Background

Enabling Technology

The interest in intuitive interfaces in human-robot collaboration (HRC) has increased in recent years. Novelties such as augmented/virtual reality, operating by demonstration, audio-visual directives or distance and material sensors are becoming applied also in construction settings. These collaborative modes combine human cognition with machine precision and may lead to improvement in the efficiency of the manufacturing process. In this section, we identify the previously conducted research on the roles and categories of the interface in HRC is introduced, with a particular focus on

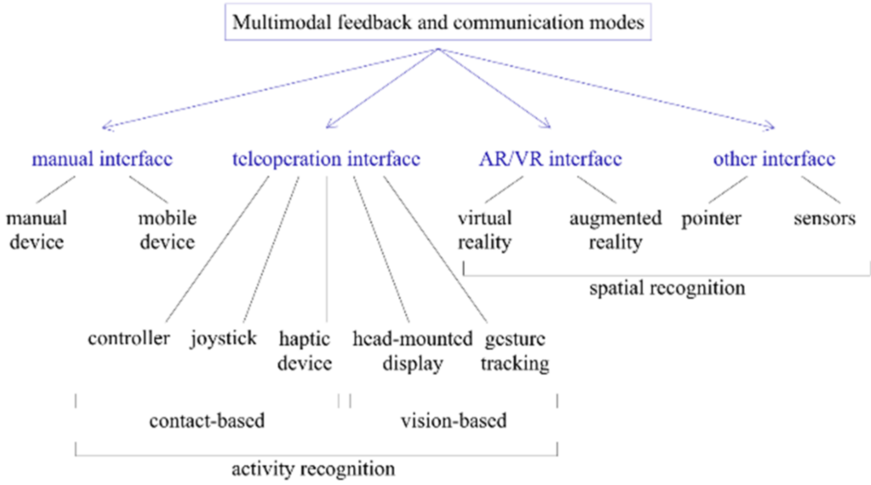

Figure 1: Multiple types of interfaces used in HRC. Based on Mukherjee, et.al., (2022) and Zhang, et.al., (2023)

problems that have not been investigated extensively or are limited to scope beyond the architecture field.

Villani, et al. (2018) provides a comprehensive overview of the challenges, advancements, and applications related to human-robot collaboration in industrial settings, emphasizing safety, intuitive user interfaces, and innovative programming methods as key areas of focus in this domain. The authors provide a comparison between traditional and collaborative industrial robots, the main collaborative modes linked to safety issues, and robot programming methods. These categories are liaised with the communication systems on various levels and might be investigated in the context of a construction setting.

Adaptability Through Continuous Feedback

Human-robot collaboration has evolved from predefined, programmed tasks to more adaptive and cooperative systems. Liang et al. (2021) propose a taxonomy for classifying HRC based on the level of robot autonomy and human effort. Construction robots are now being developed to interact with humans in shared workspaces, including unstructured environments. However seamless coordination in such settings is not yet possible. The robots perform repetitive tasks, allowing designers and operators to concentrate on strategic planning. This trend emphasizes the potential for robots to be more than just tools, but also active collaborators in creative process and decision-making strategies (Liang et al., 2021). Bruun et al. (2020) present the potential of a collaborative framework in which human and robot roles are interchangeable. In this innovative construction approach, robots act as active agents, employing the constraints of path planning and human assessment in real-time design or fabrication processes.

Studies also find that the interface supports management of the workflow, allowing for flexible task allocation, which is particularly important for open-ended design processes. An interface can inform stakeholders of errors, material constraints and enable alterations in design objectives. Parascho et al. (2021) highlights the significance of interfaces that integrate real-time sensor feedback, exemplifying robotic systems using kinematic evaluations and path-planning algorithms. Responsive interfaces, integrating different kinds of feedback, facilitate precise adjustments. Continuous feedback between human and robotic systems support workflow dynamics through exploratory problem-solving, which is crucial for design evolving during the construction process.

Supporting Different Collaboration Modes

In HRC interfaces serve as the primary medium between humans and robots. Recent studies highlight the need for user-centric designs that promote intuitiveness and adaptability in an effective open-ended fabrication process. Intuitive communication impacts the agency of

*Figure 2: Levels of interaction in hybrid fabrication for construction. R = Robot and H = Human. Adapted from Mukherjee, et.al. (2022_*

human and robotic entities, affecting overall efficiency of workflow (Liang et al., 2021). Adaptive interfaces that enable dynamic adjustments with real-time feedback promote balanced participation that not only is essential for maintaining productivity but also for responding to changing requirements or conditions (Bruun et al., 2020).

The mode of collaboration, ranging from co-presence to cooperative task execution, determines the frequency and type of interactions. Real-time adjustments and shared decision-making in direct collaboration in fabrication settings foster a deeper understanding of task dynamics. Studies by Parascho et al. (2018) demonstrate how collaborative modes combine both human intuition and robotic consistency or precision to obtain desired results. Collaborative processes also employ stochastic and bottom-up methodologies.

Challenges, Barriers to Adoption

Despite progress, seamless human-robot collaboration in construction remains a distant destination. Current systems require advancements to handle challenges related to real-time adaptability and intuitive interaction. The complexity of task allocation and coordination between different agents, stakeholder coordination along with lack of standardized regulatory frameworks cause hardships in successful integration of robots into construction workflows. Besides technological, regulatory or management issues, adoption of robotic systems in the construction industry is also contingent on social acceptance. Concerns about usability and job displacement often lead human workers to resist new technologies. In order to overcome these obstacles and address these barriers, it is important to design interfaces that are user-friendly, transparent, and accessible to users with different levels of expertise (Liang et al., 2021). Future interface development should be based on the introduction of collaborative ways of working, based on traditional workflows, to support inclusivity. In addition to user-friendly features, it is essential to reinforce adaptability of these systems. With adaptive systems, algorithms and robots may predict users' needs and preferences, adjust to them and consequently assist in building trust and acceptance among professionals. In addition, advanced technologies, such as augmented reality (AR) and machine learning, can improve the interactivity and predictive capabilities of interfaces.

Methodology

A literature review was the starting point for the research. Compiled information enabled to select the most relevant case studies for the research topic. These cases were identified through a database search. The projects represent diverse collaboration modes, allowing for comparison of interface design, task distribution, and human-robot interaction. The study examines and compares three case studies to gain deeper insights on the influence of different types of interfaces on communication between humans and machines, in particular collaborative robots. Their assessment provides the information about how the applied tools impact engagement levels and task distribution, fostering balanced participation and exploratory design processes. Subsequently, 12 interviews with researchers and practitioners involved in analysed projects offer valuable knowledge on their experience and perception on collaboration. The data obtained from 3 interviews with experts specialised in work design patterns in construction management, additionally contextualises the findings. This methodology provides a comprehensive insight into human-robot collaboration patterns, the establishment of interoperable standards, and the practical implications of HRC.

Case Selection Criteria

Numerous studies have explored the integration of various interfaces in HRC for diverse fabrication

Table 1: Case Selection Criteria

Project Name	Construction Technology	Interaction and Feedback Mode	Roles and Physical Proximity	Numer of Interviews
Tie-a-Knot	Iterative adjustments of knotting joints and components positioning	Audio-visual system	Team of 2 humans (peers) and 2 robots (collaborators) work within the same physical space (laboratory setting) on the same task within predefined grammar, having equal contribution in project execution;	3
Interactive Robotic Plastering	Plastering incorporating adaptability to surface variation	Hand-held display	Team of 3 humans (instructors) define fabrication flow, 1 robot (executor) performs along displayed patterns, working in the same physical space (laboratory setting) on independent tasks	3
Autonomous Dry-Stone Wall Construction	Material selection, context-adaptive placement, lifting, and stacking	Material and environment sensing	Human team (goal-setters) supervises construction process (on-site) and intervene when needed, allowing 1 robot (executor) to operate remotely and execute tasks autonomously	3

Figure 3: Pictures showing fabrication process in:
a) Tie-a-Knot (Mitterberger, et.al., 2022a), (b) IRoP (Mitterberger, et.al., 2022b), (c) Autonomous Dry Stone Wall Construction (Johns, et.al., 2020)

purposes. However, there remains a significant research gap in examining the role of these interfaces in shaping the collaborative process, particularly through comparative analysis.

Both control variables and variable factors are used in the analysis to ensure consistency and comparability across three case studies (see Table 1 for case selection criteria). Incorporated control variables include project execution timeframe, limited to 2020-2023, carried out at ETH, Switzerland in collaboration National Centre of Competence in Research (NCCR). To ensure comprehensive HRC in construction analysis, variable factors were taken into consideration. These include task typologies, which influence distinct interaction methods, and environmental parameters, distinguishing between controlled and uncontrolled sites. Interaction modes address adopted interfaces, feedback systems, as well as, spatial and temporal proximity in interaction.

Based on established criteria, there were three projects chosen for the case study analysis: Tie-a-Knot, Interactive Robotic Plastering, and Autonomous Dry Stone Wall Construction.

Analysis Framework

The participant interviews were recorded, transcribed, and studied, incorporating hybrid thematic analysis approach, combining deductive and inductive coding. The initial coding scheme was based on predefined categories informed by prior research and our research questions. However, it remained open to emerging themes, allowing the coding structure to adapt as new insights surfaced from the data. Coding scheme include, among others, aspects related to interface, distinguishing between types of modes, decision support, adaptability, and influence on communication. Another key term that was taken into account was open-ended design process. Exemplary codes include points liaised with fabrication cycle, task allocation or frequency of interaction. Other codes used adress issues relevant for construction management strategies, work design, roles of participants and their agency.

Case Overview

Tie-a-Knot

Tie-a-Knot presents an experimental study that introduces a novel human-robot cooperative work flow for assembling a complex wooden structure with rope joints. The system involves a dually augmented human-robot team facilitated by a shared digital-physical workspace. The cooperative assembly cycle consists of interactive design, robotic assembly, manual assembly, rope jointing, and tracking of elements. The system setup includes a computer with a CAD design environment, a mobile AR app, and a robotic unit, all connected via a ROS publish and-subscribe architecture and the rosbridge package. The hardware setup consists of two 6-DoF co-operative robotic arms with custom 3D-printed pneumatic grippers, and a mobile AR device. The project was tested and validated by producing a proof-of-concept prototypical architectural structure over a period of 5 days, demonstrating the potential for a hybrid human-robot team to open new avenues for digital fabrication in architecture (Mitterberger, et.al., 2022).

Interactive Robotic Plastering

The Interactive Robotic Plastering (IRoP) system is designed for robotic and computational applications in architecture, engineering, and construction (AEC). The system targets both designers and skilled workers, aiming to simplify the programming of robotic fabrication and make it accessible to users with limited robotic programming experience. The system combines interactive design tools, an augmented reality interface, and a robotic spraying setup to enable intuitive on-site robotic plastering. The project presents the results of two user-studies involving designers and skilled workers, demonstrating the feasibility and usability of the IRoP system. The studies show that the system was well-received, effective, and user-friendly, with potential for real-world applications. On the other hand, authors discuss the limitations of the system and propose future improvements, such as extending collaboration possibilities between skilled workers and off-site designers, implementing a fully mobile robotic setup, and addressing the limitations of the projected augmented reality system (Mitterberger, et.al., 2022).

Autonomous Dry-Stone Wall Construction

The autonomous dry stone project focuses on the on-site robotic construction of large-scale dry stone walls using a customised autonomous hydraulic excavator. The project aims to leverage context-specific, locally sourced materials that are inexpensive, abundant, and low in embodied energy. The process involves the use of LiDAR sensors for terrain map ping, stone localization, and digitization, and a planning algorithm to determine the placement position of each stone. The interface involves a highly customised Menzi Muck M545 12t walking excavator equipped with force-controllable hydraulic cylinders, inertial measurement units, and global navigation satellite system antennas. The process also includes geometric planning software for stone selection, positioning, and orienting, and LiDAR-based scene mapping for planning grasp configurations and arm motions. The project demonstrates the applicability of automated stone masonry for future construction processes and aims to reactivate irregular stone construction while enabling new modes of design expression and large-scale fabrication (Johns, et.al., 2020).

Cross-Case Findings

Interface Adaptiveness as a Determinant of Workflow Efficiency

Open-ended workflows benefit and are reliable on adaptable interfaces that may enhance user interaction, mitigate errors, and facilitate construction processes. As stated by one of participants "the line between design and production blurs" in experimental settings. Preprogrammed workflows often limit creativity unless interfaces allow dynamic adaptation. Systems constrained by rigid programming result in standardized outcomes, emphasizing the need for adjustable interfaces to specific tasks or skills. A successful interface must serve as an entry point for users to interact dynamically which enhances mutual understanding between humans and robots. As one of the socio-economic researchers noted, the challenge lies in designing interfaces that avoid miscommunication while allowing fluid, non-stop interaction. To increase user acceptance and decrease resistance to robotic systems, it's crucial to overcome these barriers.

Across case studies, interfaces used appears to be a crucial factor in shaping efficiency of the process. The researcher involved in Tie-a-Knot project pointed out that adopted iterative design, where "each fabrication step already includes one design iteration," allows for real-time adjustments during the process. This approach aligns with the observation that preprogrammed workflows limit creativity and emphasizes the value of flexible interfaces that may adapt to unforeseen issues. Augmented reality (AR) interfaces, adopted in Tie-a-Knot case, supported this principle by providing real-time tracking of elements. This solution allows fabrication process participants to adjust and verify positions directly within the physical workspace. Similarly, in the Interactive Robotic Plastering (IRoP) project, projection-based augmented reality (AR) allowed users to visualize and modify robotic trajectories as part of an iterative workflow. Another participant emphasized that "preplanned rules for translation of human actions" were essential to maintain consistent fabrication and simultaneously accommodate user involvement. In addition, another researcher involved in the project mentioned that "the malleable and unpredictable character of the material" demanded on-site design adjustments. This highlights the importance of selection of systems that could dynamically respond to real-time material behaviour and tool performance. In the Autonomous Dry Stone Wall Construction project the need for interfaces that allow real-time adjustments and system that allows dynamic problem-solving was highlighted by one of researchers, who emphasized that "you can't pre-plan an entire stone wall". It highlights that unpredictable factors like stone irregularities or environmental changes must be detected with the system. Integrated real-time visualization tools, enabled to see updates to the digital twin of the wall as stones were placed. One of experts noted that algorithms can eliminate a lot of the choices available in complex workflows, maintaining the optimal cognitive load management. By providing tools for regulating variables or specifying the scale of work zones, the project demonstrated how respective systems support efficiency. These findings show that adaptive communication modes are essential for responding to construction constraints in real time, ensuring continuous workflow functionality and enabling effective human-robot collaboration.

Effective Real-Time Feedback

Seamless communication between humans and robots is key to effective collaboration. Interfaces that reduce lag between action and outcome, supported by real-time feedback, significantly enhance trust and general usability in analysed case studies. Collaborative modes, such as human intervention during errors, also rely significantly on clear feedback systems to facilitate task allocation and reduce confusion. Scenarios involving robots relying on human creativity to eliminate uncertainties highlight the need for direct and prompt feedback mechanisms. This aligns with the statement of the work design expert that uncertainty arising from material or organizational factors can be effectively managed through human-robot interaction

In Tie-a-Knot, AR visualizations guided users on where to place elements, considering computational analyses of structural stability. The IRoP project relied on interfaces that provided immediate feedback to support task allocation. The researcher involved described the process as requiring design decisions on the fly, particularly after each cycle of plaster spraying. Next trajectory was determined after scanning with a depth camera to ensure alignment of the following operation with the previous segment. The researcher involved in the Autonomous Dry Stone Wall Construction project stressed the importance of real-time feedback in the project, describing the system as a series of state transitions where each phase - scanning, driving, and placing stones- was inspected for errors or inconsistencies before moving forward and proceeding with another cycle. This approach coincides with the work design expert's observation that clear feedback systems are essential for promoting collaborative modes. In addition, another researcher points out that robots must not only communicate but also seek human affirmation before executing critical decisions to ensure oversight and accountability.

Effective feedback may enhance precision and prevent errors. In the Autonomous Dry Stone Wall Construction project, as noted by one participant, visualization tools enabled users to "see in real time what the robot is seeing" and intervene promptly when needed. This reduced time lag in turn enabled operators to make well-informed decisions, preventing errors including collisions or misplacement. The use of AR and mobile interfaces in Tie-a-Knot facilitated task allocation and progress tracking. This supports assertion that systems must allow humans to "translate their intuitions, actions, and intentions into the digital model and be at the same time instructed by the digital model." The researcher participating in the IRoP plastering process mentioned that the system can point back to the user to signal errors or necessary adjustments, which aligns with the finding that workflow was determined by the feedback loops between the systems. Another participant pointed out that projection-based AR provided operators with an intuitive understanding of actions. Apart from visual information, feedback was also provided with audio guidance, both participants suggested that this system, initially planned to just support operations, significantly enhanced understanding of responses and communication, however it still requires enhancements for improved two-way interaction and error resolution. These findings highlight the benefits of using interfaces that reduce cognitive load, allowing to focus on creative decision-making while maintaining oversight and accountability.

Agency and Role of Interface in Communication

Interfaces are the basis of dynamic interaction and control during digital fabrication processes. They must balance machine autonomy with human oversight, as articulated by one of the experts: "Robotic systems should act autonomously to an extent but must seek positive affirmation from humans before proceeding with significant actions". This assertion underlines that the capacity of feedback systems to adapt to errors not only affects the continuity of the workflow, but also increases acceptance of and trust in robotic devices.

Integration of AR interface and computational model may facilitate balancing autonomy and human oversight, as it is demonstrated in both, Tie-a-Knot and Interactive Robotic Plastering projects. In the first one, embedding task distribution within the computational model, enabled humans to make design adjustments without disrupting robotic operations, ensuring that robots operate as "intelligent tools" rather than autonomous entities, as stated by the participant. Projection-based AR system used in IRoP enabled operators to visualize their design intentions directly on the wall. One of the participants described the system as a tool that allowed users to "design and decide on-site, on the spot, on the fly,” combining digital and physical conditions.

Interface systems may also support users in verifying and validating the robot's decisions and intervening when required, as it was in Autonomous Dry Stone Wall Construction project. As HRC was more robust than purely autonomous systems, the researcher involved emphasized the role of visual tools in allowing users to monitor the optimization of stone placements. the interface showed the point cloud of how these stones were being pulled into alignment. However, another participant mentioned a need for adaptability, stating that "replanning the position of the stone without having to stop the robot" would improve efficiency.

This insights suggest that aspects related to support for coping, time and predictability have potential to be facilitated by adequate interface. As stated by one of the researchers, "ideal setup" would allow systems to

Table 2: Considerations in Human-Robot Collaboration (HRC) Interfaces

Category	Factors in HRC Interfaces	Important Aspects
Interface Usability	Dynamic adaptation to conditions	Flexible adaptation to changes in the construction environment, materials and systems during the process
	Operation within preprogrammed rules	Grammar for procedures reduces the set of choices, streamlining the fabrication process
Effective Real-Time Feedback	Integrated feedback systems	Real-time feedback improves task allocation and reduces the lag between performance and result
	Progress tracking	The interface supports an intuitive understanding of the construction process, bringing subsequent operations in line with previous actions
Communication Mode	Balanced autonomy and oversight	Robotic systems perform with a degree of autonomy, while requiring human confirmation before a task is executed
	Translation of agents' intentions	Visualising the goals for creation allows for an overview of the trajectory of individual participants
Skill Adaptation and Accessibility	Multimodal feedback	The combination of several feedback systems reduces cognitive load, aids concentration and improves communication between human and robot
	Alignment with existing workflows	Familiar working practices support engagement and accessibility for users of different backgrounds, fostering wider adoption of HRC systems

seamlessly translate human intentions into precise outcomes, improving result accuracy.

Engagement, Skill Adaptation, Accessibility, and Inclusion

Intuitive design elements, such as multimodal feedback (e.g., color cues, haptic, and acoustic signals), enhance user engagement and accessibility by leveraging faster cognitive processing pathways. While language processing relies on the neocortex and can be slower, visual, auditory, and tactile cues allow for more immediate, intuitive responses. This is particularly relevant in construction environments, where quick decision-making and accessibility across diverse user groups are crucial. Rather than assuming universal symbols, effective interface design must prioritize adaptive and context-aware communication strategies that align with human perceptual strengths. The IRoP case, for example, prioritized accessibility by avoiding complex tools like head-mounted displays, which, as noted by one participant, could reduce interaction with the real wall. Instead, the system employed projection-based AR and gesture-based controls, offering a more direct and intuitive form of interaction. Similarly, in Tie-a-Knot, accessibility is prioritized by choosing mobile phones as the primary interface. This decision facilitated broader usability, accommodating users who might be unfamiliar with complex AR systems. This emphasizes the need of developing interfaces that are easily understood by non-experts, observed by one of the interviewees. This approach leads to more widespread adoption across industries, including construction branches, which bridges the gap between traditional and modern workflows. The Autonomous Dry Stone Wall Construction project prioritized engagement and accessibility mainly through visual tools, the researcher noted that the interface included features like sliders and checkboxes for adjusting parameters, allowing users to tailor workflows to site-specific conditions. However, another participant critiqued the system's reliance on used middleware, which limited accessibility to experts.

One of the experts observed that users prefer systems that retain familiar modes of communication and physical interaction. Interface applied in IRoP allowed users can draw directly on the wall, keeping the interface in line with traditional plastering techniques. Moreover, the system's reliance on combined tactile, auditory and visual feedback addresses the practical needs of construction workers, providing usability at a range of skill levels. The researcher involved in the plastering process supported this approach, noting that intuitive tools that align with existing workflows encourage broader adoption of robotic systems. In Tie-a-Knot case craft-specific user interfaces aligned with existing workflows. In the project, AR visualizations incorporated parameters like stability and robot reachability, presenting information in a way that complemented users' skills while introducing modern tools.

Engaging interfaces help users stay oriented. Tie-a-Knot and IRoP projects integrated multimodal feedback, as one of the researchers suggested, combining visual AR cues with additional auditory signals to maintain user focus in dynamic construction environments. The incorporation of multimodal feedback, such as audio cues, reduced cognitive workload and enhanced accessibility. However, participants of the projects emphasized the need for improving the integration of different feedback systems to facilitate two-way communication and reduce stress or frustration during error handling.

Discussion

Task Specific Adjustments

The results indicate that interfaces must be tailored and adaptable to particular fabrication tasks. This aligns with literature that highlights the need for interfaces that correspond to traditional workflows while incorporating digital enhancements (Liang et al., 2021; Parascho et al., 2018). Robotic agents complement human expertise rather than replace it. Therefore, the translation of participants intentions to computational logic is crucial in maintaining effective assembly cycle and reduce error rate.

For instance, in Tie-a-Knot, integrating augmented reality with mobile connection allowed for iterative fabrication cycles, including adjusting the project within the grammar of constrains. Similarly, in Autonomous Dry Stone Wall Construction project, interface supported decision-making processes and selection of particular components through responsive visual representation.

A considerable challenge in the implementation of HRC systems is to guarantee accessibility for a range of user groups. As Scholz (2003) mentioned, trust and adoption of robotic systems is established through the principles of transparency and user control. Following the principle of inclusivity may support smoother transition from traditional construction practices to hybrid fabrication methods. This emphasises the need for consideration of different levels of expertise in applied systems. As observed in IRoP and Tie-a-Knot, AR display enhanced the intuitive perception on real-time state of the project, reducing cognitive load.

Multimodal Feedback

Current research emphasise that real-time feedback is crucial component of adaptive interfaces. As highlighted in this study, fabrication environment control in real-time builds trust, which aligns with existing research of Bruun (2020) on importance of inclusivity and incorporation of human-centric design principles in robotic systems. Interfaces that incorporate real-time visual, auditory, and haptic signals enhance engagement of users, simultaneously taking into account different preferences of users. The study identified that immediate and clear feedback mechanisms are crucial components of effective task allocation in HRC. Several integrated feedback systems support dynamic adjustment of workflows in open-ended construction processes. AR-based scanning technique applied in IRoP project reinforced real-time corrections according to previous operations in each plastering. Likewise, Tie-a-Knot's integrated AR guidance with audio information to enhance transferring activities between humans and robots, ensuring stability of construction. In the Autonomous Dry Stone Wall Construction project, human operators were informed about necessity to intervene by visualisation and confirmation of the robot's selections.

Conclusion

This study demonstrates the potential of adequately selected interfaces in fostering fabrication in HRC systems. The findings suggest that interfaces should not only facilitate project execution but also mediate responses human and robotic agents, which consequently offer oversight on the performed actions. Nevertheless, to facilitate wider adoption of HRC technologies it is crucial to align this technology with traditional construction techniques, as well as, improve regulatory frameworks on automation. Issues related to support for coping, time and predictability in open-ended design processes may be resolved with well-designed communication mode, however, these areas require further exploration. Future advancements in interface design should also consider scalability and enhancement in their adaptation. The case studies were conducted in controlled environments, thus the responsiveness to larger unstructured sites still remains unresolved.

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