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HUMAN-ROBOT COLLABORATION IN CONSTRUCTION: TOWARDS SHARED AUTHORSHIP IN DIGITAL FABRICATION FOR ARCHITECTURE

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Abstract

The integration of automation and robotics in construction can address critical challenges such as safety hazards, inefficiencies, and cost overruns. This paper explores the evolving role of human-robot collaboration (HRC) in digital fabrication for architecture (DFAB). With a focus on robotic agency and shared authorship, three case studies—Interactive Robotic Plastering, Tie-a-Knot, and Autonomous Dry Stone Wall Construction—are analyzed to examine dynamic workflows, varying levels of robotic autonomy, and the implications of collaboration across different task phases. The findings contribute to a framework for construction practices that merge human intuition with robotic precision, enabling both efficiency and adaptability.

Introduction

The integration of automation and robotics into the construction industry presents a transformative opportunity to address persistent challenges related to safety, efficiency, and productivity. Traditionally, construction has been one of the most hazardous industries, accounting for 30–40% of work-related fatalities globally, despite employing only around 7% of the workforce (Lingard, 2013). At the same time, the industry suffers from chronic inefficiencies; according to the Global Construction Survey (KPMG, 2015), only 25% of projects between 2012 and 2014 were delivered within 10% of their original deadlines.

Automation and robotics can mitigate these issues by reducing physical strain, increasing precision, and improving safety (Maeda et al., 2004; Saidi et al., 2008; Taylor et al., 2003). However, fully autonomous systems raise complex social, economic, and technical concerns. As a more flexible alternative, Human-Robot Collaboration (HRC) integrates human expertise with robotic capabilities in shared, adaptive workflows—offering a pragmatic approach to construction automation. Human-robot collaboration (HRC) in construction can be defined as the dynamic integration of human expertise and robotic capabilities in shared environments, where construction goals are achieved through co-design and collaboration in both physical and virtual spaces (Yang et al., 2024). A key area where HRC is transforming construction is digital fabrication (DFAB). Unlike traditional construction, where design, material processing, and fabrication are typically separated into sequential phases, DFAB merges these stages into a continuous, computationally-driven process. This integration allows fabrication to be directly informed by digital design models, enabling the production of complex geometries and optimized material usage that conventional methods often cannot support. Robots in DFAB do not merely automate repetitive tasks—they execute highly specific, data-driven operations that translate algorithmic designs into non-standard physical forms. Moreover, by embedding fabrication constraints into the design logic, DFAB facilitates the construction of intricate, customized structures with reduced waste and error.

Understanding robotic agency—the capacity of robots to make autonomous yet context-sensitive decisions—is crucial to ensuring that automation enhances rather than disrupts construction workflows, particularly when aligning with human expertise in iterative and design-led processes. Without a clear framework for shared decision-making, uncertainties in authority, responsibility, and trust may lead to inefficiencies, delays, or safety risks. Poorly structured robotic agency can further exacerbate disjointed workflows instead of improving them. To prevent these challenges, HRC must be integrated through structured, human-centered strategies that balance automation with human oversight. Ongoing evaluation and refinement are essential to maintaining efficiency, trust, and adaptability in construction environments. This study addresses existing gaps by exploring how robotic agency, trust, and authority-responsibility dynamics impact effective human-robot collaboration (HRC) in digital fabrication (DFAB). It introduces a comparative framework that evaluates robotic agency beyond task execution—considering its adaptability, integration into architectural workflows, and the evolving roles of stakeholders. The findings offer insights to guide future HRC frameworks that balance automation with human expertise and enhance efficiency in DFAB contexts. The study is guided by the central research question: *"How can robotic agency in digital fabrication* *for architecture be understood?"* To address this, the research is structured around three sub-questions:

1. How can robotic agency in digital fabrication for architecture be defined and categorized?
2. What are the implications of shared authorship in human-in-the-loop construction processes within digital fabrication for architecture?
3. To what extent does robotic agency affect the roles and responsibilities of stakeholders, and what broader implications does it have on construction management?

To explore these questions, the study will investigate three case studies: [1] Interactive Robotic Plastering (IRoP), [2] Tie-a-Knot, and [3] Autonomous Dry Stone Wall construction. Through a comparative case study methodology, the project aims to enrich understanding of robotic agency within architectural digital fabrication. It will particularly scrutinize how robotic agency impacts collaborative design processes, shared authorship roles, and broader construction management practices.

Background

Human-Robot Collaboration (HRC) in construction enhances productivity, safety, and trust by integrating human expertise with robotic precision. Unlike fully autonomous systems, HRC prioritizes adaptability, enabling dynamic task allocation between humans and robots in response to complex and unpredictable construction environments (Yang et al., 2024). Existing research underscores the criticality of active human involvement for the successful integration of robotics in construction. Shayesteh and Jebelli (2020) demonstrated that HRC fosters greater worker trust compared to Human-Out-The-Loop (HOTL) approaches, reinforcing the significance of collaboration in augmenting acceptance and usability.

Historically, construction robots functioned as passive executors of predefined tasks. However, contemporary frameworks advocate for a “design-as-you-build” paradigm, facilitating real-time adjustments through advanced path-planning algorithms (Wang et al., 2021). Case studies in manufacturing demonstrate the viability of adaptive human-robot task-sharing, such as load handling and welding through RGB-D sensors and learning algorithms (Shayesteh & Jebelli, 2020). Further research is needed to enhance real-time adaptability in construction, ensuring robots can effectively respond to unpredictable conditions, directly contributing to defining robotic agency in digital fabrication.

However, while HRC is increasingly common in structured factory settings, its translation to digital fabrication for architecture (DFAB) remains underexplored in both theoretical and practical dimensions. The structured classification of Human-Robot Collaboration (HRC) is imperative for advancing collaborative construction methodologies. Various taxonomies categorize interaction levels, task allocation, and decision-making hierarchies. Kopp et al. (2021) delineate a spectrum of HRC activities, ranging from full automation to active human-robot collaboration, while Yanco (2004) integrates insights from Human-Computer Interaction (HCI) to define team composition and decision support mechanisms.

Yang et al. (2024) propose an integrative framework combining automation taxonomies, worker interviews, and timber prefabrication parameters to refine HRC classification. While timber-focused, it advances DFAB broadly, offering insights for diverse construction contexts. Their findings suggest that function allocation within HRC is highly context-dependent, with some frameworks prioritizing automation while others emphasize human expertise in decision-making processes. Addressing these variations is crucial for refining classification systems that accommodate diverse construction scenarios. Despite the proliferation of these classification frameworks, significant gaps persist in comprehending robotic agency and the extent to which robots can function as independent yet cooperative entities in construction.

This paper addresses this knowledge gap by developing a comparative lens for evaluating how robotic agency manifests across distinct DFAB use cases. It highlights under-examined dimensions such as material-driven decision-making, co-located interaction modalities, and shared authorship in construction workflows.

The complexity of teamwork structures in human-robot collaboration in construction necessitates a nuanced understanding of coordination dynamics. Van Diggelen and Johnson (2019) categorize teamwork patterns into direct work (contributing to goal achievement), indirect work (enhancing team efficiency), and off-task work (unrelated to task execution). These classifications align with prior distinctions between taskwork and teamwork (Fisher, 2014). Different collaboration models—such as joint work, supervisory models, and teleoperation—underscore the pivotal role of communication in fostering adaptability and coordination. Further research should investigate how different HRC classifications impact the structure of roles and responsibilities among stakeholders, directly addressing the implications for construction management.

Methodology

This study employs a comparative case study methodology to examine human-robot collaboration (HRC) in architectural digital fabrication. Conducted in partnership with the National Centre of Competence in Research (NCCR) Digital Fabrication at ETH Zurich (ETHZ), the research ensures a consistent technological and methodological foundation while exploring diverse HRC strategies. Focusing on three case studies—Interactive Robotic Plastering (IRoP), Tie-a-Knot, and Autonomous Dry Stone Wall Construction—it investigates varying levels of human-robot interaction, from assisted fabrication to autonomous material placement. These cases highlight the balance between structured indoor environments and material-driven workflows, emphasizing how automation complements rather than replaces human expertise.

A total of twelve interviews were conducted for this research: three per case study on human-robot collaboration in digital fabrication and three with socio-economic researchers on work design. These interviews, along with a comparative analysis of robotic integration methods, provide insights into task allocation, safety considerations, and stakeholder interactions.

Overview Case Studies

1) Interactive Robotic Plastering (IRoP): The IRoP project explores human-robot collaboration in plastering through an interactive, adaptive system (Mitterberger et al., 2022a). The robot interprets user demonstrations and executes plastering tasks with minimal explicit programming, allowing for an intuitive and flexible workflow. A hand-held visual display interface enables real-time human input, ensuring a dynamic interplay between human intuition and robotic precision (Mitterberger et al., 2022a; Jenny et al., 2022). One of its key capabilities is continuous scanning and adaptation to surface variations, making it integral to adaptive plastering. While the robot enhances precision and consistency, humans remain essential for interpreting material behaviors, refining application techniques, and managing unexpected variations.

Figure 1: IRoP, interactive robotic plastering system (Mitterberger et al., 2022a).

[2] Tie-a-Knot: The Tie-a-Knot project explores robotic collaboration in manual joining processes, where a robot assists humans in tying wooden elements together using ropes (Mitterberger et al., 2022b). The system employs audio-visual directives and real-time feedback, enabling the robot to refine its construction skills through interaction. The robot's learning capabilities evolve through collaborative experiences, contributing to a dynamic and cooperative workflow. The open-ended design allows for continuous refinement, ensuring that both human and robotic contributions shape the construction process.

Figure 2: Tie-a-Knot (Mitterberger et al., 2022b).

3) Autonomous Dry-Stone Wall Construction: The Autonomous Dry-Stone Wall Construction project explores robotic assembly in unstructured environments with heterogeneous materials (Mascaro et al., 2020). The robot demonstrates high operational autonomy, utilizing advanced sensors and heuristic-based planning to autonomously select, place, and stabilize stones without mortar, adapting to irregular material properties (Jud, 2021). While the system is capable of material-driven decision-making, human oversight remains essential for strategic planning, quality control, and adapting to unforeseen challenges. The open-ended design fosters continuous improvement, demonstrating how human-robot collaboration can push the boundaries of autonomous construction while maintaining the flexibility required for real-world conditions.

Figure 3: Autonomous Dry Stone Wall Construction (Johns et al., 2020)

Analytical Framework

Table 1 presents a comparative overview of the three case studies, highlighting architectural methods, material properties, settings, and the roles of humans and robots in task allocation. To systematically assess Human-Robot Collaboration (HRC) across diverse construction environments, this study adopts a structured framework inspired by Yang et al. (2024) and Tang. This framework is guided by four key research questions, ensuring a comprehensive evaluation of HRC effectiveness in various construction settings.

Table 1: Criteria for Selection Case Studies

System Name	DFAB construction task	Human-Robot Ratio	Autonomous Dry Stone Wall Construction
Interactive Robotic Plastering	Plastering incorporating adaptability to surface variation	3:1 (3 humans, 1 robot)	Laboratory
Tie-a-Knot	Iterative adjustments of knotting joints and components positioning	2:2 (equal human-robot ratio)	Laboratory
Autonomous Dry Stone Wall Construction	Material selection, context-adaptive placement, lifting and stacking	1+ (offsite humans: 1 robot)	On-site (robot) & off-site (humans)

First, "What do humans and robots build together?" This involves analyzing construction typologies, material properties, and fabrication strategies while also considering connection methods, assembly techniques, and project scale. Second, "How does each actor contribute?" The study defines human and robotic roles, exploring task allocation principles and autonomy levels. Humans typically handle creative decision-making, problem-solving, and supervision, while robots focus on precision tasks such as material handling, manipulation, and heuristic-based planning. Third, "How do they work together?" This question examines interaction modes, workflow integration, and the effectiveness of human-machine interfaces. It includes spatial and temporal proximity considerations, distinguishing between co-located synchronous, co-located asynchronous, and non-co-located collaboration models. Additionally, task coordination strategies, planning approaches (offsite, onsite, or hybrid), and interface design elements—such as haptic controls, augmented reality (AR) guidance, visual displays, and tactile feedback—are analyzed to assess usability and interaction efficiency. Finally, "What does the system achieve?" The study evaluates efficiency, safety, material adaptability, and overall workflow improvements. It also considers human factors such as user experience, cognitive workload, and productivity gains, aiming to identify best practices for optimizing HRC benefits while minimizing challenges.

Results

Findings by Case Study

Table 2 presents a comparative analysis of three case studies, outlining the roles of humans and robots, task allocation principles, interaction dynamics, decision support mechanisms, and physical proximity in Human-Robot Collaboration (HRC) across different construction settings.

Interactive Robotic Plastering (IRoP) involved the use of robotic systems to automate the application of plaster in construction. The process required significant human oversight due to the variability in material behaviour and site conditions. One participant highlighted the challenge of maintaining accuracy in rapidly changing material states, requiring continuous human intervention to adjust robotic operations. Humans were responsible for design decisions and material preparation, while robots executed precise spraying. However, when inconsistencies arose, manual corrections were necessary to maintain quality. A participant described how "monitoring robotic systems required juggling multiple software interfaces simultaneously," emphasizing the cognitive demands of such workflows.

Additionally, IRoP demonstrated the potential for human-machine synergy, as workers adapted workflows in real time. The system allowed iterative modifications during execution, moving away from traditional "design freezes." This flexibility was particularly crucial when material inconsistencies occurred, requiring immediate human adjustments. The case also revealed how edge-case decision-making relied on human judgment, bridging gaps where algorithmic solutions were insufficient.

One participant explained that in IRoP, human expertise was crucial for determining the optimal thickness and coverage of plaster. "The robot could spray uniformly, but only humans could assess the surface texture and environmental conditions to make final refinements," they noted. This interplay between robotic precision and human contextual awareness was fundamental to ensuring high-quality results. Another participant highlighted the limitations in sensor responsiveness, saying, "The robot sometimes failed to detect slight variations in surface consistency, which meant we had to step in frequently to adjust the settings on the fly."

The *Tie-a-Knot* project focused on robotic construction of tensile structures, where robots iteratively constructed knots while humans managed on-site adjustments. This case highlighted the balance between automation and human dexterity, as robots stabilized structures while humans handled complex assembly tasks. One participant explained how "robots performed repetitive tie-making operations efficiently, but humans had to step in for intricate adjustments," demonstrating the complementary nature of HRC.

Despite the system's efficiency in handling repetitive tasks, the absence of structural feedback limited robotic autonomy. This resulted in situations where humans needed to manually verify and refine placements, ensuring stability. The iterative process allowed for a turn-taking approach, where robots constructed foundational elements while humans intervened for intricate refinements. Participants noted that real-time collaboration required a high degree of adaptability, as robotic precision often clashed with unpredictable material behaviors.

One participant emphasized that the process required human oversight to prevent structural failures. "The robot could tighten knots, but humans had to make constant adjustments to maintain balance and tension," they

Table 2: Comparative Overview of Human-Robot Collaboration (HRC) in Construction Case Studies

System Name	Human-Robot Role Allocation	Task Allocation Principle	Interaction Roles	Decision Support for Operators	Human-Robot Physical Proximity
Interactive Robotic Plastering	Human Instructor, Robot Executor	Leftover Allocation: Robots perform structured tasks; humans adjust details	Human as Instructor: Defining robot operation & material flow	Audio-visual directives	Collocated: Humans and robots work in the same space in real time
Tie-a-Knot	Human Peer, Robot Collaborator	Knowledge & Creativity Allocation: Humans define patterns and robots execute	Human as Peer: Equally contributing with robots in real-time	Hand-held visual display	Collocated: Humans and robots are in the same physical space, but work on independent tasks
Autonomous Dry Stone Wall Construction	Human Supervisor, Robot Worker	Error Correction & Takeover: Humans intervene in material tolerances	Human as Goal-Setter: Setting large-scale objectives, allowing the robot to execute autonomously	Robot-material sensing	Non-Collocated: Robot operates remotely while humans supervise

explained. Another participant described an instance where unexpected material behavior disrupted the workflow: "We realized mid-process that the knots were slipping under stress, and we had to intervene to reinforce them before continuing." This highlights the dynamic problem-solving necessary in such HRC applications.

The *Autonomous Dry Stone Construction* project explored how robotic systems assisted in dry stone wall construction, an inherently complex task due to the irregularity of natural stones. Participants reported that while robots optimized stone placement strategies, they lacked the ability to handle unforeseen conditions, such as stones breaking or terrain irregularities. "Achieving full autonomy would require perfect submillimeter scans of every stone," explained one participant, highlighting the current limitations of robotic adaptability. The team had to make real-time adjustments, often incorporating larger stones to accelerate construction and manually guiding robots over uneven ground. These interventions illustrated the necessity of human involvement in overcoming practical constraints. The project also revealed that while robots excelled at executing predefined constraints, they struggled with adaptive problem-solving, reinforcing the importance of human oversight in HRC workflows.

One participant described how human decision-making was essential when dealing with unstable surfaces: "The robot would place the stones according to its algorithm, but sometimes the fit wasn't right due to micro-fractures. We had to manually rearrange and recalibrate." Another participant recounted a critical moment when robot navigation faltered: "The terrain was too uneven, so we had to guide the robot manually across rough patches to prevent misalignment." These experiences underscore the role of human adaptability in maintaining workflow efficiency.

Cross-Case Study Analysis

Task Allocation and Coordination

Across the three cases, task allocation was shaped by each system's ability to respond to material and environmental variability. In IRoP, the robot's close interaction with malleable, time-sensitive plaster required continuous human oversight to interpret textures and make real-time corrections, due to limited contextual awareness and feedback.

In Tie-a-Knot, collaboration appeared more balanced—as the sequential, modular task enabled predictable turn-taking. This structure reduced cognitive load and allowed humans to intervene only when necessary, with task allocation shaped by process rhythm and spatial clarity. Dry stone wall construction, by contrast, involved irregular materials and uneven terrain that exceeded the robot's sensing and planning capabilities, requiring frequent human intervention. Overall, task allocation followed a clear pattern: the more stable and structured the material and environment, the more predictable and shared the collaboration. These findings suggest that collaboration modes depend less on automation levels and more on the robot's ability to integrate with the material and environmental logic of the task.

Degrees of Agency in HRC Systems

Across the three case studies—IRoP, Tie-a-Knot, and Dry Stone Wall Construction—agency within human-robot collaboration (HRC) systems emerged not as a linear scale of autonomy, but as a situationally distributed dynamic, shaped by the nature of the task, material variability, and environmental unpredictability. The analysis focuses on how decision-making, execution, and adaptation were shared—or shifted—between human and robotic actors throughout the workflow.

In all cases, robots operated primarily as reactive agents—capable of executing precise, predefined actions but lacking situational awareness and contextual judgment. As one IRoP participant explained, "Robots can handle the technical precision, but they still lack situational awareness—something that remains entirely human-driven." This limitation was even more pronounced in the dry stone wall case, where another participant noted, "No matter how optimized the algorithm is, there are always new, unforeseen challenges where human intuition is irreplaceable."

Across the three case studies, the balance of human vs. robotic agency varies significantly—ranging from highly manual adjustments in dry stone wall construction to more predictable role-allocation in Tie-a-Knot. Figure 4 illustrates these differences, mapping human and robot contributions across key construction phases including design, execution, and adaptation by analyzing task distribution, system capabilities, and human oversight based on the interviews. The estimated percentages highlight shared authorship dynamics based on robots' autonomy versus human intervention.

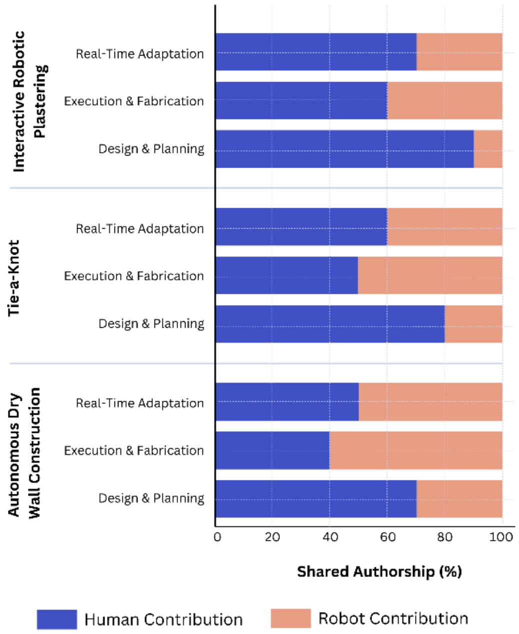

Figure 4: Comparison of human and robot contributions across different construction tasks across different Human-Robot Collaboration (HRC) systems.

Cognitive Load and Supervisory Challenges

Managing robotic workflows introduced cognitive demands, especially in IRoP, where multiple software interfaces had to be navigated simultaneously. Tie-a-Knot required continuous monitoring to ensure precise assembly, while dry stone wall construction necessitated real-time decision-making to address material variability. Participants highlighted the need for more intuitive interfaces to reduce cognitive burden and streamline supervisory tasks.

A participant from IRoP noted, "We needed to toggle between multiple monitoring screens, which made quick interventions challenging." Another participant working on Tie-a-Knot mentioned, "Even though the process was semi-automated, I still had to be fully engaged, as the robot required step-by-step validation."

Figure 5 illustrates the relationship between cognitive and physical effort in different HRC settings, showing how full human effort demands the highest physical workload, while fully automated processes require significant cognitive oversight. The trade-offs between automation levels highlight the need to balance automation with human intervention for optimal safety and efficiency. This mapping, based on qualitative insights from expert interviews, reflects perceived task complexity, mental workload, and oversight requirements across varying levels of automation, offering a comparative perspective on shared authorship in construction workflows.

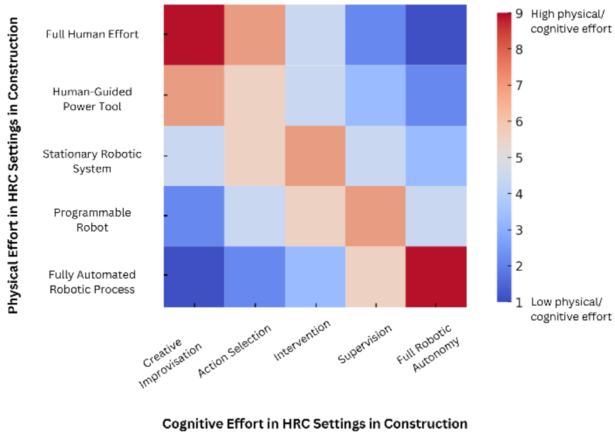

Figure 5: Matrix mapping task complexity vs. cognitive demand, balancing human expertise and robotic automation in construction. High scale = high effort, low scale = lower effort.

Discussion

This study examined human-robot collaboration (HRC) in digital fabrication for architecture, focusing on robotic agency, shared authorship, and evolving stakeholder roles. Through three case studies—Interactive Robotic Plastering (IRoP), Tie-a-Knot, and Autonomous Dry Stone Wall Construction—the research explored varying levels of robotic autonomy and their implications for construction workflows. Findings indicate that robotic agency operates on a spectrum, balancing human oversight with automation: IRoP functions as a precision tool under human control, Tie-a-Knot demonstrates real-time co-adaptation, and Dry Stone Wall Construction exhibits greater robotic independence while still requiring human input. These findings align with Yang et al. (2024), emphasizing the need for adaptable function allocation tailored to specific contexts. This study extends prior work by focusing not only on classification but also on the emergent dynamics of shared authorship and human-robot role negotiation in open-ended architectural workflows.

Building on prior HRC classifications (Kopp et al., 2021; Yang et al., 2024), this study highlights how shared authorship fosters material-responsive workflows that integrate computational precision with human intuition. Unlike traditional construction robotics that follow rigid task execution (Wang et al., 2021), the findings align with a “design-as-you-build” paradigm, enabling real-time adjustments through adaptive robotic systems. However, scaling such systems beyond controlled environments presents technical, economic, and regulatory barriers that must be addressed to enable broader adoption. From a technical perspective, the complexity of unstructured environments requires improvements in real-time sensing, AI-driven decision-making, and adaptive human-robot interfaces to handle unpredictable material behaviors (Shayesteh & Jebelli, 2020). The study contributes a new evaluative framework for robotic agency that includes not only autonomy levels but also the quality of human-robot interaction, shared decision-making, and material adaptivity. This approach allows stakeholders to assess HRC systems beyond functional performance and consider their embeddedness in architectural and construction logic. Beyond refining HRC models, this research underscores the shift from rigid "design freezes" to more flexible, iterative workflows. This aligns with Van Diggelen and Johnson's (2019) categorization of teamwork dynamics, emphasizing the need for improved communication between human and robotic agents.

Regulatory and ethical considerations further complicate scalability. While existing safety measures improve interaction (You et al., 2015; Brosque et al., 2020), current liability frameworks and building codes are not yet fully adapted to accommodate semi-autonomous robotic systems. The absence of standardized guidelines for human-robot task allocation and risk management presents obstacles to large-scale implementation. Addressing these issues will be critical to ensuring automation enhances rather than disrupts human-centered construction workflows.

Moving forward, the focus should be on improving human-machine synergy by simplifying control interfaces, enhancing robotic adaptability, and refining task allocation strategies. Future developments should prioritize flexibility, allowing robots to respond dynamically to site-specific challenges while maintaining efficiency and precision. Moreover, as workforce transformations accelerate, strengthening worker trust in HRC systems through targeted upskilling and vocational training programs (Shayesteh & Jebelli, 2020) will be key to ensuring broader acceptance. By addressing these challenges, HRC can move beyond automation tools to become truly collaborative systems, driving construction innovation in diverse contexts.

Conclusions

The integration of automation and robotics in construction is transforming traditional workflows by introducing adaptive human-robot collaboration (HRC) models. This study highlights the evolving role of robotic agency, emphasizing that automation should enhance rather than replace human expertise. By examining three case studies, the research underscores the importance of shared authorship, real-time adaptability, and intuitive human-machine interfaces in digital fabrication for architecture.

Findings indicate that HRC enables more efficient and safer construction practices by dynamically distributing tasks between humans and robots based on expertise, material variability, and environmental conditions. However, challenges remain, particularly in mitigating cognitive load and designing interfaces that facilitate seamless human-robot interaction. The shift towards more flexible construction processes necessitates new management strategies that embrace iterative design-production cycles and interdisciplinary collaboration. By articulating how shared authorship emerges in different HRC configurations, this study provides actionable insights for designers, engineers, and policymakers working to integrate robotics into construction in a way that is both efficient and collaborative.

Looking ahead, the continued refinement of HRC frameworks will play a crucial role in advancing automation in construction. Future research should focus on enhancing interface usability, and exploring scalable implementations of HRC systems across different construction environments. Ultimately, human-robot collaboration represents a promising pathway toward more innovative, efficient, and resilient construction methodologies that align with both technological advancements and human-centric design principles.

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