

Towards Heterogeneity in Collective Robotic Construction

Material Hand-Offs within a Team of Climbing and Aerial Robots

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Abstract. *Collective Robotic Construction (CRC) systems have demonstrated how robotic agents can work in parallel to build large scale structures, yet most implementations rely on homogeneous platforms and inherit their inherent limitations. This paper explores heterogeneous collaboration between aerial and ground-based robots, focusing on material handoff as a fundamental mechanism for coordination. A custom aerial robot is employed for rapid delivery of timber struts, while a modular climbing robotic system performs precise placement. Two primary handoff strategies, direct and indirect, are examined, with indirect handoff further differentiated by levels of coordination. Physical experiments evaluate the positional accuracy and stability of the aerial robot to assess feasibility across these strategies. By framing material handoff as a design variable, the study highlights how heterogeneous teams can distribute capabilities across complementary workspaces and support emerging workflows in architectural robotic construction.*

Keywords. *Collective Robotic Construction, Heterogeneous Robotic Systems, Aerial Construction, Material Handoff, Architectural Robotics.*

INTRODUCTION

Collective Robotic Construction (CRC) has emerged as a promising paradigm for increasing efficiency, sustainability and scalability in automated building processes by leveraging parallelism across multiple robotic agents (Petersen et al., 2019). Previous work has demonstrated how teams of robots can assemble structures from discrete elements, enabling distributed fabrication and redundancy within construction systems. Notable examples include aerial robots assembling masonry units (Augugliaro et al., 2014) and climbing robots collaboratively constructing spatial lattice structures

(Smith et al., 2025). While these approaches highlight the benefits of coordinated multi-robot systems, they also expose limitations that arise from reliance on a single robotic platform.

Aerial robots offer rapid material transport and global accessibility across a construction site, but they remain constrained by limited payload capacity and reduced positional accuracy during precise placement tasks. In contrast, climbing or ground-based robotic systems can achieve high placement precision and leverage partially constructed structures for locomotion, yet they often suffer from inefficient material

transport, particularly as structures grow in scale. These complementary strengths and weaknesses suggest that heterogeneous robotic teams may offer a pathway toward more effective construction systems by distributing tasks according to platform-specific capabilities as proven in other contexts (Dorigo et al., 2013).

Despite growing interest in heterogeneous multi-robot systems, interaction strategies between different robotic platforms in CRC remain underexplored. In particular, the coordination required for exchanging building materials between agents introduces challenges related to spatial accuracy, timing, and communication. This exchange, referred to in this paper as material handoff, represents a fundamental act of collaboration within heterogeneous robotic construction. The way in which materials are transferred between robots directly influences coordination requirements, spatial accuracy, and the degree of coupling between robots.

This paper investigates material handoff strategies within a heterogeneous CRC system composed of an aerial robot for rapid material

delivery and a ground-based modular climbing robotic system for precise placement. Rather than focusing on a specific construction outcome, the work examines how different handoff mechanisms structure collaboration between robots operating across complementary workspaces. Two primary categories of material handoff are explored: indirect handoff, in which materials are deposited in a shared workspace for later retrieval, and direct handoff, involving synchronized exchange between agents. Within indirect handoff, varying levels of coordination are considered, ranging from pre-planned drop-off locations to request-based delivery initiated by the receiving robot. Figure 1 illustrates the envisioned collaborative construction scenario, in which an aerial robot delivers timber elements to a climbing robotic system assembling a truss-like structure.

Through conceptual comparison and physical experiments focused on aerial robot performance, the study evaluates how spatial accuracy and positional stability influence the feasibility of different handoff strategies. By framing material handoff as a design variable in

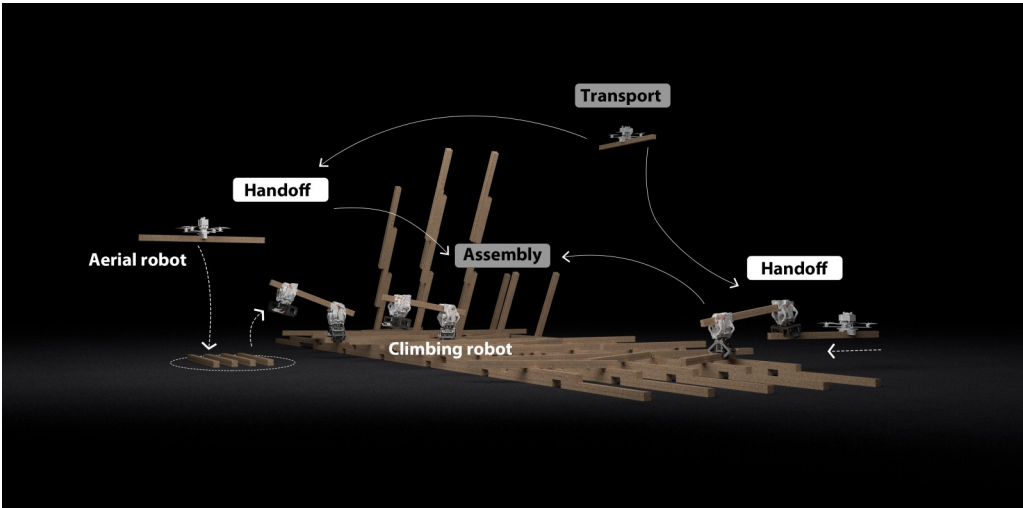


Figure 1
Conceptual
scenario of
heterogeneous
CRC, showing aerial
delivery, material
handoff, and
climbing-robot
assembly within a
shared timber
construction
workflow.

heterogeneous robotic construction, this work contributes to the development of collaborative workflows in which aerial and ground-based robotic agents operate as complementary participants in the construction process.

The contributions of this paper are threefold: (1) the definition and classification of material handoff strategies for heterogeneous CRC systems; (2) the development of a heterogeneous robotic setup enabling aerial delivery and ground-based placement; (3) an experimental evaluation of aerial robot performance relevant to different handoff coordination requirements.

STATE OF THE ART

Heterogeneous Robotic Teams in Construction

Research in the automation of construction has explored heterogeneous fabrication systems composed of task-specific robotic agents operating collaboratively. Research on fabrication machine species proposed catalogs of specialized mobile robots designed to carry, manipulate, anchor, and pass filament material, demonstrating how heterogeneous robotic “species” can expand fabrication capabilities beyond single-platform approaches (Yablonina and Menges, 2018). Similarly, the Minibuilders project developed a family of small mobile construction robots, each responsible for different phases of fabrication and coordinated through a shared control framework to 3D print structures (IAAC, 2016). These systems distribute construction roles, but mainly focus on continuous material deposition.

At larger scales, heterogeneous multi-robot systems have been explored for building-scale fabrication of timber structures. A multi-scalar robotic system for timber construction combined a clamping device, industrial robotic arm, and automated crane, enabling coordinated assembly of multi-storey timber structures through integrated workflows across different robotic

entities (Opgenorth et al., 2024). Additional research on timber assembly introduced a clamp to operate in collaboration with an industrial robotic arm (Leung et al. 2021). In contrast to filament-based approaches, these systems operate on discrete structural components, yet still rely on tightly coupled workflows with predefined task boundaries. The explicit transfer of individual building elements between mobile robotic agents operating in separate spatial domains remains largely unexplored. This gap motivates the investigation of material handoff strategies for discrete building elements presented in this work.

Aerial Robots for Construction

Early aerial construction research focused on proof-of-concept assembly with flying platforms. Examples include beam-and-column assembly (Lindsey et al., 2012) and foam brick towers (Augugliaro et al., 2014). The core contribution of these early studies was to establish that drones could serve not only as platforms for sensing and transport, but also as active agents in component-level construction, thus opening up the research direction of aerial construction.

Later work expanded aerial robots toward 3D printing (Zhang et al., 2022), bridge construction (Xie et al., 2025), and vision-guided bricklaying (Xie et al., 2025). These developments suggest that aerial robots are evolving from flying construction carriers into fabrication platforms capable of executing specific construction processes. Accordingly, the focus of research has also shifted from basic flight feasibility toward questions of trajectory control, process stability, and near-field manipulation.

However, viewed through the trajectory of existing research, the primary focus of aerial construction has remained on enhancing the construction capability of the aerial platform itself, while comparatively little attention has been paid to situating aerial robots within broader heterogeneous robotic workflows. In response to this gap, the present paper does not treat the

aerial robot as an autonomous and self-sufficient construction agent, but instead situates it within a heterogeneous collective robotic construction system, focusing specifically on the problem of material handoff that emerges when the aerial robot operates as a high-mobility material delivery agent.

SYSTEM OVERVIEW

For this research, we investigate collaboration within a heterogeneous robotic team composed of an aerial robot and a modular climbing robotic system (Samuel et al., 2022). The two platforms are assigned complementary roles: the aerial robot operates across the construction workspace to transport timber struts, while the climbing robot performs precise positioning and assembly within the growing structure. This division of tasks reflects the complementary capabilities typically observed in aerial-ground robotic teams, where agents operate in different spatial domains and contribute to the assembly of a spatial structure made from timber struts.

Their interaction centers on exchanging linear timber elements, requiring spatial alignment, timing, and workflow coordination.

Aerial Robot

In this study, an aerial robot is employed as the material transport platform within the heterogeneous construction system. Its role is to rapidly deliver linear timber elements across the workspace and transfer them to regions accessible to the climbing robotic system. Rather than assembling, it acts as a mobile carrier supporting later fine manipulation by the ground robot.

The platform is a custom-built quadrotor with a 23 cm wheelbase and 7-inch propellers, weighing 1.7 kg. Its propulsion system can generate about 5.45 kg of total thrust at 60% throttle, enabling the indoor transport of single timber elements. Through a custom gripping mechanism that mechanically locks into a predefined groove on the timber strut, the drone can stably grasp linear timber elements.

With external pose feedback provided by a motion capture system, the platform is capable of position-controlled flight and stable hovering for material handoff operations, supporting both target-zone delivery and aerial exchange scenarios. However, compared to climbing robots that are structurally attached, the aerial platform remains more susceptible to disturbances during contact-rich and high-precision alignment tasks. As such, its performance boundaries form a critical basis for the subsequent experimental evaluation of material handoff strategies.

Modular Climbing Robotic System

The ground-based robotic system consists of small mobile actuators that climb and manipulate timber struts by forming reconfigurable kinematic chains with the building material (Samuel et al., 2022). Each robotic actuator grips timber elements, allowing the robots to use the building material and structure itself for locomotion and manipulation. The timber struts act simultaneously as building material and as part of the robot's kinematic system, enabling distributed assembly of structures larger than the individual robots. The robotic actuators also have an effector that allow for them to screw timber elements together (Samuel et al., 2024).

In the most recent iteration of the system (Blinded, 2026), the robotic actuators were extended to enable spatial assembly through the integration of an actively controlled tilting mechanism in the upper gripper. This addition introduced a second rotational degree of freedom, allowing the robots to position timber elements at varying spatial orientations and transition between structural layers. The mechanism enables inter-strut angles of maximum 60°, supporting the autonomous construction of 3D truss-like assemblies.

MATERIAL HANDOFF STRATEGIES

Material handoff defines how building elements are exchanged between heterogeneous robotic agents operating in different spatial domains. The

chosen handoff strategy influences coordination requirements, spatial accuracy, and the degree of coupling between robots. In this work, two primary categories are considered: direct handoff, in which robots transfer a timber element directly to one another, and indirect handoff, where the aerial robot deposits material for later retrieval by the climbing robot. These strategies represent different levels of temporal and spatial coordination and structure the collaborative workflow between the robotic platforms.

The following subsections describe each type of handoff and a summary comparing the different types is in Figure 2 and Table 1.

Strategy 1: Direct Handoff

In a direct handoff strategy, the aerial robot transfers a timber element directly to the climbing robot through a synchronized exchange. Both robots must align spatially while maintaining temporal coordination, such that the climbing robot can grasp

the element as it is held by the aerial platform. This approach minimizes intermediate storage and reduces the need for additional locomotion by the climbing robot, but requires stable positioning of the aerial robot and precise alignment between the two agents. Physical interaction occurs as both robots briefly share control of the same timber element during the transfer. Direct handoff therefore represents the highest level of coupling between agents and places strong demands on positional accuracy and coordination timing.

Strategy 2: Indirect Handoff

In an indirect handoff strategy, the aerial robot deposits the timber element at an intermediate location from which the climbing robot retrieves it independently. This decouples the actions of the two robots in time, allowing asynchronous operation and reducing the need for precise alignment during transfer. Two variants of indirect handoff are considered. In a pre-planned approach, the drop-off

Figure 2
Comparison of
direct and indirect
handoff strategies.

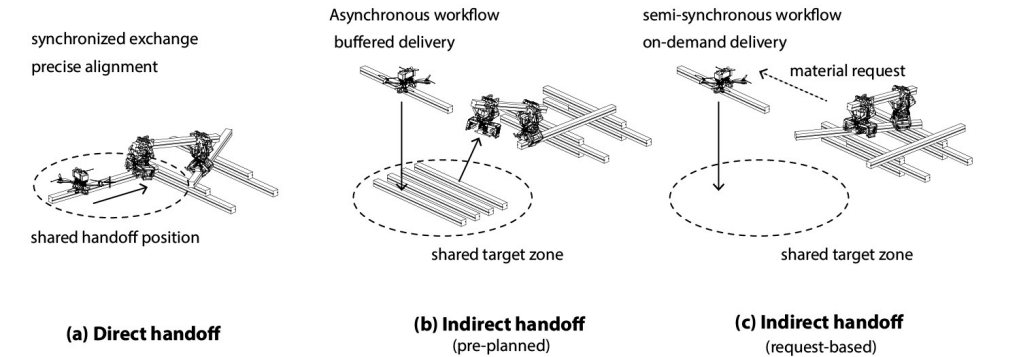


Table 1
Comparison of
direct and indirect
handoff strategies.

	Coordination Level	Spatial Accuracy Requirement	Temporal Coupling
Direct Handoff	High	High	Synchronous
Indirect Handoff (Pre-planned)	Low	Medium	Asynchronous
Indirect Handoff (Request-based)	Medium	Medium-High	Semi-Synchronous

location is defined in advance, and the aerial robot delivers material to a shared workspace accessible to the climbing robot. Alternatively, a request-based approach allows the climbing robot to specify a desired delivery location based on the current construction state, enabling adaptive and potentially emergent workflows. While indirect handoff reduces coordination requirements compared to direct exchange, it introduces additional locomotion for retrieval and requires sufficient positional accuracy to ensure that deposited elements remain accessible to the climbing robot.

EXPERIMENTS

To evaluate the feasibility of the proposed material handoff strategies, controlled experiments were conducted from the perspective of the aerial robot. The evaluation focuses on the

key spatial requirements associated with each strategy: hovering stability for direct handoff and delivery accuracy for indirect handoff.

Setup

All experiments were conducted in an indoor motion capture environment to evaluate the spatial feasibility of material handoff from the perspective of the aerial robot. The test space measured 4.5m x 11m x 4.8m and was tracked by a 12-camera motion capture system with millimeter-level measurement precision (Figure 3).

The aerial platform transported linear timber elements with a constant cross-section of 5 cm x 5 cm and varying lengths from 20 cm to 60 cm (Figure 4). Two key spatial locations were defined in the setup: a target zone, representing the accessible shared workspace used in indirect

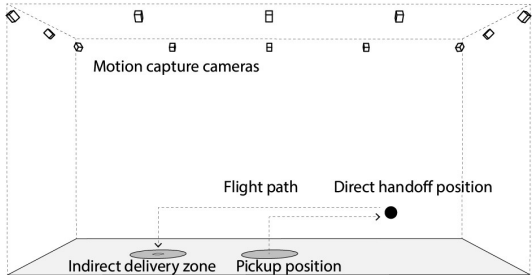


Figure 3
Experimental setup.

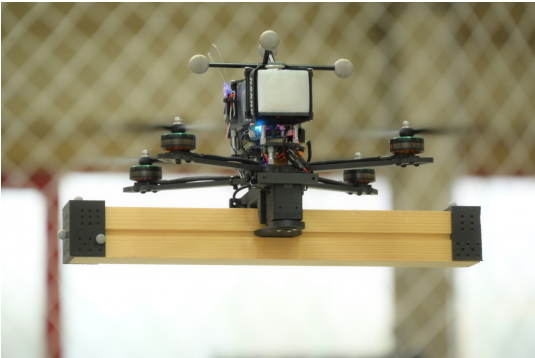


Figure 4
Aerial robot carrying a timber element during material handoff experiments.

handoff, and a handoff position, representing the fixed exchange location used in direct handoff.

The experimental setup and key spatial positions were modeled in Grasshopper, which was used to send real-time position commands to the aerial platform based on the previously developed control framework (Xie et al., 2025). During all trials, the drone’s position was continuously recorded by the motion capture system for subsequent trajectory-based analysis.

Evaluation Metrics

To compare the two handoff strategies, two sets of performance metrics were defined. For direct handoff, the evaluation focused on the aerial robot’s ability to maintain a stable exchange state while carrying the timber element. During a 10 s hovering phase at the handoff position, positional stability was quantified using hover RMSE, maximum deviation, and peak-to-peak range.

For indirect handoff, the evaluation focused on whether the timber element could be placed within a usable shared workspace of 5.0 cm. This was quantified as final planar error after landing. The metrics reported include X error, Y error, and final XY error.

Results

- Aerial-Side Stability for Direct Handoff

As shown in Table 2, the aerial robot completed the 10 s hovering task for all tested timber lengths, indicating aerial-side feasibility for direct handoff. However, hovering stability degraded as timber length increased. Figure 5 shows a representative position response, where the aerial robot reached the target position but exhibited persistent fluctuations, especially under the longest payload condition.

Hover RMSE increased from 1.6 cm at 20 cm timber length to 3.1 cm at 60 cm. Similarly, maximum deviation increased from 3.4 cm to 5.9 cm, while peak-to-peak range increased from 2.3 cm to 4.4 cm. This monotonic degradation suggests increasing sensitivity to payload length, likely due to greater inertia and disturbance effects. Direct handoff therefore imposes tighter position-holding requirements on the aerial platform.

- Delivery Accuracy for Indirect Handoff.

As summarized in Table 3, the aerial robot delivered all timber elements into the target zone across the tested length range. The final XY placement error remained relatively stable, ranging from 1.8 cm to 2.9 cm. Most errors were concentrated in the x-direction, suggesting that descent, landing, and release dominated the final error rather than free-flight transport.

Table 2
Direct handoff
performance across
timber lengths.

Timber Length (cm)	20	25	30	35	40	45	50	55	60
Hover RMSE (cm)	1.6	1.8	1.9	2.0	2.2	2.4	2.6	2.8	3.1
Max Deviation (cm)	3.4	3.7	4.0	4.2	4.5	4.8	5.1	5.4	5.9
Peak-to-Peak Range (cm)	2.3	2.6	2.8	3.0	3.2	3.4	3.7	4.0	4.4
10 s Hover Maintained	√	√	√	√	√	√	√	√	√

Table 3
Indirect handoff
performance across
timber lengths.

Timber Length (cm)	20	25	30	35	40	45	50	55	60
Final XY Error (cm)	1.9	2.1	2.4	2.3	1.8	2.0	2.2	1.9	2.9
X Error (cm)	0.2	-1.8	-2.1	-2.0	-1.7	-1.9	-2.0	-1.8	-2.8
Y Error (cm)	-1.9	0.9	1.2	-1.1	0.4	-0.6	-0.8	0.5	0.4
Delivery Within Zone	√	√	√	√	√	√	√	√	√

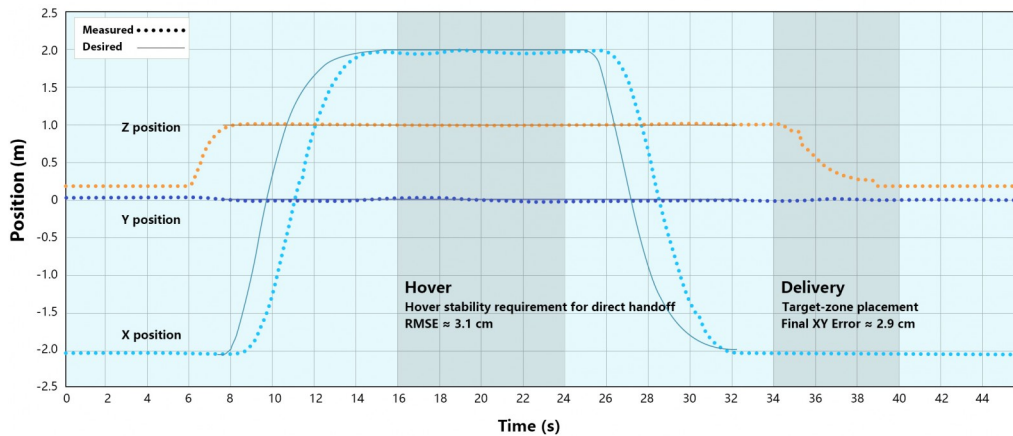


Figure 5
Representative position response of the aerial robot carrying the 60 cm timber element during hovering and delivery.

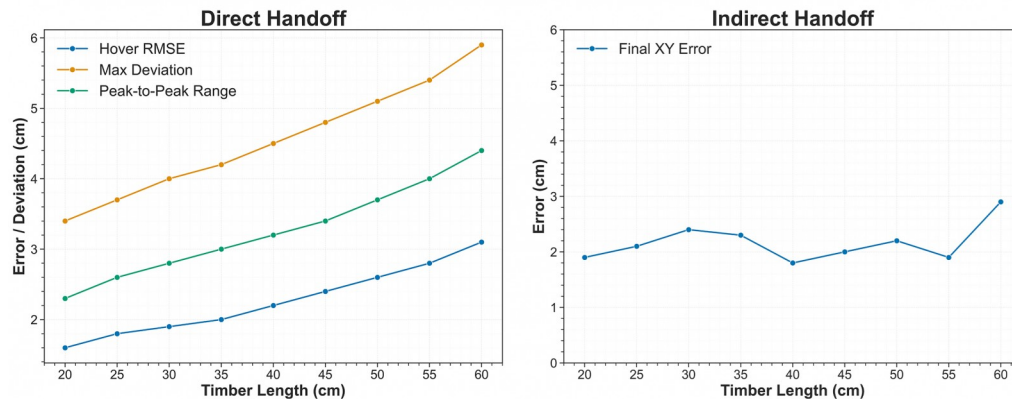


Figure 6
Comparative performance trends of direct and indirect handoff across timber lengths.

These results indicate that indirect handoff is more tolerant to payload variation than direct hovering. Since the timber element only needs to be delivered into a shared accessible region rather than aligned with another robot in real time, moderate positional deviations remain acceptable within the workflow.

Figure 6 summarizes these contrasting trends: direct handoff shows increasing

hovering-related error with payload length, while indirect handoff remains comparatively stable.

DISCUSSION AND CONCLUSION

Strategy Comparison

The experiments demonstrate that the two material handoff strategies impose fundamentally different spatial demands on the aerial platform. Direct handoff is a synchronization problem. Its

feasibility depends strongly on stable hovering performance during synchronized exchange.

By contrast, indirect handoff is primarily a delivery problem: the timber element only needs to arrive within a shared workspace accessible to the receiving robot. It therefore tolerates moderate positional error.

This distinction is important because it shows that material handoff is not merely a logistical operation, but a strategic variable that structures the coordination relationship between heterogeneous robots.

Implications for Heterogeneous CRC

From a broader CRC perspective, the results suggest that aerial robots are most effective when used as high-mobility delivery agents, while precision-sensitive assembly actions remain better suited to structure-attached or ground-based robotic systems. In this sense, heterogeneous collaboration should not be understood as multiple robots performing the same task in parallel, but as the distribution of complementary tasks across different spatial and operational domains.

Indirect handoff appears especially promising for construction workflows that benefit from asynchronous coordination and reduced inter-robot dependency. Direct handoff should be reserved for scenarios where real-time exchange justifies the additional control complexity.

Limitations and Future Work

This study has several limitations. First, the experiments focus only on the aerial side of the interaction and use hovering stability as a proxy for direct handoff feasibility rather than implementing a full physical robot-to-robot exchange. Second, the evaluation is limited to a single aerial platform and a controlled indoor environment. Outdoor deployment may introduce additional disturbances such as wind and localization uncertainty, which were not considered in the present indoor evaluation. Third,

the presented trials are intended to capture comparative trends across payload conditions rather than provide exhaustive statistical characterization.

Future work will extend this framework toward full heterogeneous handoff between aerial and climbing robots, including physical exchange tests and integrated task sequencing. These developments will support larger truss-like structures through coordinated heterogeneous robotic teams.

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