A Robot-Friendly Scaffolding System with Passive Error Correction using Tapered Screw Connectors

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Abstract. This paper presents a robot-friendly scaffolding system that enables autonomous assembly with passive error correction using a dual-function mechanical connector. Conventional tube-and-clamp scaffolding requires precise manual alignment and tightening of flexible joints, which are challenging for automation. The proposed system replaces these manual operations with male and female joints that are pre-positioned accurately along each tube. The joints make use of a tapered-screw feature that performs both alignment and fastening in a single motion, thereby eliminating the need for accurate spatial alignment.

Three experiments validated the approach. An alignment-tolerance test showed reliable engagement of the joints even with ±5 mm translational and ±3° angular deviation. A digital simulation of a multi-story structure confirmed robotic reachability, collision-free insertion, and stability throughout the assembly process. A physical structure with multiple joint arrangements demonstrated the assembly process with a real-world dual-arm robot without any external localization or alignment sensors. Together, the results demonstrate that mechanical self-correction at the joint level can propagate structural accuracy across the entire system.

Keywords: Robotic Assembly, Scaffolding, Passive Error Correction, Systemic Design.

1 Introduction

Scaffolding is one of the most common and labor-intensive temporary structures in construction. It provides access to elevated areas during building, renovation, and maintenance. Among its many forms, the tube-and-clamp system remains the most flexible and widely used. Unlike modular frames with fixed connection points, tubes in this system can be joined anywhere along their length (sec 2.2.1, [1]). This adaptability allows workers to adjust scaffold geometry to irregular façades, variable floor heights, and confined environments. However, this flexibility demands intensive manual effort. During assembly, workers must lift, position, and hold long steel tubes while attaching and tightening clamps. Maintaining plumb (vertical) and level (horizontal) alignment requires continuous monitoring and adjustment of the partially built structure. If left unchecked, small local misalignments can accumulate into global deviation. The process is repetitive, physically demanding, and carries significant safety risks.

Challenges. Although robotic construction has advanced rapidly in recent years, automating scaffolding assemblies remain uniquely challenging. Conventional tube clamps possess multiple degrees of freedom and require accurate alignment while ensuring accurate placement. To replicate the dexterity of human workers, robots would need to lift and stabilize heavy tubes while additional robots apply corrective forces to the partially assembled structure and attach the flexible clamps—an approach that quickly becomes cumbersome and impractical. Automating scaffolding assembly presents several key challenges:

- **Material handling:** transporting and positioning long tubular elements in cluttered construction environment while avoiding collision.
- **Joint alignment:** for mobile robots (without a fixed base) to perform accurate alignment between long and imperfect tubes.
- **Structural accuracy:** preventing the accumulation of small local deviations into global geometric error.
- **Connector complexity:** manipulating multi-degree-of-freedom clamps that require multiple coordinated motions for tightening.
- **System coordination:** synchronising multiple robotic agents to hold, align, and fasten components safely in unstructured environments.

Our approach. To address these challenges, we introduce a robot-friendly scaffolding system that replaces conventional clamps with pre-placed joints positioned accurately along each tube. The joints contain a tapered-screw feature that performs alignment and tightening in a single motion. By combining both requirements—alignment and fastening—into one actuation, the system enables the use of a lightweight end-effector capable of both gripping and installation tightening.

This end-effector can be mounted on a single dual-arm robot (as in our demonstration) or distributed across a coordinated team of mobile manipulators to achieve tube placement, local joint alignment, joint fastening, and global error correction simultaneously. Unlike conventional robotic assembly approaches that require precise six-degree-of-freedom spatial alignment between structurally unstable elements, our system intentionally relocates geometric precision to a prior two-dimensional joint-indexing stage that can be easily achieved on individual tubes using a jig. Furthermore, The interaction of individual elements through the precisely positioned joints propagates accuracy to the system level. This eliminates the need of additional methods to correct for structural deviation.

Our Contributions. While conventional tube-and-clamp scaffolding typically uses tubes of 40–50 mm diameter (depending on regional standards and application), laboratory constraints required our demonstration to be conducted at 50% scale using 20 mm tubes. The paper contributes:

- A new tapered-screw connector design (T20-5) capable of connecting 20mm tubes and providing ± 5 mm passive misalignment correction.
- A dual-function electric end-effector (GT1, referring to gripping and tightening).
- A systematic validation through three experiments evaluating alignment tolerance, simulated large-scale construction, and physical multi-tube assembly.
- A conceptual framework linking local and global deviation correction within robotic assembly workflows.

2 Context and Related Work

Challenges of existing scaffolding systems. Tube-and-clamp scaffolding presents automation challenges distinct from modular or prefabricated constructions. Although they offer the maximum site adaptation and geometric freedom through flexible positional and connectivity assignment [2], steel tubes must be lifted, oriented, and supported precisely in three-dimensional space while joints are attached and tightened.

In human practice, this process relies on continuous visual monitoring to maintain plumb and level alignment. Small local misalignments in each connection can accumulate into global deviation if not constantly adjusted. Conventional clamps further complicate automation: their multiple hinges and screw tightening mechanism make them forgiving to human manipulation but difficult for a robot to position and tighten autonomously [3], [4]. As a result, existing robotic systems struggle to coordinate material handling, temporary stabilisation, and precise fastening within a single, continuous workflow. Recently, the Peri group presented a conceptual dual-arm mobile robot system for modular scaffolding [5]. However, their system is limited to rectangular layouts and the joint-making process is simplified to top-down insertion of tubes.

Limitations of previous assembly automation attempts. Joints are an indispensable part of an assembly, used to connect individual elements so they behave as a system when external loads are applied. However, despite their importance, most previous architectural assembly automation focuses on utilizing robotic accuracy for element placement, but rarely automates the joint formation. Across different building materials (timber, steel, brick) [6] and connection types (screwing [3], [8], [9], [10], welding [11], rope tying [12], [13], mortar/adhesive application [14], [15], or coupler installation [3], [4], [7], human workers are still required to perform in-situ joint-making operations while robots place and hold the element in place.

While automation with human-robot collaboration may provide benefits such as in-situ design decision-making and adaptation to design changes [16], [17], [18], the motivation in our paper strives for an uninterrupted and autonomous robotic process that can potentially free human workers from repetitive tasks.

Robot-friendly connectors and self-correcting mechanisms. A growing body of research highlights the potential of holistically redesigning the connection and assembly systems to be more friendly to robotic processes to overcome these issues. For example, Distributed Robotic Tools (DiRT) [19] proposed self-contained actuators that remain attached to the structure, showing how embedded mechanical intelligence can simplify complex assembly sequences. Building on this principle, Distributed Robotic Clamps for timber joints [20], [21], [22] demonstrated that tapered geometries and synchronised actuation can overcome friction and misalignment without external sensing. In addition, exploration of designing structures with diagonal bracing and triangulation [7], [23], [24], [25] eliminated the need to construct static scaffolding or falsework, while *Leung* [19] later proposed the use of integral joints on timber (where the joint positions are precisely located) as a way for error correction. Collectively, these studies illustrate that connector design, robotic process, and structural logic can benefit from being developed as an integrated system rather than isolated components.

Positioning of this work. Our research embraces systemic thinking to redesign the tube-and-clamp scaffolding system to be friendly to both robotic agents and manual workers. This is achieved by proposing a new joint, a new assembly sequence, a robotic assembly tool and a new error-control concept. More broadly, it contributes to an emerging paradigm of redesigning our society for a better interdependency between man and machine.

3 System Design

Connector design. The proposed tapered-screw connector introduces a mechanical solution that combines alignment and fastening within a single motion. The connector consists of a male and a female component with complementary taper angles and screw profiles. As the screw rotates, the taper geometry converts the applied torque into both axial tightening and radial centring forces, allowing the two joints to self-align before the connection is fully tightened. The design achieves a theoretical self-correction range of ± 5 mm when scaled to 20 mm tubes. For clarity, this prototype is referred to as the *T20-5* connector, denoting the tube diameter and alignment tolerance. The prototype of this connector is printed in PLA plastic for use in our demonstrations. The connector's geometry, and assembly sequence are illustrated in Fig. 1. The joint has two variants for ground connection (T20-G) and for overhead sub-floor connection (T20-5-SF), which are used in Experiment 2 and 3.

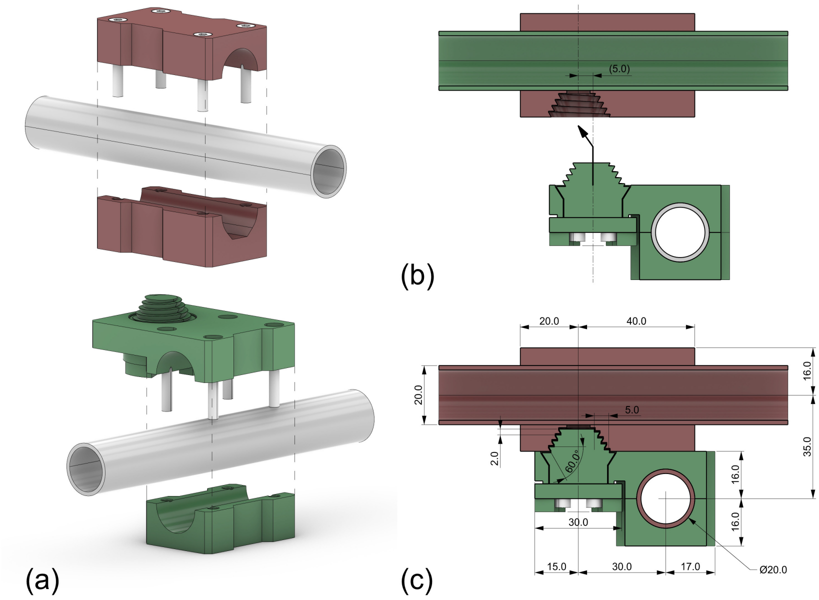

Fig. 1. Drawing of the T20-5 connector showing (a) direction of attaching the joint to tube during preassembly; (b) Joint halves positioned at maximal misalignment before assembly; (c) after assembly.

Pre-placed joints on tubes. Before robotic assembly, all joints are positioned on their respective tubes at predetermined locations to ensure that attachment points are geometrically consistent with the digital model. A custom sliding jig equipped with a laser time-of-flight distance sensor and a digital inclinometer measures both longitudinal position and rotational alignment of each joint along the tube. The jig enables a human operator—or, in future, a stationary automation setup—to install joints with an accuracy of ± 0.5 mm in translation and ± 0.05° in rotation. This pre-placement process is essential for global error correction during robotic assembly, as each tube carries its own precise attachment points. Fig. 2 shows the joint-placement jig and alignment workflow.

Robotic tool design. The assembly end-effector GT1 integrates two primary functions: tube gripping and screw tightening. A current-limiting hobby-grade servo motor (15 kg·cm torque) actuates a pair of parallel grippers through a crank-and-slider linkage. The gripper fingers are profiled to secure 20 mm tubes during handling and insertion. A brushless DC motor with a worm-drive gearbox powers a screw-driving head shaped like a three-tooth dog gear. Most of the custom parts are 3D-printed in PLA plastic for rapid iteration and reduced weight.

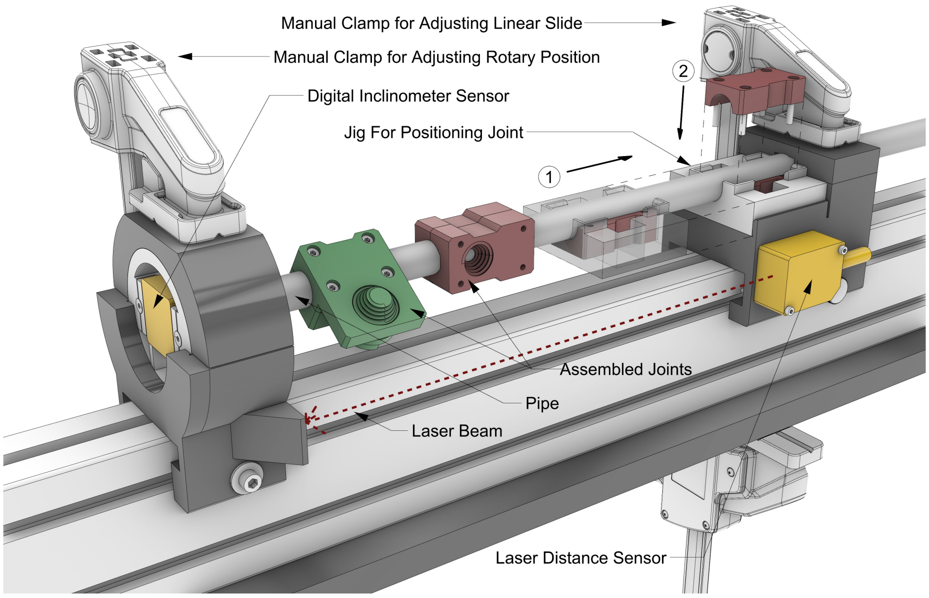

Fig. 2. Annotated diagram of the joint-placement-jig. Numbered arrows indicate the operating sequence of placing the joint half into the jig.

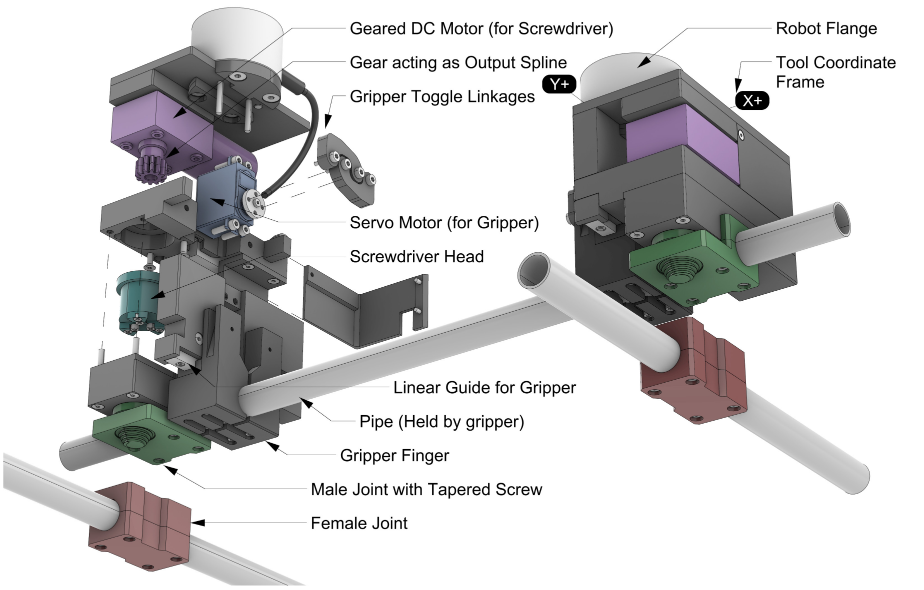

Fig. 3. Annotated drawing of two GT1 end-effectors holding onto two joints on the same tube.

The driver for the tightening motor includes encoder feedback for an Arduino-based controller that performs stall detection by monitoring speed decay. When rotational speed remains below a threshold for a set duration, the controller stops the motor automatically—an effective proxy for limiting tightening torque. This method prevents over-tightening, protects the screw head, and avoids motor overheating. Motor and gearbox selections were based on torque data from manual tightening tests, scaled by a safety factor of 2. Fig. 3 presents the tool's major components and the typical use case where two joints of the same tube are held simultaneously.

Operation sequence. Assembly is demonstrated (in Experiment 2 and 3) using a dual-arm mobile robot platform, with each arm carrying an GT1 end-effector. Because each scaffolding tube typically connects to two joints, both arms operate in coordination. In the initial phase, the arms move to a ready position with open grippers spaced to match the distance between the two mating joints. A tube is then placed in the grippers where the two male connectors are aligned with the screwdriver. This step is performed manually in this prototype, though it can be automated in future implementations. Once secured, the arms synchronously move to the initial insertion pose. Under a position-based controller, they advance linearly toward the mating joints while allowing small lateral and angular deviations. During this motion, the tightening motors rotate synchronously with the insertion speed so that alignment and fastening occur simultaneously. When the torque limit is reached, stall detection halts rotation, completing the connection. The robot then releases the tube, retracts and repositions for the next element. Fig. 4 illustrates key frames of this coordinated sequence.

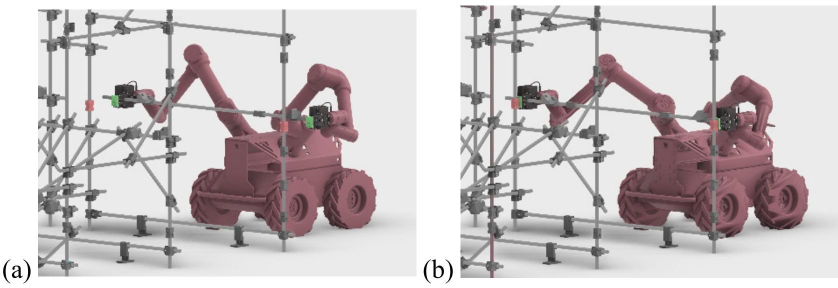

Fig. 4. Keyframes showing a mobile robot with two GT1 end-effectors holding a horizontal tube (a) before assembly, and (b) after assembly

Design, simulation, and planning. A custom software tool developed in Rhinoceros 8 using the COMPAS framework and Grasshopper plugin supports design and sequence planning. The interface enables designers to model scaffold geometry, define assembly sequences, and verify constraints such as tube spacing and joint placement. Joint positions are generated by a custom script derived from the position of the tubes, ensuring compatibility with the physical connectors. Kinematic reachability and collision checks are performed for keyframes in the sequence using custom scripts developed on top of COMPAS FAB libraries. This environment was employed in Experiments 2 and 3 for both digital validation and physical prototyping.

Execution and control. The relative positions of the two robot arms are calibrated through a shared work-object definition. The procedure requires first calibrating the position of a pointy tool using the four-point method and then calibrating a work object frame using the three-point method. Each arm's coordinate transformation is recorded to enable accurate synchronisation for Experiment 1 and 3. The assembly controller, implemented in ROS, manages trajectory execution, gripper actuation, and tightening-motor commands in real time. The tightening motor runs until stall detection confirms torque completion. This configuration delivers consistent insertion and fastening without relying on external vision or sensor feedback. After assembly, the gripper is released, and the robotic arm is retracted from the structure.

4 Experimental Validation

Three experiments were conducted to evaluate the mechanical performance, scalability, and assembly behavior of the proposed system. The first experiment measured the *alignment-tolerance* of the T20-5 connector through controlled misalignment tests. The second experiment tested *large scale constructability* through a digital simulation of multi-story scaffolding. The third experiment demonstrated *physical assembly* of a representative "folly" structure using a dual-arm robot. Together, the tests validate both the joint-level and system-level behavior of the approach.

4.1 Experiment 1 – Alignment tolerance

This experiment examined the connector's ability to compensate for positional and angular misalignment without sensing or active correction. Two robotic arms each held one half of the connector (Fig. 5) and executed insertion under position control mode. Intentional offsets were introduced in the X–Y plane (0–5 mm) and A–B rotational axes (0–5°). For each condition, the test outcome—successful or failed engagement—was recorded through the controller's stall-detection signal and confirmed by visual inspection.

Without introducing rotational misalignment, the successful cases formed an approximately circular boundary with a radius of 5 mm around the origin, representing the connector's effective correction range. The resulting scatter plot (Fig. 6a) illustrates this region of successful assemblies. Further tests introduced rotational misalignment about the A or B axis and showed that the system can consistently handle ± 3° misalignment. Additional plots (Fig. 6b–6c) show the distribution of results along the A–X and B–X axes, respectively. These observations confirm that the tapered-screw geometry tolerates translational and angular misalignment, consistent with the connector's theoretical design.

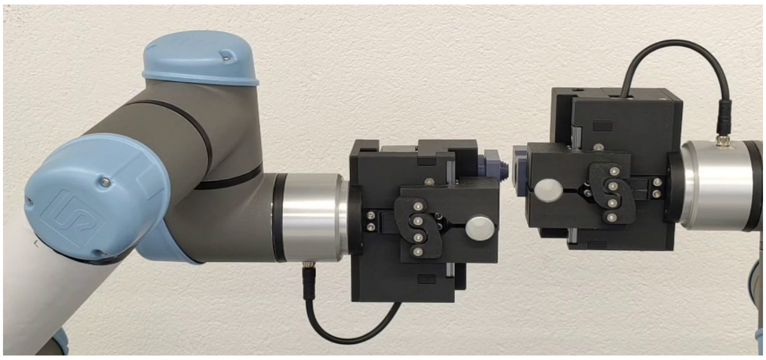

Fig. 5. Photo of the misalignment experiment setup, moments before the tapered screw engage. The actuated male-joint is on the left.

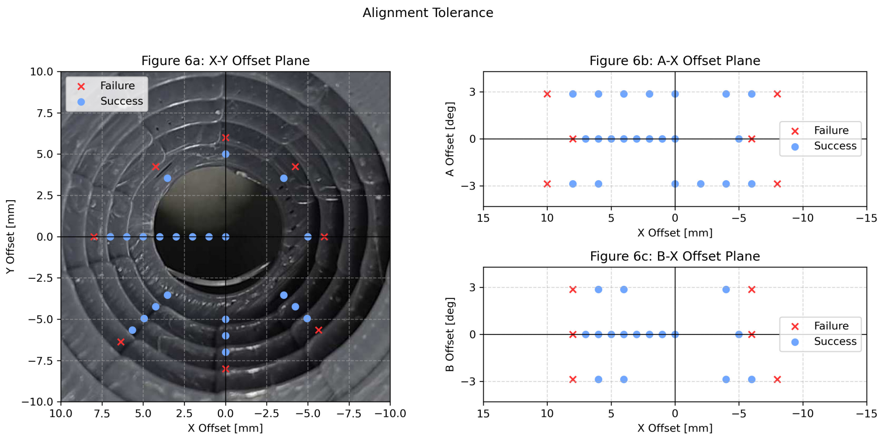

Fig. 6. Plots showing successful and unsuccessful engagement under different misalignments.

4.2 Experiment 2 – Simulated large-scale assembly

The second experiment verified the feasibility of constructing multi-story scaffolds using a single assembly robot supported by two auxiliary robots for temporary support. The simulation was performed in Rhinoceros 8 with the custom COMPAS-based design tool. Instead of continuous motion analysis, the study evaluated keyframes [26] corresponding to critical assembly poses. The mobile robot base was positioned either on the ground or on completed deckings (assembly approach of which are similar to the tubes with matching joints, but details are beyond the scope of this paper) to ensure that every element was both reachable and properly supported during construction.

For each tube, the simulation checked: (1) reachability and collision of the start and end poses, (2) stability of the partially assembled structure, and (3) feasibility of the robot base's turning radius to reach the assembly position. Structural stability was verified qualitatively by ensuring that new elements formed triangular configurations, following the rule-of-thumb method introduced by *Adel et al. and Parascho et al*. Two supporting robots are used to temporarily support the unstable tubes. Using these checks, we simulated how designers could virtually "build" the scaffolding step-by-step from the ground upward while complying to constraints.

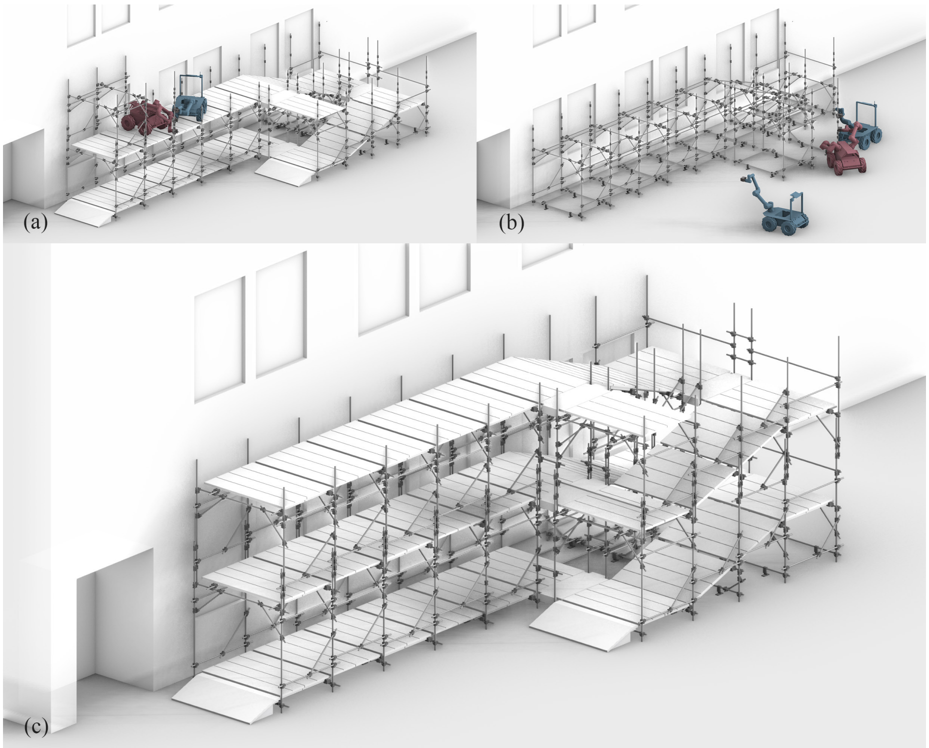

Fig. 7. Keyframes showing the assembly process of the multi-story scaffold: (a) first ramp to second level (b) third level support (c) completed. One assembly robot (red) and up to two supporting robots (blue) are used throughout the assembly.

The completed design, comprising 376 tubes, 802 joints (T20-5: 640 pairs, T20-5-SF: 132 pairs; T20-G: 30 sets), 137 deck planks (typical: 100 pcs, bridging plank: 5 pcs, inclined: 32 pcs), and 2 ground ramps. It demonstrated that a multi-story scaffold can be designed using the proposed system and that the process can conceptually extend to arbitrary height and length even with only three mobile robots. Fig. 7 shows the digital model at various assembly stages. Fig. 8 shows robot placement, and reachability verification results.

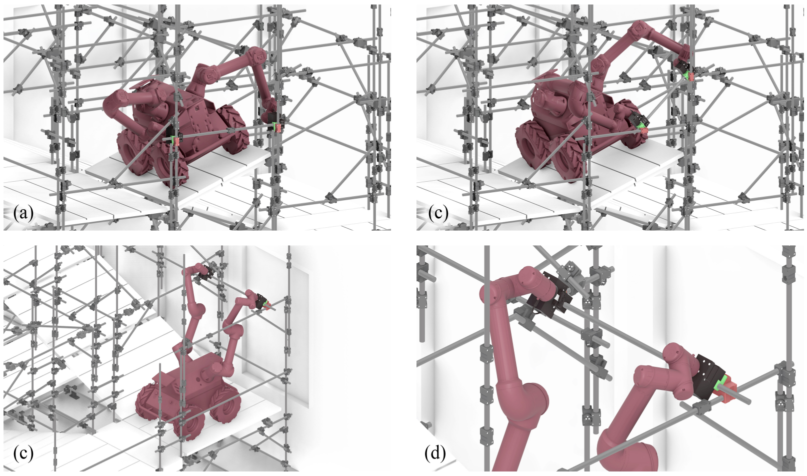

Fig. 8. Drawing showing close-up detail of the assembly process: (a) horizontal element of the ramp, (b) diagonal bracing, (c) and (d) sub-floor structure for the level above.

4.3 Experiment 3 – Physical dual-arm demonstration

The third experiment implemented the complete assembly workflow on the dual-arm robot to evaluate cumulative accuracy and operational robustness. A compact *folly* structure was designed to include all representative assembly conditions identified in the simulated scaffold—horizontal, vertical, diagonal, and extension tubes assembled using a top-down and horizontal assembly vector. The structure also incorporated the adjustable ground connection (T20-G) to accommodate ground unevenness.

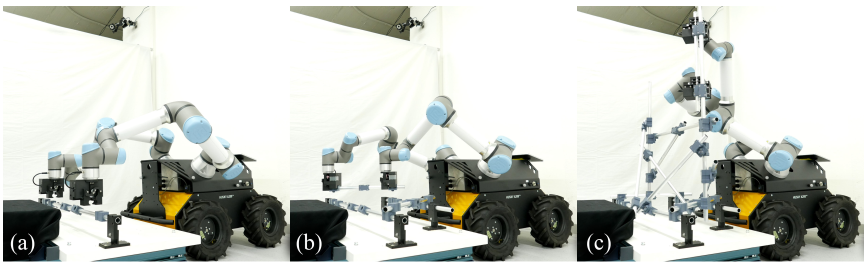

Fig. 9. Physical demonstration of the folly structure with different elements: (a) ground connection, (b) horizontal tube, and (c) vertical extension

Each tube was pre-installed with joints, and the dual-arm robot executed the planned sequence autonomously following the digital design and preplanned trajectory. Measurements taken after each assembly step confirmed that the global deviation of the structure remained within ± 2.5 mm, demonstrating that local self-alignment of individual joints effectively constrained overall error accumulation. Fig. 9 shows the assembly sequence and the completed prototype.

5 Results and Future Work

Local-to-global error correction. The three experiments demonstrate that the proposed system can achieve consistent self-alignment and that mechanical correction at the joint level propagates to the entire structure. The alignment-tolerance test confirmed that the *T20-5* connector can passively correct up to 5 mm of translational deviation and small angular errors without external localization or local alignment sensing. A future full-scale variant (*T40-10*) is expected to be made in metal to support structural load and to provide ± 10 mm correction for standard 40 mm tubes.

While these findings validate the mechanical principle of local-to-global correction, mechanisms for quality control remain absent. We expect that residual deviations may still accumulate over many assembly steps, and that methods for sensing and concepts for compensation will be required for larger structures.

Future development directions. From a usability point of view, the development of a walkable decking (seen in Experiment 2) is essential for the structure to achieve its scaffolding purpose. Furthermore, it is also important to balance the design of the newly proposed joints and decks in consideration of production cost in a systemic way. Finally, the structural performance and durability of the newly developed joints and their interactions at structural scales are yet to be characterized. Our intended construction process with multiple robotic agents (some acting as support) will also require accurate localisation of mobile robots across a larger work area and for irregular geometries, ideally invariant to outdoor conditions. Note that this has not been demonstrated in our Experiment 3 as the robotic wheelbase was fixed. Finally, real-time motion planning software will also be needed to adapt pre-planned trajectories to robot base-position errors during assembly. Once we are ready to demonstrate with full-size scaffolding (using 40 to 50mm tubes), the main bottleneck will be to construct a mobile robot with longer arms for added reachability and stronger motors for higher payload. In fact, owing to the ability of the joint to tolerate deviation, the robot stiffness, repeatability and accuracy no longer need to be as stringent as typical industrial robots, offering an optimization opportunity for a new class of on-site construction robots.

6 Discussion and Conclusion

Emerging methodologies. This research demonstrates a new methodology for robotic construction grounded in systemic design thinking. It achieves efficiency through mechanical intelligence embedded in the connector and process design. This approach moves beyond conventional "human-mimicry" workflows toward a model in which systemic design thinking simplifies—rather than complicates—robotic behaviour, aligning closely with the *Detangling Dependencies* theme of this conference.

As robotic construction continues to advance, such methodologies will free humans from hazardous and repetitive work, allowing them to focus on designing systems that make automation itself more effective. In this shift, the human role becomes that of a designer—someone who defines how robots should operate. The interdependency relationship between humans and machines is therefore not competitive but symbiotic: machines extend human capability, while humans, in turn, nurture and adapt machines toward more capable, adaptable, transparent, and ethically aligned with its environment.

Conclusion. This paper presented a robot-friendly scaffolding system that enables passive error correction and autonomous assembly through a dual-function connector and tool design. The experiments confirmed that local alignment tolerance can propagate to global accuracy without external sensing. Beyond its technical contributions, the project highlights how systemic design thinking can leverage the intrinsic qualities of robots to simplify and modernise long-standing construction processes.

Contribution Statement.

This project is partially supported by CityUHK Grant (9610746) and by the SNSF Ambizione Grant (Grant No. 223384).

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