

Sequencing optimization of stability-aware robotic assembly for discrete frame structures

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Abstract

This research paper investigates a stability-aware robotic assembly process for discrete frame structures. The approach generates sequencing for robot target assignment that provides temporal support for stabilizing the structure during construction, thereby enabling scaffold-free assembly. We integrated iterative finite element analysis to greedy search for optimal assembly sequences by: 1) assuming a temporary rigid support by robot at its current assembly location; 2) finding the next component that results in the minimal average displacements across members of the in-progress structure through greedy search; and 3) introducing penalties to re-rank low average displacement options that contain significant displacement outliers. This digitally simulated sequence-finding pipeline minimizes displacement throughout the assembly process of long-span, free-form, linear element structures joined by rigid connections. The result establishes a high-level foundation for target-sequential assignment in robotic assembly. The proposed method is generalizable to discrete frame structures, as demonstrated in this paper through case studies of funicular shell structures with a multi-robot step-up.

Keywords: Structural Analysis, Sequential Assembly, Funicular Structure, Stability Optimization

1. Introduction

Surface structures composed of linear elements (e.g., timber lattices or bar frameworks) achieve elegant, material-efficient forms. Construction of these reticular shell structures requires extensive manual labor and temporary scaffolding to maintain stability during construction. Recent research has demonstrated how structural analysis can be integrated with automated assembly sequence planning, particularly in multi-robot assembly contexts, to facilitate safe construction without excessive falsework. Among the structures with long spans or large cantilevers, the high-level target sequence is crucial for subsequent robot planning algorithms, such as *target assignment and path finding* (TAPF). Due to the interdependent relationship among targets, investigating sequence optimization while maintaining the stability of the entire structure with minimal temporary displacements during assembly becomes a unique aspect of the construction problem.

2. Background

Multi-robot systems for structural assembly are gaining increased attention as they offer new possibilities for complex construction sequencing and coordination. This applies to commonly seen robot manipulators with six degrees of freedom, including mobile bases and other conventional automation mechanisms, such as cranes, which transport and provide temporary supports to stabilize in-progress structures. Attention towards multi-robot assembly has generated research focus on mobile multi-robot planning, specifically without considering the structural relationships among assembly

members, such as Long-Horizon Multi-Robot Rearrangement Planning for Construction Assembly [1] and Cooperative Task and Motion Planning for Multi-Arm Assembly Systems [2]. Some other research couples *Finite Element Analysis* (FEA) with sequence optimization to ensure structural stability at every step. For example, Huang et al. [3] introduced a unified planning algorithm that jointly computes a construction sequence and robot motion plan for the additive assembly of bar structures. At each assembly step, the partial structure's displacements under self-weight must remain below a tolerance, assessed via linear elastic FEA of the evolving frame (fig. 1b). However, this simple threshold evaluation does not seek an optimal or suboptimal solution and only examines a single robot movement. Compared to single-robot operation, multi-robot operation involves more complex role exchanges and coordination, but also offers greater versatility in assembly tasks.

For state-of-the-art research involving multi-robot assembly and structural stability, Wang et al. presented a design-to-fabrication workflow for multi-robot construction of discrete shell structures, integrating structural form-finding, sequence assessment, reachability analysis, and motion planning (Fig. 1a) [4]. Their approach emphasizes formulating the shell geometry as a compression-only masonry structure, ensuring global stability with *Thrust Network Analysis* (TNA) [4] and evaluating the shell's stability at each incremental step. This assembly-aware design paradigm is also explored by Parascho et al. [6]. The structural design optimization was closely associated with feasible assembly sequencing. The linear member example in Parascho's thesis focuses on the vertical growth of spatial tetrahedral truss typologies, exhibiting how cooperative robotic assemblies with role switching can construct complex geometries. However, the typology differs from surface-derived frame systems that are sensitive to span, focusing more on self-sustained structural performance. It does not examine construction methods for long-span structures that frequently cantilever during assembly.

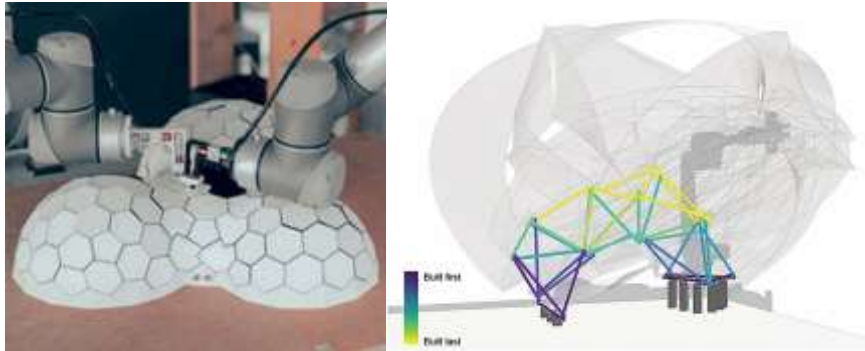


Figure 1: a) Multi-robot assembly in masonry shell structure [6]; b) unified sequencing that estimates structural stability using a deflection threshold [3].

For the practical application of robots in architectural-scale construction, there are two inherent prerequisites. First, the robots need enough payload to support material delivery and act as a temporary scaffold, as it is hard to mobilize extra-heavy payload robots. Medium-sized industrial robots with a payload of around 100 kg, such as those used for monolithic construction or lightweight timber panel assembly (Fig. 2(a)), may face fewer constraints, as evidenced by off-site mobile robot construction studies by ETH [7]. The case studies of both the mesh mould construction by ETH and the Buga wood pavilion by ICD [8] have demonstrated the practical usage of unmanned large-scale robots in construction. Therefore, a lightweight roof surface or pavilion-size assembly that inherently has ground support conditions is preferred for midsize payload robots. Secondly, a robust localization sensing system is required, enabling the robot to accurately determine its location. Without drifting, this may require calibrated markers to obtain global coordinates (Fig. 2(a)). These two studies have demonstrated that, although still relatively unexplored in situ deployment, multi-robot assembly has become increasingly mature for deployment in pre-mapped construction sites, enabling customized surface production.



Figure 2:. Application examples of mobile large payload robots in construction: a) wheel-based industrial robot for mesh bending and welding on site [7] ; and b) mobile robot in application to assemble timber wall and roof surface components for the Buga pavilion [8].

3. Research Statement

State-of-the-art research in the robotic assembly of structures at an architectural scale has demonstrated that robots can perform multiple roles, including transportation, support, and inspection. For horizontally structured forms, sequential assembling and displacement rectification are challenging in scaffold-free approaches. Therefore, we are interested in robot target sequencing involving pavilion-scale, long-span frame structures up to 80ft, where the robot can serve as temporary support in cantilevering scenarios that commonly occur during construction. Leveraging the multi-role abilities of robots and the increasing applicability of unmanned robotic arms with substantial payloads, our goal is to integrate the robot's role with structural analysis for optimal assembly sequencing, such as long-span frame structures that conventionally require many manually positioned scaffoldings.

4. Methods

4.1 Workflow and Setup

We propose a method that leverages a robot operator as mobile support for assembling frame structures. The pipeline utilizes Rhino and the Robot Operating System (ROS) [9] to facilitate iteration updates and data sharing, further advancing the application for multi-robot assembly in practice. This provides low-displacement options for robot target assignment. The method utilizes RhinoVault [9], to create a funicular structure in equilibrium as an undirected graph from basic inputs of surfaces/lines in Rhino. Then, we perform structural analysis using material and joint properties with Karamba3D [9], where the results are sent to ROS iteratively using COMPAS [11] to perform ranking updates and obtain an assembly sequence result. This output is then used to generate robot poses and trajectories using MoveIt [10] (Fig. 3).

The research conducted three types of iterative structural evaluation and decision-making to address how temporal structural support and modified z-score penalty can successfully facilitate structural stability during the construction process:

1. A basic greedy search selects the member that causes the lowest average displacement of the in-progress structure in every iteration.
2. Additional temporal support is introduced for the last-added assembly member, in addition to the ground supports. The robot support will last until another robot places the next member and establishes new joint connections, thereby informing a switch in roles, where one robot moves the pieces and the other acts as support (Fig. 4).
3. The third step incorporates ground support and temporary robot support while introducing the *modified z-score*, a statistical technique for measuring outlier strength (Equation 1) in a dataset (samples>30), to prioritize solutions with more uniform displacement patterns across the structure, which is more preferable for physical robot execution. The threshold of 3.5 for the

absolute value of the modified z-score as an indicator of potential outliers is well-established in statistical literature [11]. Then, the output average displacement is applied with a multiplier to penalize the result and consequently lower its rank; the larger the multiplier, the larger the numerical result for options containing displacement outliers. This augmented penalty increases the score for options that do not result in significant individual member displacement and will influence the subsequent decision tree.

$$mz_i = \frac{0.6745 \cdot (x_i - \bar{x})}{MAD} \quad (1)$$

Equation 1. Modified z-score equation where x_i is the observation, $\bar{x}$ is the median, and MAD is the median absolute deviation value

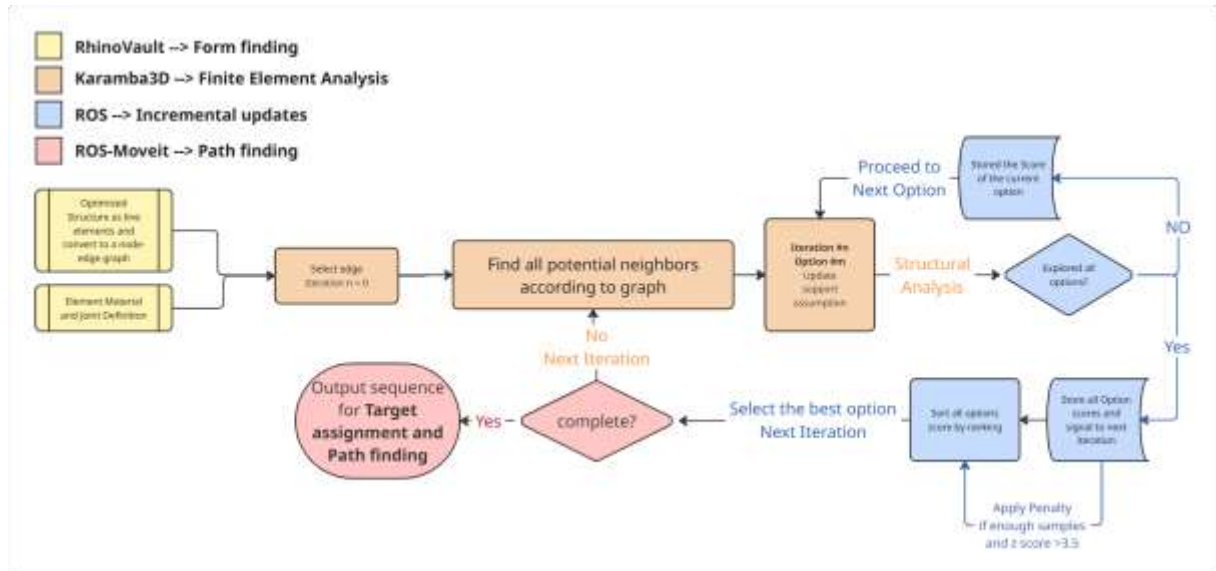


Figure 3: The workflow of sequential exploration in the best assembly sequence.

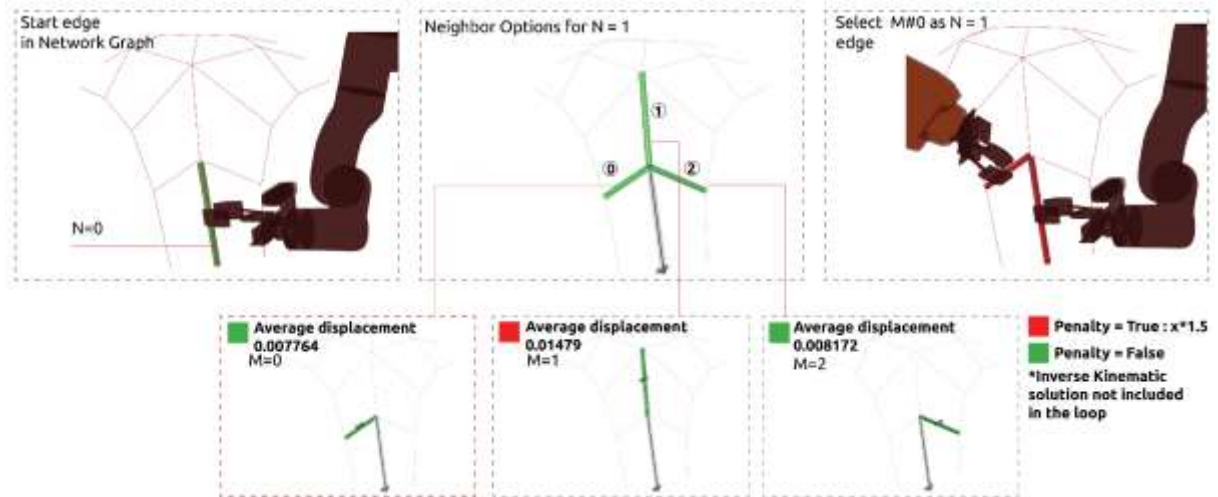


Figure 4: Basic visualization of workflow showcasing the option selected at a new iteration and the decision-making process.

4.2 Assumptions

Considering the current applicability of mobile robotic arms, this method is envisioned to be applicable at a pavilion scale, which is similar to the example applications in literature reviews, to prevent overloading of the robot's capacity. Materials are set up as 6-inch diameter circular-section timber components with up to 150 members. The joint definition assumes simple fixed connections (e.g., nailed, screwed, or bolted), where Connection stiffness is 50–500 kip/ft for timber, and load cases are defined as self-weight only with pinned footings. The models are also picked to contain long-span characteristics and multiple footing clusters. To refer to actual construction methods, timber assembly often only has options in approximate-rigid joints, such as timber-to-timber connections with engineered plates to provide high moment resistance for hybrid or mass timber structures. Another prevalent method is the use of plate and bolt sandwich connections for customized assembly members, where timber beams are sandwiched between bespoke plates that are bolted together. (Fig. 5c) In addition, the robot gripper grasping the latest-placed member also serves as an extra ground support to prevent movement. Although the pipeline is designed to provide solutions for pavilion-scale constructions using common construction materials such as steel and timber, it also functions effectively across various scales and material properties that are compatible with robots of different sizes.

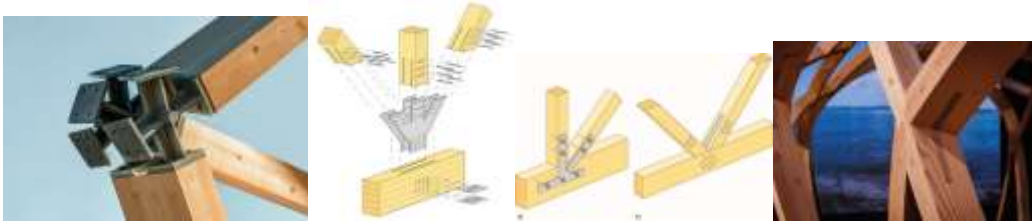


Figure 5: Approximate rigid joints for steel and timber joints as reference practices[12], [13], [14].

5. Results

The implementation of these methods is tested on two different case studies. The simulation of the larger structures generated by RhinoVault [9] benchmarks the optimized sequence that the methods can achieve and demonstrates how additional mobile support methods and z-score penalty reduce the overall average displacement during the assembly process. The second structure has fewer members on a smaller scale, designed for physical validation to demonstrate how target sequence results are output, enabling multi-robot assembly planning and actions that switch between support and delivery roles.

5.1. Sequential target search simulation and result

The case-study model (Fig. 6) features five clusters of footings and contains multiple cantilevering scenarios during the assembly process. It is modeled as a 70ft span structure with 6-inch diameter circular-section timber components with approximately rigid joints and pinned footings. Figure 6a illustrates that the structure without support experiences significant displacement due to cantilevers during the assembly process. These displacements also visually correspond to the two peaks in the chart. Both Figure 6b and 6c, with support assumptions, demonstrate that a path connecting two far footings is quickly found at iteration 22, compared to the base search that peaks at iteration 30, and therefore reduces displacements in subsequent iterations. The quantitative chart of all three types of search methods also showed a significant drop in the maximum average displacement throughout all iterations, from approximately 9ft to below 3.36 in.

Figure 7a displays the number of significant displacement outliers identified during the process, where, during critical stages, there are very few options that do not result in significant displacement. The comparison graph between with/without modified z-score penalties (Fig. 7b) demonstrates that modified

z-score yields different options, reaches local peaks earlier to reduce larger displacement over time, and results in continuous displacement reduction for iterations 30-80.

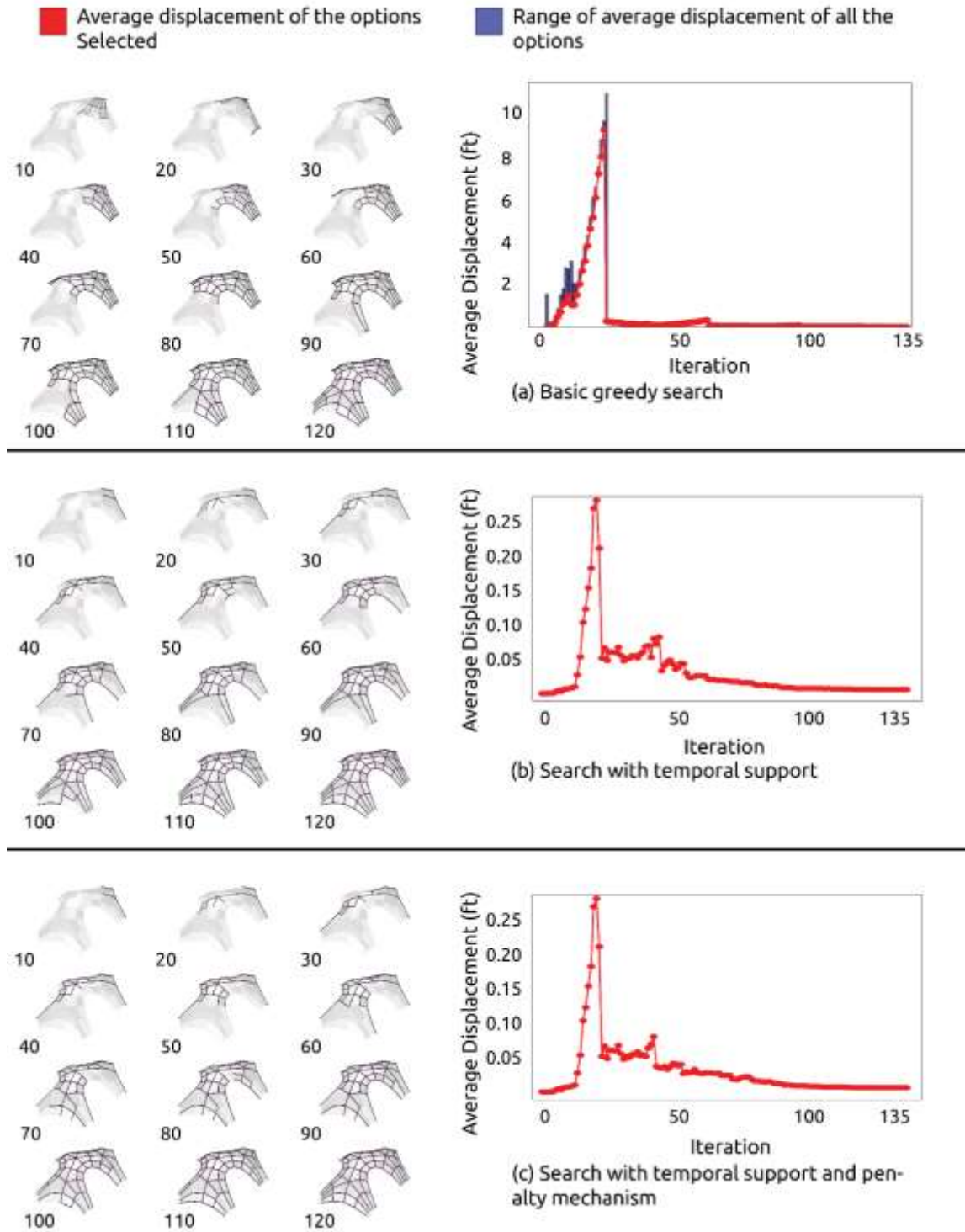


Figure 6: The amount of average displacement throughout the searching iterations, comparing with/without additional temporal support and with/without penalty.

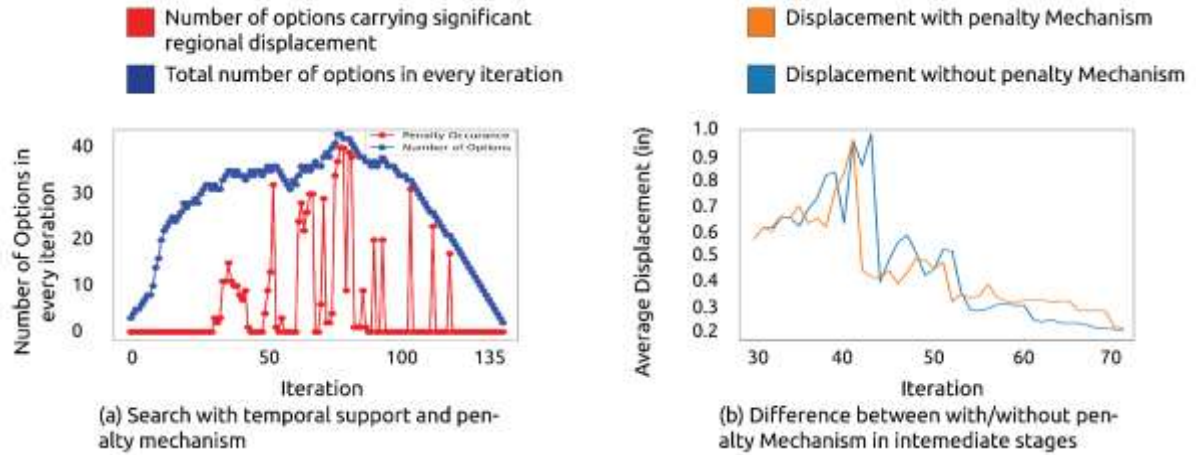


Figure 7: a) The amount of penalty occurrence throughout the searching iterations, b) comparing search with/without penalty that result in different sequencing.

5.2. 1/20 scale physical validation

The physical prototype took the form of a funicular structure with nine footing supports in total (Fig.8a). It is composed of brass rods, which range from 9 to 20 cm in length per piece and have a diameter of 1.6 mm. Although smaller in scale, the assembly faces similar cantilever challenges and is hard to complete by self-support. The stable construction process of this scaled-down, horizontally spanning structure demonstrated how a multi-robot setup plans and executes scaffold-free assembly that aligns with the digital simulation. All ground footings and temporary robot support are defined as fully rigid connections, where connections are manually soldered with tin wire to minimize translational and rotational displacement. The target sequence is fed to the two manipulators, which switch roles as placer and holder, to find executable poses through the inverse kinematic solver provided by the Open Motion Planning Library (OMPL) [16] and RRT-Connect [17] for trajectory planning, upon finding satisfactory poses (Fig. 9 and Fig.10). While the placement sequence strictly follows the output result, some limitations in the holder role are identified due to the robot configuration. There are two reachability failures where the member is out of reach for robot A; therefore, robot B acts as the holder for the same member in both steps.

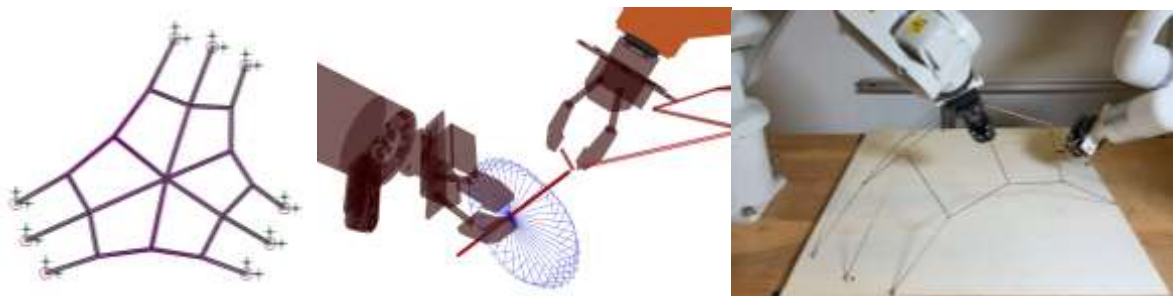


Figure 8: a) The small-scale physical validation structure has nine ground supports and 27 members in its final form. b) Inverse kinematic solver that samples 36 poses around the x-axis of the member to find satisfactory robot poses. c) The finished assembly.

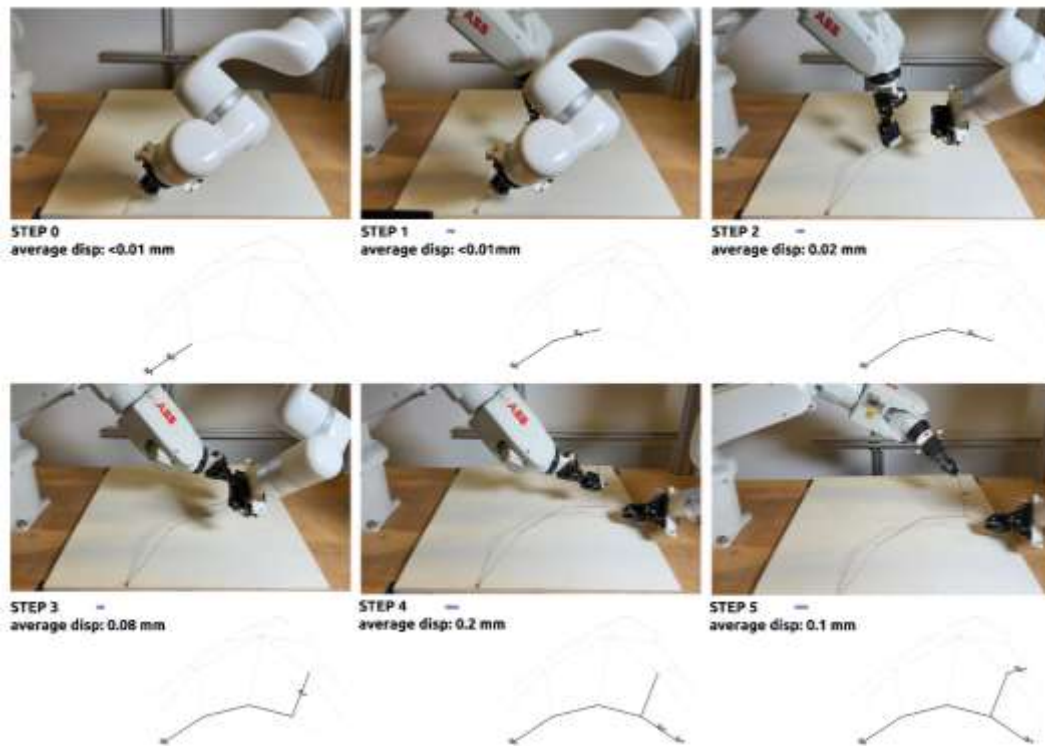


Figure 9: Physical robot motion versus Karamba3D structural analysis in simulation per iteration.



Figure 10: Interpolating robot motions to take rotary roles for placing new components and acting as additional support.

6. Conclusion

This research leverages the benefits of robotic systems as temporary support to stabilize structures during their assembly process. The methodologies in assembly sequence finding build a foundation for integrating real-time structural stability analysis and optimization during the assembly process for frame structures. The initial evaluation results have shown considerable structural improvement in integrating limited mobile support for discrete frame structures, which significantly enhances displacement performance for horizontally spanning structures. The penalty introduced in method three has also demonstrated improvement by identifying displacement outliers to re-rank the options and lower average displacements during the process.

The results have demonstrated how temporary support will significantly enhance the stability of the in-progress structure and have showcased a physical prototype built using a pair of manipulators. For pavilion-scale timber structure simulation, the reaction forces required by the robot are up to 160 N, which can be safely handled by common industrial robots with payloads of 60-120 kg. However, successful collision-free multi-robot pose findings are still strongly dependent on the robot configurations and setup optimization. Robots with mobile bases or more than 6 degrees of freedom will have fewer constraints compared to fixed-base manipulators set up in physical prototyping. In addition, the accumulation of small displacements, although minimized by the sequence finding, still requires the robot application system to detect and address in real-time for construction. Future steps will include integration of fixed-window back-tracking algorithms to prevent manipulator reachability failure, thereby eliminating the need for post-processing and fine-tuning for robot roles or poses.

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