Robotic Assembly of Timber Plate Structures

Design and assembly strategies towards autonomous assembly.

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This research paper introduces design and assembly strategies for autonomous construction of timber plate structures. Current state-of-the-art research shows robotic assembly of Integrally Attached Timber Plate Structures (IATPS) is feasible, yet achieving precise, fully automated assembly encounters challenges such as setup inaccuracies, spring back forces, material warping, and a lack of strategies for design optimization tailored to autonomous assembly. The research comprises three main areas: designing timber plate structures with an emphasis on optimizing joinery design for autonomous assembly, establishing a multi-robotic path planning that considers assembly sequence and direction of assembly, and implementing feedback-based assembly using real-time positional tracking system for accuracy and efficiency. The research investigates the constraints of design by constructing two prototypes: a folded timber plate structure and a trivalent polyhedral timber plate structure. The folded timber plate prototype serves to explore and analyze three different types of joinery. Through this experimentation, effective joinery assembly strategies are identified, which are subsequently applied in the final prototype of the trivalent polyhedral timber plate structure. This research paves the way for future exploration in the field, indicating vast potential for further innovations in design strategies for automated assembly.

Keywords: *Autonomous Robotic Assembly, Multi-Robotic Path Planning, Feedback Based Assembly, Design Strategies & Optimization*

INTRODUCTION

Integrally Attached Timber Plate Structures (IATPS) enable sustainable construction practices by using renewable wood resources, and offer strength and efficiency in building design, comparable to traditional materials like concrete and steel. In the context of IATPS, folded, grid-shell, to name a few provide exceptional strength and stability through their geometric design, and allow for efficient material usage and lighter construction, making them both environmentally friendly and cost-effective in comparison to traditional timber design methods (Stitic et al., 2015). Automated assembly of timber structures significantly enhances precision and efficiency in the construction process, reducing labor costs and construction time. Additionally, it promotes sustainability by optimizing material usage and minimizing waste, aligning with environmentally friendly building practices. Automation aids in sustainable construction by enabling efficient disassembly and reuse of materials, thereby aligning with circular economy principles, and reducing environmental impact (Robeller et al., 2016).

Prototypes developed at the Laboratory for Timber Constructions (IBOIS) at EPFL showcased structures inspired by traditional Japanese joinery, relying solely on interlocking principles without additional fasteners. While feasible with a robotic arm, experiments highlighted challenges in panel insertion, with the required force for tight-fit joints nearing the limits of standard industrial robots (Rogeau et al., 2021). ETH Zurich explored reinforcement learning to control robots in contact-rich assembly tasks, successfully demonstrating this in architectural construction (Apolinarska et al., 2021). ICD Stuttgart used automated large-scale manipulators for on-site assembly of high-payload, form-fit timber components. However, the system, lacking guides, grooves, or mechanical stops, is not optimized for force-controlled insertion (Lauer et al., 2023). Achieving precise and fully automated assembly remains challenging, primarily due to several factors. These include setup inaccuracies, which can affect the initial positioning of components, as well as spring-back forces that occur during assembly, causing components to revert to their original shape. Moreover, potential material warping, or deformation presents another obstacle that requires further development to overcome. Even though these state-of-the-art research projects demonstrates robotic assembly of IATPS, strategies and optimization of design based on the constraints for autonomous assembly are still missing.

Our research aims to identify the challenges for autonomous assembly, develop design strategies and focus on mapping the relationship between timber plate design and robotic assembly constraints for autonomous construction of IATPS. The objective of this research is divided into three key investigations. Designing timber plate structures with an emphasis on optimizing joinery design for autonomous assembly, establishing multi-robotic path planning that considers assembly sequence and direction of assembly, and implementing feedback-based assembly using real-time positional tracking system for accuracy and efficiency. The research is explored through manufacturing and assembly of large 1:1 scale prototypes (refer Figure 1).

Figure 1
Multi-Robotic Assembly of Timber Plate Structures

JOINERY DESIGN

The initial phase of prototyping focused on establishing a foundational understanding of joinery design of timber structure in the context of autonomous assembly. In order to validate the design and construction workflow a folded timber plate structure with 4 distinct timber joinery designs were created. Previous research by EPFL and ETH resulted into a software tool such as Manis (Vuilleumier, 2021) and COMPAS wood (Vestartas, 2024) offering an open source, collaborative design tool for generation of traditional wood-wood connections for IATPS. These joinery generation tools, do not assess the effectiveness of the designs and the efficiency of the autonomous workflow. Our joinery designs evolved from simple bevel and finger joints to more complex dovetail and half-lap mortise-tenon joints (refer to Figure 2).

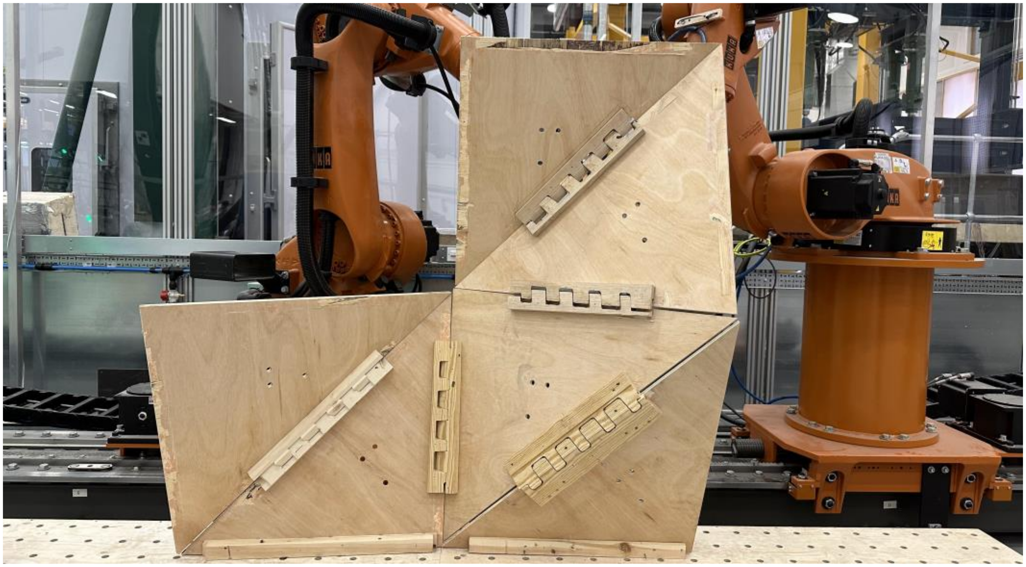


Figure 2
Testing the viability of various types of interlocking timber joinery for autonomous assembly

In the initial version, simple bevel joints on plywood plates highlighted discrepancies between physical and digital designs, problematic joint angles for robotic assembly, and challenges in securing plates, which affected the prototype's stiffness. Despite several iterations, these joints lacked sufficient load-bearing contact surfaces, failing to align with the structure's force vectors, and were too 'open' for effective rigidity. Also, as the surfaces are parallel, they require either a perfect lead-in vector without allowing much tolerance for rotational movement, or a lead in from the side, making it impractical for multiple panels.

We focused on shared plate faces as a key point for intersecting load-bearing surfaces. Similarly, the milled and tapered mortise and tenon joints, despite being robotically assembled, remained too open. Even with a milling tolerance of about 0.3mm, the self-intersecting plate design and the interplay of anticlastic and synclastic plates introduced excessive constraints in robotic assembly and insufficient self-stabilization.

We recognized that a holistic approach was needed, considering the global assembly geometry, plate size, shape, polarity, and integral joint design. Specifically, tapered joints, effective in anticlastic settings, needed to complement synclastic global assemblies, and vice versa. This approach would not only support the structure's integrity but also facilitate automated robotic assembly by reducing constraints.

The final joint designs were optimized for autonomous assembly by achieving the desired degree of freedom in assembly and ensuring structural integrity (refer to Figure 3). Our findings from earlier prototypes were validated by the completion of a anticlastic integral joints that provided self-stabilization and adequately restricted DOF to automate robotic assembly. Specifically, the anticlastic curvatures of tapering and angled mortise and tenon sides and robotically milled inside and outside corners served to stiffen the structure in the XZ plane, while the half-lapped approach to the milled joint also provided stiffness and self-stability in the YZ plane, to generalize.

Additionally, we maintained tolerance-based design strategies through tapering angles to address any potential alignment inaccuracies that may arise during the assembly process. Ultimately, we identified a 10mm insertion taper offset as an ideal initial tolerance (confirming Rogeau’s experiment results) with joint completion bringing the gap to +/-0.3mm, consistent with the shape and optimization of the joint, with priority given to load-transfer surfaces.

In our computational workflow, we utilize robotic fabrication techniques to mill intricate integral type joints that securely connect one plate to another. Therefore, our optimization methodology considers structural analysis, tolerances and direction of assembly. This direction is determined by the sequence provided by the adjacent panels, as well as the contact surface area between the panel joints, which directly affects the strength of the connection. This progression not only facilitated the assembly process but also enhanced the structural integrity of the prototypes. The findings suggest that joint design is a critical factor in the success of robotic assembly in timber construction and structural stability.

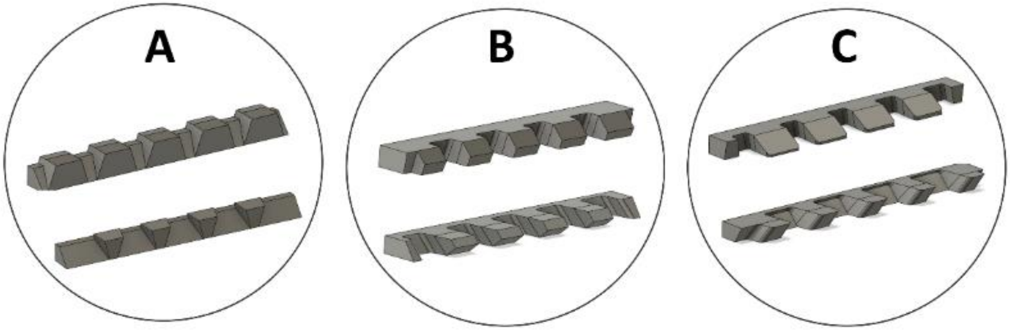


Figure 3
a) Initial Joints (without insertion direction)
b) Update Joints (with insertion direction)
c) Optimized Joints (milling, assembly constraints)

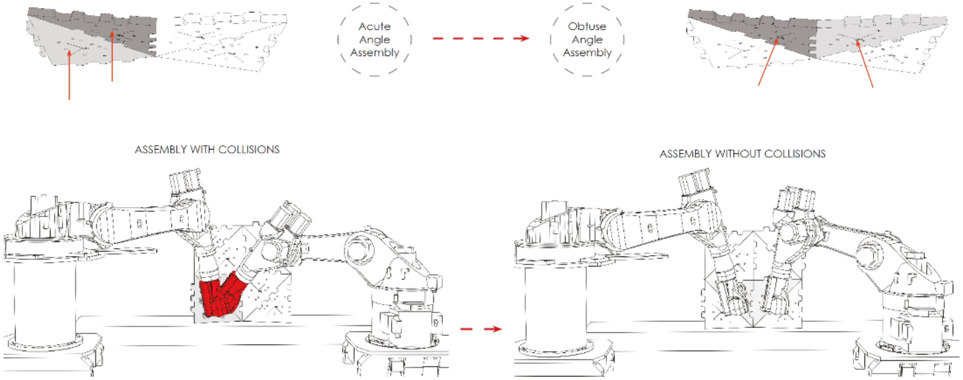
ASSEMBLY SEQUENCE, ASSEMBLY DIRECTION AND MULTI-ROBOTIC PATH PLANNING

The setup consisted of two robotic industrial arms, KUKA KR60 HA and KUKA KR60-L45-4 KS mounted on 11 meters long linear track KUKA KL4000. Each robotic arm was enabled with custom 4 suction cup vacuum gripper. The milling process was executed using Kuka KR6 robotic arm, equipped with a 10,000 rpm Kress spindle.

Prior investigations in the context of multi-timber assembly focusing on self-structural stable joints have been explored in (Koerner-Al-Rawi et al., 2020), (Thoma et al., 2019), (Bruun et al., n.d.).

In the first iteration of the multi-robot assembly for folded timber panel structure, the construction was executed with the robots aligned on the same side, following a parallel assembly direction (refer to Figure 4). Stability was the main sequencing priority in the assembly. Significant challenges occurred due to collisions between the robots and their end-effectors, particularly when assembling two panels that formed acute angles with each other. Strategic sequencing was implemented to prevent interference between one robot holding a plate and another inserting a plate, unless the adjoining plates formed an obtuse angle for safe operation (refer to Figure 4). Effective strategies included assembling of panels from bottom to top to ensure stability and from outward to inward, were explored to circumvent issues associated with acute angles during assembly. The study's diagrams (refer to Figure 4) demonstrate how different assembly techniques for plates with acute versus obtuse angles address the stiffness challenges inherent in self-intersecting geometrical designs.

Figure 4
Robotic collisions while assembly



During the assembly process, one robot is responsible for stabilizing the structure, while another robot inserts a panel. Occasionally, the stabilizing robot holds the far end of the structure, leading to deviations and potential inaccuracies due to weight-induced swaying. To address this issue, a strategy has been developed to reposition the stabilizing robot to a more effective support location, thereby improving stability. This new position is also optimized to avoid the trajectories of other robot, preventing possible collisions. This procedural adjustment can be applied at different stages throughout the assembly process (refer to Figure 5).

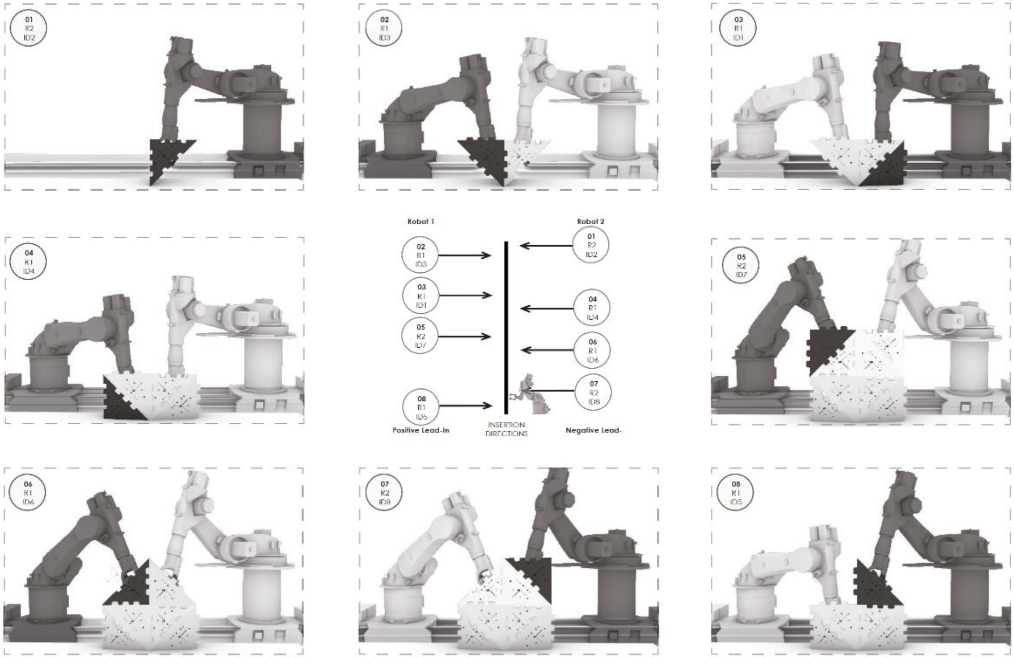


Figure 5
Sequence and Direction of Assembly Strategies

Next, the insertion direction was tested using both positive lead-in motion (moving away from the robot) and negative lead-in motion (moving towards the robot). Positive lead-in, where forces acted along the same side, resulted in a slight movement of plates that had already been assembled. In contrast, negative lead-in insertions were stiffer, as the forces acted in opposite directions. To evaluate the impact of force direction, the geometry for the subsequent assembly was rotated 90° to allow for perpendicular insertion.

In the second iteration, the timber panels were constructed at a 90° angle with robotic arms in opposite configurations, explored the advantages and disadvantages of assembling from opposite sides (refer to Figure 6). This method theorized that one robot's holding would counteract the pull from the suction cups more effectively. Sequencing was dependent on the polarity of joints/plates, with more flexibility in handling obtuse and acute angles. This configuration offered more robust work holding, allowing greater force application during joint completion. All insertion vectors directly matched the adjacent plates' polarity, but scripting was more complex due to the need for a constant offset in the placement plane.

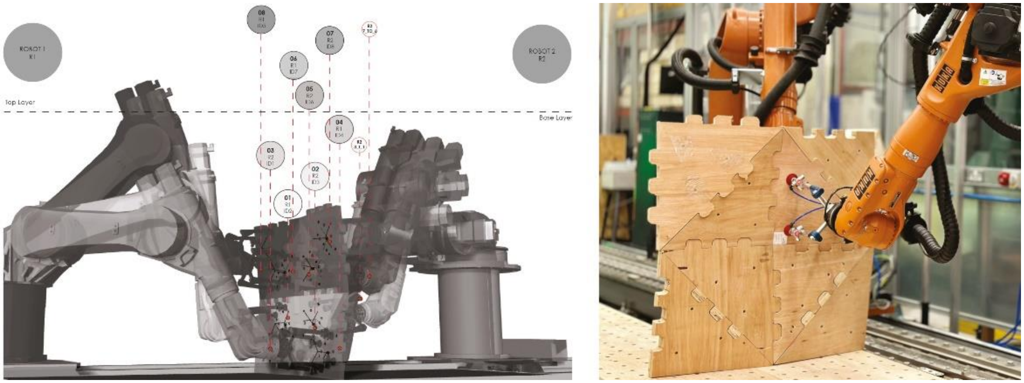


Figure 6
Sequence and Direction of Assembly Digital Optimization (left), Prototype Assembly with 90-degree robotic setup (right)

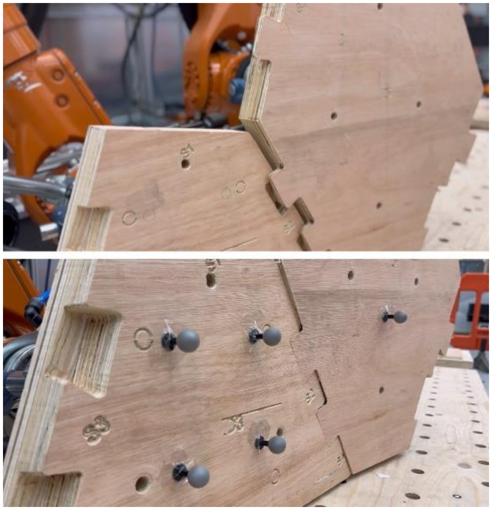


Figure 7
Inaccuracies in assembly leading to collision between panels (above).
Precise positioning of panels using Motion Capture System (below)

The digital workflow includes optimizing the assembly sequence by redesigning the timber plate structure and enhancing the assembly direction through alterations in the joinery design. This process is characterized by an iterative feedback loop where continuous, comprehensive feedback from the assembly process informs ongoing design refinements. This cycle of feedback ensures consistent improvement and adaptation in both design and manufacturing strategies, leading to a seamless, automated, and feedback-driven design workflow.

FEEDBACK BASED ASSEMBLY

As the prototypes advanced in complexity, the precision of assembly became increasingly critical. Tool calibration and base calibration by the robot, inaccuracies in manufacturing of the panels, warping and deformation of panels during manufacturing and after assembly were the main factors for inaccuracies. To enhance accuracy, OptiTrack, motion capture system, was introduced as a tool for comparative analysis between the digital model and the physical prototype (Schön et al., 2022).

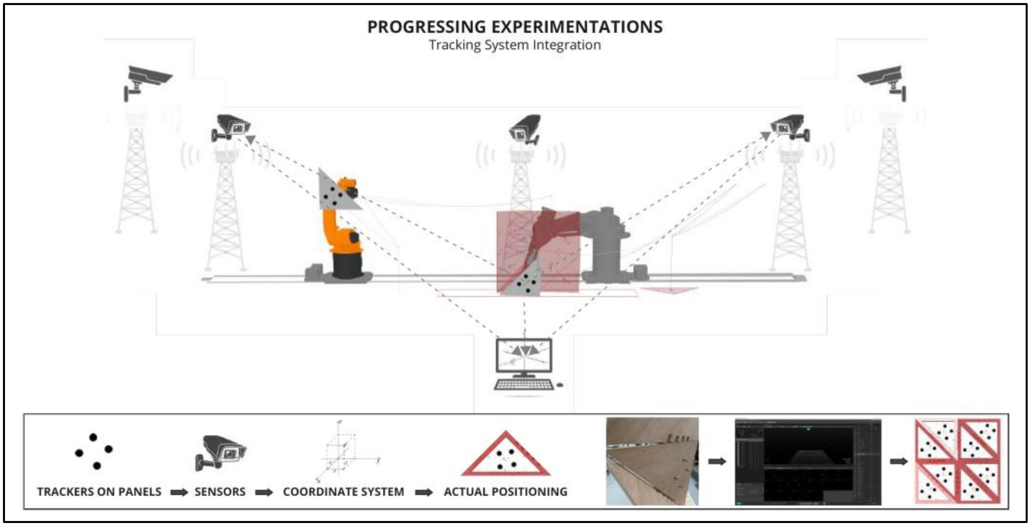


Figure 8
Feedback system for positional tracking

The OptiTrack motion capture system contributes to the accuracy and efficiency of the robotic assembly by assisting in fine-tuning the linear movement during insertion, particularly near completion when real-world constraints cause deviations from the design model (refer to Figure 7). For the setup, 8 OptiTrack Flex 13 cameras were used. Depending on the success levels of the calibration process, hardware used and placement of retro-reflective markers, a 3D precision of +/- 2 mm can be achieved. This technology also allowed for quick capture and processing of data, providing insights into deviations, and enabling near-time corrections. Additionally, the integration of OptiTrack and KUKA var Proxy to enable closed loop informed trajectory for accurate positioning of panels (refer to Figure 8), further refined the assembly process. These technologies enabled real-time adjustments and corrections during the assembly process, ensuring that the physical construction closely matched the digital models.

FINAL PROTOTYPE

The prototyping process culminated in the development of final prototypes that showcased the full potential of robotic assembly in timber construction (refer to Figure 9). These prototypes incorporated complex 8 trivalent polyhedral plates, featuring advanced dovetail and half-lap mortise-tenon joints (refer to Figure 10). The design optimization included uneven hexagonal panels with non-uniformly positioned centroids, which disrupted linear adjacency between panels. This arrangement, along with the distinct horizontal and vertical separation of face vectors in adjacent assembly plates, was instrumental in reducing collisions. The final prototypes embodied a synthesis of all learned aspects, encompassing both design and assembly strategies, and highlighted the unique features of the design.

Figure 9
Design and Assembly Workflow

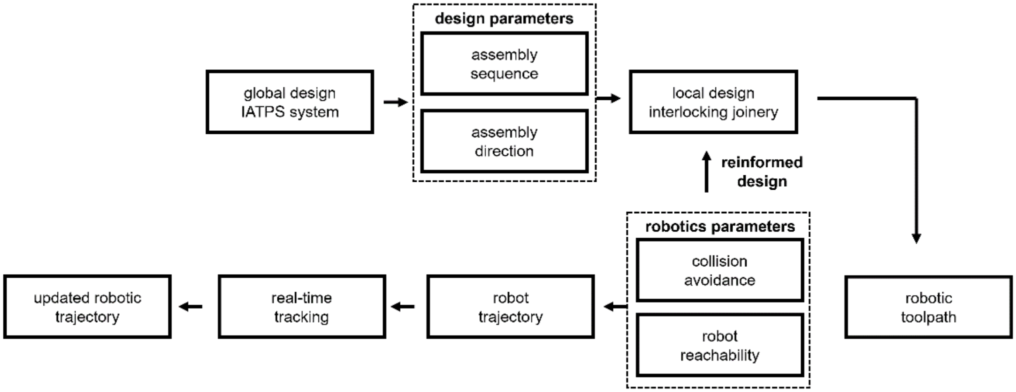


Figure 10
Final Prototype

CONCLUSION

The research enhances robotic assembly of IATPS by showcasing a method where integral joints aid in automated assembly, ensuring movement constraint for self-stabilizing plate connections. It incorporates a global design enabling multiple robotic arms to access and place panels without collision, achieved through pre-planned sequencing. This approach suggests IATPS could be a fully automated, deployable structure. The study also explores the deployability potential of IATPS in conjunction with automated assembly.

By demonstrating that closed loop feedback systems can correct positional errors and that the design and optimization of integral joints facilitate the self-guided locking of two panels, the research advances the field of robotic assembly. Moreover, this research contributes a system design beneficial to others in the field, including researchers and industry practitioners, aiming to establish a design-to-manufacture ecosystem for IATPS. The assembly techniques demonstrated are repeatable and adaptable, suggesting a standardizable approach for specific use cases and a move towards autonomous onsite assembly.

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