From Passive to Active Matter

A novel robot-material system for parallel construction

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Collective robotic construction (CRC) is an emerging automation approach that employs multiple machines to assemble large-scale structures, often relying on small robots with limited payloads. Such systems are typically developed through a co-design process that jointly evaluates the material, building, and robotic systems responsible for assembly. On the material side, research in CRC has focused on systems where active robots assemble passive materials. This has led to the development of expensive and less fault-tolerant CRC systems, undermining CRC's intended advantages of simplicity, affordability, and robustness. To address this limitation, this paper expands the co-design process in CRC to include the design of the assembled material using programmable materials—shape-changing materials that transition between predefined states. This study explores the feasibility of programmable materials for geometry aggregation, alignment, connection locking, structural stabilization, and robotic manipulation to reduce reliance on the robotic system. To test this approach, a CRC system combining a Hoberman sphere-inspired building material with a bespoke robot is introduced. By shifting from passive to active materials, this research highlights the benefits of embedding system intelligence within materials to enhance assembly efficiency and reduce robotic complexity.

Keywords: *Collective Robotic Construction, Construction Automation, Programmable Materials, Discrete Assembly, Agent-Based Modeling and Simulation (ABMS), Co-design.*

INTRODUCTION

Collective robotic construction (CRC) is an emerging paradigm for large-scale automation, where multiple robots collaborate to assemble complex structures (Petersen et al. 2019). By distributing tasks among small, agile machines, CRC achieves a level of flexibility and adaptability that existing automation methods cannot match. However, current research in CRC predominantly focuses on sophisticated robotic mechanisms and assembly algorithms, often overlooking the role of materials. This places the burden of assembly tasks entirely on the robots, necessitating expensive and less fault-tolerant robotic systems that undermine CRC's core advantages of simplicity, affordability, and robustness.

This limitation argues for a bottom-up co-design, where material intelligence contributes

directly to the CRC process. Advances in programmable materials—capable of changing form and function when activated—enable materials to self-transform, collaborating with humans and machines to achieve more than passive manipulation allows (Tibbits 2016).

This research explores the integration of programmable materials into CRC via a material-robot co-design. We present a proof-of-concept system embedding intelligence into a Hoberman sphere-inspired material module—a scissor-linkage structure capable of radial expansion and contraction—to facilitate robotic assembly (Figure 1). By distributing deployment, alignment, and connection locking between materials and robots, the system enhances collaboration and reduces robotic complexity. While CRC broadly refers to collaborative multi-robot assembly, the co-design enables parallel, decentralized construction where multiple robots work on different parts of a structure simultaneously.

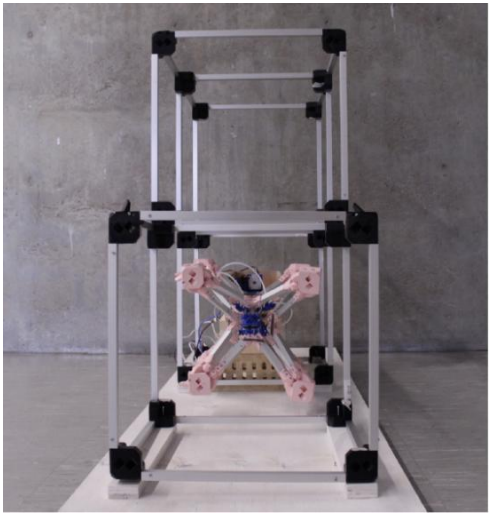

Figure 1
Prototype of the integrated system, featuring a Hoberman sphere-inspired module with a robotic actuator for collaborative assembly

BACKGROUND

This section discusses related work in CRC, discrete assembly, and programmable materials.

Towards scalable, adaptive, and sustainable CRC

The construction industry generally relies on singular large-scale machines. Although the automation of such machines is increasing, this approach to automation is often constrained by limited reach and reliance on human labor for site-specific tasks, posing risks and limiting scalability in dynamic environments.

CRC provides a promising alternative, leveraging decentralized robotic units to autonomously assemble structures larger than themselves (Petersen et al. 2019). Capitalizing on modularity, CRC enables parallel task execution among multiple robotic units, enhances resilience against environmental disruptions and part failures, and minimizes human involvement (Petersen et al. 2019).

Effective CRC considers the integration of the material, building, and robotic systems. Research on wheeled, aerial, aquatic, and climbing robots, combined with deposition techniques for discrete (e.g., bricks) and continuous materials (e.g., fibers), demonstrate the increased efficiency, adaptability, and reduced human involvement in hazardous tasks (Petersen et al. 2019). Despite advancements, hurdles persist, including assembly precision, robotic complexity, structural stability, stochastic errors, and payload limitations. Precision issues mainly stem from material tolerance and connectivity, while material size impacts structural resolution and hardware constraints. Many CRC systems rely on robots with intricate sensing and actuation to manipulate passive materials, increasing cost and mechanical complexity. The wide use of continuous or monolithic materials often leads to stochastic errors (Jenett et al. 2019), while limited payloads hinder architectural-scale applications (Leder et al. 2024).

These interdependent robotic and material constraints highlight the need for material-robot co-design in CRC.

Discrete assembly

Traditional construction relies on heterogeneous materials (e.g., concrete) and non-repetitive components (e.g., stone of varying sizes). Their lack of standardization introduces computational challenges and limits robotic adaptability (Retsin 2016). Yet, Gershenfeld et al. (2015) introduces digital materials: discrete components that can be reversibly joined with relative positions and orientations. This modular nature, where digitally computed parts directly correspond to physically assembled parts, offers advantages including improving precision through integration with computational logic, allowing scalability and reconfigurability for material reuse, and simplifying robotic assembly with standardized components (Gershenfeld et al. 2015).

Discrete assembly, rooted in digital material principles, offers a scalable and reversible strategy for constructing complex, digitally informed geometries. The Tallinn Architecture Biennale Pavilion (Retsin 2020) extends this concept through combinatorial design, generating intricate timber assemblies. Robotic technologies expand the potential of discrete assembly, enabling localized transformations and parallel assembly and disassembly. Projects like CurVoxels and INT (Retsin and Soler 2017) employ stationary industrial robots for additive fabrication of discrete units, while Bill-E (Jenett et al. 2019) is a mobile robotic system that assembles lattice structures autonomously.

Programmable materials

Programmable materials are designed to change their behaviors in response to activation energies (Tibbits 2016). Their transformation depends on three key characteristics (Papadopoulou, Laucks and Tibbits 2017): i) material composition and organization (e.g., proportions of active/non-active materials); ii) activation energy required to trigger the transformation (e.g., temperature); and iii) the material's behavior under activation (e.g., wood shrinking in response to moisture).

Research on programmable materials primarily focuses on three actuation mechanisms: i) intrinsic material properties, where materials respond to environmental changes due to its inherent characters (e.g., shape memory alloys to temperature); ii) internal kinematic constraints, where mechanically actuated structures require external forces (e.g. motors) for transformation. This includes metamaterials (Ou et al. 2018), architected tessellations and deployable linkages (Adrover and Rivas 2015); iii) pressure differentials, which power soft robotics and inflatable structures. Architectural applications have included leveraging wood's hygroscopic properties for climate-responsive structures, as seen in HygroShell (Wood et al. 2023), as well as deployable linkages in the London Tower Bridge.

Despite advances, integrating programmable materials into CRC remains underexplored. Some studies speculate that robots perform as building materials to achieve self-assembly. The noMad project (Architectural Association Design Research Lab, 2015) introduces a system where self-structuring units morph autonomously between polyhedral states via transformable linkages, each driven by an embedded robot. Likewise, Autonomous Robotic Tensegrity (Hosmer and Tigas 2019) combines robot-actuated tensegrity units for self-morphing and adaptive mobility. While these systems leverage the building material as a collaborative assembler through their encoded programmability, the use of embedded robots in each unit raises the robot count and cost. Nonetheless, these examples reveal a promising direction towards integrating active materials in CRC for adaptive, parallel assembly.

APPROACH - CO-DESIGNING MATERIAL AND ROBOT AS AN INTEGRATED SYSTEM

Typical digital-to-physical workflows in digital fabrication and construction follow a linear, top-down approach, where machines dominate, and material remains passive. Advances in materials and fabrication now invite a shift towards bottom-up,

feedback-driven interactions between material and machine (Yablonina and Menges 2019). Co-design embraces this shift by integrating fabrication and material constraints early in design, allowing negotiation between material behaviors and robotic capabilities for a collaborative and adaptive process. (Knippers et al. 2021; Skoury et al. 2024).

In CRC, co-design is crucial for managing material tolerance, coordinating material-robot interactions (Leder et al. 2024), and optimizing robotic perception and mobility (Petersen et al. 2019). While recent studies in CRC have explored material-robot co-design (Leder et al. 2022; Abdel-Rahman et al. 2022), most CRC systems treat materials as passive. This study extends co-design by embedding material behaviors into robotic construction process with three key design parameters:

- Material shape-changing mechanisms that influence robotic manipulation and assembly behaviors.
- Robot behaviors adapt to material properties (locomotion, gripping, actuation concerning the material's form and transformation)
- An assembly algorithm that governs build sequences, ensures smooth robot-material handoffs, and defines an adaptive structural progression.

By integrating these parameters, this co-designed material-robot system rethinks building materials as generative collaborators, unlocking possibilities for adaptive, parallel construction.

CRC SYSTEM DEVELOPMENT

To test this new approach, a CRC system, combining a Hoberman sphere-inspired transformable building module with a bespoke robot, was developed through the co-design of the robotic and material system (Figure 2).

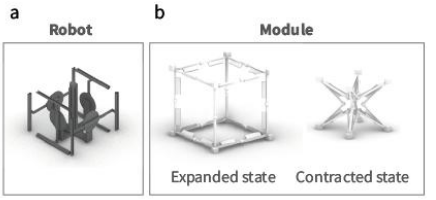

Figure 2
(a) Robot concept with an extendable arm and 8 gear wheels aligned to the module's side rails for in-structure locomotion
(b) Deployable cubic module in expanded and contracted states, featuring integrated side rails

System conceptualization

The proposed system revolves around three core material-robot interaction behaviors, which further inform robotic locomotion principles and introduce novel assembly features.

Material-robot interactions. (Figure 3). Three collaborative behaviors are conceptualized for efficient operations and continuous aggregation.

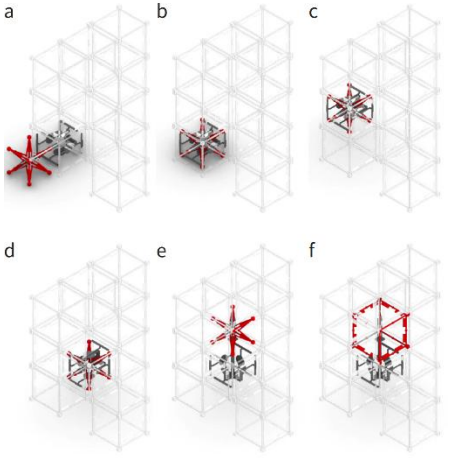

Figure 3
(a-b) Module pickup
(c-d) In-structural transversal
(e-f) Module deployment and locking

Locomotion principles. Navigation and module positioning are achieved through two principles: i) linear movement along three orthogonal axes to simplify mobility and enhance positioning accuracy; ii) controlled two-axis rotation for orientation adjustments during placement, minimizing the risk of alignment errors (Figure 4).

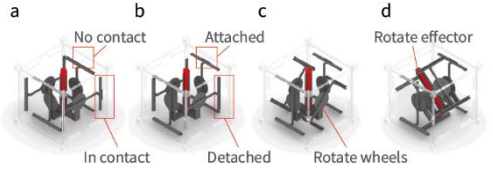

Figure 4
Two-axis rotation
(a-b) Four wheels expand along the rotation axis to brace the module, and the other four contract
(c) The contracted wheels rotate 90°
(d) The effector rotates around the selected axis for positioning

Assembly Features. (Figure 5). The system enables i) parallel construction from multiple ends; and ii) construction of structurally challenging configurations—such as overhanging and cantilevered structures—from top to bottom. These features allow the system to generate spatially complex and non-linear architectures beyond traditional bottom-up aggregation.

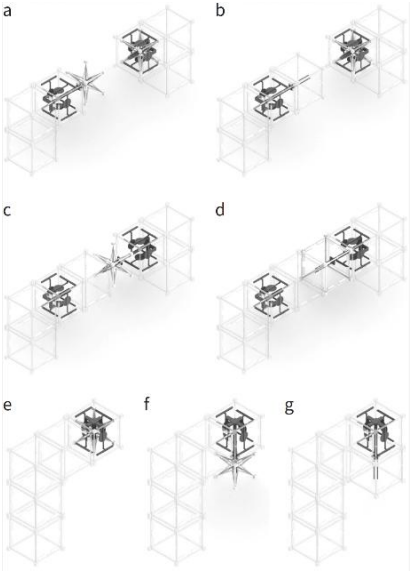

Figure 5
(a-d) Bridge structures simultaneously from multiple ends
(e-g) Construct overhanging and cantilevered structures from top to bottom

Material system

The material module enhances material-robot collaboration with simplified robotic kinematics via i) a modular cube for in-structure locomotion, ii) robot-friendly deployment using a bi-stable mechanism, and iii) self-aligning interface.

Modular cube for in-structure locomotion. The cubic module serves as the core building unit. Selected for its geometric regularity, the form allows simplified in-structure navigation along orthogonal axes, reducing path-planning complexity. It forms lightweight space frames for load transfer and stability. Local transformation is possible with a shape-changing mechanism, allowing parallel and reconfigurable assembly. The discrete modularity isolates failure within individual units, avoiding system-wide collapse.

Deployable linkage for shape transformation. (Figure 6a-b). Drawing from Hoberman-like mechanisms (Sun, Yao and Li 2019), the module uses a propagating linkage system for compact-to-expanded volumetric efficiency. Activation of four mid-joints triggers a cascading motion that engages adjacent corner joints, allowing autonomous deployment with reduced robotic actuation. Once expanded, the spring forces in the bistable mid-joints lock the structure in shape.

Material-material interface for alignment and locking. (Figure 6c). Each corner joint has a material interface enabling self-alignment and auto-locking with neighbors. Three orientation-encoded faces, designated male or female, ensure proper alignment and interlocking, while reducing computation and optimizing placement.

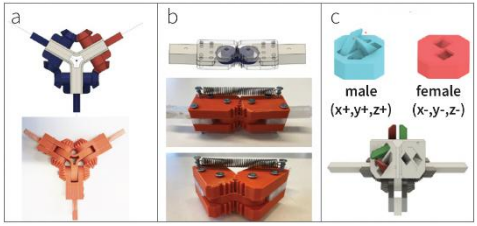

Figure 6
(a) Compliant corner joint with one pair of bevel gears activating the other two
(b) Bistable mid-joint with the same mechanism as the corner joint
(c) Three-face male/female material interface

The prototype (Figure 7) demonstrates bi-stable shape transformation and a self-aligning material interface.

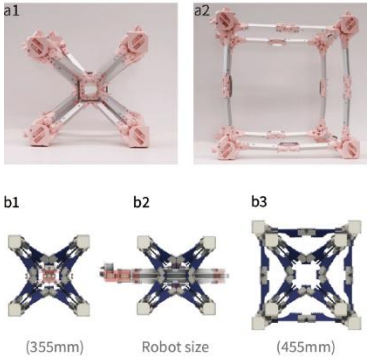

Figure 7
(a1) Undeployed module. (a2) Deployed module. (b1–b3) Size comparison: undeployed module (b1), robotic effector (b2), and deployed module (b3)

Robotic system

Designed to fit within a cubic structure, the robot consists of i) a conceptual locomotion system using gear wheels for controlled movement, which is not yet developed, and ii) an effector for material handling, comprising three main parts (Figure 8).

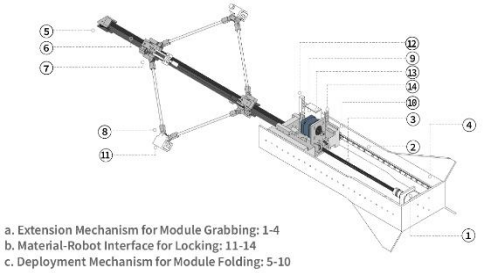

Figure 8
The mechatronic design of the effector includes: (a) extension mechanism, (b) material robot interface, and (c) deployment mechanism

Extension mechanism. (Figure 9). A stepper motor drives a threaded rod, moving a guiding screw along a carbon tube for precise effector extension to grasp new or place already held modules. Two sliding blocks on linear guide rails hold the effector to ensure stable actuation.

Material-robot interface. (Figure 10). A servo-driven Bowden tube system utilizes tension from a cord within the tube to engage the lock. The servo retracts the cord via a gear, activating a switch that locks the clamp and module interface, holding the module securely in place.

Deployment mechanism. (Figure 11). A motor-driven belt system, guided by pulleys and supported by a carbon tube at the effector's length, controls the linear motion of two sliding connectors, enabling the effector to fold and unfold to reach modules.

This robotic system supports reliable deployment, alignment, and locking to optimize material-robot collaboration in CRC.

Assembly algorithm

To apply the proposed material and robotic systems to real-world architectural scenarios, a computational tool is required to coordinate the building sequence. We developed a voxel-based robotic assembly algorithm that integrates an Agent-Based Modeling System (ABMS) with the A* shortest-path algorithm to optimize construction (Figure 12).

Preprocessing the input geometry for supports and raft generation. Voxelization simplifies designs by retaining only intersecting voxels within bounding box. Support structures are generated from voxel centers using 3D printing-inspired heuristics (e.g., layer height, support area, overhang angle). Rafts are created by projecting the voxel centers onto the XY plane.

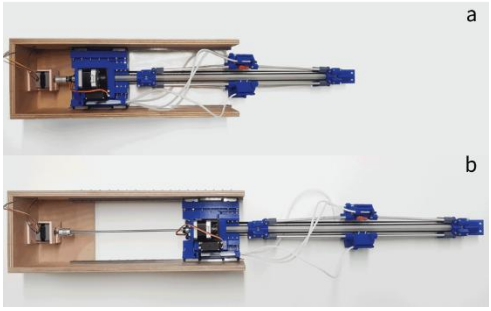

Figure 9
Extension mechanism: (a) The robotic effector in contracted state (b) The robotic effector is extended

Figure 10
The material-robot interface

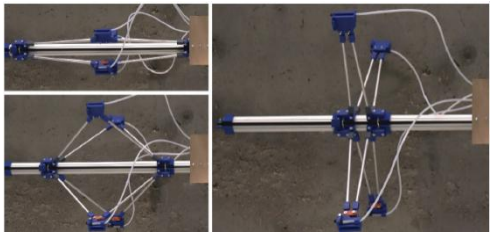

Figure 11
Deployment mechanism: Adjusting the elbow folding of the effector extension to deploy the module

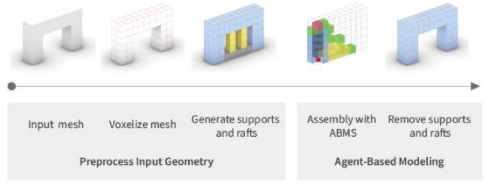

Figure 12
Workflow of the assembly algorithm

Agent-based modeling system (ABMS) with A* algorithm for motion path planning. ABMS can merge architectural design and robotic planning into a unified workflow for CRC (Leder and Menges, 2024), supporting decentralized robotic coordination and real-time decision making. In this research, an A* algorithm (García et al. 2022) was integrated into an ABM, computing cost-effective routes between start and goal positions at each iteration of the model. This combination allows robots to adapt their paths in response to structural changes and neighboring agents, improving collaboration and assembly efficiency.

This system is built on the agent-based modeling framework ABxM (Nguyen et al. 2022) where robots act as autonomous agents that track their work state (Figure 13), target, path, and position, while the environment maintains a global record of their starting points, available targets, and voxel status. Integrating the A* algorithm, the system evaluates travel cost to select the most efficient, obstacle-free path.

Assembly and disassembly process. (Figure 14). The construction process—encompassing structural voxels, supports, and rafts—follows an ordered logic informed during preprocessing. Structural voxels become available once their required supports are placed, and supports are assembled after the completion of the voxel directly beneath them.

As each robot reaches its target and completes a task, a post-processing routine is triggered to update the environment and determine the agent's next target based on resolved structural dependencies. The system dynamically adjusts relevant voxel status depending on the robot's current task—whether building structures, disassembling supports, or removing rafts. For support voxels, the system verifies the voxel beneath is already placed before including them in the candidate pool. Once dependent voxels are built, the support can be removed and reused for other structural voxels.

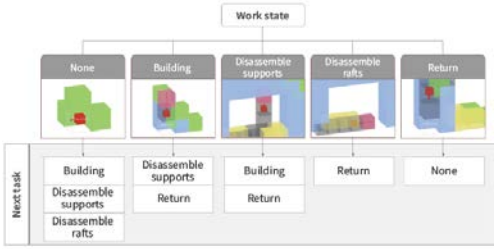

Figure 13
Work states of the agents

After all structural voxels are in place, agents proceed to disassemble all supports, followed by raft removal. Completion of disassembly marks the end of the construction process.

Through this logic, the ABM continually updates build states and distributes tasks, while the A* algorithm ensures efficient navigation. Together, they enable adaptive, bottom-up coordination of large-scale construction.

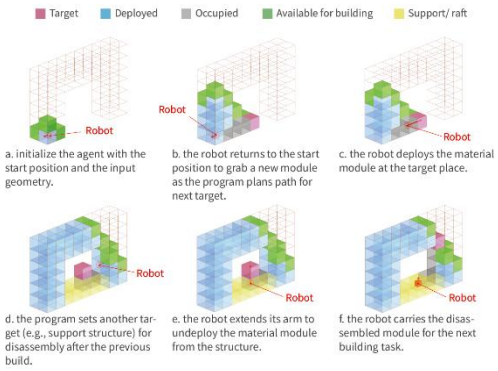

Figure 14
A simulation scenario where a robot starts with an assembly task (a-c), followed by a disassembly task (d-f)

EXPERIMENT

Physical prototypes were assembled to explore the system in practice (Figure 15). Several challenges emerged while attempting to perform assembly, disassembly, and departure scenarios, including misalignment due to material non-uniformity from low quality 3D printing, actuation smoothness due to limited power efficiency, and weight constraints. These limitations underscore the need for future enhancements in both material and robotic design, which will be discussed in the following section.

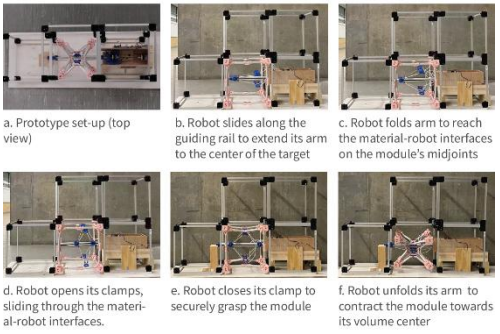

Figure 15
Physical disassembly experiment
(a) Set-up top view
(b) Robot to extend the arm
(c) Robot to fold the arm
(d) Robot to slide into the material-robot interface
(e) Robot to lock the module
(f) Robot to unfold the arm

DISCUSSION AND CONCLUSION

This research introduces a co-design framework that embeds system intelligence into materials, showcasing the use of programmable materials in CRC. By combining discrete assembly with shape-changing modular materials, the system enhances material-robot collaboration, and enables localized, reconfigurable construction. The assembly algorithm optimizes build sequences and navigation paths, creating a synergistic system that allows the construction logic to emerge through interaction rather than prescription.

While this study focuses on a small-scale prototype, future iterations must consider how the system can scale across different building sizes and types. At larger scales, factors such as material stiffness, joint tolerances, robotic payload, and structural performance become more prominent. Designing for scalability requires exploring more efficient shape-changing mechanisms, enhancing robotic capabilities, and developing a Cyber-Physical system (Skoury et al. 2024). Addressing these limitations will unlock CRC's full potential.

Ultimately, this research lays a groundwork for a future where materials are not passive elements but active collaborators in construction. By framing building as a dynamic interplay between programmable matter and distributed robotic agents, it envisions an architecture that is intelligent, adaptive and co-assembled.

Further development is needed across all levels of the proposed CRC system.

Material system. Future iterations must improve the size ratio between deployed and undeployed states and optimize the shape-changing mechanism to reduce material-robot interfaces, which currently limits robot mobility and increases collision risks. Stiffer materials and refined joint connections can potentially enhance the overall structural stability. Greater fabrication precision is required to mitigate misalignment and decrease material weight without compromising strength.

Robotic system. Robot geometry should be optimized for better maneuverability—a shorter effector, for instance, would allow smoother rotation in confined spaces. Increased power efficiency will

enhance payload capacity and enable reliable weight support and fast actuation. Equipping robots with sensors would also facilitate local communication, structural monitoring, and decentralized control for task allocation and error handling. Finally, the orthogonal locomotion mechanism of the robot is missing and would need to be developed.

Assembly algorithm. Current limitations include inadequate handling of structurally sensitive geometries like shells, which constrain the A* algorithm's applicability. Future development should integrate structural performance metrics into support generation logic and allow for multiple start/home bases for robots to increase flexibility. Incorporate feedback loops from the physical assembly process into digital planning would enable real-time error correction and adaptation. Additionally, material modules should also be digitized with embedded orientation data to refine the pathfinding and placement.

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AUTHORSHIP INFORMATION

The first two authors contributed equally to the project and are listed alphabetically by last name.

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