Self-Folding Modular Chain Robot for Shape-Changing Objects

Sergio Mutis
Massachusetts Institute of Technology
Cambridge, MA, United States
smutis@mit.edu

Alexander Htet Kyaw
Massachusetts Institute of Technology
Cambridges, MA, United States
alexkyaws@mit.edu

Rodrigo Gallardo
Massachusetts Institute of Technology
Cambridge, MA, United States
ragallar@mit.edu

Diana Mykhaylychenko
Massachusetts Institute of Technology
Cambridge, MA, United States
diana_mk@mit.edu

Erik Demaine
Massachusetts Institute of Technology
Cambridge, MA, United States
edemaine@mit.edu

Figure 1: Self-Folding Chain Robot Reconfiguration Catalog

Abstract

We present a programmable self-folding modular robotic chain capable of transforming input 3D geometries into reconfigurable objects. Our system integrates three components: geometric discretization of target volumes, a path-finding and folding algorithm, and the design of modular robotic chain hardware. To validate the approach, we constructed a 12-module robotic chain and demonstrated folding sequences that approximate everyday objects such as a table, stool, and steps. Preliminary results show that the system can transition between 2D and 3D configurations, achieving stable forms under limited load-bearing conditions.

CCS Concepts

• **Computing methodologies** → **Motion planning**; *Modeling and simulation*; • **Computer systems organization** → *Robotics.*

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Keywords

Modular Robots, Programmable Matter, Self Assembly, Folding, Shape Changing Interfaces

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1 Introduction

Shape-changing objects have the potential to enable adaptive structures that respond to tasks, environments, and user needs [Nakagaki et al. 2016]. Prior work has demonstrated the feasibility of reconfigurable structures and on-demand creation using generative AI and discrete components, but these approaches typically require separate robotic assemblers [Hosmer et al. 2024; Kyaw et al. 2025a,b]. Research in modular, self-assembling, and foldable robots has further highlighted the potential of programmable folding and reconfiguration, yet scaling such systems to occupy large 3D volumes with continuous connectivity remains challenging [Knaian et al. 2012]. A central difficulty lies in translating geometries into actuation commands that satisfy both geometric and robotic constraints [Cheung et al. 2011; Luo and Lam 2023]. In this paper, we introduce a programmable self-folding modular robotic chain that addresses this challenge through three features: (1) a continuous foldable chain structure, (2) the use of fixed-angle tessellations to decompose geometry, and (3) a chain robot system that requires only two motors per module to control yaw and pitch angles.

2 Method

Our method translates an input 3D geometry into a continuous, physically foldable chain of connected robotic modules. The system requires: (1) geometric discretization, (2) path-finding and folding algorithm, and (3) modular robot chain deployment. (Figure 2)

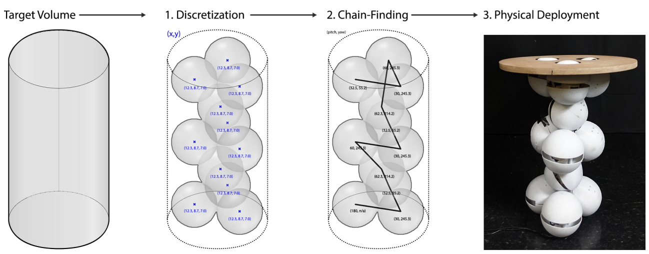

Figure 2: 12-Module Robot Chain and 2 DoF Module Detail

2.1 Geometric Discretization

The process begins by packing a 3d tessellation of polyhedral units into a target volume. These polyhedra fit precisely in a 15cm diameter sphere, which matches the robotic modules. We explored rhombic dodecahedra tessellations, representing a 90°-based chain angle, and truncated octahedra tessellations, representing a 60°-based chain angle. Finally, the centroids of these polyhedra are extracted as the base of the chain-finding calculation.

2.2 Chain Finding and Folding Algorithm

We developed a chain-finding algorithm that connects the centroids. We frame this as a Hamiltonian path problem, where all centroids must be visited exactly once [Abel et al. 2013]. Our approach uses a modified depth-first search (DFS) with a distance-constrained neighbor graph, where connections are allowed only if modules are within 150 mm. The algorithm prioritizes nearest unvisited neighbors, prunes infeasible paths early, and employs stack-based DFS with backtracking to ensure each module is visited once while minimizing total path length, yielding viable solutions in real-time for chains of 0-20 modules. Once a chain is determined, its yaw and pitch angles are calculated at each node, corresponding to the two joint rotations in each module.

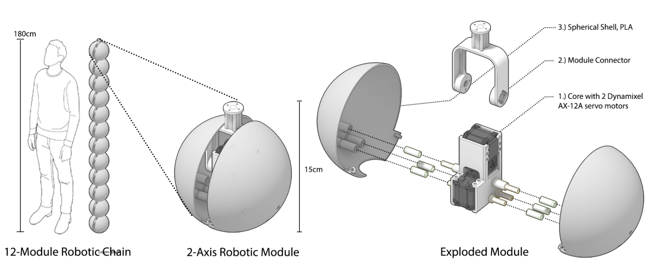

Figure 3: 12-Module Robot Chain and 2 DoF Module Detail

2.3 Modular Chain Robot Design

To validate that computed angles translate into physical motion, we built a 12-module robotic chain and tested the full geometry-to-actuation pipeline. Each chain module consists of three main components: (1) a core housing two AX-12A Dynamixel servos (two degrees of freedom), (2) an arm connecting modules, and (3) a 3D-printed shell (14 cm diameter) protecting the interior.

The starting module hosts a U2D2 for command translation and a U2D2 power hub for distribution. Daisy-chain wiring minimizes cable management and enables modularity. The spherical shell mitigates collisions during folding and supports folded assemblies. With the 12-module chain assembled, we evaluated transitions between two-dimensional and three-dimensional configurations.

The robot can easily fold and unfold in two dimensions without overloads or clashes. For three-dimensional configurations, a single module can lift at most two others. To account for physical constraint and robot feasibility, three-dimensional configurations are completed through coordinated multi-joint actuation (Figure 4).

3 Results

We modeled three everyday objects: a table, a stool, and a set of steps. Then, our pipeline calculated the angles and folding sequence for a straight chain to transform into those objects. We also designed flat surface components that can interface with the chain robot to add stability and improve usability. During physical deployment, among the three, the step configuration was most successful, folding in 2D before lifting itself into its final form. The stool sequence was similarly successful, with a minor mismatch ($\tilde{5}$cm) from the target shape. The table sequence, though successful, remained unstable and required careful handling. These studies are spatial demonstrations rather than structural evaluations, showing how one programmable chain can shift into a range of forms.

4 Conclusions

We demonstrated how programmable angle chains can generate reconfigurable geometries by combining computational folding with a modular robotic system. Future directions include developing generalizable folding methods grounded in torque, reachability, and collision avoidance to enable reliable 3D folding and transferable planning, as well as extending beyond shape-changing objects to load-bearing functional objects such as furniture or larger-scale structural assemblies.

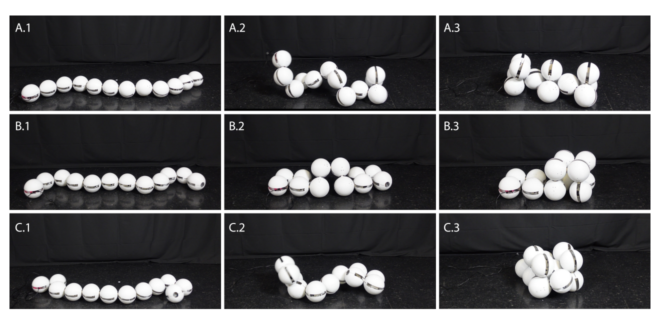

Figure 4: 3D folding sequences of various shapes

References

Zachary Abel, Erik D. Demaine, Martin L. Demaine, Sarah Eisenstat, Jayson Lynch, and Tao B. Schardl. 2013. Finding a Hamiltonian Path in a Cube with Specified Turns is Hard. *Journal of Information Processing* 21, 3 (2013), 368–377. doi:10.2197/ipsjjip.21.368

Kenneth C. Cheung, Erik D. Demaine, Jonathan R. Bachrach, and Saul Griffith. 2011. Programmable Assembly With Universally Foldable Strings (Moteins). *IEEE Transactions on Robotics* 27, 4 (Aug. 2011), 718–729. doi:10.1109/TRO.2011.2132951

Tyson Hosmer, Sergio Mutis, Octavian Gheorghiu, Philipp Siedler, Ziming He, and Baris Erdincer. 2024. Autonomous ecologies of construction: Collaborative modular robotic material eco-systems with deep multi-agent reinforcement learning. *International Journal of Architectural Computing* 22, 4 (Dec. 2024), 661–688. doi:10.1177/14780771241287827 Publisher: SAGE Publications.

Ara N. Knaian, Kenneth C. Cheung, Maxim B. Lobovsky, Asa J. Oines, Peter Schmidt-Neilsen, and Neil A. Gershenfeld. 2012. The Milli-Motein: A self-folding chain of programmable matter with a one centimeter module pitch. In *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 1447–1453. doi:10.1109/IROS.2012.6385904 ISSN: 2153-0866.

Alexander Htet Kyaw, Richa Gupta, Dhruv Shah, Anoop Sinha, Kory Mathewson, Stefanie Pender, Sachin Chitta, Yotto Koga, Faez Ahmed, Lawrence Sass, and Randall Davis. 2025a. Text to Robotic Assembly of Multi Component Objects using 3D Generative AI and Vision Language Models. doi:10.48550/arXiv.2511.02162 arXiv:2511.02162 [cs].

Alexander Htet Kyaw, Miana Smith, Se Hwan Jeon, and Neil Gershenfeld. 2025b. Speech to Reality: On-Demand Production using Natural Language, 3D Generative AI, and Discrete Robotic Assembly. In *Proceedings of the ACM Symposium on Computational Fabrication (SCF '25)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3745778.3766670

Haobo Luo and Tin Lun Lam. 2023. Auto-Optimizing Connection Planning Method for Chain-Type Modular Self-Reconfiguration Robots. *IEEE Transactions on Robotics* 39, 2 (April 2023), 1353–1372. doi:10.1109/TRO.2022.3218992

Ken Nakagaki, Artem Dementyev, Sean Follmer, Joseph A. Paradiso, and Hiroshi Ishii. 2016. ChainFORM: A Linear Integrated Modular Hardware System for Shape Changing Interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. Association for Computing Machinery, New York, NY, USA, 87–96. doi:10.1145/2984511.2984587