Self-Assembling Modular Robots Enabled by an Articulated Multi-Axis Connector

Grant Proposal

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Chenghao (Chris) Xu conducted this research independently under the mentorship of Dr. Crowthers. The author declares no conflicts of interest. Correspondence concerning this work should be addressed to Chenghao Xu.

Executive Summary

Self-assembling robots have shown promise in many laboratory environments, yet their performance and application remain limited to those environments due to their rigid units, fragile docking, and poor tolerance. This work introduces a novel type of soft-rigid hybrid modular robot inspired by origami structures and includes a new mechanical coupling mechanism designed to accommodate errors and misalignment. Each module contains a soft deformable body with a novel connector combining previous magnetic and mechanical methods, allowing passive alignment and locking even under imperfect scenarios. Mechanical testing shows that the connector withstands significant force loads while maintaining reversibility and success rate. Connector prototypes were assessed based on six criteria: alignment tolerance, maximum strength, reversibility, simplicity, scalability, and cost. Each prototype was also mounted onto a custom ball joint mechanism with yaw and roll rotational abilities to allow for more advanced functionality of robot assembly. After the components were integrated, the module was tested for critical positions the robot could reach to evaluate the effectiveness of the utilization of the origami deformation; the connecting mechanism was tested for maximum withstand-able force; and the self-assembly was tested for alignment reliability from different start orientations. This approach advances the practicality of modular swarms and offers insights into the effectiveness of origami deformation for self-assembly.

Keywords: modular robots, self-assembly, soft robots, mechanical engineering

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Self-Assembling Soft Origami Modules with Novel Latching for Modular Multidimensional Motion

Section I: Background Knowledge

Current research in self-assembling robots often has limitations in physical docking because existing connectors are purely magnetic or purely mechanical. Magnetic connections are weak, while mechanical connectors are often too rigid to tolerate error or deformation. As a result, modules often fail to assemble correctly outside of controlled laboratory conditions, reducing the real-world application in limited. There is a need for a connection mechanism that addresses these issues to allow modules to form both stable chains and lattice structures. Purely magnetic or purely mechanical connectors offer unique strengths while retaining limitations that could be overcome by cross-integration. The goal of this engineering project is to bridge those gaps by developing a latch that can form chain-like structures when applied to a soft worm robot system and prove feasibility in lattice configurations as well using more traditional modular robot models.

Self-Assembling Modular Robots

Self-assembling modular robots are robotic systems composed of several autonomous units that can physically connect or detach to reconfigure into different shapes. These different configurations allow robots to tackle more complicated tasks individual robots cannot accomplish. In this way, modular systems can be rearranged to optimize physical shape to suit a task, terrain, or environment. This concept allows robots to adapt to different situations and obstacles, enabling adaptability, versatility, and scalability. The robustness of modular systems is well-suited towards unstructured or confined environments.

There are two main types of modular systems: chain-connecting and lattice connecting. Chain type systems connect in a line or snake configuration that allow for a continuous geometry, allowing for locomotion like slithering and wrapping. Chain robots are useful in complex environments because they facilitate advanced maneuvers (Xu et al., 2017). Modules using chain connecting are flexible and allow the robot to navigate confined spaces and adapt to terrain. Lattice type systems connect in more grid-like structures forming large structures including walls, platforms, or bridges (Romanishin et al., 2013). Both chain and lattice systems offer distinct functional advantages, but both are dependent on reliable docking mechanisms, which remain a challenge. Often, reliable and strong physical docking are tradeoffs, limiting the true practicality of self-assembly in real-world conditions.

Wyder et al. designed Truss Links (a swarm robot system) in 2025 that could connect to each other and form complicated configurations. Independently, a single Truss Link can only move in 1D, and its mobility is enhanced when it combines with more. Then, they can self-assemble and reconfigure themselves into shapes such as triangles, ratchets, and tetrahedrons. In addition to forming complicated patterns, Truss Links also can dispose of broken segments and substitute them for working ones, which is like a self-healing ability. However, Truss Links is limited by its simplicity in locomotion and its high-producing cost.

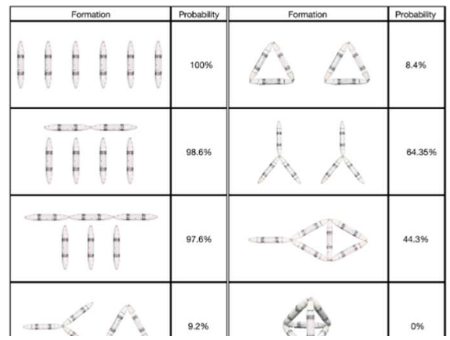

Figure 1: Truss Links can be oriented into eight different forms. These formations were created by individual modules connected by ball shaped magnets from each module (Wyder et al., 2025).

Existing Connecting Approaches

Current docking mechanisms for modular robots typically fall into three categories: magnetic, mechanical, and hybrid connectors. Magnetic docking systems are widely used because of the natural attraction of magnets and tolerance to slight errors (Nagy et al., 2007). However, they are limited in the holding force, which may cause failures holding robots together during locomotion states. In contrast, purely mechanical latches generate strong strength between robots, but self-assembly becomes more difficult as the latches need precise positional and angular orientations (Eckenstein & Yim, 2014). In real world scenarios, it is improbable to achieve no positional errors, so mechanical latching lacks applicability. There are also hybrid systems, such as SMORES-EP, that combine magnetic attraction and mechanical locking to improve the overall docking ability (Davey et al., 2012). As a result, the gap of an articulated multi-axis latching mechanism can strongly benefit and support adaptive configuration during and after self-assembly.

Application for Soft Robotics

Soft robots are robotic systems built from flexible, deformable materials instead of rigid metal frames that most traditional robots use. Traditional robots often have rigid connectors or joints, but soft robots bend, stretch, and compress, resembling biological organisms like worms, octopi, or caterpillars. The flexibility soft robots have allowed them to interact with environments safely without damaging themselves or nearby objects. They are especially well suited for tasks traditional robots struggle with, such as squeezing into gaps, navigating fragile environments, or physically adapting their shape to the environment (Seyidoğlu & Rafsanjani, 2024). Some common applications for soft robots are in search and rescue, pipe surveying, archaeology, and exploration applications where their flexibility allows for the traversal of highly cluttered environments.

Traditional soft robots are made with materials such as silicone, rubber, textiles, or origami-based structures. They can be driven by a variety of mechanisms, including pneumatics or hydraulics, shape-memory polymers, dielectric elastomers, and cable-and-tendon systems, but many of these actuation methods still require an external power source, such as tethered electrical wires, pressurized air or water, or an applied magnetic field (Yang et al. 2020). These tethered robots are limited in mobility because of their dependence on exterior sources. Furthermore, most existing mobile soft robots are not fast or powerful enough to effectively traverse three-dimensional environments (Sun et al., 2020).

Origami in Robotics

Origami robotics is a subfield of soft robotics using origami (folding) or kirigami (cutting techniques) to create transformations within the robotic structure. These robots rely on specific geometric folding or cutting patterns such as Miura, Yoshimura, Kresling, or waterbomb tessellations, producing controlled three-dimensional motion when actuated with simple mechanical inputs (Ai et al., 2021).

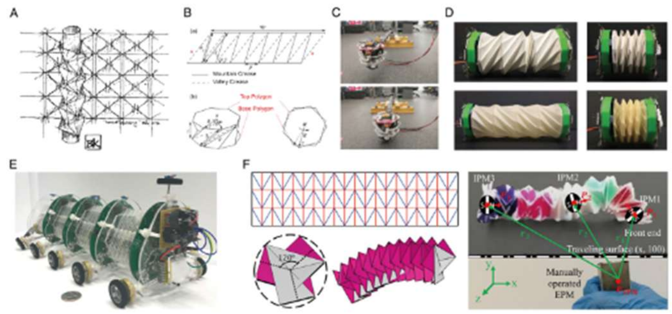

Figure 2: This figure shows the Yoshimura Folding Pattern and its application in Robotics (Ai et al., 2021).

In 2020, Sun et al. designed a soft origami robot (Salamanderbot) that could handle complex terrain. The Yoshimura technique was used, allowing for compression, extension, and deformation to fit into tight spaces. The purpose of the design was to tackle the locomotion problems that soft robots face by using gear and belt transmission designs while maintaining the ability to fit into narrow spaces. Compared to other robots, Salamanderbot performed much more effectively in traversing the environment.

The benefits of origami designs are that they are lightweight, scalable, and inherently flexible, allowing a single structure to serve both as the body and as the mechanism of actuation. Because the folds are predictable and repeatable, the robot can bend, expand, or contract controllably without any mechanical joints. This makes the robot cheaper, easier to fabricate, and more resilient to impact or deformation. Origami-inspired robots often excel at specific tasks but face limitations when needed to perform multiple different tasks in isolation. These constraints make them suitable for working in large swarms, where they can utilize their strength in numbers. In this way, the limitations of individual origami-based robots make them a potential candidate for a swarm module (Kabutz & Jayaram, 2023).

Swarm Robotics

Swarm robots is a field of robotics that uses many simple agents that cooperate to accomplish complex tasks. Many swarm robots are inspired by collective behavior in nature such as ants, bees, and fish shoals. By relying on each other instead of a centralized controller, the intelligence of the robots is distributed throughout the system instead of a single controller. These coordination actions often include gathering, dispersing, and specific types of behavior specific to certain animals (Berlinger et al., 2021). In this way, the strength of robotic swarms lies in its scalability, robustness, and task distribution. The swarm will continue to operate if a singular robot fails. They can also organize by dividing tasks and covering large areas. They are very suited for searching, mapping, exploration, and payload transport. Although swarm robots are very useful, one limitation current swarm robots have been their rigidness. Most swarm robots are tested in laboratory settings, so they are unable to adapt to real environments. Swarms often perform well in simulations but rarely cooperate well in physical coupling or linking, limiting their usefulness in irregular terrain (Yi et al., 2021).

AprilTags

AprilTags are a visual fiducial marker system that is used to provide detection and identification of objects in computer vision applications. Structurally, AprilTags are very similar to QR codes with a unique black-and-white square pattern, and they can store information about location and orientation. They mainly provide accurate pose data and geometric precision by looking at the x-, y-, and z-direction offsets between the camera and tag, allowing the computer system to detect the tag to calculate its 3D orientation with respect to it (Richter et al., 2022). Thus, AprilTags are useful in autonomous systems where special awareness is crucial.

Section II: Specific Aims

This proposal's objective is to address the knowledge gaps pertaining to soft robotics and swarm robotics by employing an approach that focuses on improved modular robot applications by using a novel mechanical coupling mechanism and incorporating soft robotic components. Current modular robots depend on rigid designs with magnetic or mechanical latching not always applicable in uneven terrain or irregular module alignment. The use of a soft robot design compensates for imprecise docking by providing compliance, shock absorption, and shape adaptation. Additionally, a new mechanical coupling technique will allow for multidimensional flexibility and movement while enabling a stronger and more stable connection than popular electromagnetic coupling. Combining these features enables a shift from lab testing to practical real-world demonstrations and deployments of self-assembling robots.

The work that is proposed develops, models, and experimentally validates a new design of soft-hybrid modular robot to demonstrate self-assembly at a practical level.

Specific Aim 1: Design and fabricate soft-rigid hybrid modular units

Specific Aim 2: Develop and test a novel mechanical coupling mechanism

Specific Aim 3: Demonstrate autonomous swarm self-assembly and reconfiguration

The expected outcome of this work is a proof-of-concept robot swarm that demonstrates a robust ability to self-assembly.

Section III: Project Goals and Methodology

Relevance/Significance

This project opens new scientific and engineering insights into the application of soft robots and modular self-assembly since it will help to bridge the gap between lab demonstrations and real-world environments. Soft deformable exteriors in cooperation with strong mechanical coupling allow robots to assemble outside of controlled conditions. These features make the robot system highly adaptable and appliable for many tasks including but not limited to search and rescue, exploration, and risk assessment. With these capabilities, large swarms of these simple units can accomplish complicated tasks that would be very challenging for a single rigid robot. Ultimately, both push modular robots to practicality and integrate several cutting-edge insights together to broaden the field.

Innovation

There are two core innovations of the project: the fusion of soft origami robotics in modular robots and the novel mechanical coupling mechanism. First, the incorporation of origami helps improve connection for modular docking as it works to allow for there to be adjustments made up to the point of connection. It tolerates tilt, misalignment, and dynamic control that naturally occurs during self-assembly in complex environments. Meanwhile, the coupling mechanism works to allow freedom when the module units are connected. This coupling allows there to be some adjustments to be made between connections while maintaining structural stability. Together, these features create a module that is fundamentally a new building block that behaves more like a biological organism than a machine.

Methodology

Initially, the approach is to design and try prototypes of the Yoshimura design using CAD software and those designs will be prototyped to better understand the folding technique. Of all the prototypes, the most effective design was saved for the robot module. Next, the front and back plates that drive the robot and control its cables were designed using CAD software, and the iterations were finalized. The individual module was then completely assembled, and the electrical units were all connected to understand the performance of a singular module. After the basic module was created, three prototypes of the coupling mechanism were designed using CAD, and they were prototyped with PLA. The coupling accuracy and strength of each of the prototypes were recorded and compared to existing designs. The best coupling design was then attached onto a module, and multiple robots were assembled to test the capabilities of assembling and the performance of the assembled system. Lastly, the capabilities and performance of the modular system was lastly compared to existing models of self-assembling robots.

Specific Aim #1:

The objective of the first aim is to determine and develop an optimal design for a single modular unit, including the design for the Yoshimura pattern, plates, and electrical diagram. The approach involves iterative designing of the module using CAD software to prototype integrating the Yoshimura fold pattern with 3D plates. The rationale for this approach is because the combination of origami-inspired geometry and plates allows the iterative approach for coupling to be rapidly implemented and tested. Flexibility allows deformation of each unit to better understand the coupling effectiveness that comes later in the project.

Justification and Feasibility. These designs are crucial in addressing the mechanical and electrical aspects of the module, which are necessary for self-assembly. The feasibility of the approach is supported by Sun et al. (2020), who developed a soft robot, Salamanderbot, capable of multimodal locomotion through integration of separated origami bending structures. Each structure was inspired by the Yoshimura folding design, demonstrating adept deformation and flexibility. Salamanderbot is a key example of a soft robot maintaining locomotion abilities like a traditional robot, which makes it a strong candidate for transitioning from rigid robots to soft structures in self-assembling modular robot designs.

Summary of Preliminary Data. After the model was completed, data was collected on the maximum extension, compression, and angle of deformation that the module could accomplish. This demonstrates the flexibility of the robot for calculations on how the robot can self-assemble because the robot will need to bend in and drive to orient itself correctly for the coupling process.

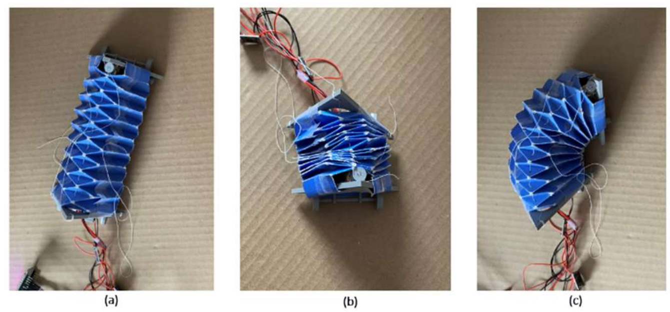

Figure 3: (a) The module has a length of 170 mm when it is fully extended, (b) The fully compressed module has a length of 61 mm when it is fully compressed, (c) The maximum bending angle of the module is approximately 110 degrees.

Expected Outcomes. The overall outcome of this aim is to identify an optimal modular unit that demonstrates deformation capabilities on par with current soft robot designs. This knowledge will be imperative for future designs considering multiple modules because self-assembly consists of complicated motion and logic.

Potential Pitfalls and Alternative Strategies. We expect to face pitfalls balancing mechanical flexibility and electrical reliability. If the initial designs show insufficient capabilities of locomotion, there will be alternative strategies to address each of the limitations. Series of iterative testing for each component will help mitigate the risks.

Specific Aim #2:

The objective of this aim is to design, prototype, and evaluate a new mechanical coupling mechanism that uses magnets as a supporting mechanism. This addition enables the modular units to attach, detach, and reconfigure effectively in different orientations and conditions. The approach is to create a multi-stage latching system where the magnetic coupling is the first stage of attachment, and mechanical features will firmly lock the mechanism in place. The rationale for this approach is since magnetic coupling is often weak in self-assembling systems, and mechanical systems may require too much accuracy. By combining the two, the robots will be able to first connect to a comfortable position and then be mechanically reinforced.

Justification and Feasibility. The feasibility of using magnets and mechanical coupling is supported by SMORES-EP, a design created by Davey et al. (2012). Four magnets and one mechanical key were used in the coupling mechanism. The magnet-only connectors had limitations supporting larger loads, so the magnets served as a low precision capturing mechanism and the mechanical key supplied much greater reinforcement. Together, the prior evidence from SMORES-EP demonstrates the effectiveness of a multi-stage latching system combing magnetic and mechanical connectors.

Summary of Preliminary Data.

Finite Element Analysis was completed to analyze the maximum tensile strength of the prototype. The von Mises stress, a scalar that combines the three principal stresses, was used to analyze the force distribution on the connector prototype. The critical points on the connector were evaluated at numerous force thresholds.

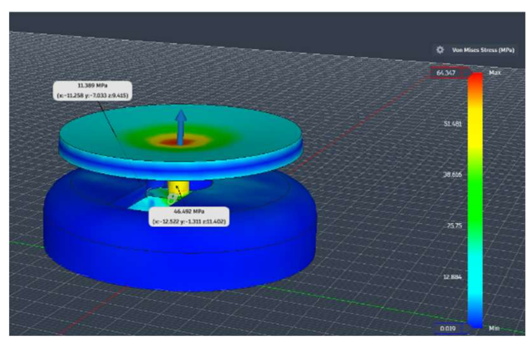

Figure 4: Finite element simulation of the connector under tensile load. The heatmap displays von Mises stress, highlighting peak stresses near the latch and reduced stress in the soft funnel.

Expected Outcomes. The overall outcome of this aim is to identify a coupling mechanism that repeatedly allows the robots to assemble under operational uncertainties. This mechanism will become the core for work in autonomous self-assembly as a connection mechanism will be crucial for the robots to be able to self-assemble. This knowledge will help better understand if combining magnetic and mechanical techniques are applicable.

Potential Pitfalls and Alternative Strategies.

I expect challenges such as insufficient load capacity, latch fatigue, and misalignment. If the load capacity is insufficient, there will be more reinforced components that will be introduced to compare to current research. If fatigue is a limiting factor, different materials will be explored to find the best alternative to minimize the effect of fatigue. Lastly, if misalignment is an issue, there will be aids developed to support the initial magnetic alignment or mechanical geometries to improve the reliability of the integrated coupling.

Specific Aim #3:

The objective of this aim is to demonstrate autonomous self-assembly and reconfiguration using the coupling mechanism from the second specific aim. This approach is to demonstrate a proof-of-concept of using a computer vision-based control algorithm to navigate, align, attach, and arrange into different configurations. Each robot relies on local computer sensing from the ESP32 CAM module to engage in connecting.

Justification and Feasibility. The use of camera vision for alignment widely implemented in a variety of autonomous robot systems. Fiducial markers such as AprilTags enable robust 6 pose estimations, making them well suited for alignment tasks. The ESP32-CAM module is a lightweight and low power system that is capable of real-time tag detection and low-power onboard sensing that allows for a proof-of-concept model to be demonstrated.

Summary of Preliminary Data. Initial data from the model helped determine what size of AprilTag would serve the best for the distances and ranges used for the purpose of alignment in these robots. The distribution of values suggests that a tag of 6 centimeters in side length is the most optimal for the vision module to analyze.

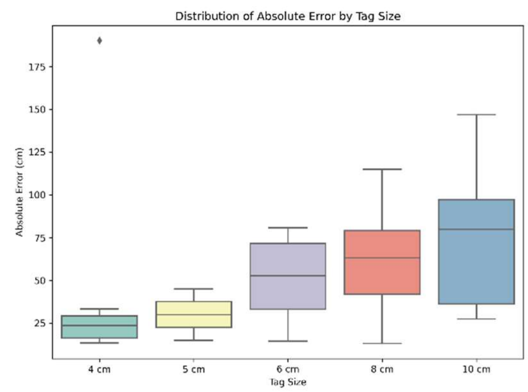

Figure 5: Distribution of absolute pose error (cm) for five AprilTag sizes. Boxes depict median and quartiles. The whiskers extend to ±1.5 IQR and the dots mark outliers

Expected Outcomes. I expect this test will allow successful demonstrations of autonomous self-assembly. Quantitative metrics including accuracy and consistency will help validate mechanical alignment with local vision.

Potential Pitfalls and Alternative Strategies. I expect challenges in coordination failures, attachment deadlocks, and incomplete assemblies. The behavior rules will need to be optimized to include better alignment and decision for success in multiple orientations.

Section III: Resources/Equipment

The materials are paper, screws, ESP 32 CAM Modules, PET, PLA, wires, string, servos, N20 motors, and solder. The equipment is available from the school or from my home including a laser cutter, 3D printer, multimeter, and soldering iron.

Section IV: Ethical Considerations

There are no serious ethical considerations for my project. However, standard safety protocols still matter.

Section VI: Timeline

Section VII: Appendix

Section VIII: References

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