Project Proposal

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

Author: Xu, Chenghao
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Project Description:

The aim of the project is to design a modular robotic system capable of autonomous self-assembly with a novel mechanical latching connector. The key innovation is the articulated, multi-axis latching mechanism, allowing individual modules to tolerate angular misalignment during docking and have mechanical deformation even during assembly. In this way, it enables stronger connecting and adaptability between robots during self-assembly. The latch is used in a traditional rigid robot system of cube-like modules to demonstrate functionality in both chain and lattice configurations. Later, they will be applied to a novel system of origami modules integrating soft components into modular robotics. These applications will demonstrate a proof-of-concept design of how small adaptable modules can autonomously form larger, and more complex structures, extending the application of self-assembling robots to the real-world.

Background:

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. Chains are useful as robots 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.

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 a articulated multi-axis latching mechanism can strongly benefit and support adaptive configuration during and after self-assembly.

Application with Soft and Origami Robots

Unlike traditional rigid robots. soft robots are robotic systems built from flexible, deformable materials instead of rigid metal frames that most traditional robots use. The flexibility of soft robots allows 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. However, most existing mobile soft robots are not fast or powerful enough to effectively traverse three dimensional environments (Sun et al., 2020).

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). 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).

Application with 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 current limit is that they are unable to adapt to real environments. Swarms often perform well in simulations but rarely cooperate well in physical cooperation or linking, limiting their usefulness in irregular terrain (Yi et al., 2021).

Experimental Design/Research Plan Goals:

SMART Goals

Prototype of Robot
    Origami Shape
    Mechanical Design
    Actuation and electronics
    Control Algorithms
Simulations
Docking Interface
Testing and Iteration

- Prototype Evaluation: each individual module will be tested on its individual performance including flexibility, maximum extension, minimum compression, and maximum speeds.
- Coupling Strength: the maximum force that the coupling mechanism can hold will be assessed by a Universal Testing Machine.
- Self-Coupling: successful coupling will be recorded in multiple trials from different orientations.
- Environmental Performance: modules will be tested under different conditions such as decreased lighting, a slope, or uneven terrain.

Data Analysis

- Performance Metrics: key variables such as locomotion, connection success rate, will be quantified.
- Comparative Analysis: performance will be compared to existing work in the field to determine the effectiveness of the design
- Failure Analysis: failures will be recorded and categorized to identify weak points in the design.

Independent Variable	Dependent Variable	Controls
Number of Modules Number of Trials	Docking Success Maximum/Minimum Length Angle of Deformation Energy Consumption Speed Docking Alignment	Testing Floor Lighting

Materials List

ESP 32 CAM modules

Construction Paper
PET
3D printer
Laser Cutter
Wires
Multimeter
String
Servos
Motors
Solder Iron and Solder

Risk/Safety Concerns:

Risk 1: Soldering and Fume Exposure
Mitigation: When soldering any components, it will occur in an area that is in an open well-ventilated area with safety glasses and gloves. A soldering stand and heat-resistant mat will always be used. All flammable items will be kept away from the soldering iron. It will be made sure the iron tip is also never put in a place where it can accidentally contact any living organisms.

Data Analysis:

The performance of each robot and the robot system will be evaluated quantitatively by measuring dependent variables as independent variable values are changed. Performance trends on reliability will utilize statistics to determine consistency and significance. Later, this data will be compared to current robots and systems that exist. If time permits, improvements between each prototype will also be evaluated to measure the progress of the robots.

References:

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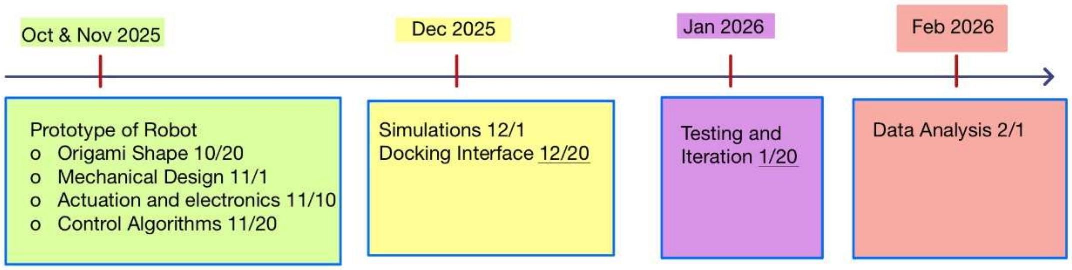
Timeline:



Timeline made with Notability.