Modular Kirigami Snakebot

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I. INTRODUCTION

The motion of snakes exhibits many degrees of freedom with a relatively simple skeletal structure. However, while snake-like robots ("snakebots") have been attempted, demonstrated, and perfected by various researchers, they have yet to be able to package them efficiently [1]. We were inspired by the field of origami mechanics and deployable structures to improve a snakebot's packaging and size constraints. Our goal was to have our snakebot expand to a state that was large enough to behave like a traditional snakebot, yet be collapsible to a small size such that it could fit on the bottom of a drone ready to be deployed (similar to the implementation in [1]). To further our pursuit for simplicity and repairability, we sought to approach this collapsible snakebot via a modular segment approach. To achieve this, we sought to take advantage of kirigami metamaterials [2]. In the end, our overarching goal is to create a deployable snake-like robotic arm from modular segments that would be fixed to a base.

II. MOTIVATION AND RELATED WORK

Our system can be broadly categorized as a modular continuum robot – each subsection adds additional degrees of motion along a main axis, resulting in a highly configurable system that resembles a tentacle/snake/elephant's trunk. Often, these continuum robots are actuated by wire tendons [4], inspired in part by the longitudinal muscles found along the length of an octopus arm [5], [6]. While these systems bring with them high mobility and path configurability, they are often quite big and hard to collapse and transport due to the size and length of the wire tendons. Bellows and accordion shaped mechanisms can be used to provide a collapsible/deployable structure but come with the caveats of not being able to twist at an axis without deforming, and not being able to hold much weight (due to the weak rigid strength of the flexible bellow).

We intended to build on the work of snake robots and bellow based deployable structures to create a robot that could easily be mounted to the bottom of a drone. This way the drone would still be able to operate fly without a major impact on its aerodynamics due to the robot's small collapsed footprint. One could therefore imagine use cases where a drone could perform maintenance on structures that are hard to reach. For example, the drone could fly on an oil rig, hover while deploying the snakebot which would grab on to a hard to reach valve and twist it open or closed. Similarly, such a drone+robot combination could be used for search and rescue where a drone flies through a fallen house, deploying the snakebot arm to move small rubble out of the way to make a path for the drone to fly through.

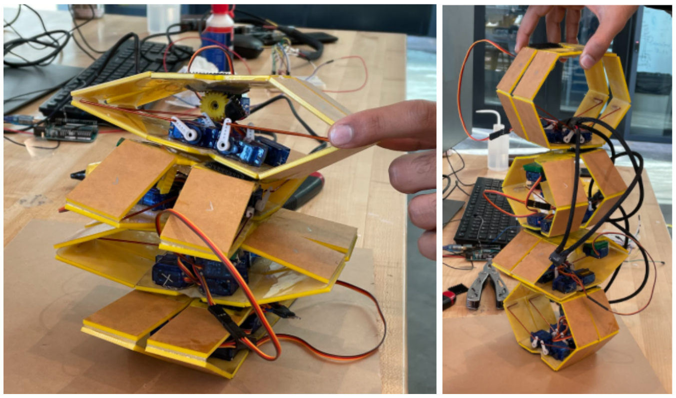

Fig. 1. Our modular, kirigami-inspired robot, in collapsed (left) and deployed (right) configurations. This version consists of four individually-actuated modules, each capable of vertical extension, outward rotation, and bidirectional tilting. The modules are each constructed from a single sheet of "rigid-flex" composite material.

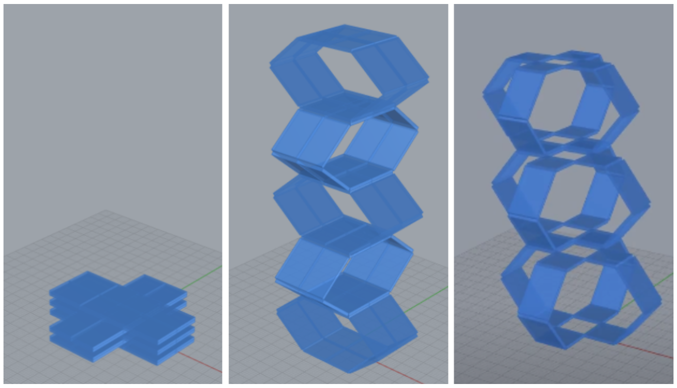

Fig. 2. Simulation of combined module configurations. Because of the way modules are combined, we can achieve compactness (left) with large expansion (middle) and robust twisting (right).

III. PROJECT DESCRIPTION

Our system consists of four kirigami-inspired robotic modules, stacked vertically (Figure 1). Each module can be actuated with 3 degrees of freedom: vertical expansion in the z axis, vertical angling (tilt) in the y axis, and axial twisting (inward/outward rotation) allowed by the square kirigami pattern along the z axis. Each module is 2.5 dimensions (small z height) in the collapsed state and 3 dimensions in the expanded state. Combining the modules via vertical stacking creates

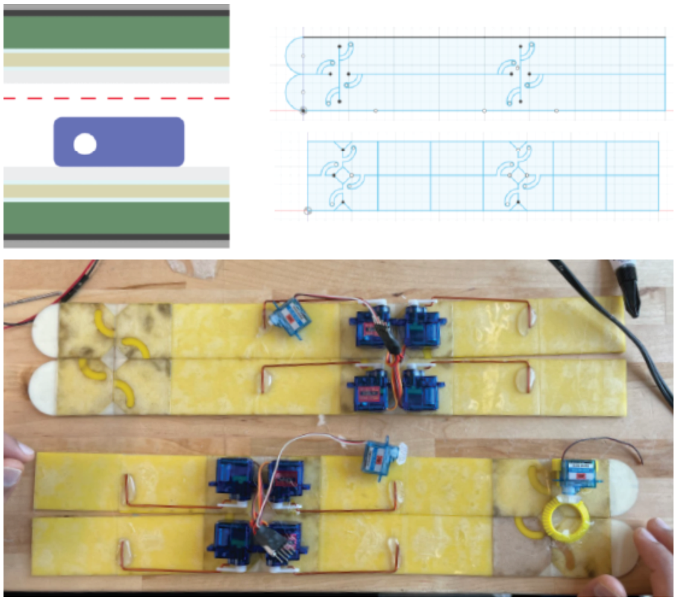

Fig. 3. Composite material layering (top left): From the red line down, there are the servo motor, Mylar, adhesive, rubber, adhesive, rigid acrylic, Mylar, Velcro. One-cut files (top right) allowed for rapid assembly (bottom) of both the vertical and rotational expansion mechanisms.

a snake-like deployable structure. This combined structure enables even further degrees of freedom than each sub-module that comprises it.

IV. METHODOLOGY

Our aim at the outset of this project was to build a collection of stackable modules, each capable of vertical expansion, outward rotation, and bidirectional tilt. By connecting these modules at variable pivot points, and actuating each module individually, we aimed to achieve a variety of deployed configurations, all arising from the same compact formation (Figure 2). Working backwards from this intended functionality, we constructed a set of design requirements that guided the development of our system.

A. Design Requirements

1) 3-DOF Module Actuation: In order to generate a wide range of motion for the system as a whole, we determined that each module must be capable of vertical expansion, outward rotation, and bidirectional tilt.

2) Tear-Resistant Composite Material: Kirigami-inspired rotational elements are prone to tearing at the hinges when fully deployed [3]. We mitigated this issue by constructing our modules from a rubber-reinforced composite material, which was robust after repeated consecutive actuations. The other major requirement of the composite material is to accept the hot glue which mounts the servos and the pin joints. With some light sanding, the inner Mylar layer achieves this.

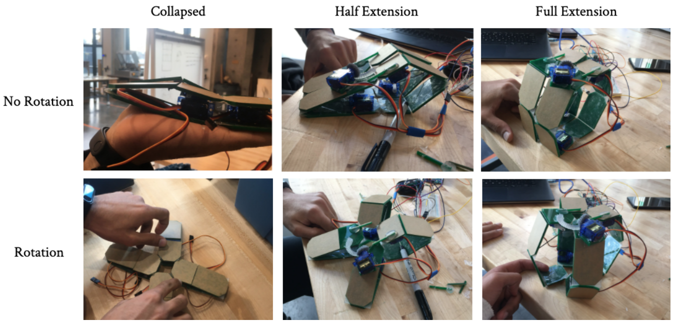

Fig. 4. Demonstration of key module states. By actuating one set of Sarrus linkages, the module transitions from the collapsed state (left column) to the half-extended or tilted state (middle column). By actuating both sets of linkages, the module transitions to the fully-extended state (right column). In each of these configurations, the module can either be inwardly rotated (top row) or outwardly rotated (bottom row).

3) Single-Sheet Assembly: A feature of modular systems is their extensibility – if we would like to create a larger structure, or add degrees of freedom to our system, we can build and attach additional modules. To facilitate this process, we attempted to make the module fabrication and assembly procedure both simple and repeatable. Each of the modules in our system is assembled from a single sheet of a composite material. There are two main profiles which are laser-cut, the rigid layer and the stabilized flexible layer (Figure 3). To simplify manufacturing, these layers were cut in one file and assembled manually.

4) Reconfigurable Stacking: The deployed state of our modular structure is dependent upon both the module actuations and the interconnections between modules. To maximize reconfigurability, we chose to include a Velcro interface on the exterior of the modules, allowing stacked modules to be connected at variable ”pivot points”. However, the added height that the Velcro introduced disrupted the balance of the overall structure, which we discuss further in Section 5.

B. Design Concepts

There are six key module states (Figure 4). Three of these are core states (collapsed, half-extended, fully-extended) and the other three are the core states with the addition of a twist (outward rotation). Having each module of the snake robot in

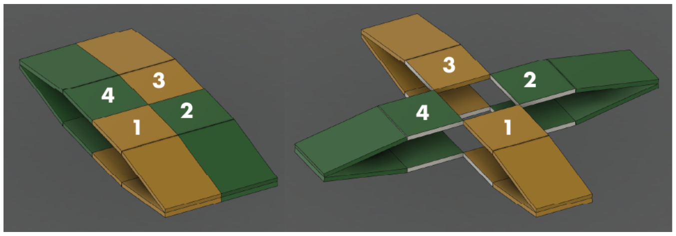

Fig. 5. Demonstration of the four module quadrants before (left) and after (right) an outward twisting rotation.

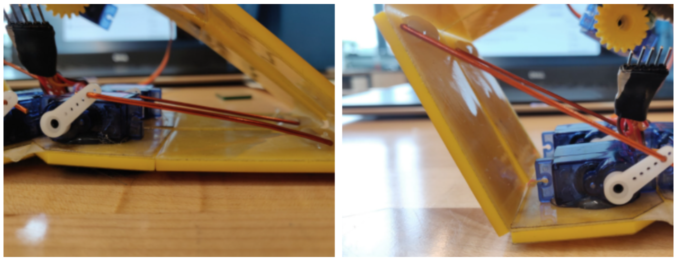

Fig. 6. Vertical expansion using a four bar linkage. Both the collapsed (left) and expanded (right) states are enabled by the pivot joint between the copper wire and the module elbow. Expansion is actuated via servos.

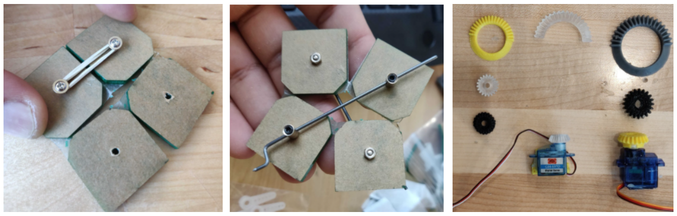

Fig. 7. Outward rotation mechanism prototypes. Experimentation with elastic (left) and rigid sliders (middle) were too complex for rapid production. The bevel gear system (right) was the final choice.

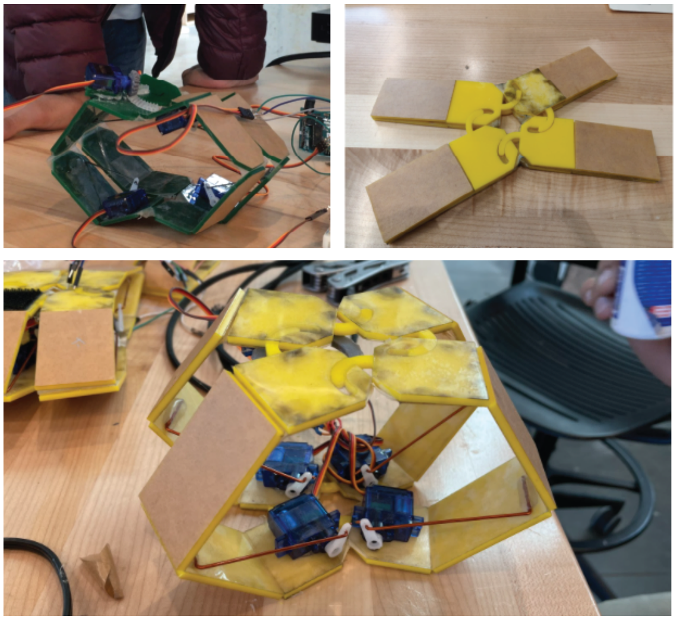

Fig. 8. The initial prototypes without stabilization (top left) buckled with vertical expansion. In order to overcome this, we laser-cut arms into the square Kirigami pattern itself for stability (top right). The final module (bottom) was able to vertically expand without going out-of-plane.

a different state enables larger, more complex motions from the overall system.

Each module consists of four quadrants, as shown in Figure 5. When transitioning from a non-rotated state to an outwardly rotated state, the position of one quadrant is always fixed, either to a static base or to the module directly beneath it (in Figure 5, for example, quadrant 1 remains stationary). By varying the quadrant that is fixed, modules can pivot about different points, resulting in different deployed states. In our system, we use Velcro patches to fix these quadrants in place.

1) Vertical Expansion: To create vertical expansion using servo motors, we applied a simple four bar linkage system with a pivot joint at the module elbow and a servo horn as the primary actuator. Figure 6 shows the various extended states. In order to make the controls, power-delivery, and wiring simpler, we paired the four vertical servos into ”left-raise” and ”right-raise” sections, effectively combining the two servos on the left and two servos in the right (each servo pair shares a signal pin). This controls simplification did not impair our core expanded, collapsed, and tilted states.

C. Functional Architecture

1) Composite Material: Each module in our system can be folded from a single sheet of composite material, which contains both rigid and flexible layers (Figure 3). From top to bottom, these layers are:

- A Mylar sheet (250 um), which serves as a flexible hinge.
- A double-sided adhesive (Scor-Pal 208).
- A tear-resistant rubber sheet (150 um, McMaster-Carr 85995K12), which reinforces the flexible Mylar layer.
- A double-sided adhesive (Scor-Pal 208).
- A rigid acrylic layer (3.1 mm), which serves as the load-bearing elements in our modules.
- A double-sided adhesive (Scor-Pal 208).
- A Mylar sheet (250 um), covering the rotational elements, keeping them in-plane.

This composite stack allowed us to maintain flexibility while introducing redundancy for if the Mylar tore, by having the the rubber act in as a tear resistant material.

2) Outward Rotation: We experimented with several rotation mechanisms such as cams and various linear linkages (Figure 7), but ultimately settled on bevel gears centered at the kirigami pivot points to transition each module between its ‘open’ twist and ‘closed’ twist states. In the initial prototypes, we encountered issues with each face of our module not being stable and collapsing out of plane due to the kirigami fold mechanics. To solve this problem, we created a simple track-based stabilization system which only required us to modify the cut files (Figure 8) and add cover plates. There were several other issues that came with this switch that are discussed later in the paper.

3) Cable Harness: In order to simplify controlling the various electronics, we created a quick-disconnect cable harness. This allowed us to reduce the electrical connections to each module to just five electrical pins: one power, one ground, and three control pins (2 control each side of the lift servos, and 1 controls the twist servo). The cable harness also allowed for rapid quality testing, quickly swapping damaged modules, and reconfiguring the orientation of each module to enable different motions of the robot.

D. Final System Design

Our final system consists of four modules (Figure 1), connected to a master microcontroller (Arduino Mega) and an external 5V power supply. Through a custom protocol (similar to G-code), we can individually control both the paired linkages and the degree of outward rotation for each module. Alternatively, we can command the modules to transition directly to any of the six states shown in Figure 4.

V. EVALUATION AND RESULTS

The individual modules in our system meet our first three design requirements – they are actuated with three degrees of freedom (expansion, rotation, and tilt), they are tear resistant after repeated actuations, and they are constructed from a single sheet of composite material. In Figure 9, we can see one of these modules transitioning from its fully-compact state to its fully deployed state, alongside a rendering that shows the intended (matching) behavior.

While our testing of individual modules was successful, there were many unforeseen challenges that came with stacking modules. Some of these issues boil down to material choice. Other issues are a result of our design choices. All our actuation testing happened prior to our design switch to a track stabilised system (Figure 8). Transitioning to the track system brought many friction challenges which our servos struggled to overcome. To remedy the friction issue we had to trim our composite material around hinges to prevent pinching, we also had to lubricate all our tracks, and increase our servo gear diameter to have it provide additional torque via a larger moment arm. We also ran into various issues with servo quality. Most of our servos had very weak internal gears which were prone to stripping. The servos also came with poor strain relief on the electrical connection to the housing, which meant the connector kept breaking and we had to often disassemble the entire servo to repair it.

VI. FUTURE DIRECTIONS

To build on our work and improve our current design limitations, we have various directions one could take this project.

Firstly, a future iteration should use a tapered, tree like, design where modules lower in the robot are bigger and stronger to carry and support the weight of all the modules above it. The modules could get smaller towards the top, as they could get away with smaller, weaker motors since they don't need to carry the weight of many modules above them.

Secondly, one could explore thinner mounting interfaces other than velcro. A potential option is pop-rivets since those are easy to install and remove, while offering a secure and flush connection.

Thirdly, one could implement a I2C or other similar protocol for communication between the modules if one intends to use any more than 5 modules. This would cap the number of wires the cable harness would have to carry to 3 total wires regardless of the number of modules (2 wires for power and ground, and the third wire for I2C).

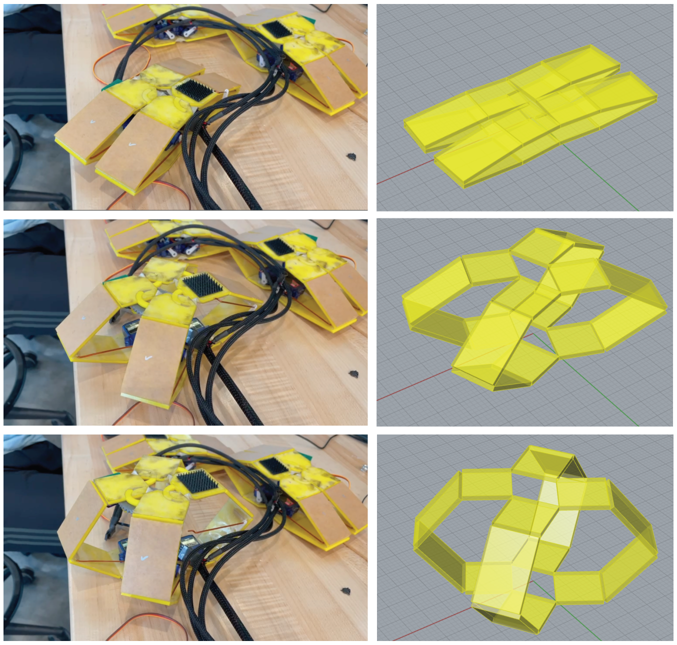

Fig. 9. A single module transitioning from the fully-compact state (top) to the fully-deployed state (bottom).

VII. PROJECT MANAGEMENT

Early in our project, once we had established some of our basic design requirements, we outlined our core tasks and created a Gantt chart to structure our project development. Over the course of the project, as new problems were discovered and new features were explored, these tasks were refined and assigned to individual team members. We initially used email as our primary means of communication, but migrated to Slack shortly after the project began, in order to facilitate more fluent conversation.

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