DOCUMENT TYPE: TECHNICAL REPORT	PROJECT: SPIRAL	

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1 Introduction

1.1 In recent years, there has been a growing trend to develop biomimetic machines. These machines draw inspiration from various biological organisms.[1] Notably, certain animals, such as chameleons, octopuses, and elephants, utilize spiral structures in their tails, limbs, and trunks (Figure 1A).[1-3] These spirals allow for a wide range of motion and enable efficient manipulation of objects.

1.2 Research in this field is typically categorized into two main approaches: developing machines using hard materials.[2,5] and creating soft machines using soft materials.[1,3,4] Soft machines have an advantage over hard machines in terms of environmental adaptability, making them particularly effective. Among soft machines, pneumatic systems are frequently employed for actuation,[1,4] though other methods, such as magnetic and alternative actuation techniques, are also explored.[2-3,5].

1.3 However, pneumatic systems require precise control of airflow for actuation, making them difficult to operate. Additionally, using spiral structures alone limits the range of motion, which poses challenges for grasping objects effectively. To address these limitations, we drew inspiration from biological spiral structures and developed a novel design based on the structural concept proposed by John Edmark(Figure 1B).[6] In this study proposes a novel gripper that utilizes helical motion in a soft robot, actuated by a magnetic system.

2 Materials and methods

2.1 The current prototype was fabricated using 2mm plywood. The plywood was laser-cut into quadrilateral segments, which were assembled using masking tape. The angles of the quadrilaterals were adjusted in various ways to determine which configuration would be most effective for Spiral's object-gripping performance. As a result, Spiral was engineered with gentle-angled quadrilaterals near the base to maximize movement range, while steeper angles were applied toward the tip to enhance gripping precision(Figure 1C).

Two thin magnets were attached along the edges of the inner surfaces of the largest quadrilateral, while three additional magnets were affixed to the outer surfaces. All magnets were aligned with the same pole orientation(Figure 1D). This configuration facilitated controlled movement of Spiral through the application of strong permanent magnets(Figure 1E).

Although the final version of Spiral is intended to be made from soft, flexible materials, the prototype was constructed with rigid plywood to facilitate initial testing. Additionally, since the current design only permits spiral motion, future iterations will aim to achieve helical motion to expand the functional capabilities of the structure.

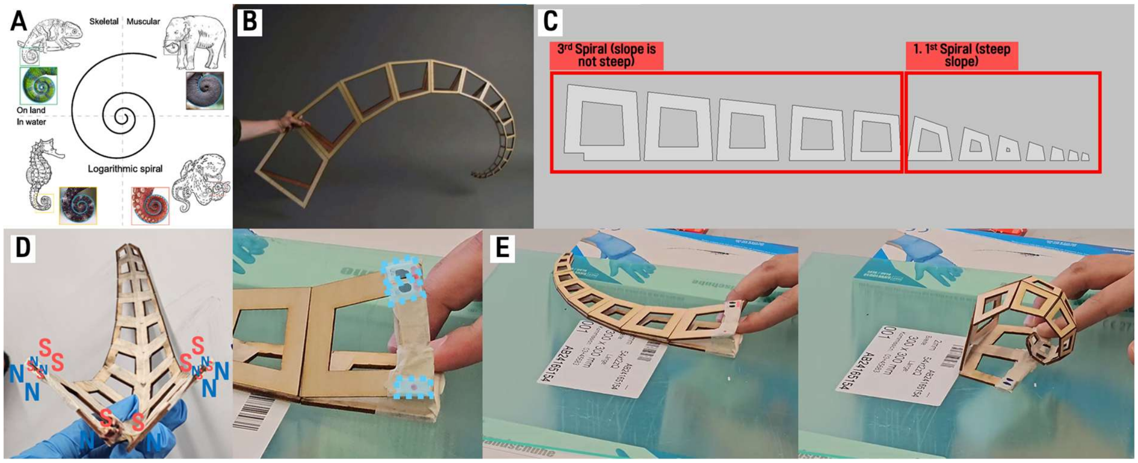

Figure. 1 Design and movement of Spiral
(A) Examples of animals exhibiting spiral structures.[2] (B) The spiral structure of John Edmark's design.[6] (C) Spiral assembly composed of quadrilaterals with varying angles. (D) Magnetic pole alignment: magnets attached to the spiral (left) and three magnets affixed to the outer surface (right). (E) Folding of Spiral induced by a hard magnet (left) and unfolding of Spiral (right).

3 Research Plan

3.1 This research plan has been developed to show the step by step development for this technology in the context of an internship program. The progression of which begins with typical onboarding practices and progresses into reproduction of prior technology, improvement of our understanding of the design space, merging of the prior work with magnetic actuation, and finally into a fully realized robotic concept. These larger steps are organized into phases, which describe larger research goals to be achieved throughout this process. These phases are broken up into subsections known as tasks, which describe on a much finer scale the individual steps which must be taken to fulfill the goal of the phase. There are three different criteria within each of these task definitions, input criteria, objective criteria, and exit criteria. Input criteria describe the input variables of the given task, namely the values or attributes which we can control. These input criteria then affect the objective criteria, which describe the individual pieces of information which we are trying to extract from a given task. These could also be described as the dependent variables in the case of an experiment. Exit criteria describe the goals which must be completed before moving on to the next task in a phase.

3.1.1 It is important to note that this research plan is flexible, and that not all aspects of a prior phase must be completed before working on an object in a different phase. The research plan rather entails the 'ideal' progression of research given a long enough period of time. However, time constraints may require for multiple phases to be active at the same time and that is okay. It is up to the discretion of the research team whether such decisions are appropriate.

Phase	Questions	Input Criteria	Objective Criteria	Exit Criteria
Phase 1: Onboarding and Literature review				
P1T1: Onboarding Steps Complete the onboarding steps required to start using equipment and working in the lab				Transponder access to the lab Laser Printer training Download necessary software
P1T2: Literature Review Conduct a comprehensive literature review to understand the	What salient parameters are measured in the elephant trunk/octopus tentacle gripper space? How does one fabricate the John Edwards "Spiral" Constructs?			Understanding on how to characterize trunk/tentacle type actuators are characterized Understanding of the fabrication process of the "spiral" constructs

norms of the field and the important properties to measure.				
Phase 2. Reproducing prior work				
P2T1: Reproduce the John Edwards Spiral Create a first draft of the John Edwards Spiral and characterize it	What are potential difficulties in constructing the spiral? What potential design improvements could be implemented in the design geometry?	Geometry of the Spiral Material decisions	Loading capacity Curvature	Reproduction of the John Edwards Spiral Characterization of the John Edwards Spiral
P2T2: Characterize effects of altered design parameters on performance Vary geometric design parameters to determine the overall effect that they will have on the performance of the spiral	How does altering the angles of the quadrilaterals change the deformation? Is there any way to induce larger curvature for a smaller incremental closing or opening motion?	Angles of the quadrilaterals	Curvature of the spiral	Understanding of how design parameters affect the performance of the spiral structure
Phase 3. Introducing Magnetic Functionality to the Gripper				
P3T1: Brainstorm incorporation of magnetic responsiveness Identify methods for introducing magnetic functionality to the spiral	What methods of introducing magnetic functionality are possible? What are the advantages and disadvantages of each method?	Fabrication ease Repeatability Hard magnets vs soft functional material	Choice of implementation method to pursue	Complete table describing the advantages and disadvantages of each method Final decision on which implementation to pursue
P3T2: Introducing Magnetic Functionality Perform the implementation of magnetic functionality and characterize	What is the dynamic motion profile of the spiral under magnetic actuation? What is the final state of the spiral using magnetic actuation? What are the limitations of this?	Strength of actuating magnetic field Magnetic field strength of magnetic material	Dynamic deformation profile of spiral Curvature of magnetic spiral at max actuation Maximum Load	Successful construction of the magnetic spiral Characterization of the magnetic spiral

	What kind of loads can the spiral handle with magnetic actuation?			
Phase 4. Expanding Magnetic Functionality to robots				
P4T1: Brainstorm incorporation of device into a robot Identify interesting ways in which the spiral could be used in a robot	What design limitations are inherent to a robot that uses magnetic actuation? What purpose would this robot serve?	Challenges with each implementation Ease of fabrication	Choice of design to pursue	Complete table describing each design proposition along with advantages and disadvantages of each option Final decision on which implementation to pursue
P4T2: Fabricate and Characterize performance of robot Build the robot and characterize its performance	How well does the robot perform its intended task? Are there any other use cases for the robot?	Design of the robot	Success at performing desired task	Successful demonstration of the robot Complete characterization of the robot

4 Results and Discussion

4.1 Design of Spiral

4.1.1 Spiral was constructed by arranging multiple quadrilaterals symmetrically on both sides. Each quadrilateral on either side maintains identical angles at its vertices, and the ratio of edge lengths between adjacent quadrilaterals is consistent. In other words, similar quadrilaterals with proportional dimensions are used in adjacent positions. Changes in the angles formed by the edges of the quadrilaterals result in variations in the assembled Spiral's motion. In this study, we modified the angles of the quadrilaterals to observe the resulting movement(Table 1). The observations are summarized(Table 2).
The results indicate that increasing the angle enlarges Spiral's workspace. However, this also causes the tip part to form a gentler angle, making it difficult to create precise gripping motions for small objects. Based on these experimental results, we designed Spiral with gentle-angled quadrilaterals arranged in the base part to achieve a wide workspace. In contrast, steep-angled quadrilaterals were arranged in the tip part to enable precise gripping motions, allowing the spiral to function effectively as a gripper.

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Table 1. The parameters of the largest quadrilateral

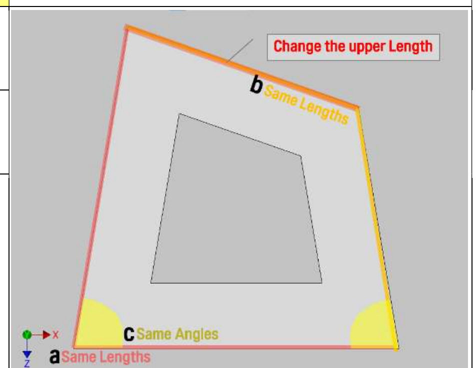
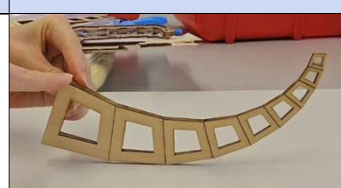
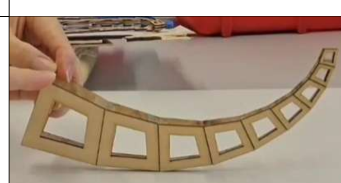
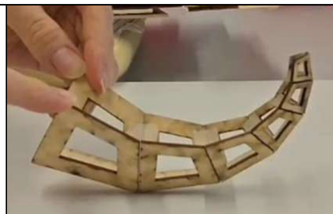
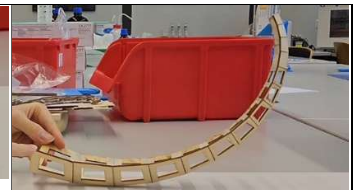
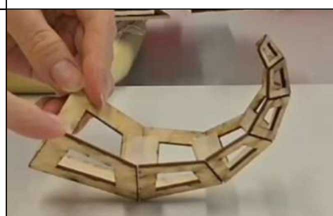
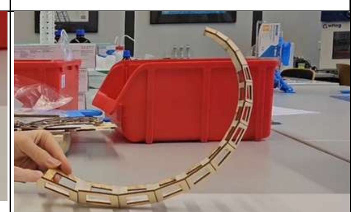
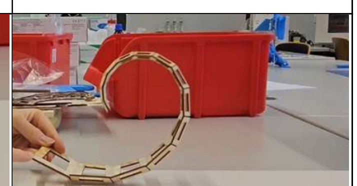
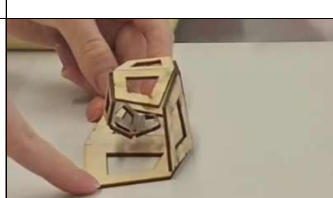
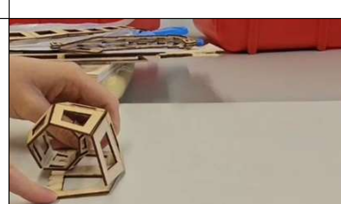
Spiral No.	**a** (Length)	**b** (Length)	**c** (Angle, dependent on a, b)	Reference
1st	50mm	37.5mm	80.41˚	
2nd	50mm	41.25mm	83.91˚	
3rd	50mm	45mm	86.82˚	

Table 2. Comparison of Spiral Motion depending on different angles

Angle (about)	Curvature		
	1st Spiral	2nd Spiral	3rd Spiral
10°			
20°			
30°			

40°			
50°			
60°			
70°			
80°			
90°			

4.2 Enhancing Spiral Actuation through Optimized Thin Magnet Attachment Points

4.2.1 In this study, we explored the actuation of Spiral using magnetic fields. For this purpose, thin magnets were attached to both the left and right sides of Spiral. The attached thin magnets were aligned with the same magnetic pole direction(Table 3). We conducted experiments by varying the attachment positions of the magnets to determine which configuration would be most effective for actuating Spiral. In particular, we compared and analyzed the degree of curling and the ease of user control for each case, summarizing the results(Table 4).

4.2.2 As a result, when comparing the actuation quality of Spiral with priorities given to the degree of curling and ease of user control, the configuration with magnets on both sides showed the best performance, followed by the configuration with magnets inside, and lastly, the one with magnets outside.

Table 3 Example of Thin Magnet Attachment

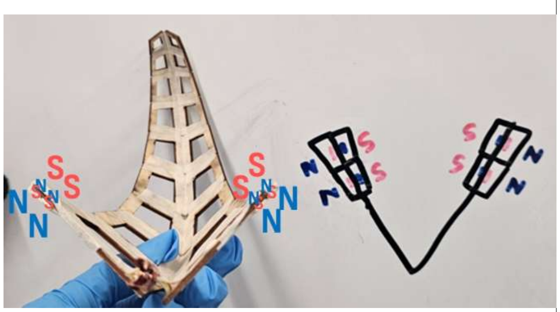
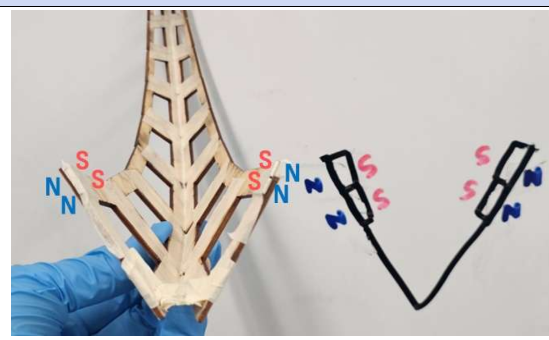
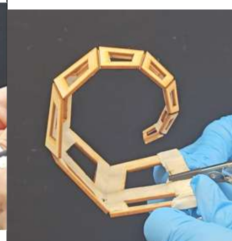
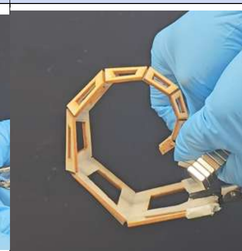
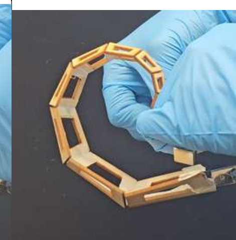
Attaching magnets to both sides	Attaching magnets to the inside
	

Table 4 Comparison of Spiral Movement Based on Thin Magnet Attachment Points

Magnets outside	Magnets on both sides		Magnets inside	Reference (Maximum degree of curling)
	Actuation from outside using attraction	Actuation from inside using repulsion		
				
less curled	well curled	well curled	well curled	-
difficult actuation	Relatively easy actuation	Relatively easy actuation	the most difficult actuation	-

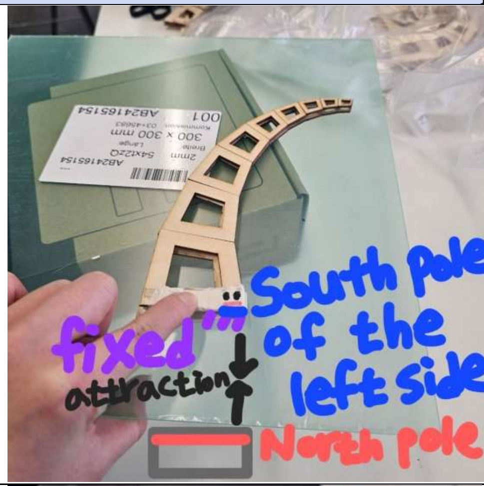
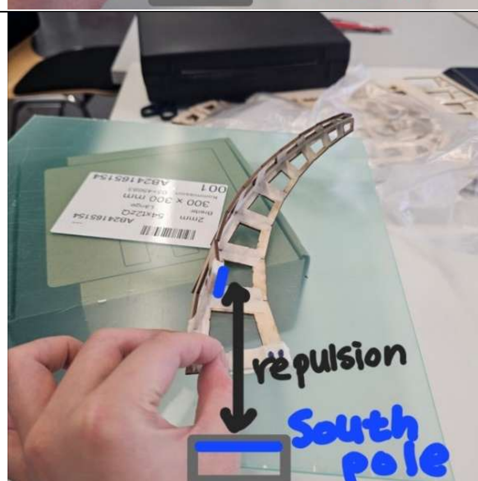
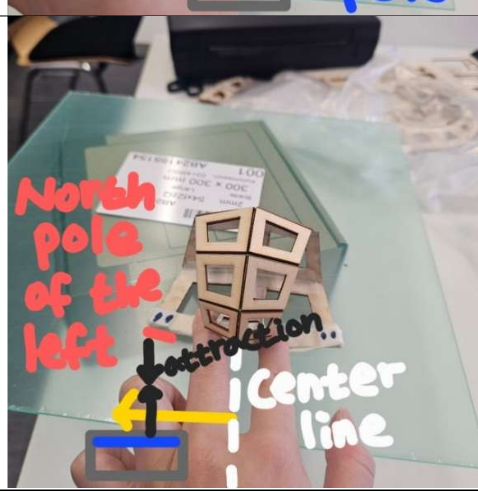
4.3 Spiral Actuation Using a Strong Magnet

4.3.1 We have observed the behavior of Spiral motion when thin magnets are attached to the edges of the largest quadrilateral with relatively moderate magnetic forces. Building on these observations, this study aims to explore how Spiral moves when a strong magnet is used instead.

We conducted experiments using Spiral with thin magnets attached to both sides. Specifically, four thin magnets were attached to each side of the spiral—two on the outside and two on the inside of both the left and right sides—resulting in a total of eight thin magnets. The experimental setup involved mounting an acrylic plate on boxes to create space beneath Spiral, allowing for the placement of a strong magnet(Figure 2). The experiments followed a three-step procedure(Table 5).

Figure 2. Experimental Environment

Table 5. Experimental Steps

<table>
<tr><th>No.</th><th colspan="2">Description</th></tr>
<tr><td>1st step</td><td>
</td><td>The right side of Spiral was pressed and held by hand. And a strong magnet was placed with its north pole facing upward.
The south pole of the thin magnet attached to the inside of the left side was attracted to the strong magnet's north pole, causing Spiral to fold.</td></tr>
<tr><td>2nd step</td><td>
</td><td>The strong magnet was repositioned so that its south pole faced upward.
The south pole of the thin magnet inside Spiral repelled the south pole of the strong magnet, causing Spiral to unfold.</td></tr>
<tr><td>3rd step</td><td>
</td><td>When the strong magnet is moved to the left with its south pole facing upward, and crosses the centerline(defined as the line where the left and right sides of Spiral meet), the north pole of the thin magnet on the outside of the left side of Spiral is attracted to the south pole of the strong magnet, causing Spiral to unfold.</td></tr>
</table>

4.3.2 The results showed distinct motion patterns depending on the orientation of the strong magnet. When the spiral was folded and the strong magnet's south pole faced upward, moving the magnet to the left caused Spiral to unfold as soon as the magnet crossed the centerline to the left. Conversely, when the north pole faced upward and the magnet was moved to the right,Spiral began to fold as soon as the magnet crossed the centerline to the right.

4.3.3 While the overall process was effective, we encountered difficulties in transitioning from the second to the third step of the experiment, making it challenging to achieve continuous actuation of Spiral. To address this, we attached an additional thin magnet to each side of the spiral (Figure 3), which improved Spiral's folding and unfolding behavior, making the motion more effective.

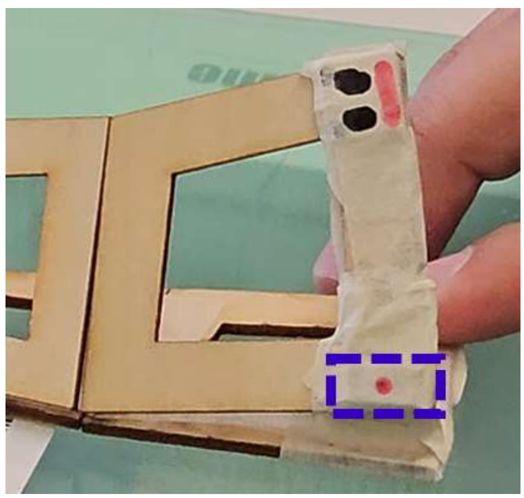


Figure 3. Attachment of an additional thin magnet to each side of Spiral

5 Conclusions

5.1 In this study, we proposed a new spiral gripper inspired by biomimetic ideas derived from spirals found in nature. The current Spiral was designed using hard material, specifically plywood, with steeply sloped quadrilaterals to enable precise object grasping. Additionally, thin magnets were attached to the outer surface, allowing actuation through a strong magnetic field. This mechanism enables the spiral to fold and unfold, facilitating object gripping.

5.2 However, to achieve the intended soft gripper, future work should focus on replacing the spiral's material with a soft alternative. Furthermore, the gripper must be developed to generate helical motion, allowing for a wider range of actuation and more precise gripping performance.

6 References

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