Seahorse Tail-inspired Soft Pneumatic Actuator Utilizing Dual-mode Actuation

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***Abstract*—In this article, a 3D-printed soft pneumatic actuator inspired by the structure of a seahorse's tail is proposed. Unlike previous pre-curved soft pneumatic actuator designs, which primarily focus on straightening action when subjected to positive pressure, our actuator offers a dual-mode actuation capability to mimic the movement of the seahorse tail controlled by muscle contraction. Specifically, it can be straightened under negative pressure and further rolled under positive pressure. Also, its material composition allows it to generate gripping forces. Under atmospheric pressure, the actuator can produce a maximum gripping force of 23N. When subjected to positive pressure, this force increases drastically to 79N. This dual-mode actuation and substantial high force generation capabilities allow for a more appropriate replication of the seahorse tail's natural movements, making our actuator suitable for diverse tasks such as delicate passive and active grasping, as well as object anchoring.**

I. INTRODUCTION

In the past decades, soft robots employing various actuation methods have emerged as a prominent design concept within the field of robotics, which is characterized by using highly deformable materials to impart significant flexibility to their design [1]. This material adaptability renders soft robots particularly well-suited to cope with dynamic and unknown environments [2]. Among the diverse actuation methods, pneumatic actuators have gained preeminence in soft robot design because of their advantageous properties of lightweight, high force-to-weight ratio, rapid actuation response, straightforward control strategies, as well as simple and cost-effective fabrication processes [3].

In general, wildlife requires moving and morphing in the wild to survive through their body's softness and flexibility [4]. Therefore, bio-inspiration, which reproduces a functional outcome by drawing on ideas from nature or understanding the principles that underlie natural processes, is becoming a promising method to generate ideas for designing soft robots [5]. Numerous living organisms were used as a reference to the soft actuator design, such as octopus tentacle [6], elephant trunk [7] and human muscle [8]. Actuators originating from these organisms usually resume in straightened posture and bending/elongation actions are generated under external stimuli.

On the other hand, living organisms that maintain a perpetually curled posture offer intriguing biological insights and practical inspirations. Notable examples include the seahorse tail [9], the monkey tail [10], and the chameleon tail [11]. The seahorse tail particularly stands out for its remarkable adaptability and functionality. It belongs to a biological family known as the hippocampus and is renowned for its unique tail structure. This biological design allows the seahorse to attach to seagrass effectively as an anchor to resist water currents. This natural design also enables the seahorse to dexterously conform and grip objects through muscle contraction [12]. Such natural adaptations have inspired the development of soft robots with similar capabilities. A few seahorse tail-inspired soft pneumatic actuators were proposed [13] [14] [15]. However, their primary focus was replicating the seahorse tail's ability to straighten under positive pressure. Nevertheless, the emulation of its curling action remains an area with limited exploration and research. Additionally, the fabrication method constrained the force generated, resulting in relatively low output.

Symbol	Description	Value
w_{first}	Width of the first unit	5mm
w_{last}	Width of the last unit	12mm
h_{first}	Height of the last unit	12mm
h_{last}	Height of the last unit	32mm
a	Starting radius of the spiral	2mm
n	Actuation unit number	15
q_{width}	Geometric ratio for the width	1.07
q_{height}	Geometric ratio for the height	1.06
a	Parameter in Eq. 1	2
b	Parameter in Eq. 1	0.306

TABLE I
PARAMETERS USED IN THE ANALYSIS.

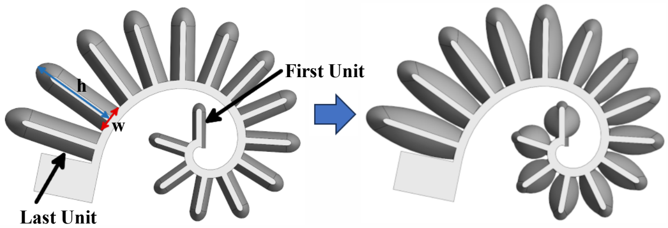
In this article, a 3D-printed soft pneumatic actuator inspired by the seahorse tail is proposed. The actuator incorporates a dual-mode actuation mechanism to imitate the muscle contraction of the seahorse tail, which enables the actuator to perform both active and passive grasping, as well as object anchoring. In its default state, the actuator exhibits a curled posture, which can be manipulated to straighten through vacuum application and curl via a positive pressure supply. Additionally, using advanced 3D-printed materials significantly enhances the actuator's holding force, demonstrating a notable improvement over previous seahorse tail-inspired soft actuators.

II. DESIGN AND FABRICATION

The design of the proposed actuator is primarily based on the geometry of a logarithmic spiral, which can be mathematically described by the following polar equation:

$$r = ae^{b\theta} \tag{1}$$

Here, r and θ are the polar coordinates, a is the distance from the starting point of the spiral to the origin of the polar coordinate system, and b indicates the rate at which the spiral's



(a)


(b)

Fig. 1. Design of the proposed soft pneumatic actuator. The definition of the first and last actuation units, as well as the width and height, is shown in the figure. (a) The actuator was modeled based on the given parameter, as shown in the left image. h and w denote the actuation unit width and height, respectively. Curved surfaces were then added to minimize the gap between actuation units, as shown in the right image. (b) The image of the 3D-printed actuator.

radius r changes with respect to the spiral's angle θ. Notably, the shape of the seahorse tail closely approximates the shape of a golden spiral [9]. Therefore, in the design of the actuator, the golden spiral was adopted by setting the value of b in Eq. 1 to 0.306.

Several key requirements were considered in the actuator's design. First is the geometric progression of actuation units. The width and height of the actuation units increase in a geometric sequence, determined by the dimensions of the first and last units. These dimensions can be calculated using the following equation:

$$q = \sqrt[n-1]{\frac{x_{last}}{x_{first}}} \tag{2}$$

where x_{first} and x_{last} are the dimensions (width or height) of the first and last units, respectively, q is the geometric ratio and n is the actuation unit number.

Second is the non-interference of actuation units. It is crucial to ensure that the actuation units do not interfere with other portions of the actuation body. Based on these design principles, the actuator was designed based on the parameters listed in Table I.

In modeling the actuator, an initial model was created based on specific parameters, as illustrated in the left side of Fig. 1(a). Curved surfaces were then incorporated between the actuation units to minimize the gap distance and optimize the actuation performance, as depicted in the right side of Fig. 1(a). The actuator was subsequently fabricated using Fused Deposition Modeling (FDM) 3D printing technology, employing NinjaTek Ninjaflex® Edge thermoplastic elastomer (TPE) as the printing material. The final fabricated actuator is presented in Fig. 1(b).


(a) (b) (c)

Fig. 2. Performance of the actuator under (a) Negative pressure of -50kPa. (b) Atmospheric pressure. (c) Positive pressure of 100kPa.


Fig. 3. Hardware setup for the holding force test.

III. Results and Discussions

A. Actuation Performance Test

Two tests were conducted to evaluate the performance of the actuator. The first test focused on assessing the actuator's response to both positive and negative pressure conditions, as shown in Fig. 2. Initially, the actuator was placed under atmospheric pressure, as shown in Fig. 2(b). The actuator was then subjected to a vacuum environment with a negative pressure of -50kPa. As shown in Fig. 2(a), under these vacuum conditions, the actuator effectively straightened, demonstrating its capability to respond to negative pressure. Following this, the actuator was supplied with a positive pressure of 100kPa, as depicted in Fig. 2(c). Under this positive pressure, the actuator performed a further bending action from its original curled posture, indicating its functionality under positive pressure conditions. The outcomes of these tests demonstrate the proposed actuator's ability to operate under dual pressure

TABLE II
COMPARISON OF PRE-CURVED PNEUMATIC ACTUATORS

Bioinsiration	Fabrication Method	Material	Passive Gripping	Active Gripping	Maximum Force Generation	Reference
Seahorse	Molding	Silicone	Yes	No	9.81N (Passive, Three-finger Gripping Force)	[13]
Seahorse	Molding	Silicone, PLA	Yes	No	1.47N (Active Pushing Force when Straightening)	[14]
Seahorse	Molding	Silicone, TPU	Yes	Yes	11.9N (Passive Gripping Force)	[15]
Avian	Molding	Silicone	Yes	Yes	0.49N (Passive Block Force) 4.61N (Active Block Force)	[16]
Inchworm	Molding	Silicone, Nylon Fiber	No	Yes	12.3N (Maximum Carrying Weight)	[17]
Spider	Molding	Silicone, Nylon Fiber	No	Yes	14.7N (Active, Four-finger Gripping Force)	[18]
Seahorse	3D Printing	Ninjaflex® Edge TPE	Yes	Yes	23N (Passive Holding Force) 79N (Active Holding Force)	Our Work

conditions, successfully performing actuation when subjected to both negative and positive pressures.

B. Holding Force Test

Subsequently, a holding force test was conducted to evaluate the force generation capability of the actuator. The test setup is illustrated in Fig. 3. In this configuration, a force sensor (SBT673-10kg, Simabtouch) was mounted at the top of the apparatus. A 3mm diameter inextensible string was connected to the force sensor and positioned at the base of the actuator. The actuator was firmly attached to a moving platform. During the test, the actuator was lowered at a velocity of 8mm/s until the string was detached from the actuator. At this point, the maximum force was recorded. Two distinct conditions were evaluated during the test: operating at atmospheric pressure and under a positive pressure of 100 kPa. Under the first condition, without any external pressure, the actuator demonstrated its ability to generate a maximum holding force of 23N. In contrast, when the actuator was subjected to a positive pressure of 100 kPa, it exhibited a significant increase in performance, achieving a maximum holding force of 79N. These results underscore the actuator's force generation capability when operating under increased pressure, highlighting its potential for applications requiring variable force outputs.

C. Actuators Comparison

Several typical of pre-curved soft pneumatic actuator are shown in Table II, in which their materials, fabrication method, action, and force generation are compared. This comparative analysis highlights the distinctive advantages of our proposed actuator over existing designs.

In examining the materials used, our actuator utilizes easily accessible 3D printing material that streamlines the fabrication process, which contrasts with the others that require complex, multi-step fabrication processes involving specialized materials that may not be readily available. The simplicity and efficiency of our fabrication method significantly reduce production time and cost.

The actuation mechanisms have also been compared in the table. While most actuators primarily focus on generating straightening action under positive pressure, our actuator exhibits a dual-mode actuation capability. It can be straightened under negative pressure and further curled under positive pressure, offering a versatile range of movements. This functionality enhances the actuator's adaptability for various applications, from delicate tasks requiring precision to those demanding robust force.

Moreover, the force generation capabilities of our actuator are notably superior. While other actuators may offer limited force outputs, our design can generate a maximum holding force of 23N under atmospheric pressure and 79N under positive pressure. This substantial force generation is crucial for applications that require strong, reliable holding. To the authors' best knowledge, this is the first pre-curved soft pneumatic actuator design that combines dual-mode actuation with high holding force generation.

IV. CONCLUSION

In conclusion, this article presents a 3D-printed soft pneumatic actuator inspired by the motion of a seahorse tail by muscle contraction. Unlike traditional pre-curved soft pneumatic actuators, which primarily emphasize straightening under positive pressure, our design offers a dual-mode actuation capability. This actuator can straighten under negative pressure and further curl under positive pressure, which has been demonstrated experimentally, providing a versatile range of movements. The material composition of our actuator, coupled with the 3D printing fabrication method, allows for holding forces generation. Specifically, the actuator can produce a maximum holding force of 23N under atmospheric pressure and an 79N under positive pressure. Also, the 3D-printing method highlights the simplicity and efficiency of our fabrication process, which significantly reduces production time and cost compared to other actuators requiring complex, multi-step fabrication methods. Overall, our actuator's superior force generation capabilities, ease of fabrication, and versatile actuation mechanisms make it an up-and-coming solution to cope with different grasping and anchoring situations.

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