Variable Volume Soft Robot Actuator with String Constraint System

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***Abstract*—In this paper, we explore a new style of actuator that combines the positive aspects of conventional actuators in current literature. In the past decade, a wide scope of object manipulation mechanisms have been proposed, but most are limited to a single defined motion and volume. Creating an actuator system that is both flexible in shape and range of motion will increase the utility of soft robotics actuators. This paper explores this design proposal with an inflatable system encased by string-embedded cloth casing. The resulting system can change its length by controlling the length of the guiding strings and manipulating the air volume within the actuator, with multiple angles achieved through control of relative length of the strings, all without human intervention.**

***Index Terms*—Soft robotics, Actuator, Variable volume, Variable motion, String constraint system**

I. Introduction

The field of soft robotics has seen a rapid growth in development and adaptation of various systems. These new systems created new ways of manipulating objects in a cheap and adaptable way without requiring complex analysis of the motion taken, creating a distinct advantage over hard-bodied counterparts. This advance in adaptability along with the resilience of the actuators make them desirable for operation under numerous settings and conditions. This growth is evidenced by literature surveys [1] and [2], which show soft robotics as a relatively new field filled with promising applications in areas current hard-bodied mechanisms struggle.

However, while there have been numerous adaptations of the natural world like cephalopods as inspiration for new actuators, these actuators often have the same constraints their inspirations do. Current object manipulators and structures are limited in its function due to the lack of range of motion capable, mostly by its definitive nature of post-construction design. A new mechanism that combines the flexibility of soft materials with the adaptability and strength of the conventional stiff-bodied string driven actuators will introduce a new wave of object manipulation methods.

The objective of the paper is to create and test a flexible movement actuator that has re-programmable volume and direction of movement without a need for human interference. This new actuator has two main significance points. One is that no current mechanism has more than two pathways of motion despite the flexibility of the material and amazing amount of degrees of freedom. That is, once a motion is defined, the actuator is incapable of exploring other ranges of motion, greatly decreasing its versatility. This terminal and definitive nature of programming in movement limits the adaptability of actuators as it requires either the manufacturing of a new mechanism for different functions or a human intervention to make adjustments. The second significance is that the actuator will have adaptable volume, meaning that it is much more applicable in areas where space is limited. Physical settings that require more flexible and lighter materials are often cramped, greatly reducing the space available to be occupied. Variable volume function further improve soft robots' application in areas current hard-bodied mechanisms cannot perform, namely in aerospace where less volume packaging greatly benefits the transportation process.

II. Background

A current literature survey shows that the majority of actuator are silicon-based, pneumatically-powered actuators, as listed in [3] and [4]. These actuators are very versatile and efficient, requiring almost no complex fabrication process and providing great programmability achieved through 3D printing of the molds. Through a variety of channel structures and configuration of fingers, the actuators can take different actions and interact with variously shaped objects with the help of cushioning material properties.

These simple actuators have a major downfall, however. They have a very limited and final range of motion, defined from the moment of fabrication and dictated by the shape of the printed mold. This definitive nature of the actuator's function limits the versatility and thus the implementation of the system, whereas a hard-bodied system can simply be repurposed without being entirely replaced. The lack of multiple functionality within a single system is a huge detriment to the adaptation of soft robotics.

There have been efforts to explore reprogrammability of these pneumatic actuators as done in [5]. While this enables multiple shapes and range of motion, the variability comes at a cost. This method of wrapping a jacket around relevant parts would require human intervention whenever a new movement is desired, drastically reducing the independence the actuator would need. This is even more concerning for implementations

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in unreachable environments, like the depth of the ocean or in the hazards.

In order to give these conventional pneumatic actuators more flexibility of achievable motion, the number of channels and the complexity of the control system can be increased. With an addition of multiple channels, the pneumatic actuator is able to achieve far greater and complex range of motion, explored in [6]. This increases the versatility and general usefulness of the actuator, enabling new manipulations.

This adaptation, however, would require a very convoluted and excessive powering and controlling system to be present, thereby limiting the overall adaptability of the system. This is quite contrary to the primary reason for using soft robotic actuators - simplicity. If such bulky actuation system can be used, current hard-bodied systems can be much more efficient and powerful than its soft-bodied counterpart.

Among other types of actuators, those that draw inspiration from nature is common, most notably in forms of stiff-bodied, cable-driven systems. A cephalopod-like mechanism observed in [7] or an elephant trunk-like system from [8] show great flexibility and precise control of the long mechanism. Similar mechanisms that combined string constraint into a pneumatic actuator is shown in [9].

While these require less complex driving system than [6], there rises another problem. Compared to the foldable hard-bodied actuators, these cable-driven soft material actuators have predefined volume that cannot be shrunk to occupy less space. They require a setting that allows the movement of not only the end effector, but also the arm itself, making the environment state a primary concern before their implementation.

Other unconventional forms of actuation that enable variable volume and length exist. [10] tests an expandable pneumatic system, while shape memory polymers like the one explored in [11] are able to achieve actuation by extreme physical property change.

There has been a attempt at dealing with the aforementioned challenges in [12]. However, this robot still requires human reset to the initial state before being able to deploy again, lacking the independence.

In summary, the current state of actuators in the field of soft robotics has three major limits:

- Fixed shape/volume
- Limited/fixed range of motion
- Requirement of human intervention to achieve variable motion

III. Manufacturing

In order to solve the three major problems in soft robotic actuators, an inflatable flexible material embedding guidelines for the constraining cables is considered. Throughout the series of different designs, new materials and structures are considered and tested.

A. *Evolution of Design*

The first design of embedding guide plates in an expandable silicon-based pneumatic actuator, shown in Fig. 1, drew inspiration from [10]. A mold for the silicon finger is 3D printed

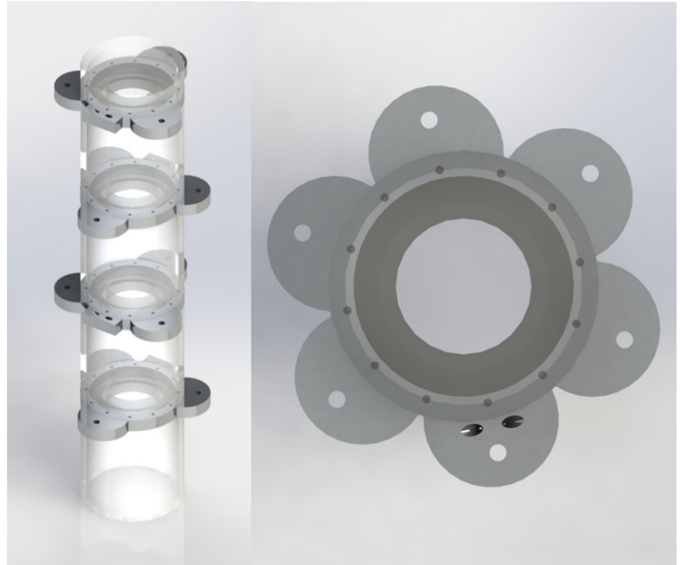

Fig. 1. Acrylic cable guiding plates embedded in silicon finger. The silicon finger has a single pneumatic channel in the middle while the guiding cables are fixed at the end plate and strung through the rest of the plates. The plate has three linear constraint holes for directional constraints and two diagonal constraint holes for roll constraints.

Fig. 2. Hermetic plastic sheet pouch with guiding cables. The channels for the cables are also heat-sealed onto the sheet before creating the finger.

in PLA while the guiding plates are laser cut from acrylic. Then the plates are placed in position on the mold and silicon is poured, curing with the plates inside. While the design showed some promise, the execution turned out to be much more difficult than anticipated. The silicon finger needed to be thin enough in order to produce significant volume change, but it would no longer be able to hold the guiding plates in place. There was also a considerable amount of friction between the cable and the silicon body, leading to points of jamming and resulting in uneven curvature.

In order to overcome the initial design problems, a new design inspired by [13] was considered, shown in Fig. 2. Instead of using silicon, a flexible plastic sheet would be used to create a pouch-like finger, with guides embedded onto the sheets. A rectangular sheet is cut and heat-sealed to create a hermetic pouch. With guiding slits sealed onto the material, cables are strung through and held in place at the end. The material allowed for a better volume displacement, but due to the inherent initial state shape, the shrinkage happened only in the width and not the height of the actuator. Also the addition of channel material led to a lot of material buckling that hindered the volume change process.

B. Final Design

The final design, shown in Fig. 3, resulted from an attempt to separate the mechanism for storing the air and the mechanism for holding the guiding cables. By making it an independent element for air holding, the constraint layer did not need to be hermetically sealed, increasing the flexibility of the material. A common cloth was chosen due to its great shrinkage and the ability to embed cables. The resulting actuator was able to achieve the greatest amount of volume change, shown in Fig. 4, without minimal buckling, and the cable constraints were able to create more even curvatures.

The finger is attached to a base with two motors, controlled by an Arduino and a simple motor control code. The motors have reels with the cable fixed at a point, controlling the length and the curvature of the actuator by varying the relative lengths of the cables.

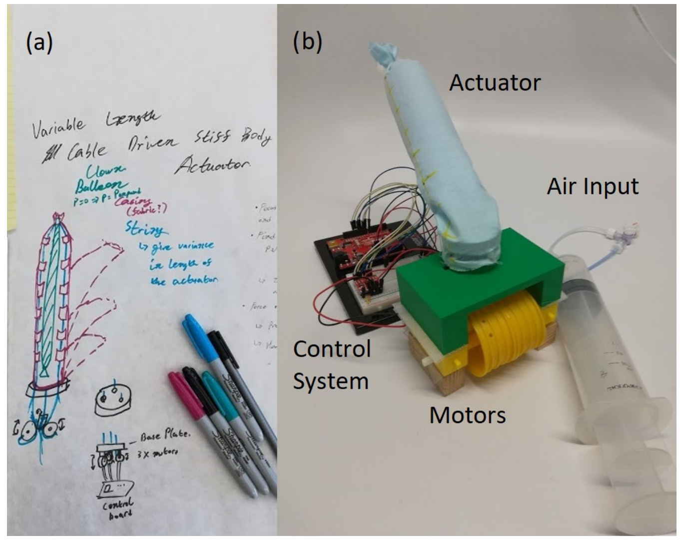

Fig. 3. Inner air storage wrapped in a fabric layer, with guiding cables sewn into the fabric. (a) A basic drawing of the actuator, with different layers and elements color-coded. (b) The full mechanism with the control system and the actuator. For the actuator, the inner layer is a commercial balloon, enclosed by a fabric layer that was sewn together into a cylindrical shape. The constraint cables are sewn through the fabric. The control system is an Arduino connected to two motors. An air input allows for pressure from either a piston or a compressor.

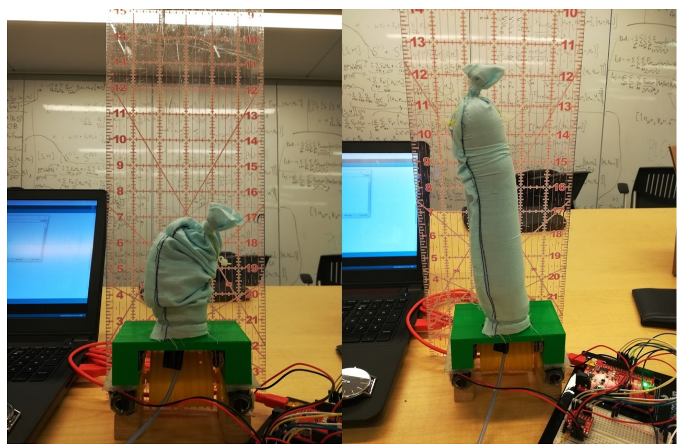

Fig. 4. Volume change of the actuator. The initial length of the actuator is 3 inches. The full length of the actuator is 8 inches.

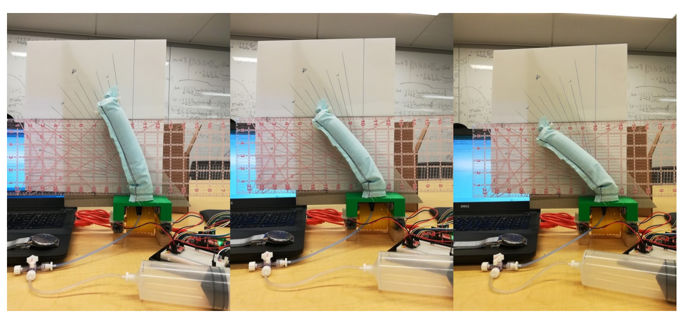

Fig. 5. Characterization setup. The actuator is tested at various lengths and curvature in order to gather data to create a mathematical model of its pathway.

IV. Characterization

In order to evaluate the functionality of this new actuator, the following characterization tests were done, with the setup shown in Fig. 5:

A. $L_{actuator}$ vs P

A characterization between the pressure within the actuator p and the length of the actuator $L_{actuator}$ is done to gauge the amount of air pressure required to operate this actuator. The data, shown in Table I, shows that a consistent inner pressure of around 2.3 psi is required for maximum inflation at any given length.

B. L_{cable} vs D and θ

A characterization between the displacement distance D and angle θ for given curvature at different lengths of the cable

TABLE I
$L_{actuator}$ VS P CHARACTERIZATION

Pressure (psi)	Actuator Length (in)
2.497	8
2.357	7
2.497	6
2.497	5
2.217	4
0.717	3

TABLE II
L_{cable} VS D AND θ CHARACTERIZATION

String Length (in)	Deviation (cm)	Angle
8	0	0
7.5	0.7	15
7	2	25
6.5	3	38
6	3.5	45
5.5	3.8	55
5	4	60
4.5	4.2	65
4	4.3	65

L_{cable} is done to record the pathway of the actuator. The data, shown in Table II, shows that the initial displacement is far greater with diminishing changes as string length change increases.

V. RESULTS & DISCUSSION

The characterization demonstrated the actuator's capabilities of changing volume and the position of the end effector without the need of human assistance. While these characterizations are a good indicator of the actuator's functionality, the data collected is by no means exhaustive or completely precise. This is due to several limitations of the current design.

The first limitation is that the type and the shape of the encased balloon has a great impact on the movement of the actuator. A regular balloon used for this paper leaves the base of the actuator relatively weak, leading to a steeper curvature concentrated at the bottom of the actuator.

The second limitation is that since the system requires a constant pressure maintained within the actuator regardless of its length, there needs to be a pressure regulator control system. This control system could be run through the same controller board, although a mechanisms using a solenoid and a pressure reader is necessary to program the PID loop.

Lastly, at shorter string lengths, the torque applied onto the motor increased significantly. This may have been due to the lack of pressure regulation and can be solved by the implementation mentioned previously. However, stronger motors with higher stall torque will be helpful, especially for scaled up actuators and to achieve more extreme actuation.

VI. CONCLUSION & FUTURE WORK

In this paper, we have created and demonstrated a new type of actuator that has variable length and curvature without the need for human intervention for its variability. We show the development process of creating a mechanism that combines the compactness of variable volume actuator and the versatility of stiff-bodied, cable-driven systems. This new system both combines benefits of several types of actuators while eliminating each one's faults, and can be a new step forward for soft robot actuators.

The development of the actuator was divided largely into three parts. The first is the actuator itself. It is a pneumatically powered volume encased by a flexible material, with the outer layer having attachment points for the strings in order to give constraints to the volume. The direction of the actuation is dictated by the length of the strings, controlled by motors attached to a control system. The second part is the control system itself, which is Arduino-based. It has the capabilities of keeping track of and manipulating the length of the strings. The last part is the pneumatic power system, which needs to apply different amount of pressure depending on the desired length and shape of the actuator.

For this actuator to see implementation in real settings, however, a systemic mathematical analysis of the actuator is needed. While a couple of characterizations were done, there needs to be more benchmarks such as strength, strain, and durability tests performed, as well as a larger volume of current characterizations collected. Using these data, it will be possible to create a program that maps out different variables and constraints in order to achieve a desired motion. The hope is this new actuator will create a new interest in alternative methods of achieving motion in the field of soft robotics.

REFERENCES

[1] F. Ilievski, A. D. Mazzeo, R. F. Shepherd, X. Chen, and G. M. Whitesides, "Soft robotics for chemists," *Angewandte Chemie International Edition*, vol. 50, no. 8, pp. 1890–1895, 2011.

[2] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, no. 7553, p. 467, 2015.

[3] A. D. Marchese, C. D. Onal, and D. Rus, "Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators," *Soft Robotics*, vol. 1, no. 1, pp. 75–87, 2014.

[4] M. T. Tolley, R. F. Shepherd, B. Mosadegh, K. C. Galloway, M. Wehner, M. Karpelson, R. J. Wood, and G. M. Whitesides, "A resilient, untethered soft robot," *Soft robotics*, vol. 1, no. 3, pp. 213–223, 2014.

[5] K. C. Galloway, P. Polygerinos, C. J. Walsh, and R. J. Wood, "Mechanically programmable bend radius for fiber-reinforced soft actuators," in *2013 16th International Conference on Advanced Robotics (ICAR)*. IEEE, 2013, pp. 1–6.

[6] A. D. Marchese and D. Rus, "Design, kinematics, and control of a soft spatial fluidic elastomer manipulator," *The International Journal of Robotics Research*, vol. 35, no. 7, pp. 840–869, 2016.

[7] F. Renda, M. Giorelli, M. Calisti, M. Cianchetti, and C. Laschi, "Dynamic model of a multibending soft robot arm driven by cables," *IEEE Transactions on Robotics*, vol. 30, no. 5, pp. 1109–1122, 2014.

[8] M. D. Grissom, V. Chitrakaran, D. Dienno, M. Csencits, M. Pritts, B. Jones, W. McMahan, D. Dawson, C. Rahn, and I. Walker, "Design and experimental testing of the octarm soft robot manipulator," in *Unmanned Systems Technology VIII*, vol. 6230. International Society for Optics and Photonics, 2006, p. 62301F.

[9] K. C. Galloway, K. P. Becker, B. Phillips, J. Kirby, S. Licht, D. Tchernov, R. J. Wood, and D. F. Gruber, "Soft robotic grippers for biological sampling on deep reefs," *Soft robotics*, vol. 3, no. 1, pp. 23–33, 2016.

[10] R. V. Martinez, C. R. Fish, X. Chen, and G. M. Whitesides, "Elastomeric origami: programmable paper-elastomer composites as pneumatic actuators," *Advanced functional materials*, vol. 22, no. 7, pp. 1376–1384, 2012.

[11] A. Lendlein, H. Jiang, O. Jünger, and R. Langer, "Light-induced shape-memory polymers," *Nature*, vol. 434, no. 7035, p. 879, 2005.

[12] E. W. Hawkes, L. H. Blumenschein, J. D. Greer, and A. M. Okamura, "A soft robot that navigates its environment through growth," *Science Robotics*, vol. 2, no. 8, p. eaan3028, 2017.

[13] R. Niiyama, D. Rus, and S. Kim, "Pouch motors: Printable/inflatable soft actuators for robotics," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2014, pp. 6332–6337.