



Digumarti, K., Conn, A., & Rossiter, J. (2017). Euglenoid-inspired Giant Shape Change for Highly Deformable Soft Robots. *IEEE Robotics and Automation Letters*. <https://doi.org/10.1109/LRA.2017.2726113>

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# Euglenoid-inspired Giant Shape Change for Highly Deformable Soft Robots

K. M. Digumarti<sup>1</sup>, Andrew T. Conn<sup>1,2</sup> and Jonathan Rossiter<sup>1,3</sup>

**Abstract**—Nature has exploited softness and compliance in many different forms, from large cephalopods to microbial bacteria and algae. In all these cases large body deformations are used for both object manipulation and locomotion. The great potential of Soft Robotics is to capture and replicate these capabilities in controllable robotic form. This paper presents the design of a bio-inspired actuator capable of achieving a large volumetric change. Inspired by the changes in body shape seen in the euglena *Eutreptiella spirogyra* during its characteristic locomotion, a novel soft pneumatic actuator has been designed which exploits the hyper-elastic properties of elastomers. We call this the Hyper-Elastic Bellows (HEB) actuator. The result is a structure that works under both positive and negative pressure to achieve euglenoid like multi-modal actuation. Axial expansion of 450% and a radial expansion of 80% have been observed, along with a volumetric change of 300 times. Further, the design of a segmented robot with multiple chambers is presented which demonstrates several of the characteristic shapes adopted by the euglenoid in its locomotion cycle. This work shows the potential of this new soft actuation mechanism to realise biomimetic soft robotics with giant shape changes.

**Index Terms**—Soft Material Robotics, Biologically-Inspired Robots, Flexible Robots

## I. INTRODUCTION

CEPHALOPODS are able to deform their bodies in order to squeeze into extremely small holes, to manipulate objects of different shapes and even to open bottles and jars [1]. Smaller organisms such as bacteria and algae are also able to deform their bodies to overcome the challenges of their environments. The ability to drastically change body shape is particularly attractive in future robots and would be extremely useful in traversing cluttered environments or squeezing through tight spaces. Example scenarios include negotiating collapsed rubble for search and rescue and overcoming uneven terrain. Invasive medical procedures for endoscopy are equally demanding. In this paper we consider

Manuscript received: February 15, 2017; revised: May 09, 2017; accepted: June 22, 2017. This paper was recommended for publication by Y. Sun upon evaluation of the Associate Editor and Reviewers' comments. This work was supported by the EPSRC centre for doctoral training in Future Autonomous and Robotic Systems (FARSCOPE) at the Bristol Robotics Laboratory where KMD is a PhD student. JR was supported by EPSRC grants EP/M020460/1 and EP/M026388/1. JR and AC were supported by RoboSoft, the FP7 Coordination Action on Soft Robotics. Data access: applied for a university research database number. Shall be updated when online.

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Digital Object Identifier (DOI): see top of this page.

the problem of replicating the giant body deformations of soft-body organisms in a soft robot. We take inspiration from the shape-changing capabilities of the Euglena family of microorganisms and present an artificial body unit that can be used to develop multi-segment soft robots that show giant actuation and which can exploit the benefits of this actuation in locomotion and manipulation. We call this unit the Hyper-Elastic Bellows (HEB) actuator.

### A. Bioinspiration from Euglenoid Movement

Euglenoids are soft-body single-cell microorganisms commonly found in fresh waters that typically have one or more flagella. See fig. 1 (top). Depending on their environment they may utilise their flagella to swim or exhibit a slower characteristic type of locomotion called euglenoid movement in which the cell undergoes a drastic change in shape. It is this second form of motion that we address in this study. These body changes range from an elongated rod-like form to a spherical shape, with a wide range of intermediate shapes [2]. Shown in fig. 1 (bottom) are outlines of the cell obtained from video recordings made by the Euglenoid Project [3] of the organism *Eutreptiella spirogyra* when exhibiting euglenoid movement. A thorough analysis of the shape including methods of modelling is presented in [4] and [5]. In [6], measurements were taken along the length of *E. fusca* and the shape of the cell was approximated by a mathematical function. The analysis showed a contraction in length of about 37% in the longitudinal direction and a near doubling of radius during rounding, or balling, of the cell.

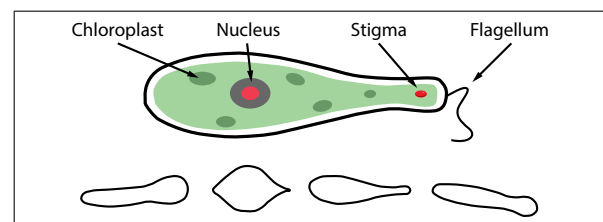


Fig. 1. (Top) Schematic of euglenoid. (Bottom) Different cell shapes exhibited during euglenoid movement. The cell can transform from a slender elongated rod-like form to a rounded up ball-like form, showing a drastic change in shape.

### B. Biomimetic Soft Actuation

Several soft robotic actuator technologies exist that could be used to reproduce the high strains seen in euglenoids. The prominent technologies are briefly reviewed here.

Taking inspiration from nature, are actuators based on hydrostatic skeletons. Purely mechanical examples include

the SoftWorm [7] and the CMMWorm [8]. These designs are mechanically complex and require large structures to accommodate large actuators. In contrast, the Meshworm presented in [9] is completely soft and flexible. It uses coiled shape memory alloy actuators [10] and can handle large strain. However, these actuators have a slow actuation-relaxation cycle. Their antagonistic arrangement results in limited stroke length. Another tendon based design is presented in [11] which uses nylon cables for actuation. The soft actuator inspired by the tentacle structure of an octopus [12] is based on the principle of a muscular hydrostat. Active cannula robots have also been explored in [13]. These designs are capable of exhibiting bending and twisting motions, but are not well suited for large volumetric change because of the tight integration of muscle-like actuators and hydrostatic structures needed to deliver significant forces.

Origami inspired structures have been used for designing worm like robots [14] and soft actuators [15]. Expanding structures using shape memory polymers have also been developed [16]. Such actuators could be used to achieve local deformations. However, their design and control is not straightforward. Soft active materials such as dielectric elastomers (DE) have been used in a worm like robot [17]. Though large strains have been reported in DE literature [18], they are not sufficient enough for this study.

A different approach to realising soft robot actuators is the use of pneumatic chambers [19]. These have been used in many applications ranging from micro scale actuators [20] to macro scale robot locomotion [21]. Ease of fabrication makes them a popular choice. Another approach that is easy to fabricate is based on granular jamming [22]. This technique has been used in [23] to design a soft robot that moves by changing stiffness of individual sections. This concept could be extended to euglenoid-like shapes. However, it is not clear if this actuation produces the desired amount of strain in the material to show a drastic change in shape. Additionally, the ability to modulate stiffness is not, at present, seen as a requirement in a robot that mimics euglenoid motion.

Exploiting the ease of fabrication, benefits of rapid expansion [24], minimal control and repeatability of actuation, we concentrate on soft fluidic actuators. We have designed a novel bellows-like pneumatic device that captures and separates the two key features of euglenoid motion: axial extension and contraction, and radial expansion. This is termed the Hyper-Elastic Bellows (HEB) actuator. A soft elastomeric folded structure forms the basic shape of the chamber, which changes shape as the internal pressure varies. The hyper-elastic property of elastomers is exploited to achieve a linear expansion followed by a huge change in volume when a positive pressure is applied. The folded structure has also been designed to collapse to a minimum configuration under vacuum. Hence the device functions both under positive and negative pressure, and can exhibit both radial and axial expansion.

Visually, the design appears similar to that of [25], a flexible manipulator for surgery. However, that design aimed to constrain radial expansion. In contrast, we exploit unconstrained expansion in radius to deliver greater activation sophistication. A second relevant design is presented in [26], where the aim was to induce a curvature in the actuator by constraining one side of the bellows. Radial and axial expansion were not considered in isolation in that study.

## II. PRINCIPLE OF OPERATION

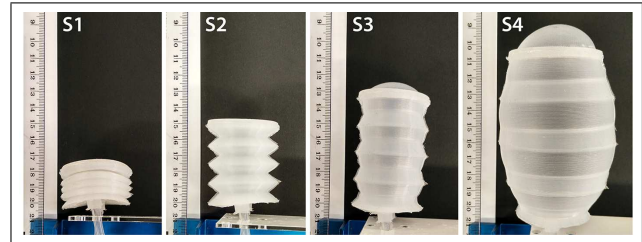


Fig. 2. The four states of actuation. S2 is the neutral state of the actuator when both internal and external pressure are equal. Upon application of vacuum, the structure contracts axially to S1. When inflated, the membrane first stretches axially (S3), then balloons out (S4). An extremely large change in volume is observed from S1 to S4.

Traditional bellows are designed to actuate only along the axial direction. There is negligible change in radius. The materials and the geometry of the design maximise uniaxial actuation whilst minimising radial expansion. While this is desired behaviour for many engineering solutions it is less attractive for capturing euglenoid motion, where both axial and radial strains are large.

The design presented here is a soft HEB actuator that, when inflated at low pressures works in a similar manner as conventional bellows, expanding axially. In contrast to conventional bellows however, the material and design of the actuator are chosen such that when it inflates to higher pressures, the structure starts to expand radially. Due to the elastic nature of the material, the chamber now expands out like a balloon. This ballooning phase can be seen in fig. 2 (S4). In this way a slowly increasing pressure causes the actuator to transition from its rest shape, first to an elongated shape and then to a spherical shape.

The elasticity of the material and the bellows design also ensures that it returns to its original shape when deflated. When pressure in the fully inflated state is released the balloon shrinks and returns first to an elongated bellows shape. As all pressure is released it returns to its original length with all folds intact. Now a negative pressure can be applied to the actuator which causes the structure to compress axially and to collapse to a minimal-length configuration in which it is entirely folded. See fig. 2 (S1). In this way we can describe the actuator as having 4 states:

- S1 Minimal length axially-compressed state ( $L < L_r$ ,  $R = R_r$ ,  $P < P_a$ ),
- S2 Rest bellows state ( $L = L_r$ ,  $R = R_r$ ,  $P = P_a$ ),
- S3 Axially expanded state ( $L > L_r$ ,  $R = R_r$ ,  $P > P_a$ ),
- S4 Ballooned state ( $L > L_r$ ,  $R > R_r$ ,  $P \gg P_a$ ),

where  $L_r$  is rest length,  $R_r$  is rest radius,  $P_a$  is atmospheric pressure,  $L$  is current length,  $R$  is current radius and  $P$  is current pressure of the actuator. By exploiting these four states we can design multi-segment soft robots that mimics the giant shape changes of euglenoid motion.

### III. METHODS

#### A. Fabrication

The HEB actuator was fabricated by casting silicone elastomer in a 3D printed mould, made up of two halves and a central core. A sealed cap containing ports was affixed to one end for attaching inlet and outlet tubes. The material used was Dragon Skin 10 SLOW (Smooth-On). The other end of the chamber was cast separately and bonded to the main structure using an adhesive, Sil-Poxy (Smooth-On).

At rest (state S2), each chamber measures 50mm in length with an inner diameter of 30mm and outer diameter of 45mm. Thickness of the wall is 2mm throughout. Bellows half angle was chosen to be  $38.66^\circ$ , similar to that of commercially available rubber bellows. See fig. 3. The particular design has four folds spanning the entire length. Other configurations were examined, including designs with more corrugations for the same length, but these resulted in actuators that did not expand or contract as effectively. Designs with other possible corrugated shapes are presented in [27] but were not fabricated in this study.

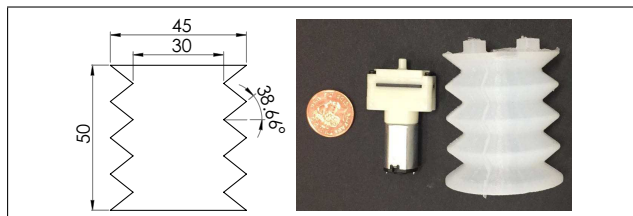


Fig. 3. Design and dimensions of the HEB actuator. On the right is a comparison of the actuator and pump size with that of an English penny.

#### B. Experimental Set-up

Fig. 4 shows the experimental set-up used to measure axial and radial elongation and compression of the actuator. One chamber with two ports was suspended from a rigid support. A micro pump (KPM14A, Yujin Electric), with a maximum dimension of 46mm and volumetric flow rate of 1.16ml/s, was connected to one of the ports to inflate or deflate the chamber. The other port was connected to a pressure sensor that measured the difference in pressure between the inside of the chamber and the atmosphere. A laser displacement sensor (KEYENCE LK-G152) was positioned below the chamber pointing upwards at its base. This measured the change in length in the axial direction. Actuation of the chamber was also recorded on video (Canon G9 camera). Expansion in the radial direction was measured through processing video frames at 1s intervals. The width at the widest point of the actuator was extracted on each frame. Ten trials were recorded for each of the inflation and the deflation phases. The results are

presented below. Volumetric change was measured separately using a syringe.

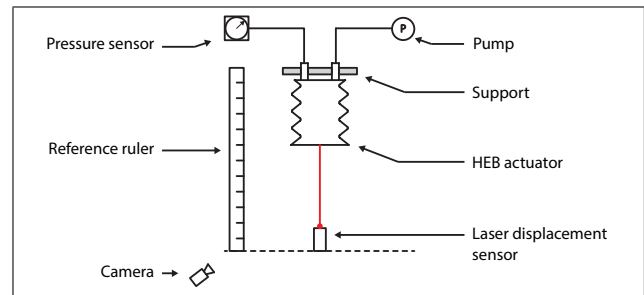


Fig. 4. The experimental set-up used to measure axial and radial change in dimension of the HEB actuator.

#### C. Finite Element Analysis

A finite element analysis (FEA) of the expansion of a single fold of the bellows with varying half angle,  $\theta$  (see fig. 5) was performed. The model had the same wall thickness and diameter values as the HEB prototype. A second order reduced polynomial model was used for the constitutive relation based on material data from [28]. Fig. 5 shows strain in the axial direction as a function of internal pressure. As the half angle increases, the transition from axially expanded state (S3) to ballooned state (S4) occurs at a lower pressure. The FEA model provides a basis for optimization of the structure for different goals which shall be considered in a future work.

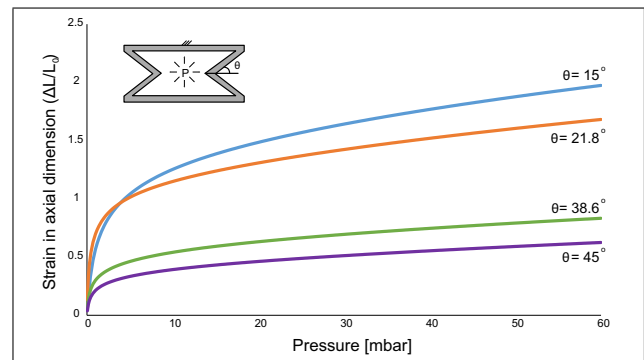


Fig. 5. Axial strain as a function of internal pressure, obtained from finite element analysis of the expansion of a single fold of the bellows, with varying half angles,  $\theta$ . As the angle increases, transition from the axially expanded state (S3) to the ballooned state (S4) occurs at a lower internal pressure. Inset shows a sectional view of the 3D model used for FEA.

## IV. RESULTS

#### A. Inflation Phase

During the inflation phase from state S2 to S4, when air is pumped into the chamber, two distinct behaviours are observed. First, the bellows extend, resulting in a quick linear change in length. See the steep section of the length change curve in fig. 6, labelled S3. This initial period lasts for a relatively short time (7s). There is a slight but negligible change in radius to accommodate the extension of the folds. Internal pressure increases linearly as seen in fig. 7. Once the bellows fully extend, the second behaviour is observed. This is the ballooning state, S4. There is comparatively gradual increase in length and simultaneous increase in diameter (fig.

6). The pressure increases slightly, but has a flatter profile indicative of ballooning (S4, fig. 7). Radial and axial expansion as functions of internal pressure are shown in fig. 8.

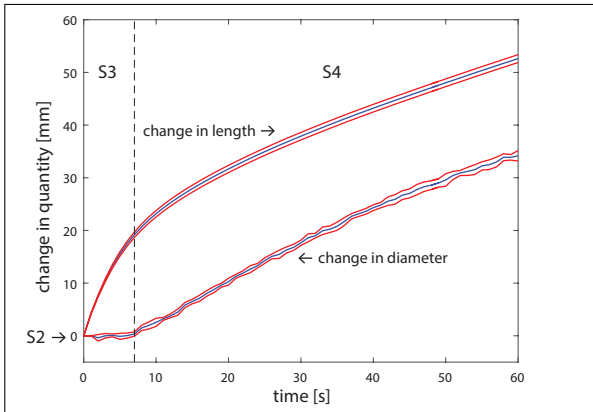


Fig. 6. Mean change in length and diameter of the chamber as a function of time during inflation. The upper and lower curves for each plot represent one standard deviation from the mean. The actuator starts in the neutral state (S2). As the actuator is extending (S3), there is a steep increase in length and no significant change in diameter. Once the folds are fully extended, both length and diameter start to increase in the ballooning state (S4).

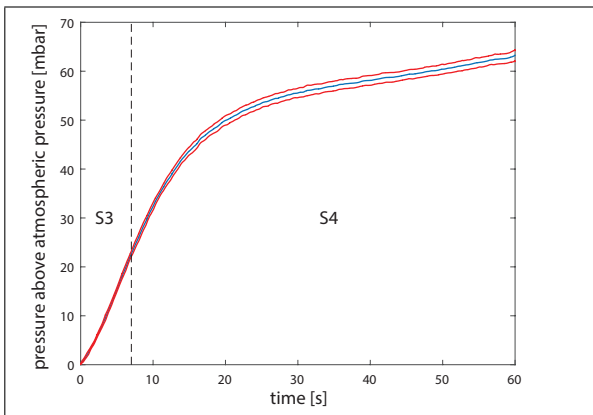


Fig. 7. Mean internal pressure (above atmospheric pressure) as a function of time, measured over ten trials of inflation. The upper and lower curves represent one standard deviation from the mean. The beginning of the curve where there is a linear increase in pressure corresponds to the period in which the bellows are extending (S3). The later part corresponds to the ballooning period (S4).

### B. Deflation Phase

Starting from the rest position (S2), as air is pumped out of the chamber, no change in radius was observed. The bellows contract in length to state S1 and the trend is linear as can be seen in fig. 9. Fig. 10 shows the change in internal pressure. A sudden drop in pressure towards the negative side indicates that the actuator has fully compressed. Fig. 11 shows the contraction in length as a function of pressure. As read from right to left on the horizontal axis, a small negative pressure (less than 80mbar) is sufficient to cause the structure to attain a minimum configuration (length of 20mm when folds of the bellows are fully compressed, see S1 in fig. 2).

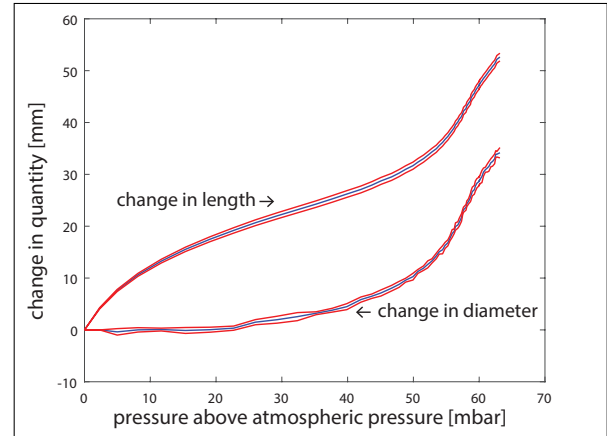


Fig. 8. Mean change in length and diameter as a function of internal pressure computed over ten trials of inflation. The upper and lower curves for each plot represent one standard deviation from the mean.

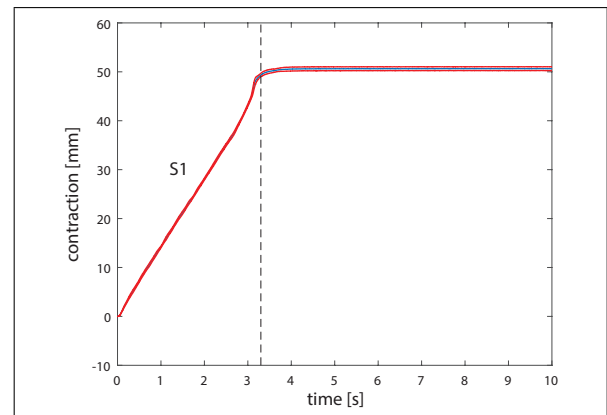


Fig. 9. Mean contraction as a function of time measured over ten trials of deflation (S1). The upper and lower curves represent one standard deviation from the mean. A linear decrease in length is observed as the structure compresses to its minimum configuration.

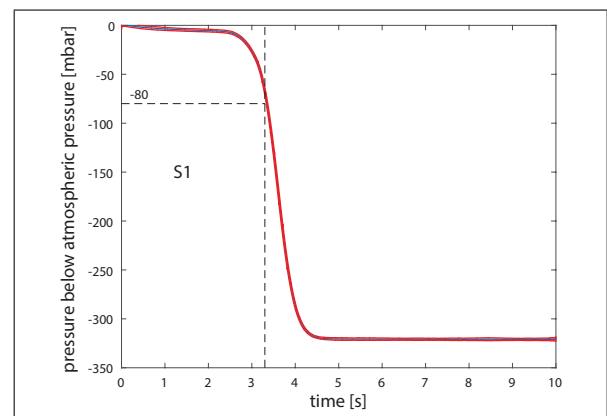


Fig. 10. Internal pressure (below atmospheric pressure) as a function of time during deflation (S1), measured over ten trials. The upper and lower curves represent one standard deviation from the mean. A sudden drop and high negative pressure indicates that the structure has reached its minimum configuration at 80mbar.

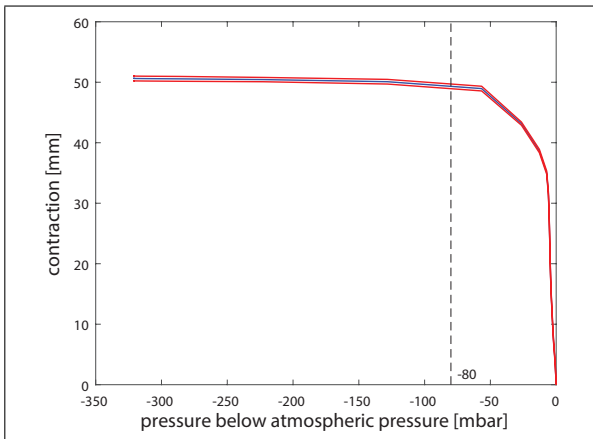


Fig. 11. Mean compression as a function of internal pressure computed over ten trials of deflation. Reading from the right on the horizontal axis, the curve indicates that only a small change in pressure (80mbar) is required to reach a fully compressed state, starting from the rest state. The upper and lower curves represent one standard deviation from the mean.

## V. DISCUSSION

The results show that the length of the soft pneumatic actuator more than doubles during the inflation phase (S2→S4). During the deflation phase (S2→S1) the structure compresses to its minimum possible configuration. This amounts to a total change in length of 450%. In the radial direction, there is 80% increase in diameter during expansion. The overall volumetric change from the fully compressed state to the expanded state was close to 300 times the minimum volume. The low standard deviation observed in all parameters, displacement, radial expansion and internal pressure suggests that the shape change is highly repeatable and readily controllable by adjusting the internal pressure accordingly.

### Comparison with Other Classes of Actuators

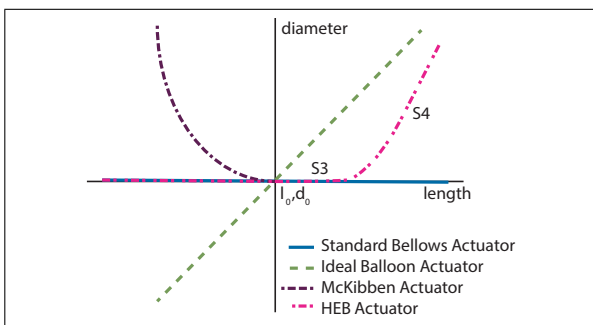


Fig. 12. Comparison of different classes of actuator showing the relationship between diameter and length during actuation. All actuators are assumed to have an initial length of  $l_o$  and diameter  $d_o$ .

The conceptual relation between diameter and length for different classes of actuators is shown in fig. 12 and for the HEB design presented here in fig. 13. The HEB actuator is compared to standard bellows, an ideal balloon [29] and McKibben actuators. When actuated from an initial length of  $l_o$  and diameter  $d_o$ , a standard bellows actuator changes in length with negligible change in diameter. This is represented by the nearly horizontal line in the figure. An ideal balloon

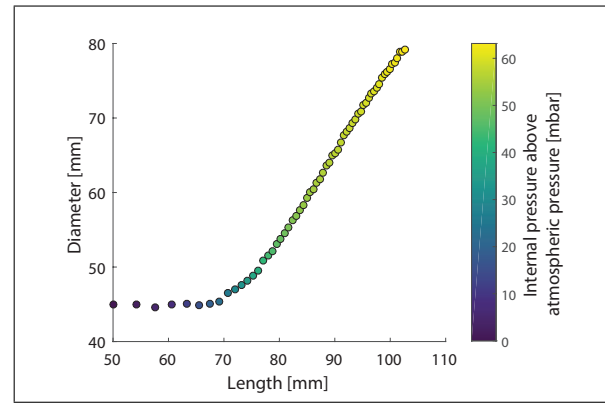


Fig. 13. Relation between diameter and length for the actuator design considered in this study. Internal pressure is indicated by the colour of the data point. Initially there is no change in diameter as the actuator elongates axially. This is followed by the ballooning state in which a large radial and axial expansion is observed.

actuator shows a linear relationship between its diameter and length. In a McKibben actuator, the diameter increases as it is pressurised causing a decrease in length. The HEB actuator presented here demonstrates a state of expansion in length with no change in diameter (S3) followed by a state in which both length and diameter increase (S4). Thus, it belongs to a class of actuators whose behaviour lies in between that of the standard bellows and ideal balloon actuators. Design parameters such as dimensions, the angle of the bellows, shape of the folds and their density would influence the point of transition between states and the steepness of change in diameter with change in length.

## VI. APPLICATION

To demonstrate the potential of the HEB actuator module in realising sophisticated soft robots with euglenoid-like locomotion, a multi-segmented robot was fabricated by bonding together three actuators. Internal connections between the actuator chambers through a set of tubes allow individual control over their expansion and contraction. The cross section is shown in fig. 14. External valves and pumps direct the flow of air. Fig. 15a shows different shapes that the robot can take by moving fluid between its segments. As can be seen, the shapes closely resemble those of the euglenoids in fig. 1. The similarity can be quantified in terms of percentage change in length and radius. Another qualitative measure is the number of inflection points on the curve that represents the body of the robot. Note the ability to balloon one segment while axially compressing the others, thus maintaining a constant robot length. Many other activation schemes are possible with this robot.

Fig. 15b demonstrates compliance of the soft body of the robot when it expands between stainless steel rods. Further tests with the three-segment robot will examine details of locomotion such as efficient patterns of fluid movement and whether or not a closed volume system is preferable.

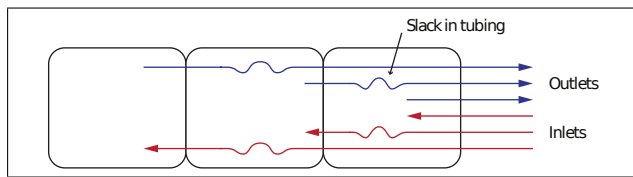


Fig. 14. Schematic of the robot showing multiple chambers and tubing to control flow. Sufficient slack is provided within each chamber to allow for expansion. The ports are connected externally through pumps and valves.

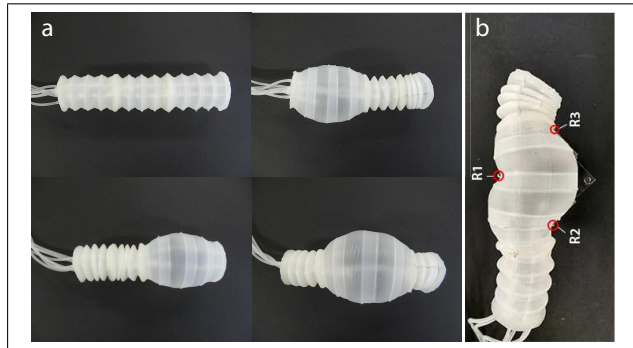


Fig. 15. a. Different shapes of the three segment robot. These closely resemble the ones exhibited by euglenoids, fig. 1. b. Robot expanding between stainless steel rods R1-3 (marked in red). Compliant nature of the soft body allows it to bend around the obstruction.

## VII. CONCLUSIONS

A novel solution for achieving multi-modal actuation and large volumetric change in biomimetic soft robotics has been presented. This is achieved by designing a custom pneumatic bellows-like actuator with soft elastomer materials that exhibits four distinct states, depending on internal pressure. The actuator both extends and contracts axially and can, in a high pressure state, balloon out radially. We characterise actuation in extension and compression in terms of pressure and axial and radial displacement. To demonstrate the potential of this versatile actuator and suitability for euglenoid-like biomimetic soft robots we fabricated a three-segment robot that shows the large body deformations of the euglenoid. The giant volume changing soft actuator presented has the potential to deliver a wide range of soft robotic devices suitable for operation in challenging scenarios including those found in disaster zones, medical procedures and environmental monitoring and remediation.

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