Growing Soft Robots: Design and Control

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DECLARATION

This report entitled

Growing Soft Robotics: Design and Control

Was composed by me and is based on my own work. Where the work of others has been used, it is fully acknowledged in the text and in captions to table illustrations. This report has not been submitted for any other qualification.

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Abstract

In the field of robotics, most people are familiar with the traditional robot system involving rigid links, sensors and actuators. This report familiarises the user with robotics demonology and reviews the state of the art techniques used to control soft robots. It also discusses the current systems that utilise growth based navigation such as the eversion method which allows for systems with extensions way beyond the reach of traditional elastic soft robots. Implemented techniques for control using chambers, tendons and latches are explored. The report also analyses the design of a pressurised base that allows for the control of robot using flexible plastics or fabrics for their chambers.

CONTENTS

I. Introduction

”With regard to robots, in the early days of robots people said, ’Oh, let’s build a robot’ and what’s the first thought? You make a robot look like a human and do human things. That’s so 1950s. We are so past that.” [1]. With so many developments in the fields of robotics, material science and control systems, people have been developing systems that push the boundaries of what an artificial system can do. One of the current goals within robotics is to develop systems that are capable of interacting with humans in a safe manner. This goal is due to increases in human facing robotic systems compared to the industrial robots which are often isolated from humans during operation, with multiple fail-safes in place to stop the system if someone were to enter the environment. This has pushed innovation in systems that are inherently compliant. Some researchers have moved away from rigid links and actuators found in discrete systems, and explore the field of soft robotics and the use of biologically inspired actuators. These robots have been achieving compliance through designs incorporating soft materials to form structures capable of actuating. We even see developments in mechanisms to control the stiffness of the system and therefore vary compliance dynamically. This article reviews various approaches and techniques to create actuated soft robotic systems, and how growth based locomotive systems [2] can be designed and controlled using pre-existing techniques. We will review various actuation methods, designs and materials and compare their suitability for different actuation methods.

II. Biological Inspiration

Within biological creatures there are a variety of mechanisms that have developed to allow them to interact with their environment. One soft example of this would be a muscular-hydrostat [3] such as an octopus arm.

A. Muscular Hydrostats

A muscular-hydrostat is an muscular organ which lacks skeletal support [4]. These structures utilise contractions of a three dimensional array of muscles. Figure 1 shows a cross sectional diagram of the muscles inside an octopus arm. W. Kier mentions that the muscle fibres in this structure can ”be orientated in three general directions, perpendicular to the long axis, parallel to the long axis, and helical or oblique around the axis of the organ”. Through contractions in multiple muscle groups, this soft organ is capable of controlling its bending, stiffness, torsion, and elongation properties.

While preforming these movements, a key feature of these organs is their ability to maintain constant volume regardless of their contraction. This is due to muscle tissue being primarily composed of a practically in-compressible aqueous liquid that is contained within the muscle [4]. By maintaining a constant volume, any changes in physical size of the muscle will result in changes in the properties in other dimensions. This can be seen when a bending motion is desired. This motion is preformed by contractions along the longitudinal muscle towards the direction of bending which cause a decrease in length of the limb in that direction. If we treat the object as a constant volume we see that a longitudinal contraction would result in shortening of the limb and an increase in cross sectional area. Helical/oblique or transverse muscles would contract in multiple directions to maintain a constant diameter which would therefore result in bending. This can also be seen in elongation, stiffening and torsion motion where activity in antagonist muscles is required to preform desired actuation. Chameleon tongues which are able to increase in length through rapid contraction muscles that decrease the diameter of a sphincter-like muscle which causes extension longitudinally due to the conservation of volume [6]. However, the tongue of a chameleon lacks the ability to control itself beyond retracting after extension, and uses its contractions to explosively target prey.

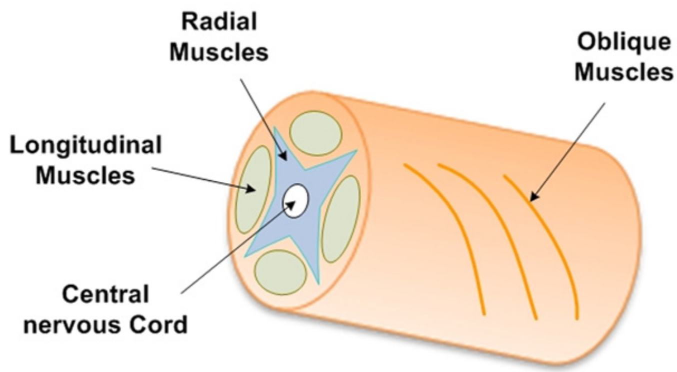

Fig. 1. Cross sectional diagram of an octopus tentacle illustrating the muscle orientation inside a muscular-hydrostat organ. The longitudinal muscles are tendons parallel to the tentacle length. When contracting, these muscles result in longitudinal compression of the tentacle. The radial muscles are muscles oriented perpendicular to the length of the tentacle and can cause localised contractions in the cross sectional area of the tentacle. Oblique muscles surround the radial and longitudinal muscles in a helical structure along the tentacle and will provide torsional forces. These muscle groups are used in tandem to create motion such as bending, twisting, stiffening and elongation [5].

The chameleon uses elastic connective tissue to provide the guiding forces needed to correctly fold the system during contraction [7]. The resulting folded structure as can be seen in figure 2. The folding mechanism employed in the retractor muscle aids in the chameleon’s ability to retract it’s tongue up to less than 0.2% of its fully extended length.

One limitation of muscular hydrostats is their constant external volume. If we were able to maintain the muscle density while varying the total external volume, these organs could be used to extend their elongation capability while still maintaining their actuation ability. Due to limited volume, elongation in a muscular hydrostat requires decreases in the cross sectional circumference of the hydrostat which results in a decrease in actuation capability [4].

B. Hydraulic work in nature

Within nature, some creatures utilise body fluids to preform hydraulic work [8]. EE. Zuckerkandl lists examples such as the swelling the foot of a pelecypod mollusc due to hydraulic action of the blood, or the mechanical use of hydro static pressure of blood to result in penis erection in mammals .

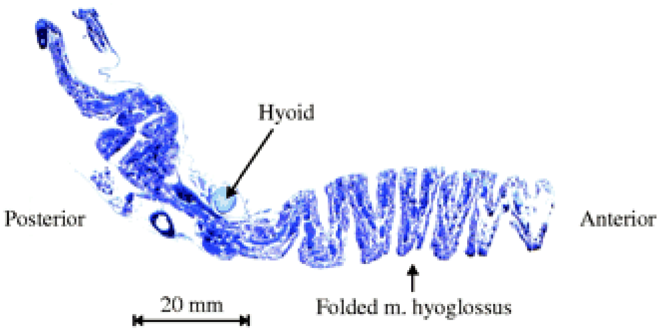

Fig. 2. Longitudinal section view of a retracted chameleon's tongue. The Hyoid bone indicated is a U shaped bone which is used to launch its tongue. Accelerator muscles push the Hyoid bone against the hyoglossus (the part of the tongue that extends from the mouth) which compresses it rapidly, resulting in rapid longitudinal acceleration along the tongue due to its tapered structure. In this image we see the hyoglossus in its retracted position. The chameleon utilises elastic properties of connective tissues placed on the hyoglossus to fold passively upon retraction. Image and information taken from [7].

C. Eversion in Nature

Some of the existing growth based robots [2] have taken inspiration from the Sipunculus Nudus, also known as the Peanut worm. These creatures have a proboscis that extends out of their body which is capable of everting into the body as a method of defence. The sipunculus nudus primarily utilises increasing pressure within its coelom (fluidic body cavity) to evert its proboscis in water, with longitudinal and circular muscles along the proboscis being used for maintaining the everted position [8].

D. Plant Growth

Another example of a growth based system [9] is inspired by the locomotion of plant roots within soil. It aimed to mimic environment-based growth of roots as they follow the path of least resistance. This results in higher energy efficiency. Plant roots rely on tip based growth where cell division (mitosis) occurs at the tip with no sliding required to extend. This can be capable of exerting large forces and navigating through tough environments with large opposing forces. A. Sandeghi mentions that tip based growth results in no longitudinal frictional resistance between the structure and the surrounding environment during longitudinal translation of the tip. Utilisation of tip based growth within a robot could minimise the frictional resistance due to sliding. This mechanism is occurring due to cellular division so an alternative system would need to be developed to utilise tip based growth in a larger robotic system.

III. Robotics

A. Robotic Categories

Most robotic systems can be categorised into one of three mechanisms: Discrete, Serpentine and Continuum systems [10]. These 3 systems preforming a similar curvature can be seen in figure 3.

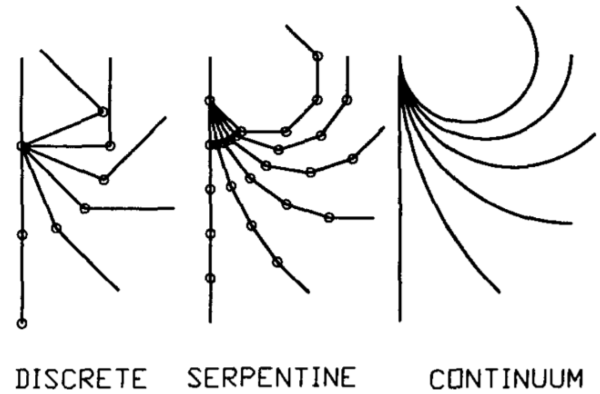

Fig. 3. Illustration of different robot mechanism categories attempting to create a counter-clockwise curvature. Illustration of discrete systems on the left of the diagram shows long rigid links connecting single degree of freedom joints, with circles indicating joints and straight lines indicating links. Serpentine systems seen in the middle are formed from a large number of single degree of freedom joints connected by short links. This creates a more curved shape than the discrete system. Continuous systems seen on the right. These systems do not have joints, but bend along their length via deformation. This system can often be seen in soft robotics [10]

1) Discrete systems: A discrete system is a mechanism made of single degree of freedom joints that are connected by rigid links. Most industrial robots are discrete systems. This is similar to how a human limb operates, with rigid bones connecting actuated joints [10]. Robinson also mentions that while discrete systems might be ideal for use in "industrial applications where speed of operation and accuracy are paramount.", there are applications where different features prove to provide improved performance.

2) Serpentine systems: also utilise single degree of freedom joints and rigid links but utilise more joints for the same length as a discrete system.

3) Continuum systems: According to G. Robinson, continuum robots are robots that "do not contain rigid links and identifiable rotational joints. Instead the structures bend continuously along their length via elastic deformation and produce motion through the generation of smooth curves, similar to the tentacles or tongues of the animal kingdom" [10] [10] [11].

Continuum robots can be classified into categories based on their method and location of actuation. The three broad categories are Intrinsic, Extrinsic, and hybrid.

Intrinsic devices have actuators located on the device and forming part of the mechanism. Extrinsic devices have actuators located remotely with the motion being transferred mechanically. A hybrid device is a mechanism that combines both intrinsic and extrinsic actuation methods [10].

A pneumatic actuator such as the one seen in figure 11 would be an intrinsic actuator even though it is pneumatically powered from an external source, as the motion is occurring at the actuator rather than being mechanically transferred.

An example of an extrinsic actuator can be seen in figure 4. 3 strings are fixed to the top ring and act as tendons providing tension while a spring opposes the tension/gravitational force. Pulling on one of the strings would shorten the distance between the base and the point where the ring is fixed to the string. The springs provide opposing force resulting in bending in a continuous curve. The string acting as a medium of transferring mechanical motion makes this an extrinsic actuator.

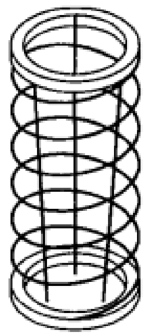

Fig. 4. Example of an extrinsic actuator consisting of an extension spring seperating 2 rings. 3 strings are connected to the top ring and can be pulled to curve the structure by reducing the distance in their disrection [10]

A hybrid actuator consists of a combination of both methods, for example if we were to surround the mechanism used in figure 4 with a single pneumatic chamber for added control. An example of this is found in the Tendon Embedded Pneumatic Muscle (TEPM) actuator developed by R.Kang [12] seen in figure 5. This actuator uses the pneumatic system to provide large movements, while the tendons are used to achieve accurate position control. Variations in tendon length and air pressure control the length of the actuator and the stiffness of the actuator.

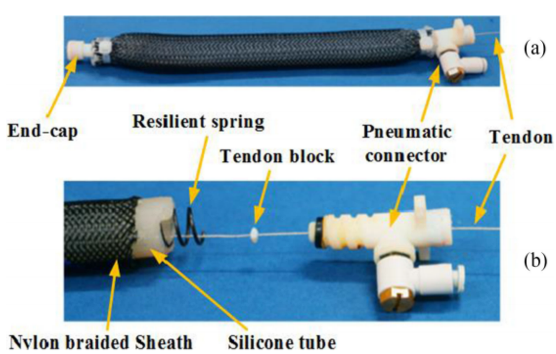

Fig. 5. Overview (a) and an exploded view (b) of the TEPM Hybrid actuator developed by R. Kang. The system consists of a compression spring which provides opposing outwards force while a tendon provides a pulling force. A pneumatic chamber surrounded by a braided sheath can be used to vary the damping and expansion properties of this actuator. [12]

B. Actuation methods

According to the Collins Dictionary [13], "An actuator is a machine or part of a machine which moves or controls another part in response to an input."

In the field of robotics there is a variety of actuation methods that can be used to provide motion. Systems can apply multiple actuation methods to create one actuator capable of complex operations. This can be seen in the TEPM hybrid actuator in figure 5.

1) Electrical Motors: One of the fundamental actuators used in robotics are electrical motors. These motors convert electrical power to mechanical movement that can be used in systems such as extrinsic actuators as is seen in figure 4 or directly to provide mechanical actuation such as in discrete robot joints. They can be also be used to drive a liquid/gas to provide intrinsic robots with pneumatic/hydraulic pressure control required for actuation.

When used with a string such as the extrinsic example in figure 4, the motor would provide rotational motion which would then be transformed into linear motion through the use of mechanisms such as screws, cranks or pulleys.

The most commonly employed electrical motor types in robotics are brushed DC, brush-less DC, alternating current (AC) synchronous motors, and AC asynchronous motors.

DC brushed have the ability to alter their torque to speed ratio which makes them an interesting candidate for high torque applications, such as industrial robots [14].

Brush-less DC motors do not use current carrying commutators, resulting in longer lifespans and better thermal/electrical efficiency. However the added complexity does add cost to the system [14].

These motors are often combined with other electronics/mechanisms to form more complex actuators. For example, a DC motor can be used to drive a roller screw as is seen in figures 6 and 7 to provide linear actuation. In these figures, we see figure 6 shows the actuator in its extended position. The displacement between the mount (labelled 117) and the tip of the actuator(labelled 119) is at its minimum. The DC motor would rotate the lead screw (labelled 114) which drives the actuator in a direction perpendicular to the axis of rotation, as is seen by the increase in displacement in figure 6. In this system the speed of rotation is proportional to the speed of extension. The direction of rotation of the motor will determine the direction of movement of the actuator. The gearing ratio between the motor and the screw will determine the torque/speed of the linear actuation. We can change the properties of the actuator by changing these variables. This will change the low torque and high velocity of the DC motor used into high torque low velocity actuation that would be needed for robotic applications [15].

2) Fluidic actuation: Pneumatic and hydraulic actuators rely on the use of a gases (often air) or a liquids respectively to create motion. This is done by variations of internal pressure inside a chamber that result in mechanical changes in the system. These systems have been used in high-load applications such as rigid industrial robots or construction machinery due to their ability to transfer energy from a remote large high torque motor that generates the actuation forces to a low weight limb that's located inside the work area [17]. By increasing pressure inside of a chamber, the forces acting on the chamber walls increase. This property is utilised in mechanical hydraulic/pneumatic actuators, where if sufficient, the force due to pressure will result in movement of a piston.

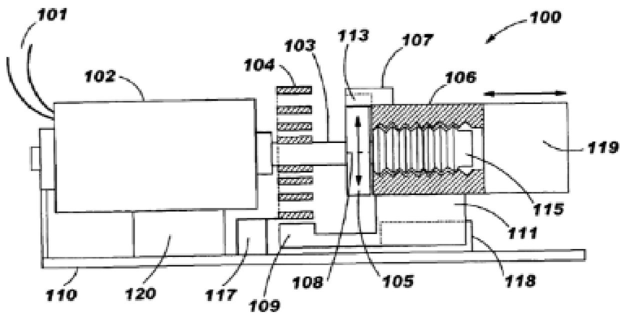

Fig. 6. Linear actuator using a DC motor at unextended position. This system uses a lead screw to convert rotational motion from a motor to linear motion [16]

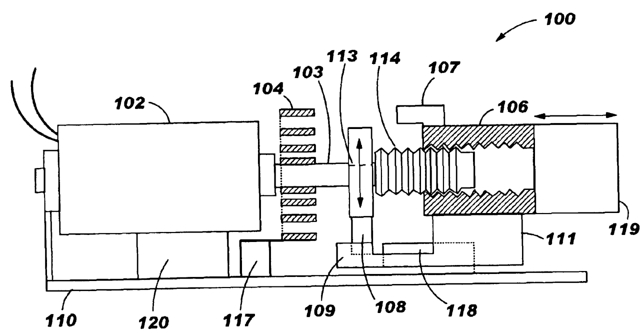

Fig. 7. Linear actuator using a DC motor at extended position due to rotation of the motor which exterted a linear force/motion on the tip. [16]

Properties of soft fluidic actuators are determined by elastic and viscoelastic properties of materials and asymmetry in the design [5]. As mentioned previously we often rely on the pressure force in fluidic actuators. An elastic chamber would inflate under increases in pressure. By varying the inflation locations of a structure we can form complex actuation geometries [18].

Another use of fluidic actuation is to vary the stiffness of a structure. An example of this is the variable stiffness link (VSL) developed by A. Stilli [19] seen in figure 8. It utilises variations in pneumatic pressure to vary the stiffness of a flexible but inelastic chamber. The chamber consisted This chamber was used as a link in a rigid robot, allowing for variable compliance within the links connecting the two revolute joints. In order to vary the stiffness of a chamber we would need to be able to maintain a constant volume while increasing internal pressure.

Another example of stiffness control is the variable stiffness structure developed by Y. Shan [20]. This plant inspired composite system utilises miniature flexible fluidic tubes that can be used to exert axial compression or elongation. Multiple of these flexible fluidic tubes could be arranged to form a fluidic flexible matrix composite (FFMC) where the alternating direction of tubes and fluid pressures allow of variable stiffness properties. An example Shan gives is weaving this FFMC around an internal inner lining to create a pipe that is capable of changing its stiffness in order to adapt to variable internal forces of the pipe. This system could be interesting to develop in a soft actuated robot tentacle to mimic the oblique muscles seen in figure 1.

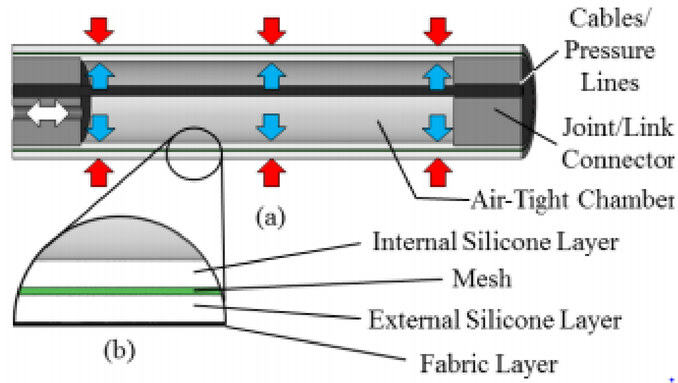

Fig. 8. Longitudinal section view of a pneumatic variable stiffness link. The link utilises an airtight silicone chamber that can be pressurised. The air-tight chamber is surrounded by a relatively in-expansive external fabric shell that reinforces the chamber to prevent ballooning while still maintaining soft qualities of the link. A layer of plastic mesh between two silicone layers allows the structure to maintain its shape when there is little internal pressure. [19]

A basic illustration of a bending soft actuator can be seen in figure 9. A difference in the length between 2 sides of a structure results in bending forces inwards towards the shorter length. This difference in length within soft actuators can be induced through an asymmetrical design such as the pleated channel design seen in figure 10. In this example, figure 10A un-actuated state.

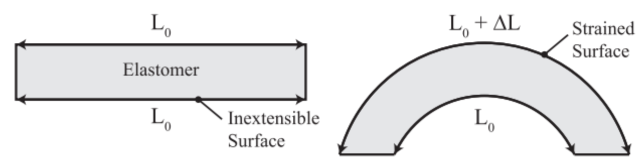

Fig. 9. [21]

3) Other methods of Actuation: There are actuation technologies developed that utilise different properties to cause actuation. Examples of this include SMA which utilise temperature change to actuate and SMP which use electromagnetic or chemical stimuli to actuate.

C. Soft Robotics

There have been efforts to develop robots that are different from their rigid counterparts before terminology was established [22]. Examples of this can be seen in the 1950s where McKibben developed braided pneumatic actuators to assist polio patients in 1950 [23]. He invented the braided outer shield pneumatic muscle that's still used in a variety of different types of robot designs [24]. An example of this mechanism can be seen in figure 11.

1) What is soft robotics: The field of soft robotics is one of the fastest growing topics in current academia [22]. The field focuses on the use of soft materials to create robots that

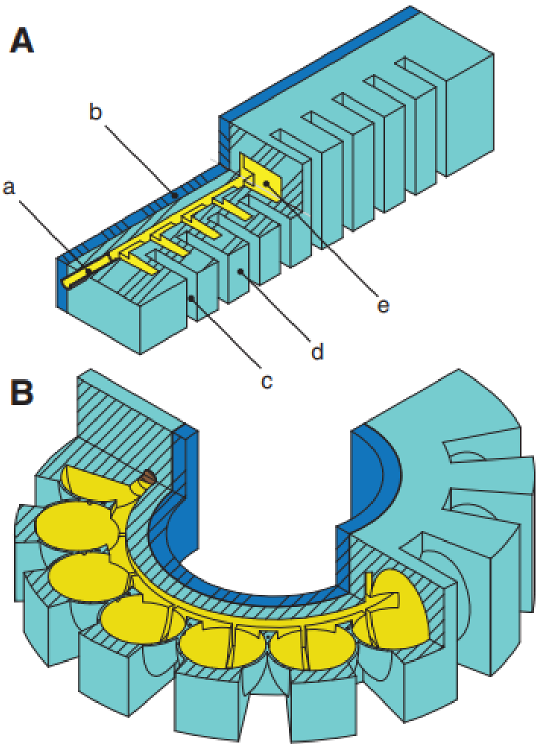

Fig. 10. The figure depicts a pleated channel fluidic actuator in its un-actuated (10A)and actuated states (10B).The part indicated by (a) is the fluidic chamber used for actuation with internal actuation channels (e). (d) and (c) indicate the pleats and the gaps in between the pleats which improve elasticity along that side. The material used for the pleated chambers is an elastic material that deforms under pressure, while (b) indicates an in-extensible layer [21]. Increases in pressure within the chambers result in expansion longitudinally, while the in-extensible layer maintains a constant length. The difference in length results in bending towards the shorter, unexpansive side b.

are compliant and capable of conforming to their surrounding environment [25] [11] [26]. Their compliant nature makes them excellent for use in human-robot interactive applications [25]. This can be seen in the medical field where rigid robots have to be designed to be application specific, while developments in soft robotics have allowed for development of robots that could reach remote areas of the body due to their controlled compliance [27].

2) Artificial muscles: One of the mostly widely investigated and employed artificial muscles is the braided muscle such as the McKibben muscle [22]. The muscle consisted of a gas tight elastic inner tube/bladder, which was surrounded by a double helical braid as is seen in figure 11 [28]. By pressurising the fluidic chamber it inflates outwards to form a shape with a larger circumference. This larger circumference pushes against the braided sleeve which is made from a relatively inelastic material that is secured from both ends. The constant length of braid having to travel a longer distance due to the curvature would exert a contraction force longitudinally along the actuator [29]. This results in contraction of the artificial muscle. While similar in structure to the variable stiffness link seen in figure 8, the main notable difference between these designs is the braided mesh sleeve. In the variable stiffness link, the braided sleeve is used to maintain constant structural

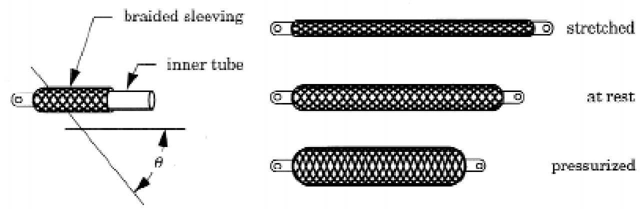

Fig. 11. Braided Muscle. The figure on the left shows the construction of the muscle. The muscle consists of a cylindrical inner tube formed from an elastic fluidic chamber(pneumatic). The inner chamber is surrounded by a braided sleeve consisting of helically wrapped fibres in 2 opposing orientations at θ and -θ. The braided sleeve and the inner tube are mechanically attached to the fitting from both sides. On the right we see this muscle in different states. The top diagram shows the muscle at an unpressurised state with a force applied outwards longitudinally causing it to stretch. The braiding and elastic material allow for the muscle to be stretched. The muscle can be seen at rest in the middle with no external forces acting on it, while the bottom figure shows the muscle once pressurised. We see the muscle contracts longitudinally under pressure due to the increase in diameter/circumference as a result of expansion of the inner tube in a direction perpendicular to the orientation [28]

geometry, while in a braided muscle, the braid is a helically parallel fibres in two opposing orientations at the same angle which allows for expansion of the gaps between the fibres. These muscles are only capable of contraction due to increases in pneumatic pressures which does not make them suitable for a growing soft robot. The variable contraction properties as a result of incorporating a braided sleeve present interesting possibilities for using braiding patterns in braided sleeves to provide further control.

Other variants of this muscle exist that utilise perpendicular expansion due to increased pressure resulting in contraction. Variations on materials, designs and structures allow for varying actuation properties [28].

IV. Growth Based Systems

The field of growth based robotics is an emerging field of robotics with a few competing designs and implementations that have been developed in the past few years. These designs can be vaguely categorised into two mechanisms. Permanent growth systems which build permanent structures that they can't retract as they grow, and systems that are able to retract after extension.

A. Permanent growth

Permanent growth systems that have been developed [30] [9] [31] utilising additive manufacturing techniques to construct a rigid structure that propels the robot forwards. The device contained a heater block that was supplied with a thermoplastic material. The heater block would heat up the thermoplastic to above its glass temperature which allowed it to be extruded. This plastic could be extruded in a direction and left to cool. The plastic solidifies as it cools down. This is used to draw a 3d shape by drawing 2d shapes (the cross sectional area) in layers, which is the additive manufacturing technique used by Fused filament fabrication [32]. One key factor is allowing the previous layer to become rigid so it can support the next layer. This device draws a constant stream of circular cross sections, thus resulting in a tube. By varying the extrusion amounts in certain directions they are able to control the curvature. More filament in one direction results in a difference in length which results in bending (as was demonstrated in figure 9.

This system requires rotational constraining of the tip to be able to function as it uses rotation of an internal system to create longitudinal motion. This system also requires exertion of an axial force towards the structure to keep the rotary mechanism on the structure. This makes the current system not ideal for growth through a less viscous and frictional medium than soil. During testing, contraptions were built to provide this axial and rotational support when outside of soil, however this limits the system to materials which provide opposing forces to necessary for operation [32].

Implementing this design in a different medium would be difficult as it relies on the surrounding medium being semi rigid to preform its basic functions. The friction from the soil is used to prevent the tip of the cone from rotation which allows motors inside the cone to rotate the mechanism responsible for the filament placement. If the cone rotation was not constrained this device would not be able to provide the rotational force required to operate.

B. Retractable growing robots

This type of growing device is able to control its growth and is capable of returning to its original shape after growing. One example of this would be a elastic chambered fluidic actuators that were mentioned previously where an actuator can increase its volume through increases in internal pressure as mentioned in the fluidic actuation section. Due to their reliance on material elasticity for expansion, the maximum growth of these elastic actuators is limited by their straining capability within the elastic region (prior to reaching its yield stress). Complex structures that increase the maximum extension capabilities of these actuators such as pleats as seen in figure 10 have been used but are simply ways to increase the maximum extension and suffer drawbacks to properties such as strength as the chamber walls become thinner during expansion. Stiffness control cant be achieved with a purely elastic material, however it could be implemented into a growth based system if we were able to combine multiple actuation methods similarly to how an octopus tendon operates. By combining actuation in longitudinal and transverse directions we could achieve the same stiffness control as an octopus tentacle. In this example if we were to control the size of the actuator through the use of smart materials with variable elasticity, by limiting it we could increase stiffness.

One alternative to using elasticity as an expansion medium is to use materials that are inelastic but shrinkable to create a chamber that expands in volume under pneumatic pressure. Figure 12 shows an example of a hybrid actuator developed [11] that is capable of theoretical extension factors of over 20 which exceeds the capabilities of elastic actuators. The manipulator proposed in this paper has a chamber composed from a non-extensible fabric (polyester) outer shell with an integrated inner air-tight chamber. The designed system has tendons that travel through its length to provide control of the length of the system which in turn allow it to control its stiffness. By combining 3 or more of these tendons within a sleeve at at equal intervals around the centre, they would have variable control of the stiffness and position of a tentacle. One limitation that can be seen in this system is the excess material that occurs when the actuator is not at full expansion. As you can see in figure 12, images (b) and (C) show complex folding geometries in the fabric shell which could make this system less reliable due to the lack of repeatability in the folding. This also makes the system hard to model precisely. Another limitation of this system is the friction caused during expansion. If we were to utilise this system in the proposed tentacle in the paper, we would expect irregular friction between the fabric on the actuator and the sleeves that hold the three actuators in the limb. This could cause irregular wear on the device at set positions therefore causing an earlier failure.

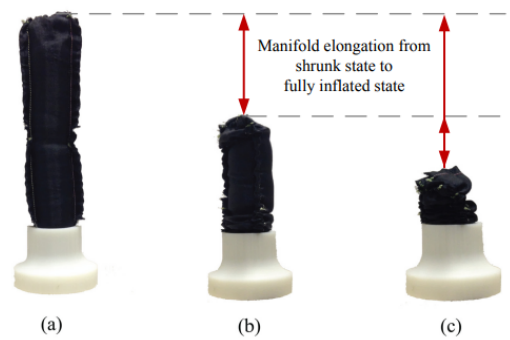

Fig. 12. Example of a shrinkable and stiffness controllable hybrid actuator that uses a non-extensible fabric outer layer with an air tight layer inside to provide large growth ratios. Th system seen also incorporates a tendon that is attached to the tip that allows for control of the overall length of the system which can be used to vary stiffness by maintaining a constant volume but increasing pressure. The fabric prevents expansion/ballooning due to the increases in pressure. It shows the system at its stiff and elongated (a), partial extension (b) and fully shrunk (c) states. [11]

This use of an non-expansive material has led to development of an eversion based system [25] that also utilises a non expansive fabric with an internal air tight layer (rubber). Unlike the previous design, this system utilises the eversion technique seen in Sipunculus Nudus species discussed in section II. While the previously discussed system [11] varies the length without any regard for excess chamber material. The system developed in [25] everts the material in on itself from the tip as can be seen in figure 13. This system is capable of extending longitudinally as is seen in figure 14. Here the system is shown in its low inflation (a), intermediary (b)(C)(d) and full extension(e) stages. The external structure seen in (a) remains stationary while the device extends as the material that provides the extension is everting from the tip. This eversion mechanism is interesting as it minimises friction between the actuator and the surrounding environment during elongation compared to other methods which require sliding along the material. The system developed in this paper is a longitudinally extending actuator with stiffness and length control capabilities, It does lack the ability to control its direction of eversion which could be implemented to extend the capabilities of this system, This could be done by incorporating 3 actuators of this type into a tentacle based mechanism similar to the one discussed in [11]. Another limitation of this paper is the lack of a developed system for control of this type of actuator. This also lacks the development of a kinematic and mathematical model of the system that could be used to provide small variations in the properties. These are all systems that could be developed for this system to provide increased functionality.

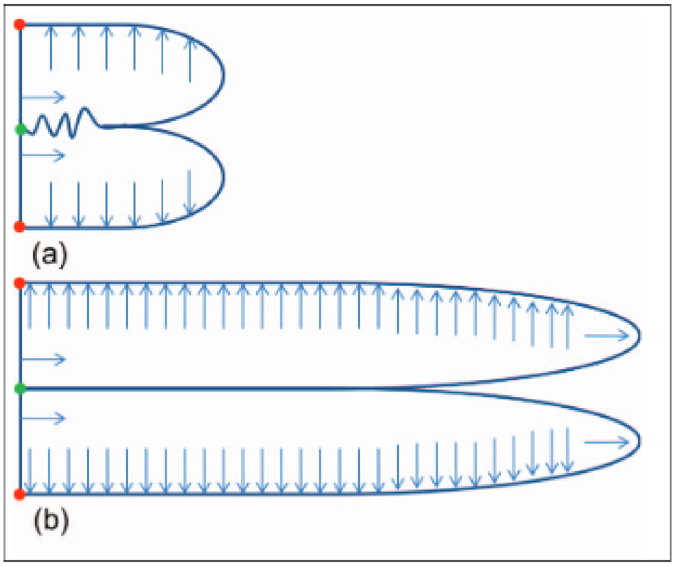

Fig. 13. figure illustrating how the eversion based actuator extends. (a) illustrates the system in its folded state. (b) shows the actuator in its extended state. In this example we see the excess material is folded inside the structure to reduce excess material on the outside of the system [25]

Another implementation [2] of an eversion based growth mechanism utilises the use of a thin-walled polyethylene tubing as the shell instead of fabric/rubber. The polyethylene membrane produces an airtight, relatively inelastic chamber that makes up the majority of the soft body of the robot. The system has a developed control mechanism that consists of control chambers along the sides of the everting body that can be inflated to provide selective lengthening of the sides during eversion as is seen in figure 15. By inflating one of the control chambers during extension the dimensions of the system become asymmetric which causes the system to curve away from the pressurised control chamber. An interesting property of this system is the retention of its curvature along the length even after the control chamber is no longer pressurised. This means the system is capable of preforming turns and then continuing moving forwards after the turning is complete. This is due to a digital chamber system controlled by a latch mechanism employed within the control chambers as seen in figure 16. The control chamber consists of small pneumatic chambers along the sides which allow for digital control of the system. The latch opening access to the chamber is only open when the chamber is pressurised and the latch is located at the tip of the chamber. This system utilises the high curvature due to eversion at the tip to only enable inflation of the chambers for the newly everted sections, thus causing each turn to become permanent. This enables the system to have non-holonomic control of direction. The author mentions that implementation of the digital system decreases the resolution of the curvature in the system compared to using a single chamber along the side.

Fig. 14. Extension stages of a fabric-based actuator going from (a) being the least extended, (b)(c)(d) showing intermediate stages (e) being the maximum extension and inflation. In this system the external structure shown in (a) remains stationary while the material needed to extend everts from the centre of the actuator. [25]

In this design they also incorporated a camera that was kept at the tip using constant tension from the wires for the camera, which were routed along the inside of the robot's main chamber. By creating a pressurised chamber they are able to contain any electronics and actuators for use in this system within the pressurised region which prevented leakages and other complexities that come from sealing a pneumatic chamber with moving/sliding parts.

Another key development within device is the base of the system. This system has a pressurised chamber designed which provides pneumatic pressure to the main chamber. The pressure level was controlled using a pressure regulator. Unlike the fabric based system which folds inwards during contraction, this system utilises a winching motor that controls the rotation of a spool on which the chamber material is rolled. By controlling the rotation of this reel, they are able to control the length of the actuator through winding/unwinding. In their design, they selectively pressurised the control chambers using electronic solenoid valves.

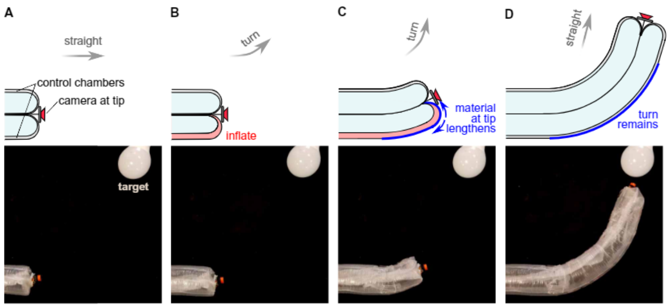

Fig. 15. Controlled turning of an eversion system using control pneumatic chambers placed along the sides for the length of the everting structure which influence the direction of growth. (A) shows the system with no pressure in the control chambers, thus the robot grows longitudinally. (B) shows the application of pressure in the control chamber at the bottom, thus resulting in asymmetry. This causes the robot to start curving upwards away from the pressurised control chamber which is seen in (C). In (D) we see the robot is capable of retaining a curve after the control chamber is deflated allowing the body to continue grow in a straight path longitudinally after the curve. [2]

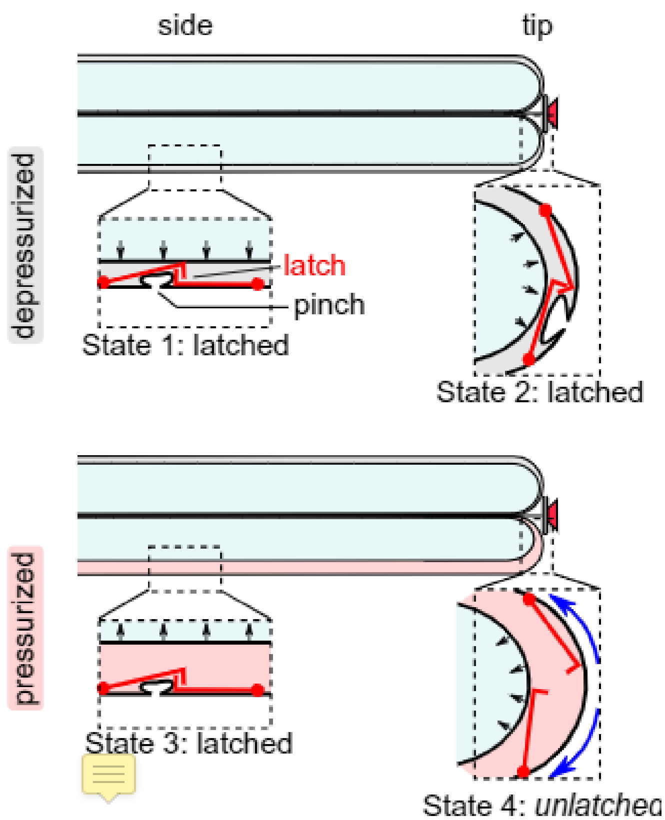

Fig. 16. A section cut diagram illustrating the operation of latches in a digital control chamber design. These latches will close access to the rows of pneumatic chambers located along the control chamber if it is depressurised. It also remains closed if the latch is located along the side. The latch will only open access to a chamber when the system is pressurised and the latch is located on the tip as the high curvature of the tip overcomes the interlocking mechanism employed. [2]

V. Conclusions

In investigating existing actuation and locomotion techniques within soft robotics we find growth based techniques, especially systems involving eversion mechanisms to be a very promising field that is in its early stages of development. These systems exceed the capabilities of traditional soft, flexible robots due to their ability to vary stiffness alongside changes in their length. Retractable growth based systems show the most promise in terms of usage for robotics systems as they are capable of preforming controlled repetitive actuation rather than moving in 1 direction. Fabric and braided structures appear to be the most promising candidate to develop further due to their ease of use and variable properties by controlling things such as weave. The ability to create a woven material from other materials also allows for possible expansion of such a system to meet requirements such as temperature properties. The growth system using control chambers shows interesting concepts that could be combined with other features such as helical tendons to create actuators capable of movement control within the 3d space as well as rotation about the axis of elongation. Implementing such a system using the fabric system could prove interesting for further research and development.

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