Simple and Scalable Soft Actuation Through Coupled Inflatable Tubes

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ABSTRACT The manufacturing and assembly of soft actuators may seem like a straightforward affair, but various tools, equipment and specific know-how are required to build these actuators. Assembling them into soft robots can sometimes lead to numerous difficulties and often requires permanent assemblies of the components. Similarly, minimizing the number of components in more complex designs and the scaling of component to build larger structures can often require significant redesigns. There is a need for an easy to assemble and disassemble soft robotic actuator that helps minimize the number of components and is easy to scale in size. This paper introduces a simple assembly method for a soft inflatable joint capable of bidirectional motion that uses a rigid constriction with parallel slits in which inflatable tubes are inserted and whose ratio of pressures determines the bending angle of the joint. This concept enables the non-permanent and reversible assembly of inflatable robots, is highly scalable, and can help minimize the number of parts in a soft robot by placing multiple constriction-based joints on a single load-bearing inflatable tube. This concept is then implemented in a robotic manipulator with three degrees of freedom and a robotic hand as well as a large-scale quadruped robot with a leg length exceeding one meter.

INDEX TERMS Inflatable robots, pneumatic joints and actuators, soft robot assembly, soft robotics.

I. INTRODUCTION
Soft pneumatic robots and actuators produce mechanical work through a pressure differential with their environment [1]–[4]. Their low cost, low weight, good performance, lifelike motion, and inherent compliance has made them an ideal candidate for robots meant to operate in direct proximity with human. They are relatively simple to understand at first sight, and the general procedure of their manufacturing process can generally be well understood from the numerous tutorials found online [5], [6]. However, finding the materials, the manufacturing equipment, figuring out the sizing of the components, their relative scaling, and other small fabrication details can become a daunting task for a newcomer to the field or a hobbyist [7]. Other potentials issues can arise when trying to increase the size of components or even disassemble them. An actuator said to be “simple” should aim at solving some of these problems by being easy to manufacture, easy to assemble, easy to disassemble, minimize the number of components and materials, and not require very high pressures. But it should also have sufficient performance for accomplishing a wide range of tasks at a wide range of scales.

The materials most commonly associated with soft robots are rubbers and polymers. Rubber structures have been used to form pneumatic artificial muscles (PAMs) capable of linear contraction through the lateral expansion of the rubber [8]. These have been used for a wide range of applications ranging from robotic arms to wearable devices [9], [10]. PAMs coupled in a radially symmetric configuration using plastic rings at intervals have been used to realize bending modules for implementation in a soft robotic arm based on continuum principles [11]. Different principles have been proposed to improve PAMs such as the use of an origamic chamber to rely on unfolding rather than stretching [12], using the longitudinal expansion of a polymeric structure to produce the contraction of an attached diamond-shape band [13], using vacuum-pressure to contract the actuator longitudinally [14], [15], and using depressurization from...
the inflated state to produce a contraction [16]. Silicone elastomers molded through soft lithography have been used to produce actuators that can produce complex bending motions and were implemented in grippers, wearable exogloves, crawling robots and underwater robots [17]–[19]. However, the process of manufacturing these rubber and polymer actuators remains challenging and requires a multi-step casting process involving devices such as vacuum degassing chambers. Direct 3D printing of soft pneumatic actuators has been proposed as an alternative that allows bypassing the use of molds, but the finicky process of extruding soft materials is often problematic [20]–[22]. Rather than having to make customized actuators for every robot, the concept of re-usable soft pneumatic actuators with a modular architecture have been proposed but at the cost of further complications in the manufacturing process [23], [24].

These relatively thick polymeric structures can be replaced by thin materials such as thermoplastics, fabrics with embedded bladders, and technical textiles to form inflatable soft actuators. The thinness of these materials means that the methods used to manufacture and assemble these structures should be modified in consequence. Pouch motors consisting of sealed rectangular pouches capable of linear contractile forces have been used to form various small-shaped devices by attaching them to structures with rigid hinges [25]–[29]. The main advantages of these actuators are that simple devices such as impulse sealers or tools with hot tips can be used as the main manufacturing tool and that they are extremely lightweight [25]. Bonded or indented patterns can be used to produce patternable but weak deformations or inflatable textures [30], [31], and inflatable tubes with protruding folds on one side of the tube have been used to make inflatable structures with pre-defined jointed angles once inflated [32]. Textiles with anisotropic properties and an internal bladder have been used to realize controllable bending deformations through the gradual stretching of the anisotropic material and have been used for wearable applications [33], [34]. The pairing of multiple pouch motors at their seam can use their lateral expansion to produce more complex bending deformations that can be used in robotic fingers or jointed robotic arms [35], [36]. Inflatable tubes that are folded repeatedly can be attached to a surface to produce large bending deformations upon inflation and were implemented in robotic joints as well as wearable elbow exoskeletons [37], [38]. McKibben actuators can also be used to produce the bending of a soft hinged inflated member [39]. Other more specialized designs have been developed such as extremely long helium-filled balloons forming a floating robotic arm for building inspection [40], and eversion robots have been developed that can grow from the tip to extreme lengths [41]. However, one of the main issues with these inflatable structures is that joining them with other elements is difficult and often requires permanent attachment at specific points. This makes their assembly process difficult and their disassembly process often nearly impossible.

This paper introduces a simple and reversible assembly method for a soft inflatable joint capable of bidirectional motion that uses a rigid constriction with parallel slits in which inflatable tubes are inserted and whose ratio of pressures determines the bending angle of the joint. This joint design allows for the non-permanent and reversible assembly of soft mechanisms and soft robots, can help minimize the number of parts, and is highly scalable. Section II introduces the design and manufacturing of the joint followed by a simple numerical model in Section III to analyze the behavior of a single tube and verified against experimental data. Section IV shows the experimental investigation of the behavior of the joint in terms of the bending angle, response time, controllability, and torque. This joint concept is then implemented as a soft robotic manipulator with a robotic gripper and as a large-scale quadruped robot in Section V.

II. DESIGN AND MANUFACTURING

The proposed soft inflatable joint consists of a rigid constriction with multiple parallel slits positioned close to one another into which inflatable tubes are inserted in their uninflated state (Fig. 1). Inflating these tubes to a given pressure causes the tubes to bend away from each other as they try to maximize their volume around the constriction. As will be demonstrated later in this paper, the equilibrium between the exit angles of the tubes from the constriction will depend on the ratio of pressures within each tube. This makes this design usable as a simple soft pneumatic joint where one of the tubes is used as an inflatable member that can be connected to multiple such joints along its length. When the tubes are inflated, the inflation of the tube on both sides of the constriction creates an opposing force on each side which maintains it firmly in place. As the tubes do not rely on permanent and non-reversible attachment methods, it is possible to disassemble the tubes from the constriction once deflated.

The manufacturing of inflatable tubes made from heat sealable materials can be realized through the simultaneous application of heat and pressure, and various tools have been used to seal these tubes including impulse sealers, hot presses, or tools with hot tips. The tubes used in this paper are made from a technical textile consisting of nylon coated with a thermoplastic polyurethane (TPU) coating which is bonded on the coated side to one another using an impulse sealer. This material has a thickness of 0.16 mm such that the thickness of the uninflated tube is 0.32 mm. The constrictions used for all characterization experiments are made from 3D printed acrylonitrile butadiene styrene (ABS) with a thickness of 5 mm, but they can be made from any rigid material. The width of the opening of the tubes was set to be equal to the width of the slits such that the additional bonded width of the tube creates sufficient friction with the slit to prevent slipping while the tubes are unpressurized, and the tubes are held firmly in place once pressurized. This assembly process is demonstrated in the Supplementary Video. The pressure within the actuator was supplied using an air compressor.
(MD 75/250, Bambi) and the pressure was regulated using an electro-pneumatic regulator (ITV1030, SMC).

All elements of the proposed soft robotic system are simple to make as the tubes themselves are easy to manufacture and require low-cost equipment while the constrictions can be made from any rigid material. Their assembly is non-permanent and reversible which makes it simple to assemble and disassemble a prototype. One of the tubes passing in the joint can be used as an inflatable member which helps to minimize the number of parts and allows multiple joints to be added on a single inflatable member. Also, as will be shown later, the elements of the structure can be easily scaled up in size.

III. NUMERICAL MODEL

The behavior of the system can be simplified as a single tube with an initial deformation which is being compressed symmetrically by adjacent tubes and rigid constrictions (Fig. 2a). It is assumed that the volume of the tube is constant throughout its width D and that the initial opening angle $\theta_0$ remains constant throughout the motion. The arc length $L$ of any compressed segment of the tube with a compression angle of $\theta$ has a radius $r$ and can be calculated as

$$L = 2r \theta$$  \hspace{1cm} (1)

where $r$ is constant throughout the entire deformation. The area $A$ of the compressed segment can be calculated as

$$A(\theta) = 2r^2\theta - 2r^2 \sin \theta \cos \theta$$  \hspace{1cm} (2)

The volume $V$ of the compressed segment can then be calculated as

$$V(\theta) = A(\theta)D = 2r^2D(\theta - \sin \theta \cos \theta)$$  \hspace{1cm} (3)

The initial arc length $L_0$ of the tube volume, the initial area $A_0$ of the tube and the initial volume $V_0$ of the tube can be calculated using (1) to (3) by replacing $\theta$ with $\theta_0$ as they share the same radius $r$. The opening angle $\phi$ of the compressed tube can then be related with $\theta$ and $\theta_0$ (Fig. 2b), and can be written as

$$\phi = \theta_0 - \theta$$  \hspace{1cm} (4)

The volume $V_1$ of the compressed portion of the tube can then be calculated as

$$V_1(\phi) = V(\theta_0) - V(\theta) = 2r^2D(\phi - \sin \phi \cos \phi)$$  \hspace{1cm} (5)

The conservation of energy can then be used to find a relation between the pneumatic work input and the mechanical power output as

$$dW_{\text{out}} = dW_{\text{in}}$$  \hspace{1cm} (6)
Which can be written to find the torque $M$ produced by the tube as

$$Md(2\phi) = PdV_1 \tag{7}$$

This expression can be re-arranged as

$$M = \frac{P dV_1}{2d\phi} = Pr^2D(1 + \sin^2 \phi - \cos^2 \phi) \tag{8}$$

This formula can be used for values of $\phi$ ranging from 0 to $\theta_0$.

IV. RESULTS

A. MODEL VALIDATION

The model was validated using a tube with a width $D$ of 50 mm and a length $L_0$ of 50 mm which results in an initial opening angle $\theta_0$ of 70° as measured through experiments. The tube was placed within a jig containing two surfaces connected to a rotation point where one surface is fixed and the other surface’s opening angle is adjusted using a stepper motor (NEMA 23H245-03S/D, Prostepper). One side of the jig is connected to a force/torque sensor (RFT40-SA01, ROBOTOUS) measuring the force at a moment arm of 25 mm from the point of rotation. The torque generated by the tube can then be obtained from this force and moment arm (Fig. 2c). The tube was tested at pressures of 20, 40, 60, 80 and 100 kPa. Some error can be seen between the model and experimental results due to errors in the experimental setup, due to volume approximation errors and due to potential effects of the material. But these results are sufficient to predict the torque generated by the tube at different angles and that it can predict the equilibrium angle of the tube.

B. NUMBER OF TUBES

The basic configuration of the actuator used in this paper will be one where an uneven number of inflatable tubes are inserted through the constriction. The middle tube will be used as the main inflatable member and the other tubes exert a force on this middle tube as they try to expand through a change in pressure. It is possible to make changes to this basic configuration by, for example, moving the main inflatable member to non-central slits, but the analysis of such modifications is omitted from the current paper. The first test will be used to determine the effect of the number of tubes on the bending range of the actuator for different pressures of the side tubes. The bending range of the actuator was measured by setting the pressure of the middle tube to 5 kPa, setting the pressure of the tubes on one side of the middle tube to zero, and then increasing the pressure of the tubes on the other side. The bending angle was then measured with respect to the straight position (Fig. 3a). This process was then repeated with the uninflated and inflated tubes being switched, and the bending angle in this configuration was added to the corresponding one previously obtained to obtain the bending range at a given pressure. This process was repeated for actuators with three, five, and seven tubes each with a tube width and length of 50 and 200 mm, respectively, a slit width of 1 mm, and a distance between slits of 1 mm (Fig. 3b).

Results show that the bending range increases rapidly at low pressures and then increases more slowly as the pressure
is further increased. As could be predicted, adding more tubes results in an increase in the bending range of the actuator, but the increasing in bending range achieved by changing from three to five tubes is greater than changing from five to seven tubes. The value obtained is the largest possible bending angle for the given configuration and range of pressure as most applications will have some pressure in the antagonistic tubes which will reduce the maximum bending angle. Subsequent experiments will be conducted using five tubes as this number of tubes offers a good compromise between performance and the minimization of the number of parts.

C. HYSTERESIS

Many soft actuators are made from a monolithic block of polymer or from a single inflatable volume such that friction or interaction between parts is minimized. As the proposed actuator is made from multiple moving parts that interact physically without being bonded together, friction between elements could cause poor repeatability or high hysteresis in the motion. Using an actuator with five tubes with the same configuration as in the previous experiment (Fig. 3e), the pressure within all tubes was set at 10 kPa and then the pressure within the bottom tubes was increased in increments of 10 kPa up to 100 kPa and then decreased back to 10 kPa (Fig. 3d). This process was repeated two more times without resetting the position of the tubes of the actuator.

From this experiment, a few observations can be made. First, the antagonistic pressure gives the resistance needed to be able to change gradually the bending angle of the actuator, which was not possible in the previous experiment where the antagonistic tubes were uninflated. Second, a slight hysteresis is visible between the inflation and deflation curves, but this hysteresis is in line with comparable inflatable actuators. The last observation is that the actuator does not fully go back to its original position after going back to its original pressure point and that this position becomes stable in the subsequent cycles. This is due to the interaction force between tubes being small at low pressures, friction between elements, and slight creases that might occur on the tubes during motion. But this change in the initial angle is not permanent and the position can be easily reset to the straight position manually.

The next repeatability test is done using the same actuator but varying the top and bottom tube pressures from 0 to 100 kPa and back to 0 kPa three times sequentially while keeping their sum of pressure at 100 kPa (Fig. 3e). This will produce a repeated back-and-forth and left-to-right motion. As in the previous experiment, a slight hysteresis is present throughout the entire motion but is steady between all three cycles of actuation. However, in this case, the change in position is more linear with the change in pressure as the pressure of both chambers is changed in tandem. These two experiments demonstrate that the actuator has good repeatability of motion, that a little hysteresis is present in the motion, and that the motion of the actuator is controllable.

D. RESPONSE TIME

The response time of the actuator was measured by attaching an inertial measurement unit (IMU, EBIMU24GV4, E2BOX) at the tip of the central tube which has a length of 10 mm (Fig. 4a). Actuators with three and five tubes were tested for tube widths of 30, 50, 100 and 150 mm with air inlet diameters of 3.175 mm and 6.35 mm. The tubes with widths of 30 and 50 mm could not accommodate the air inlet with a diameter of 6.35 mm due to the width of the overall inlet including its attachment mechanism. This means that a total of 12 different configurations of number of tubes, tube widths and air inlet diameters were tested to see their effect on the response time of the actuator.

A pressure of 80 kPa is applied to the central tube and target pressures of 80 kPa are assigned to each pair of side tubes. One side of the side tubes are inflated with the given target pressure while the other pair is given a target pressure of zero and the pressures are reversed every 5 seconds (Fig. 4b,c). The IMU and the jig used to attach it to the tube have a combined weight of 39 g. The response time is then measured as the average of the time required to reach 63.2% of the change in angle between the minimum and maximum angles reached over 10 cycles. The results of these experiments are shown in Table 1.

These results show that the response time increases with a larger tube width. But that the difference in response time between the 30 mm and 50 mm width tubes is quite small and gets larger as the tubes increase in size. The number of tubes increases the response time by 20% for a tube width of 30 mm and by nearly 250% for a tube width of 150 mm. These behaviors are potentially due to the time required to inflate the smaller tubes being small compared to the time required for the air to move from the regulators to the tube inlets. In the case of the diameter of the air inlets, doubling the air inlet diameter divided by two to three times the response times of the 100 mm and 150 mm width actuators which shows that it has a significant effect on the response time. It is to be noted that the response also heavily depends on the pneumatic system used.

E. JOINT CONTROL

Due to the absence of sensors integrated within joints, there are two possible solutions to measure the angle of the joint, which are either using IMU sensors or using a vision-based method. The use of IMU to measure the angle was demonstrated in the previous section for a single module and this section will use a vision-based method to measure the angle of the proposed actuator for feedback control.

A soft arm with two joints was built with visual markers attached to the base and tip of the arm as well as on the body of the middle tube of the first actuator segment (Fig. 5a). The first joint has 5 tubes and a tube width of 100 mm while the second joint contains 3 tubes with a width of 30 mm. The first arm segment has a length of 15 cm and the second segment has a length of 10 cm, and a payload of 33 g is fixed at the end.
of the arm. Markers are attached in pairs on the same axis such that a perpendicular line is drawn crossing at the midpoint of the paired markers (Fig. 5b). These lines eventually intersect each other and the angle between these lines can be used to measure the angle of the joint based on simple trigonometry. The markers are detected using a streaming camera (Intel Realsense d435) at a frame rate of 60 fps. This detected angle was then used in a simple PID controller used to control the angle of each joint.

The result for the control of the base joint of the soft arm is shown in Fig. 5c. The result of this experiment shows satisfactory results and demonstrates the controllability of this design. The overall control frequency was limited at 60Hz due to the vision system used for the detection of the markers and joint angles but could be improved by higher a higher frame rate camera. The control of both joints of the arm is demonstrated in the Supplementary Video.

### F. bending torque

The actuator functions as a joint and can produce a bending force or torque as it tries to reach its equilibrium angle at which point it produces no torque or is in equilibrium with the resistance from its environment. This torque was evaluated using three tubes where one tube serves as the force transmitting element and the other two tubes are positioned on the same side of the actuator pushing on the force transmitting tube.

The length and width of the force transmitting tube were set at 100 mm and 50 mm, respectively, while side tubes with a length of 50 mm and widths of 30, 40, and 50 mm were tested.

A force/torque sensor (Robotous, RTF40-SA01-C) was used to measure the torque using a pin located 100 mm away from the center of rotation of the sensors, and a guide was used to adjust the bending angle from $-50^\circ$ to $70^\circ$ in steps of $10^\circ$. A pressure of 50 kPa was inputted into the force transmitting tube and pressures ranging from 0 to 100 kPa in steps of 10 kPa were inputted into the side tubes. The values of the torque were measured for all angles where the torque produced was positive, and the equilibrium angle when the actuator is not in contact with the sensor was also measured and input into the graph as the point of zero torque.

The maximum torque produced occurred at an angle of $-50^\circ$ for all three side tube widths. It was equal to 1.30 Nm with a side tube width of 30 mm (Fig. 6a), which increased to 2.03 Nm for a side tube width of 40 mm (Fig. 6b), and 2.84 Nm for a side tube width of 50 mm (Fig. 6c). Equilibrium was reached at $56^\circ$, $63^\circ$ and $65^\circ$ for side tube widths of 30, 40, and 50 mm, respectively. This shows that the increase in performance of the joint is nearly linear with the side tube

### Table 1. Comparison of response time.

| Air inlet diameter | 3.175 mm | 6.350 mm |
|--------------------|----------|----------|
| Number of side tube| 1        | 2        | 1        | 2        |
| 30 mm              | 0.256 s  | 0.307 s  | -        | -        |
| Tube width         |          |          |          |          |
| 50 mm              | 0.274 s  | 0.448 s  | -        | -        |
| 100 mm             | 0.394 s  | 0.757 s  | 0.203 s  | 0.296 s  |
| 150 mm             | 0.785 s  | 1.959 s  | 0.303 s  | 0.693 s  |
width in terms of torque and that there is a slight increase in maximum bending angle with an increasing side tube width. It is to be noted that the torque is often measured to scale proportionally with the pressure in other soft pneumatic actuators, but that this is when the actuating element is directly connected to a rigid element. This allows for direct force transmittance from the inflatable volume to the sensor element. One of the advantages of the present actuator is that the actuator inherently includes an inflatable tube that can be used as the inflatable member of the soft robot, and that this member itself has compliance which lowers the force transmittance to the sensing element. This causes the torque response to be non-linear with an increase in pressure but is also a realistic scenario of how the proposed actuator is meant to be used.

G. ACTUATOR STIFFNESS

When at equilibrium, an external force or impact can deform the actuator and change its deflection angle. But changing the pressure within the tubes can be used to adjust the actuator’s stiffness and reduce how much it will deflect from its equilibrium. An actuator with five tubes where the middle tube has a length of 10 cm and other tubes have a length of 4 cm was built and a pressure of 50 kPa was applied to the middle tube. Then, an equal pressure ranging from 20 to 100 kPa was applied to the other four tubes before attaching a weight ranging from 0 to 1000 g at the tip of the middle tube and measuring its deflection angle from the horizontal position (Fig. 6d). At low pressures, the actuator deflects slightly from the horizontal even without any payload and the deflection increases steadily with an increase in payload.

The deflection angle reaches more than 40° with a payload of 1000 g at a pressure of 20 kPa. Increasing the pressure within the side tubes decreases the deflection angle at all loads and little difference can be observed between 80 and 100 kPa, which is due to a significant portion of the deflection being due to the deflection of the middle tube which has a fixed pressure of 50 kPa. These results show that varying the pressure within the side tubes can be used to change the actuator stiffness. Higher pressures within the middle tube and the side tubes could be used to change the stiffness and could potentially further reduce the deflection angle at high loads.

H. INFLATABLE JOINT COMPARISON

A comparison of the proposed inflatable joint with similar fabric or thermoplastic-based inflatable joints is shown in Table 2. This comparison shows that the proposed inflatable joint has a bending range slightly larger than comparable actuators. This is because these actuators can be divided between those that produce a higher unidirectional bending angle but that would self-hinder in an antagonistic

| Name                        | Bending Range (°) | Torque (N·m) | Reversible Assembly |
|-----------------------------|-------------------|--------------|---------------------|
| Coupled Inflatable Tubes (This work) | 160              | 2.84         | O                   |
| Pouch Motors [25]           | 80                | 0.2          | X                   |
| Pleated Fabric Actuators [33]| 120               | 0.153        | X                   |
| Folded-tube SPAs [37]       | 136               | 10.22        | X                   |
| McKibben-based Arm [38]     | 70.8              | 4.77         | X                   |
configuration and those that can produce bidirectional bending but have a smaller bending range. The torque produced by the proposed inflatable joint is not the highest but presents a reasonable trade-off between bending range and torque. However, the proposed inflatable joint is the only one capable of reversible assembly.

V. APPLICATIONS
A. 3-DOFS INFLATABLE ARM
The experiments in the previous section demonstrated the basic properties of the proposed actuator design but did not highlight any of its advantages in terms of implementation. As a first application, a simple inflatable arm was built using a single central tube with a length of 50 cm. Three constrictions with three slits each were slid onto the tube with two near the base of the arm and the third located along its length (Fig. 7a). The second joint was also rotated with respect to the axis of the central tube to produce a perpendicular motion to the other joints by rotating the constriction 90° during the assembly process. A gripper was built with three fingers where each finger is connected to a gripper base constriction which corresponds to their first joint and have a finger middle joint along their length.

The manipulator assembly consisting of the inflatable arm and gripper was then used to lift a tubular object, move it laterally over an obstacle, place it back down and then release it (Fig. 7b). This process is already demonstrated in the Supplementary Video. This concept is suitable for simple robotic arms meant to execute simple tasks but may be limited when producing more complex motions. One of the main limitations of the proposed joint design is that it cannot produce rotations along the axis of the main inflatable tube as a motor can. It would also struggle with simple maneuvers such as twisting a door handle. However, it could be paired with other inflatable joint designs capable of such torsional motions to overcome this limitation.

This assembly process highlights four of the advantages of the proposed joint assembly method. First, a single inflatable member can be used to connect multiple joints which help minimizes the number of parts. Second, additional joints can be added by simply sliding on more constrictions and then removed by sliding them off. Third, the joints can be rotated when adding them onto the central tube which allows
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FIGURE 8. (a) Quadruped robot with a height of 115 cm and a length of 120 cm compared to a human, (b) configuration of the leg of the quadruped robot with two joints and a foot, (c) complete stride of the quadruped robot, and (d) motion of the quadruped robot over five strides.

the joint to produce deformations in different orientations without requiring a modification in design. Fourth, a single constriction can be used to connect multiple elements as shown by the gripper base constriction of the gripper that connects the central tube of the arm with the three fingers.

B. LARGE QUADRUPED ROBOT

The next implementation of the proposed actuator design is a large quadruped robot with a body length of 120 cm whose legs have a height of 115 cm (Fig. 8a). Each leg contains two joints with one located at the waist and the second at the knee (Fig. 8b). The first joint contains two lateral tubes, and the second joint has a single lateral tube. The constrictions are made from aluminum profile frames with a side length of 20 mm, and the foot contains an internal circular acrylic plate, which means it is located inside of the tube, connected using bolts to a Styrofoam layer located at the base of the foot.

A simple walking locomotion gait was programmed manually such that the quadruped robot moves its left back foot first followed by the front right foot, right back foot and finally, the front left foot (Fig. 8c). Operation of the robot is demonstrated in the Supplementary Video. This stride has a length of 12 cm, or 0.1 body lengths, but is currently mainly limited by the robot dynamics as the body of the robot is very light and the motion of the legs creates significant momentum that can make the robot lose balance when taking longer steps. Five successive strides were realized by the quadruped robot over a period of 194 s resulting in the robot moving forward by 60 cm, which is equivalent to 0.155 body lengths per minute (Fig. 8d). The momentum of the body and of the legs coupled with the compliance of the joint results in the swaying of the robot after each step. This swaying motion is only an issue when trying to increase the speed of the robot and could be eliminated using feedback control methods.

This quadruped robot highlights further advantages and disadvantages of the proposed actuator design. The design is easily scalable to larger dimensions by simply increasing the size of the tubes and of the constrictions which will scale the forces and displacements correspondingly. However, the constrictions undergo tremendous forces produced by the tubes
trying to expand laterally. This means that the constrictions should be made from increasingly stronger materials at larger scales. For example, small carbon rods and smaller aluminum frames were not able to sustain these lateral loads. Another significant disadvantage is that the volume of the lateral tubes is proportional to the cube of the tube width and that the time required to inflate and deflate the tube scales with the volume for a given flow rate. So, the capabilities of the pneumatic setup should be scaled in consequence to produce fast motions.

VI. CONCLUSION

This paper introduces a simple assembly method for a soft inflatable joint that combines a soft robotic member with lateral inflatable tubes using a constriction with parallel slits. This concept enables the non-permanent and reversible assembly of soft mechanisms and soft robots, is highly scalable, and can help minimize the number of parts in a soft robot by having a single central tube that can be connected to multiple joints. The individual parts of the joint are also simple to manufacture and can be made from a wide range of materials and manufacturing processes. The actuation mechanism itself is quite similar to other existing inflatable joints made from folded or stacked pouches or tubes, but the main contribution of this work is in the assembly method of this joint, which is simpler, intrinsically capable of bidirectional motion and reversible. It is also easy to scale up this soft inflatable joint in size as the inflatable elements are lightweight and their performance scales with their dimensions.

Although the proposed design scales well in terms of forces and deformations, it had some limitations in terms of scale as the constrictions need to be strong enough to sustain the lateral forces from the tube and the actuator requires significantly more air inflow and outflow to maintain its speed at larger sizes. However, similar limitations will also likely apply for different inflatable joint designs at larger sizes, so this is partially a limitation of large-scale pneumatic actuators. Future work will focus on improving airflow to the tubes, on decreasing the loads on the constrictions at higher loads, on implementing the method for other types of soft actuators and improving the locomotion gait of the large quadruped robot.

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