Soft Autonomous Materials — Using Active Elasticity and Embedded Distributed Computation

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Abstract The impressive agility of living systems seems to stem from modular sensing, actuation and communication capabilities, as well as intelligence embedded in the mechanics in the form of active compliance. As a step towards bridging the gap between man-made machines and their biological counterparts, we developed a class of soft mechanisms that can undergo shape change and locomotion under pneumatic actuation. Sensing, computation, communication and actuation are embedded in the material leading to an amorphous, soft material. Soft mechanisms are harder to control than stiff mechanisms as their kinematics are difficult to model and their degrees of freedom are large. Here we show instances of such mechanisms made from identical cellular elements and demonstrate shape changing, and autonomous, sensor-based locomotion using distributed control. We show that the flexible system is accurately modeled by an equivalent spring-mass model and that shape change of each element is linear with applied pressure. We also derive a distributed feedback control law that lets a belt-shaped robot made of flexible elements locomote and climb up inclinations. These mechanisms and algorithms may provide a basis for creating a new generation of biomimetic soft robots that can negotiate openings and manipulate objects with an unprecedented level of compliance and robustness.

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1 Introduction

Biological systems outclass man-made robots in many aspects, especially in unstructured environments. They are safe, highly adaptable, and elegant in design, at least partially due to controlled flexibility in their body. Birds can land on light poles with ease by adjusting their wing shape. Octopi can grasp objects with unknown geometry, thanks to their tentacles. To match these capabilities, the field of robotics faces a challenge to incorporate some form of controlled elasticity in their designs [23].

Here we show soft robots that can autonomously undergo shape-change and generate locomotion. The robots move using a novel pneumatic actuation system, inspired by a physical phenomenon: inflating bubbles. Specifically, we theoretically characterize the inflation of embedded pneumatic channels inside a soft substrate, which is the core building-block of our robotic designs. The resulting mathematical model is used as a basis for controlling the motion of such a robot. Our robots achive crawling or rolling locomotion, and morphing into a range of shapes using this approach.

Traditionally, any non-rigidity in a robotic system is avoided due to the complexity it introduces for its control. Yet, compliance allows conformation, which is desirable when negotiating rough terrain with a mobile robot or unstructured object geometries for a manipulator or when safe interaction with humans is desired [2]. Active elasticity, in the form of controlling the amount of elasticity or deflection, may help reduce complexities while benefiting from the adaptability in the mechanics of the design. However, utilizing soft components is still a largely unknown territory for robotics, and collaboration at the intersection of material science, mechanical engineering, and computer science will be crucial for its success.

Recent innovation in polymer actuators [9], polymer electronics [8], polymer sensors [14], and manufacturing of precision 3D polymer structures using lithography and holography [21, 16] might enable the creation of a physical substrate for soft autonomous materials. Advances in decentralized algorithms for self-organizing machines [1, 15], understanding of self-organizing biological systems [5] and large networks [7], enable the embedded scalable computation required by autonomous materials.

In this paper, we combine pneumatically actuated soft materials with decentralized computation grounded in the physics of elasticity to demonstrate how a soft intelligent material composed of multiple cells can generate motion by inflation and how coordinating across cells leads to programmed fluidic motion. Using the many degrees of freedom of distributed actuation, such a material can change its shape to form spline-like geometries. This paper details the physics of active elasticity and distributed computation leading to the realization of a soft intelligent material capable of motion and shape change utilizing distributed sensing, computation, and actuation.

Unlike the McKibben artificial muscle [10], which behaves similar to a natural muscle, the actuator we propose bases on bending of bi-layer materials. The core mechanism consists of two silicone layers (Figure 1); a thin layer that embeds an inextensible fabric mesh, and a thicker layer which can be expanded by injecting pressurized air into a meandering silicone channel. This expansion leads to a change in curvature.

The bimorph bending actuation principle has been demonstrated for shape memory alloys (SMA), dielectric elastomers [3], piezoelectric materials [19], thermomechanical actuation [22], and a wide range of polymers, including those activated by chemical [4] and optical [9] processes. There already are many instances of SMA application on mobile robotics. An earthworm-inspired crawling robot [17] and a roller [13] are some examples. The most important limitation of SMAs is their low efficiency, which leads to a high power consumption.

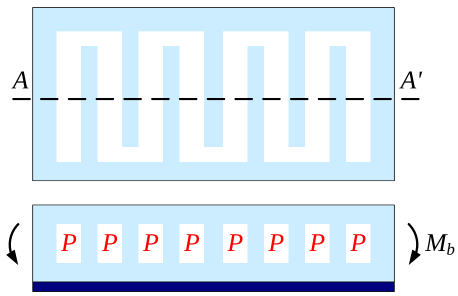

Fig. 1: Top- and side-views of a single active cell. Embedded serpentine channels are pressurized to induce an axial deflection of the top silicone layer, resulting in bending of the bimorph structure.

2 Modeling of soft pneumatic actuators

Given the Young's modulus of the material E with thickness h, and assuming axial stiffness and moment of inertias to be homogeneous throughout the material, we can calculate the induced curvature in the system shown in Figure 1 as a function of the expansion strain ε_g in one of its layers. The axial spring energy of the deflected beam is equivalent to its bending energy given by the Bernoulli beam equation

$$\frac{1}{2}Eh\varepsilon_g^2 = \frac{1}{2}\frac{Eh^3}{12}\kappa_g^2, \tag{1}$$

and it follows

$$\kappa_g = 2\sqrt{3}\frac{\varepsilon_g}{h} \tag{2}$$

i.e. the resulting curvature is a linear function of the applied strain and larger for thinner materials. In turn, the axial strain is a linear function of the pressure input.

Combining these unit cells in different arrangements, we can achieve distributed actuation embedded inside the body of a flexible robot. As the cells can bend in one direction when actuated, one can also use a tri-layer design composed of two thick layers with pneumatic channels sandwiching a thin fabric layer. A tri-layer design allows bending in both directions by antagonistically actuating opposing channels.

Another interesting property of pneumatic actuation is that as the pressure inside the channels increases, the stiffness of the material also increases. When used with the tri-layer design, this gives us a method of actively controlling stiffness without inducing bending. When both sides of the tri-layer cell are actuated, there will be no bending deformation but an increase in stiffness. Direct control on the stiffness is an efficient way to adjust the body for variable conditions. For instance, a manipulator arm made of this mechanism can alter its stiffness to passively hold an object or position joints and links arbitrarily to reorganize its own structure.

One possible arrangement is to combine the unit cells as a chain. Figures 2 and 3 demonstrate a pneumatic strip robot composed of six tri-layer segments. By selectively actuating these cells, one can induce a traveling wave over its length to crawl in a peristaltic manner similar to an inch-worm. Similarly, it can morph into spline-like shapes in 1-D.

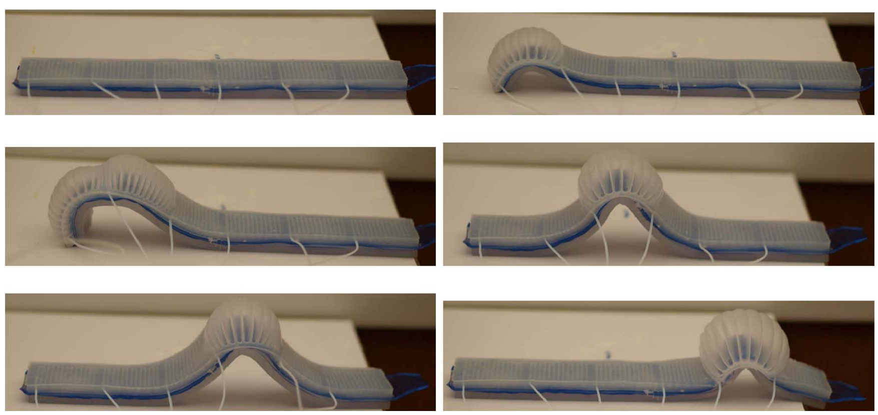

Fig. 2: Crawling locomotion of the chain structure. Locomotion is achieved in a peristaltic manner using a traveling wave over the length of the body.

In order to study possible gaits for such arrangements in simulation we implemented a spring-mass model similar to that described in [20] and [18]. A spring-mass model consists of a mesh of points, each with a specific mass, that are connected by torsional springs and dampers and are subject to spring and external forces such as gravity. Parameters for this simulation have been chosen ad-hoc as we are investigating qualitative behavior, specifically possible locomotion gaits. In future work, parameters of this simulation can be identified from real material prototypes and lead to quantitative insight into the required forces.

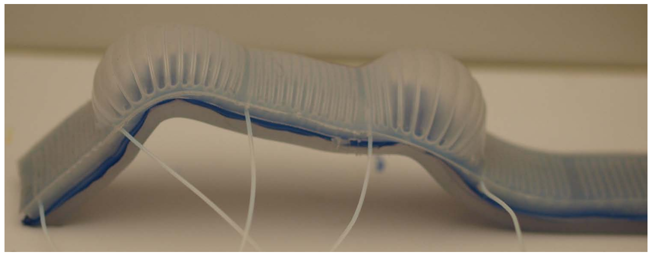

Fig. 3: Shape-change induced by controlled deformation of individual cells.

Figure 4 shows an ensemble of 1000 elements that can change their curvature arranged in a belt-like structure. Each element is modeled as a torsional spring connected to its neighbors and changes in curvature are simulated by changing the torsional stiffness of each element in longitudinal direction. The altered stiffness changes the minimum energy state of the structure. We made extensive use of this simulation to get an understanding of possible shapes and control schemes for locomotion gaits where actuation by horizontal expansion generated with programmed elasticity is most effective. The simulation also suggests that the actuation mechanisms are scalable.

Figure 4 shows a series of simulation snapshots that illustrate the dynamics of the system. Initially, the system is in equilibrium in a circular shape. Under the affect of gravity and the constraint of a surface, the system deforms to a new equilibrium corresponding to an elliptic shape. Changing the curvature at any point in the structure breaks this equilibrium and leads to either forward or backward motion as the system tries to fall into its new minimum-energy state.

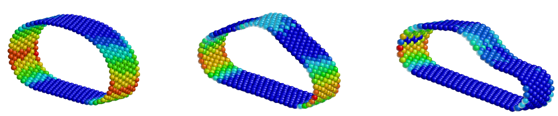

Fig. 4: From left to right: a closed kinematic chain made of a series of pre-strained cellular actuators will form a ring. Under the influence of gravity, the structure deforms into a tank-thread shaped structure. Changing the curvature at an arbitrary point on the chain will unbalance the system and lead to a forward motion until equilibrium is reached. Colors show the simulated bending energy for selected areas of the belt with areas of high bending energy being red and blue for those with low bending energy.

3 Control of distributed soft actuators

Simulation results suggest that in order to create motion, a shift of mass in the desired direction is needed and actuating the cells that are closest to the points of strongest curvature is found to be the most effective way forward. The overall moment of the structure can be increased by activating not only cells of high curvature close to the direction of motion, i.e. cells that pull the structure forwards, but also by activating cells on the opposite part of the belt. In order to scale to large numbers of cellular actuators, such a locomotion scheme needs to be implemented using distributed control.

A possible open-loop control scheme would be to have individual cells activate their neighboring cell after a certain delay and deflate themselves. Whereas such an approach might lead to locomotion if tuned right (see below) it is not able to adapt to changing slopes, variances within the material, or obstacles in the way.

For a closed-loop implementation, we need to unambiguously distinguish each cell that we wish to inflate. A possible way of doing this is to identify which cells have ground contact using an appopriate sensor . Let $c_i(k)$ be the sensor response of cell i at time k and let the sensor respond with '0' if a cell is touching the ground and '1' otherwise. Due to the geometry of the actuator chain, the system can be parameterized by contiguous trains of '0' and '1' that correspond to areas where the chain touches the ground or not, respectively. Then, each cell's position is uniquely defined relative to the ground by its distance to the discrete transitions '0'→'1' and '1'→'0', *i.e.* the transition points of the structure between ground and air, a property that can be evaluated by each cell using local, multi-hop communication [1].

Depending on the discretization of the material, i.e. the number of discrete actuator cells in the chain N, localization of a cell requires the ability to inquire about the status of its $N/2$ neighbors to the left and right of each cell (assuming a circular structure). This requirement can be relaxed to $n < \frac{N}{2}$ neighbors if a candidate control scheme requires information only of cells at most n "hops" away from the distinct sensor transition points to actuate.

The following distributed algorithm generates forward motion. Inflate cell i if it is in the air, i.e. $c_i(k) = 1$, and the cell $i+n$ (n cells *ahead*) is on the ground, i.e. $c_{i+n} = 0$. For n smaller than the contiguous number of cells touching the ground, this algorithm will let at most n cells from the '0'→'1' transition inflate. A sequence of experimental rolling snapshots using this algorithm is depicted in Fig. 9. For high-torque operation, i.e. activation of multiple areas of cells at the same time, a cell should fire if it is above the floor and either n_1 cells *behind* a '0'→'1' transition *or* n_2 cells *ahead* a '1'→'0' transition.

Note that the proposed closed-loop controller does not require knowledge of the time required to fill or vent a cell as the conditions whether cell i is actuated is simply a function of its physical location. That is, a cell will be continuously inflated until the desired forward motion occurs, which will cause a change in the sensor readings. Also, the proposed distributed control scheme does not require implicit knowledge on the total number of elements but will generate arbitrary short pulses for larger number of cells.

Algorithm 1: GAIT GENERATION FOR FORWARD MOTION WITH INCREASED TORQUE

Data: Sensor state of cell i and cells up to $i+n_1$ and $i-n_2$, desired distance from '1'→'0', n.
Result: Actuation of cell i

while *true* **do**
  if $(c_i(k)$==*1* $\wedge$ $(c_{i+n_1}$==*0* $\vee$ c_{i-n_2}=*0*)) **then**
    inflate i
  else
    vent i

4 Combining actuation, sensing, communication and control

In order to construct a robot that can autonomously move by rolling using the described distributed control scheme, we embedded miniature pneumatic valves, sensors, and microcontrollers for each cell into the silicone actuators. We used light sensors — which we consider to be representative for a large class of sensors to this purpose — to decide whether a cell touches the ground in this implementation.

The thick layer containing pneumatic channels is placed inside and the thin fabric-embedded layer is on the outside of the robot. Inflating chambers in the inner layer works toward changing the curvature of a particular cell (by bending it inside), which results in a shift in the center of gravity and the corresponding rolling moment.

The silicone-parts of the system have been created using a custom multi-part mold that has been created using an FDM process (Figure 5). This mold is used to create a belt consisting of eight actuators. Each actuator consists of two highly flexible silicone (Ecoflex ® Supersoft 0030) layers. One layer contains a serpentine pneumatic channel that can be inflated with air, thus inducing expansion strain in this layer. The other layer is made of solid silicone with an embeded textile ribbon that constrains the direction of the expansion strain of the inflatable layer as well as the overall length of the outer layer as shown in Figure 1. Each cell optionally also hosts a miniature 3-way valve that can direct air pressure into the cell or vent it using a 10ms current pulse (5mJ) of either +5V or -5V for switching between pressurizing and venting the cell, respectively. The valve is magnetically locking and thus requires a pulse for every switching operation as opposed to solenoid-based valves that require holding currents for the duration of actuation.The sensing, communication and control layer has been implemented by eight independent circuits each of which contains dedicated sensing, computation, and power electronics and are arranged on a flexible circuit board (Figure 6) that also provides a communication and power bus connecting each circuit directly with its two left and right most neighbors. The control logic has been implemented in an Atmega88PA micro-controller (one for each cell) that provides an analog-digital converter, and numerous digital inputs and outputs for communication with neighboring micro-controllers and controlling an H-Bridge to drive the valves. For sensing, we are using a photo-resistor, which

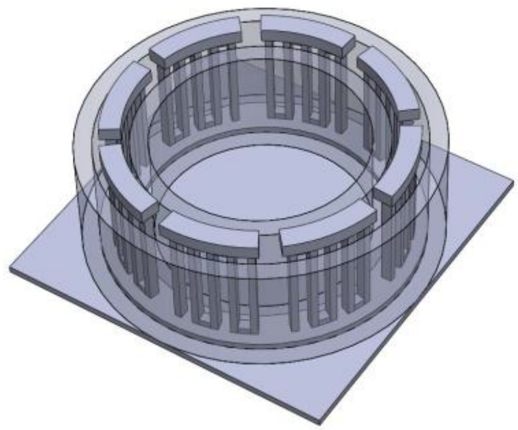

Fig. 5: The actuator arrays are molded from Silicone using an ABS mold that has been fabricated using a rapid prototyping FDM process. The inflatable sections are protected from silicone during the molding process by removable inserts. Access points for the side-actions are then sealed using silicone glue.

reliably determines whether a specific cell is facing the ground or facing up and thus is exposed to ambient light. Each PCB is also equipped with a Wheatstone bridge and an operational amplifier for measuring milli-volt signals such as generated by a strain-gauge sensor (not used in this paper). For open-loop control experiments we use an array of eight MOSFETs that are all connected to a single Atmega88PA and a ZigBee serial port bridge. This centralized setup simplifies the investigation of different gaits controlled by a host PC. Closed-loop control algorithm are implemented on individual micro-controllers.

5 Experimental results

We first examine the properties of a single cell and in particular the limitations of the theoretical linear relation between applied pressure and curvature as a function of applied pressure. We fixed a silicone beam consisting of a single cell in a vice so that the expected motion is orthogonal to gravity and observed the setup using an overhead camera, tracking [12] a red marker at the tip of the beam at around 8Hz.

We then manually applied compressed air with at 5 psi and 10 psi until the silicone beam reached its maximum curvature. Notice that we did not allow the cell to actually reach an equilibrium state, i.e. actually reaching 5 or 10 psi of pressure, as this might permanently damage the cell. (In fact, pressure of more than 3 psi leads to explosion of individual cells for this design.) Rather, the pressure on the regulator

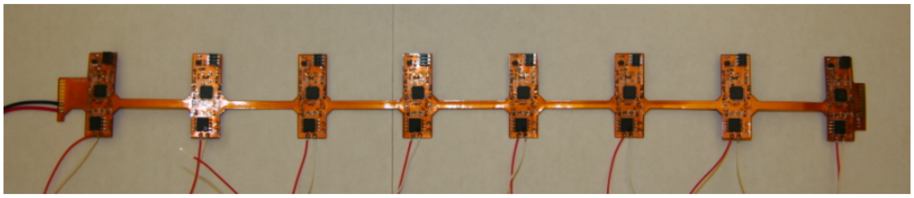

Fig. 6: Computation, communication and power electronics are assembled on a flexible PCB of 12 inch length that can be wrapped around the silicone structure. Each cell can communicate with its left and right neighbor using a one-wire connection as well with all other cells using a shared, addressable, 2-wire bus. The MCU (5x5 mm) is located In the center of each PCB, the H-Bridge on its bottom, an operational amplifier is shown in the top left and a 6 pin connector for programming the MCU is shown in the right.

is proportional to the speed at which the cell fills and thus proportional to the rate of curvature change. A sample experiment is depicted in Figure 7.

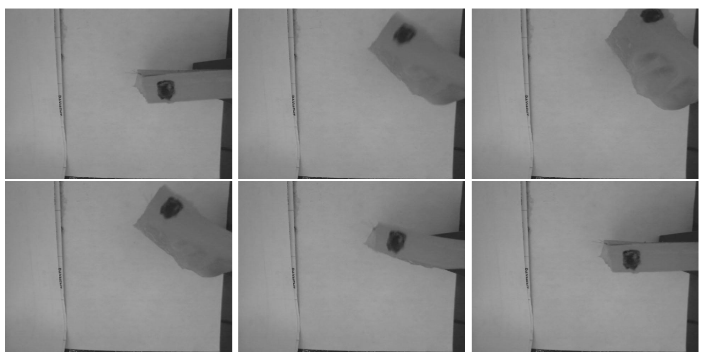

Fig. 7: Inflation of a single cell using a maximum pressure of 5 PSI. Curvature increases linearly with time until the silicone bloats. When the system is vented, the actuator returns to its original shape.

We then measured the curvature of the beam using the following equation

$$\kappa = \frac{|\Delta y|}{L^2} \tag{3}$$

where Δy is the displacement of the marker orthogonally to the beam and L is the length of the beam for $K = 0$.

The resulting curvature is plotted in Figure 8.

An initial study of the pneumatic rolling locomotion involved a central open-loop controller to generate a forward gait. We tried both normal-torque (single cell

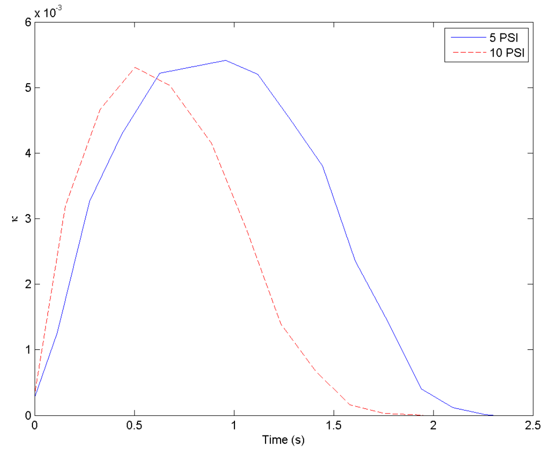

Fig. 8: Induced curvature as a function of time and maximum pressure for a sample experiment. The cell was vented as soon as it reached its maximum deflection.

actuation) and high-torque (opposite cell pair actuation) variances of Algorithm 1, although without taking sensor feedback into account. Instead, the open-loop controller simply inflates a cell (pair) for τ_{on} seconds and then vents it for τ_{off} seconds before switching to the next cell (pair) in a timed sequence. The parameters of the gait have been identified by trial and error and are $\tau_{on} = 1s$, $\tau_{off} = 0.3s$ at 7 psi pressure.

We found that this simple open-loop algorithm yields satisfactory locomotion on a flat surface regardless of the starting cell (pair). The timed sequence reaches the correct cell (pair) eventually, and starts rolling the belt. For the loaded case on an incline, however, an open-loop policy does not reliably work as the timing parameters need to be readjusted for longer actuation, but the controller does not incorporate such an adaptation. We found that the normal-torque algorithm fails after a 5^o incline and the high-torque algorithm fails after a 10^o incline. The mode of failure is rolling backward.

This problem is removed with the closed-loop controller as the timings are now adapting to changing conditions and even when the belt cannot move up an incline, it does not fall back, but rather gets stuck at a rolling step. A motion sequence controlled by closed-loop distributed control is shown in Figure 9.

To characterize the speed of forward motion of the system and its capability to adapt to varying slopes, we measured the time required to roll the material a predefined distance on an adjustable ramp. In order to vary loading conditions, we varied the angle of inclination from $\alpha = 0$ to 10 degrees. Given the weight of the robot $P = 0.64$ lb, we calculate the load as $l = P \sin \alpha$.

We performed a total of 63 experiments for varying inclination angles and pressure inputs and measured the average speed of the robot as seen in Figures 10 and 11

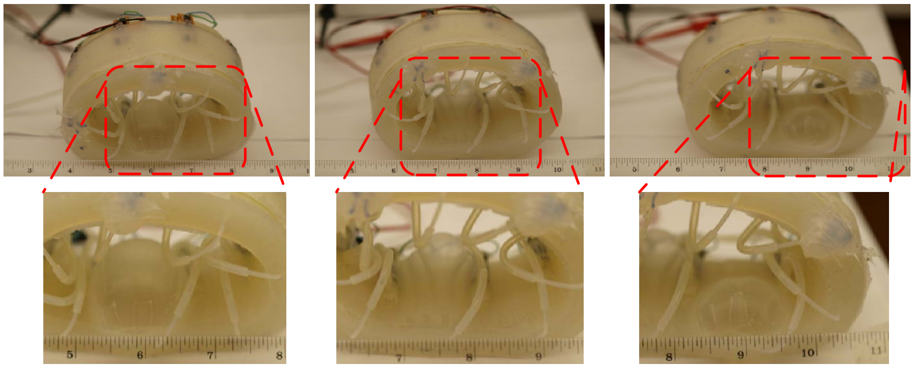

Fig. 9: Pneumatic belt rolling autonomously on a flat surface using distributed closed-loop control. Three rolling steps are shown from left to right. Bubbles forming on the inside layer to induce a bending moment are visible on the close-up snapshots shown below each rolling step.

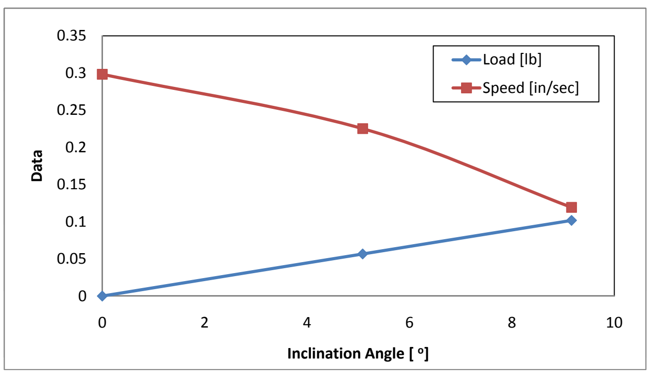

Fig. 10: Speed and load as a function of the inclination angle for 4.5 psi pressure input.

as a function of inclination and input pressure, respectively. Autonomously actuating one cell at a time, to "pull" its center of mass forward, the robot could handle inclinations up to 10^o corresponding to a load of around 0.1 lb.

6 Discussion and Conclusion

Computational materials are getting within reach given today's state of knowledge in polymers, material science, embedded systems, and robotics. The computational material described in this paper is much more general than our case studies. It could, for instance, be arranged in a tube structure, with three cells over the periphery at

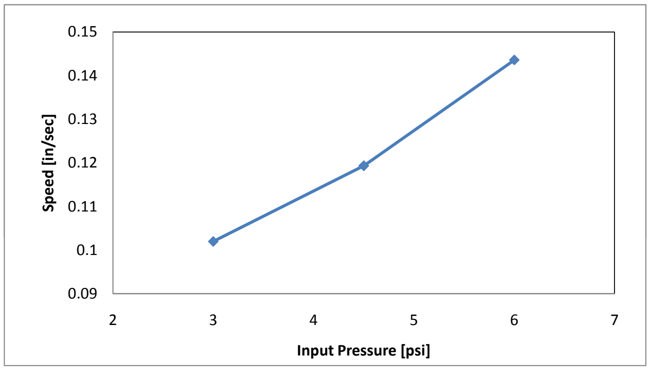

Fig. 11: Speed as a function of pressure for a 10^o inclination angle.

120 degree separation, to achieve both worm-like locomotion and tentacle-like manipulation capabilities. Such a manipulator could adjust its joint and link positions by stiffness control or even change its degrees of freedom. On the same note, a soft gripper that can pick-up objects with arbitrary shape can be developed. Using reversible attachment methods, a pneumatic strip robot can roll up to form a roller, or vice versa, depending on the conditions. Similarly, our demonstration of 1-D shape-change can be generalized by arranging the cells in a matrix to achieve 2-D operation.

For capable intelligent soft material made out of a large number of independent cells that sense, compute, actuate, and communicate, the actuation method is crucial. Specifically for pneumatic actuation, miniaturization of our prototypes is currently limited by available off-the-shelf mechatronic parts (valves).

An obvious limitation of pneumatic systems is the necessity of a pressure supply. While there exist commercial miniature pumps using a DC motor and the pressure requirements of our systems are low, for a truly autonomous and soft robotic system, we need to design soft pumps as well. To this end, we are currently working on a chemical approach to pressure generation. Such a pump will reduce the electrical power consumption of our robots by offloading pressure generation to a controlled chemical process.

The algorithms for distributed control of a belt-like arrangement of multiple cells demonstrated shape deformation and locomotion using light as a sensor. In our present work, we are investigating other sensors and actuators, such as optical polymer force sensors [14], embedded electronics for sensing [6] and valves made entirely from polymer. We are also interested in investigating other mechanisms that result from arranging large numbers of curvature changing elements such as artificial muscles and tentacles [23], and algorithms to control them.

The presented mechanism has been constructed by molding and manual insertion of stiffeners and mechatronic parts into the silicone. In order to enable production of materials with a large number of cells, further research is needed not only into polymer electronics, sensors and actuators, but also into processes to fabricate polymer materials, e.g. a combination of photo-lithography, novel sacrificial layers [11], fused deposition modeling, ink-jet printing, and laser holography.

We have shown that computational materials are controllable at large scale. They are the basis for creating a new generation of biomimetic soft robot systems. Computational materials provide an important step towards bringing machines and materials closer together so that materials become smarter and machines become softer.

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