System-level Challenges in Pressure-Operated Soft Robotics

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ABSTRACT

Last decade witnessed the revival of fluidic soft actuation. As pressure-operated soft robotics becomes more popular with promising recent results, system integration remains an outstanding challenge. Inspired greatly by biology, we envision future robotic systems to embrace mechanical compliance with bodies composed of soft and hard components as well as electronic and sensing sub-systems, such that robot maintenance starts to resemble surgery. In this vision, portable energy sources and driving infrastructure plays a key role to offer autonomous many-DoF soft actuation. On the other hand, while offering many advantages in safety and adaptability to interact with unstructured environments, objects, and human bodies, mechanical compliance also violates many inherent assumptions in traditional rigid-body robotics. Thus, a complete soft robotic system requires new approaches to utilize proprioception that provides rich sensory information while remaining flexible, and motion control under significant time delay. This paper discusses our proposed solutions for each of these system-level challenges in soft robotics research.

Keywords: Soft robotics, Fluidic elastomer actuators, Magnetic soft sensing, Portable pressure generation, Electropermanent magnet valves, Sliding mode control.

1. INTRODUCTION

Soft robotics represents a fundamentally different research avenue to develop intelligent systems that are physically safer and more adaptive to desired or undesired contact with the environment or human users/co-workers than traditional rigid robots. Nature provides existence proofs in a variety of mobility and manipulation contexts for highly dexterous and versatile robotic functionality, such as squeezing into tight spaces, handling fragile objects, and being robust to collisions.[1]

Recent soft robotic research has been mostly bioinspired,[2,3] to synthetically reproduce the functionality demonstrated by worms, octopus arms, and other model animals. These results rely on new soft actuation technologies, and hence focus more on design, fabrication, and analysis of actuation performance, providing a solid foundation for further research on challenges blocking complete robotic systems that include power sources, driving hardware (valving), perception, computation, and actuation.

While there exist recent studies on enabling sensing and control approaches to individual soft actuation technologies,[4–7] as well as the development of portable pressure sources,[8,9] soft robotics needs a standard system-level treatment of a multitude of challenges due to a lack of accurate dynamic models, system integration methodologies that harness the advantages of compliance, feedback control algorithms for low-bandwidth nonlinear actuators, and accounting for increased levels of motion uncertainty. We expect that the solutions to these challenges will be based on a body of work developed for rigid systems, with significant modifications to be compatible with elastomeric soft robots.

To address these challenges, our research envisions fully-integrated pressure-operated soft robotic modules composed together to achieve arbitrary levels of complexity. Our approach to enable these composite robotic bodies is to explore standardized modular design and fabrication techniques and processes. Our proposed solutions utilize composite magnetic deformation and force sensing, portable and self-controlled chemical pressure generation, low-profile valving, and sliding mode feedback control of soft robots to address each of these issues, while remaining compatible with the mechanical compliance of a soft body. The rest of this paper overviews our recent results to offer a holistic framework for complete pressure-operated soft robotic systems.

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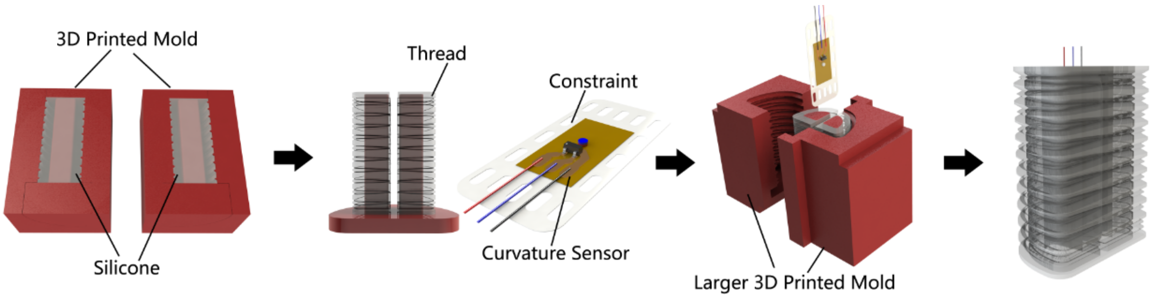

Figure 1. Fabrication process of our soft bending modules.[20]

2. SYSTEM ARCHITECTURE OF A PRESSURE-OPERATED SOFT ROBOT

2.1 Actuation: Modular Multi-Material Composite Soft Pneumatic Actuators

Our research on soft actuation focuses on pressure-driven soft robots that are actuated by the modular composition of *fluidic elastomer actuators* (FEAs).[10] This modular design methodology resulted in a range of robotic systems; including self-rolling cylinders,[11,12] snakes,[13–15] fish,[16] and continuously deformable manipulator arms.[17] Similarly, we developed extensile fiber reinforced soft actuators called *reverse pneumatic artificial muscles* (rPAMs) that relieve contractile stresses upon pressurization to apply antagonistic forces on underlying kinematic chains with large displacement ranges.[18,19] If bending deformation is required (for a snake-like robot[15]), a semi-circular cross-sectional area is used as well as an inextensible (e.g. fabric, plastic, paper) thin constraint layer on the flat edge such that axial stresses are converted to bending deformations[20] as shown in Figure 1.

Note that the central inextensible constraint layer doubles as an optimal location to integrate flexible sensing (and control) circuitry within our bending actuation modules, since this layer constitutes the neutral axis of bending, and hence it undergoes minimal axial strain. The integrated custom curvature sensor (described in Section 2.2) shown in this figure provides the possibility of proprioceptive feedback motion control (Section 2.5).

In addition, we recognize that all functional fluidic soft actuation happens by constraining the deformation of a soft chamber by geometry, external threading, or internal inextensible layers. Building up on this concept, we study foldable exoskeletal constraints around soft linear muscles to "program" the response of these actuators to follow prescribed shapes. This research combines our work on origami-inspired robotic systems[21] with soft actuation. Three kinds of exoskeletal constraints (L-, U-, and Z-Shaped) are presented in Figure 2, where the same linear muscle is used for all cases, demonstrating the versatility of this approach in designing and modifying the motion response of soft actuation modules.[20]

This approach is inspired by insect exoskeletons, especially those of jumping spiders that utilize hydraulic pressurization of joint bladders for rapid motions. The exoskeleton is folded from a laser-patterned 177.8 μm (7 mil) PET plastic sheet. In Figure 2, red dashed and black solid lines indicate folding and cutting patterns. When folded, the box shaped portion wraps around the soft actuator. At desired places, only a single surface of plastic sheet is connected (and the rest of the surface creates a folded spring), operating similarly to the constraint layer of the bending actuator and causing the linear muscle to bend. Several strips are used to fix the relative position of the actuator and skeleton. Therefore, when the soft actuator is pressurized, the skeleton will force the actuator to convert its increase in length into bending at specified locations, approximating an articulated body.

2.2 Sensing: Magnetic Deformation Measurement in a Flexible Elastomeric Substrate

Soft robotic approaches require a re-evaluation of sensor technologies for compatibility and embedded operation, especially for feedback control applications. On-board sensors for soft robots should ideally offer accurate measurement with high bandwidth and minimal effect on the mechanical response of the robot body. The compliance and morphology of these robots complicate the use of many traditional sensors including encoders, potentiometers, or metal strain gauges. Therefore, we limit our sensing solutions to non-contact devices,[22] through embedded sensing on a flexible electronics layer.

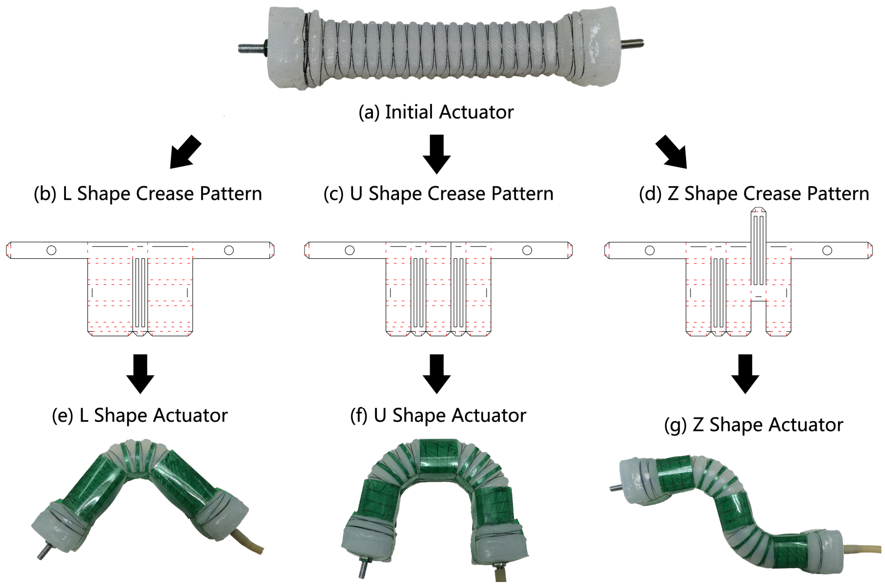

Figure 2. Our linear soft muscle can be programmed to undergo a desired shape change using a foldable exoskeleton constraint.[20]

There exist commercially available sensors to detect stretch in a rubber or bending in a flexible material. These sensors are usually based on resistance change of conductive materials under strain. While very useful for quick development and qualitative information, in a preliminary evaluation, we concluded that resistive sensors tend to suffer from a lagged response as well as creep and drift issues, especially under rapidly changing inputs. Recent approaches that incorporate conductive liquids in fluidic channels embedded in the elastomer show promising results,[23] compatible with our soft actuator fabrication process. However, a drawback of these solutions is the relative complexity of encapsulating liquid metals inside elastomeric substrates with uniformity and repeatability and limited dynamic characterization.

To address this challenge, we study custom magnet and hall-effect sensor pairs in engineered geometric arrangements to monitor the deflection of soft substrates with higher accuracy, repeatability, and bandwidth compared to commercially available resistive sensing solutions.[24] Two versions of these sensors are demonstrated in Figure 3. This approach utilizes our custom flexible circuit fabrication technology to achieve non-contact magnetic field measurement due to the relative motion of the magnet with respect to the Hall element, to detect the corresponding curvature of a bending segment (Figure 3-A) or distributed (currently 5 mm spatial resolution) normal deflection of a soft tactile skin (Figure 3-C).

To optimize the placement of the magnet, we utilize finite element analysis combined with a model of the position and orientation of the magnet with respect to the Hall-element for the range of relevant deflection values. Our custom magnetic sensors offer accurate measurement of a periodic curvature waveform under a range of rates for soft actuation, as we have shown in Ref. 24, and Figure 3-B, where expected curvature waveform and measured signals overlap for three different frequencies (verified up to 7.5 Hz). Dynamic loading of the normal deflection sensors yielded similar results (Figure 3-D), where the displacement waveform and the magnetic sensor response agree, evidencing the feasibility of the proposed approach. Since the proposed sensors respond to a change in geometry and not material strains, the presented magnetic sensing modality is useful to track deformations, better than resistive or capacitive solutions.

2.3 Energy: Portable Pneumatic Battery

One important challenge for portable operation of fluidic soft robots is the power source requirement for actuation. Current off-the-shelf pressure sources are generally limited to compressors and compressed air cylinders,[25] while recent literature has shown a promising explosive actuation modality for soft robots by combustion.[8] In previous work, we have utilized both pressure sources. Our autonomous soft robotic snake uses an on-board miniature

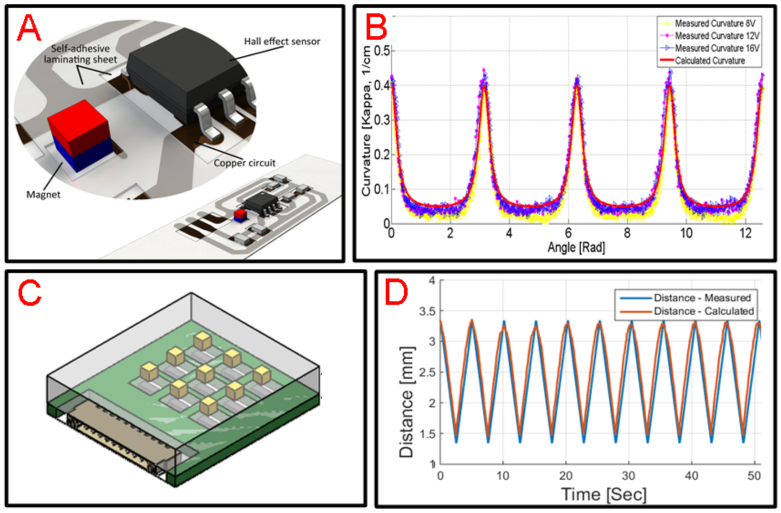

Figure 3. Two embedded magnetic deformation sensing modalities: curvature[15, 24] (top row) and distributed normal deflection (bottom row). Accurate dynamic measurement is observed for both cases (B and D).

compressor to convert electrical energy to mechanical energy[13, 15] and we have developed a soft robotic fish that uses on-board compressed air cylinders.[26] Both of the existing mechanical power systems provide solutions to achieve self-contained fluidic mobile robots, but they lack in a number of aspects limiting their use for portable and everyday use. Miniature compressors are noisy and use valuable electrical energy; and cylinders in useful form factors do not offer longevity. What is required is a portable and silent source of pressure, the equivalent of an electrical battery where a chemical reaction generates the actuation energy using a fuel.

We recently presented such a device, tagged a *pneumatic battery*, which is a chemically operated portable pressure source.[11] Figure 4 shows a recent design. This plug-and-play device creates a controlled pressure output by the catalyzed decomposition of hydrogen peroxide (H_2O_2) into oxygen gas and water in a closed cylindrical container. A spring (left) deforms with increasing pressure and seals off the catalyst (red) from the solution at a critical pressure, stopping the gas generating reaction. This mechanical self-regulation system controls the amount of generated pressure to remain around a prescribed critical value. The latest design introduces plug-and-play operation to enable setting the generated pressure using a knob as compared to our initial prototype where the critical pressure was a design variable that is tuned by modifying the thickness of a deflector membrane using a set of analytical equations of self-regulation detailed in Ref. 11.

We have implemented three improvements to the original pneumatic battery design. First, we replaced the silver catalyst with platinum. Silver oxidizes and gets poisoned by some of the inhibitors present in the H_2O_2 solution. Second, the geometry of the catalyst is changed from a 2-D sheet to a 3-D hollow cylinder for improved surface area. Finally, to accommodate for the third dimension, the deflector is also modified appropriately to properly seal around the catalyst and stop the reaction at the critical pressure value.

The resulting oxygen gas is filtered through a hydrophobic membrane filter with sub-micron pores before the outlet, which enables the operation of the pneumatic battery in any orientation. The pneumatic battery is capable of generating relatively large pressure values (up to 100 psi), which may seem like a safety issue. The alternative is to use compressed air cylinders that are commonly rated up to much larger pressure values (3000 psi) and routinely used by divers. Therefore, our method of generating gas on-demand to keep a constant actuation pressure is indeed safer. Not to mention, the device can be stored with zero internal gauge pressure and the negative mechanical feedback loop provides another level of safety.

Pure H_2O_2 has a theoretical maximum energy density of 2.7 kJ/g,[11] one of the highest in common mono-propellants. The decomposition produces oxygen and water, without harmful byproducts. We note that due to the exothermic nature of this reaction, the pneumatic battery heats up during operation, but the resulting temperature increase is limited (a 50% H_2O_2 solution has a steady-state temperature of 70^{o}C if it is allowed to decompose freely, well within the thermal operational limits of silicone rubber).

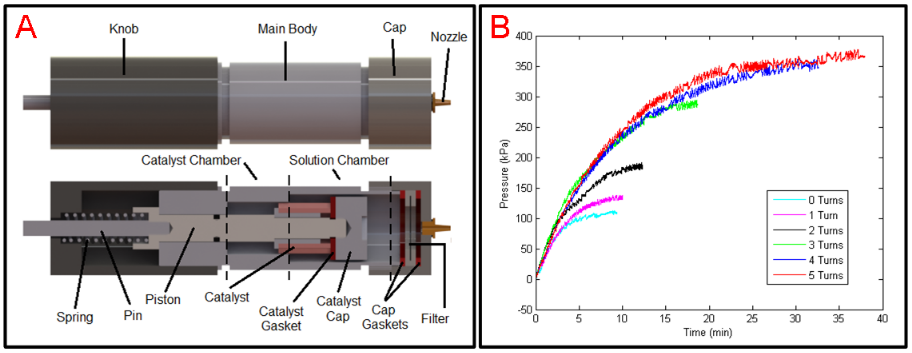

Figure 4. A) Plug-and-play pneumatic battery assembly in full (top) and cross sectional (bottom) views. The dotted lines bound the internally located catalyst and solution chambers. B) Pneumatic battery pressure responses at various pressure adjustment knob positions.

2.4 Valving: Miniature Electro-permanent Magnet (EPM) Latching Valves

Given a single pressure source, multiple fluidic soft actuators, and a conventional electrical computation system, a network of valves is necessary to isolate and address each actuator. Existing commercial solenoid valves are typically too large and they may require continuous current to remain open. For portable soft robotics applications, it is a challenge to embed valving within the system, resulting in bulky and rigid bases to mount supporting hardware.[13,15] Therefore, future soft devices based on fluidic elastomer actuators will require novel solutions to valving, to control force, displacement, or stiffness output of FEAs.

The ideal valve for many-DoF portable operation is a flat and compact design that can be readily embedded in the elastomer during molding fabrication. This reduces bulky tubing and external valving hardware by directly acting on the fluidic channels close to the actuators. To address this challenge, we study miniature latching valves based on the electropermanent magnet (EPM) technology.[27,28] Manipulating the flux output of an EPM enables the control of the outlet flow in a custom check valve.[29] When the EPM is switched off, a ferrous ball seals the orifice within a plastic tubing and the valve is closed. To open the valve, a current pulse is applied through the coil around AlNiCo and NeFeB magnets, orienting them in the same direction to switch on the EPM. Magnetic flux is channeled through the ball, pulling it away from the orifice enabling flow. A short (5 ms) of current through the coil permanently switches the EPM. The valve consumes no energy to maintain either state. We have determined a static pressure-flow relationship of the valve experimentally using a flow meter and a pressure transducer. At flows above 2 lpm, an approximately constant valve impedance of 0.97 psig/lpm is observed. Finally, we demonstrated the functionality of EPM valves on a soft mobile robot made of six FEA flaps bending out to roll a cylindrical body forward.[29]

2.5 Control: Robust Sliding Mode Motion Control of Soft Robotic Systems

Control in the context of soft robotics has little precedent in the literature. In fact, controlling soft robotic systems was recently declared a new grand challenge by the Soft Robotics Journal.[30] Compared to traditional electromechanical actuation, our soft actuators are low-bandwidth systems, which increases the burden on control to achieve precise positioning, although the inherent safety of soft robotic systems compensates for small positioning errors without resulting in large contact forces. To decouple potential sources of error due to sensing difficulties in a soft body, we studied motion control on sensorized bench-top rigid kinematic modules, including a simple revolute joint operated by two antagonistic fluidic soft muscles,[18] and more recently, a 2-DoF universal joint module operated by three fluidic soft muscles[31] as shown in Figure 5-A. For operation, these muscles articulating the module are connected to a pressure source and each controlled by a separate miniature fast-response solenoid valve. To approximate analog pressure input, valves are operated using pulse-width modulation (PWM).

For feedback control, we derive an iterative sliding-mode controller of the form:

$$u(t) = u(t - \Delta t) + K(\dot{e_x} + De_x), \tag{1}$$

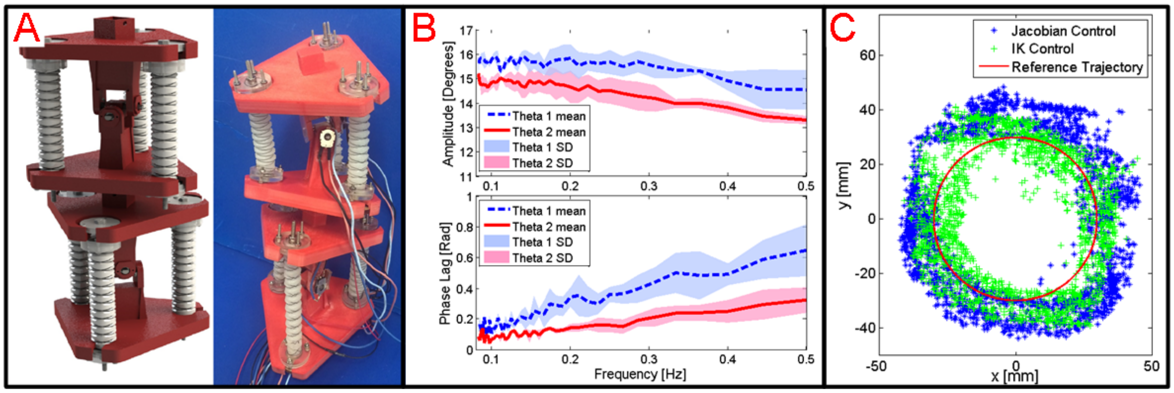

Figure 5. Feedback motion control studies utilized custom bench-top systems comprising multiple soft muscles operating underlying skeletal linkage modules. Serial arrangement of a number of these modules results in a soft-actuated manipulator system (A). Iterative sliding-mode motion controllers were evaluated for each DoF of the modules and their closed-loop frequency response was extracted while following sinusoidal reference curves (B). The trace of a soft-actuated manipulator made of two modules in series while following a circular reference trajectory validates our control approach andcompares two inverse kinematics solvers[31] (C).

where $u(t)$ is the feedback control input (corresponding to the PWM duty cycle) for each actuator iterated at every time step Δt to regulate position error e_x, using positive tunable coefficients K and D. We performed rigorous analysis of this control approach to determine the closed-loop frequency response of each degree of freedom (shown in Figure 5-B) and studied the combined multi-input-multi-output (MIMO) motion control of two-modules in series as a simple soft-actuated manipulator arm to track circular trajectories. In these experiments, we utilized and compared two fundamental approaches to solve the inverse kinematics of the arm on the fly: 1) a direct inverse kinematics formulation that relies on a look-up table of actuator pressure inputs corresponding to end-effector positions; and 2) a geometric Jacobian solution (traces of end effector motion and the reference trajectory are shown in Figure 5-C). Our initial results indicate that the direct inverse kinematics approach is more accurate while the Jacobian solver is more precise, especially under payload.[31]

3. CONCLUSION AND FUTURE WORK

This paper describes our recent results towards a complete pressure-operated soft robotic system in a modular structure that offers power autonomy, integrated sensing, valving, and sliding mode feedback motion control solutions. While we reported some of these studies individually in separate publications, they have so far not been integrated into a single soft robotic system, which constitutes our current work; to develop a modular soft robotic snake with integrated sensing and control.

In addition, we are currently exploring a number of advancements in our sensing and control methodologies, including (1) a 3-D magnetic deformation sensor that can detect axial and bending motions of a soft manipulator module with accuracy and high-bandwidth, and (2) a direct sliding-mode controller that modulates discrete valve actions and not the duty cycle of a PWM signal, which considerably decreases control bandwidth.

Finally, we notice that the traditional feedback control approaches to robotics relying on precise positioning may not be appropriate for a soft robotic system, which by nature does not have to avoid contact with obstacles or operators. Thus, we plan to focus on force control approaches for soft robots in future work.

ACKNOWLEDGMENTS

This work was supported in part by National Science Foundation under Grants CNS-1544636 and IIS-1551219. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

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