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EDITORIAL

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EDITORIAL

Bioinspired soft robotics: preface to the special issue

D A Paley[1], C Majidi[2], E Tytell[3] and N Wereley[4]

[1] Department of Aerospace Engineering and the Institute for Systems Research, University of Maryland, College Park, MD 20742, USA
[2] Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[3] Department of Biology, Tufts University, Medford, MA 02155, USA
[4] Department of Aerospace Engineering, University of Maryland, College Park, MD 20742, USA

E-mail: dpaley@umd.edu

This issue describes basic research in the new area of bioinspired soft robotics, with an emphasis on distributed sensing, actuation, and control. These developments in robotics research incorporate smart materials, flexible electronics, and 3D printing to emulate both the physical flexibility and the versatility of animals such as fish, caterpillars, snakes, and worms. Biomedical applications include artificial muscles and skin.

Editorial opinion

The University of Maryland Workshop on Distributed Sensing, Actuation, and Control for Bioinspired Soft Robotics was held in College Park, Maryland, on September 11 and 12, 2014. The workshop brought together 40 scientists, mathematicians, and engineers from a range of STEM disciplines including neurobiology, applied mathematics, and control theory for discussions on the fundamental challenges of distributed sensing, actuation, and control of soft elastic continua. The workshop spanned two days and included a combination of short talks and breakout sessions. The workshop emphasized working discussions on open and cutting-edge research questions, rather than review presentations on the state of the art. A subset of the workshop participants submitted articles to this special issue. It was evident from the workshop that numerous research challenges and opportunities currently exist in the areas of distributed sensing, actuation, and control for bioinspired soft robotics due to recent advancements in smart materials and additive manufacturing. The following is a summary of the workshop's sessions and group discussions.

Workshop participants identified a need for unification and standardization, including model systems and test beds for soft robotics. Indeed, providing a common set of materials and physical architectures may unleash innovation and creativity. Moreover, defining a catalog of target materials and properties would enable the robotics community to address existing and future challenges in material supply. For example, the polyurethanes used in stretchable electronics are sold in units of tons, whereas most research purposes require much smaller amounts. Also, vendors frequently change the recipes for materials, resulting in varying properties. A data sheet for properties of soft materials, including non-standard considerations like washability, would be useful. However, since many measures of mechanical compliance (e.g., flexural rigidity) depend on the length scale, an equivalent set of non-dimensional parameters and figures of merit for soft materials needs to be identified. There was also a discussion of developing a grand-challenge environment, which has precedence in other fields. Ground rules for a soft-robotics grand challenge might include constraints on cost, power, weight, and structure. Proposed tasks might include object manipulation, locomotion, and exploration using tactile sensing. A soft-robotics educational kit that anyone can download and use would help attract participants.

Research in soft robotics promises to impact a variety of fields in science and engineering and has many applications in areas of societal need. For example, control theory and control engineering with distributed, multi-modal, and adaptive sensors, actuators, energy sources, and materials requires new canonical plant models with complex spatiotemporal characteristics. The ability to mass-produce soft robots might provide incentive to the machine-learning community to tackle the challenges of control for high-degree-of-freedom dynamical systems. Other fields potentially impacted include tissue engineering and biology (e.g., incorporating tissues and cells into soft robotics); control engineering (sensing, control, and actuation); additive manufacturing (new fabrication tools); biomedical engineering (intelligent drug design and delivery); medical devices (soft surgical tools); and ethics (public opinion and policy). A wide array of relevant advances were identified for autonomous underwater and aerial vehicles, including maritime vehicles that are increasingly efficient, stealthy, maneuverable and capable of long duration missions; soft or flexible underwater vehicles that survive impacts while maneuvering in shallow or deep water, the surf zone, and/or strong currents; and hybrid vehicles that transition between operating domains (ground, air, and water). Other capabilities and components potentially advanced or provided by soft-robotics technologies include energy harvesting; bioinspired wings, bodies, and control surfaces; collision avoidance and resilience; reversible adhesion; flexible sensor arrays; explosive ordinance mitigation; and compliant manipulators.

Contents of issue

Befitting an emerging discipline impacting sensor and actuator technology and robotic designs in a range of mediums, the articles in this special issue describe soft architectures for ground, air, and underwater robots. A soft robotic skin inspired by human skin is described in 'Texture recognition and localization in amorphous robotic skin,' by Dana Hughes and Nikolaus Correll at the University of Colorado, Boulder. The skin uses a spatially distributed network of microphones embedded in a soft silicone elastomer to detect and localize the source of a stimulus such as rubbing or slipping. The source position uncertainty depends on the sound intensity, sensor node spacing, and source position. Texture identification performed using a logistic regression model experimentally distinguished between up to 15 sample textures with more than 70% accuracy.

Applications of soft-robotic technology to actuators inspired by artificial muscles are described in two articles. '3D printing antagonistic systems of artificial muscle using projection stereolithography,' by Robert Shepherd *et al* at Cornell University, assesses the capabilities of a commercially available, photopolymerizable elastomeric material for use in direct printing of high-degree-of-freedom actuators. They describe a tentacle-like actuator capable of high-frequency, three-dimensional movement by combining two pairs of antagonistic pressure chambers. Each chamber has a pleated architecture that reliably deforms according to the inlet pressure. 'Effect of bladder wall thickness on miniature pneumatic artificial muscle performance,' by Thomas E Pillsbury and Norman M Wereley at the University of Maryland and Curt Kothera from InnoVital Systems Inc., investigates the effect that bladder thickness has on static actuation performance of a small-scale pneumatic artificial muscle that produces an axial tension force when pressurized. A force-balance model with a nonlinear stress-strain relationship including a linear variation in pressure matches well with experimental performance metrics indicating the benefits of a thin bladder.

The underwater domain provides ample inspiration and application for soft robotics. 'A biomimetic underwater vehicle actuated by waves with ionic polymer–metal composite soft sensors,' by Qi Shen and Tianmiao Wang from Beihang University and Kwang J Kim from the University of Nevada, Las Vegas, describes a biomimetic underwater vehicle consisting of a surface float connected by cables to an underwater glider with soft fins. Laboratory experiments in freshwater indicate the vehicle can be propelled by wave energy, independent of wave direction, at speeds well predicted by a dynamic model of thrust and drag. The inclusion of ionic polymer–metal composite sensors indicates their potential use in underwater applications such as energy harvesting. 'Distributed flow sensing for closed-loop speed control of a flexible fish robot,' by Feitian Zhang *et al* in the lab of Derek A Paley at the University of Maryland, presents a fish-inspired soft robot equipped with distributed pressure sensors for flow sensing. Closed-loop control of one-dimensional swimming motion is achieved in a flow channel by regulating flapping amplitude according to the combination of a feed-forward control based on an averaged dynamic model and a feedback control based on the estimated flow speed and angle of attack. 'Evolutionary multiobjective design of a flexible caudal fin for robotic fish,' by Anthony J Clark and Xiaobo Tan and Philip K McKinley at Michigan State University, proposes an evolutionary optimization approach to selecting morphological parameters of a rectangular fin, including length and height, and control parameters including frequency and pulse-width ratio that optimize swimming speed and power usage. Experimental validation using a small robotic fish confirm the effectiveness of several fin designs. 'Design considerations for an underwater soft-robot inspired from marine invertebrates,' by Michael Krieg, Isaac Sledge, and Kamran Mohseni at the University of Florida, relates the internal pressure of a jellyfish-inspired soft-bodied thruster to its propulsive performance in order to derive a control of volume flux that minimizes energy. The proposed design of a feedback control for the volume flux uses potentiometer measurements of cavity height and is valid for any flexible cavity geometry.

Non-traditional air and ground vehicles leveraging soft robotics are described in the remaining three articles. 'Analytical model and stability analysis of the leading edge spar of a passively morphing ornithopter wing,' by Aimy Wissa at the University of Illinois at Urbana Champaign, Joseph Calogero at Pennsylvania State University, and James Hubbard Jr *et al* at the University of Maryland, considers the stability properties of the leading edge spar of a flapping wing equipped with a compliant spine. Theoretical predictions from a torsional spring model are within 7% agreement with high-speed experimental measurements of the bending deflections collected in a vacuum. Including damping favorably impacts the transition boundaries between stable and unstable motions parametrized by the spine's up- and down-stroke torsional stiffnesses. 'Slithering towards autonomy: a self-contained soft robotic snake platform with integrated curvature sensing,' by Ming Luo *et al* from Cagdas Onal's lab at Worcester Polytech, describes a pressure-operated soft robotic snake platform (depicted in the cover photo of this special issue) fabricated with integrated flexible electronics, including embedded magnetic sensors to monitor the curvature of its four bending segments. The snake's translational and rotational motions are described by a dynamic model that includes frictional moments. Undulatory locomotion is generated by open-loop control of miniature solenoid valves according to the frequency and offset of a traveling wave based on the serpenoid equation. Lastly, '*Softworms*: the design and control of non-pneumatic, 3D-printed, deformable robots,' by T Umedachi *et al* in the lab of Barry Trimmer at Tufts University, describes an electrically powered and actuated soft-robotic platform inspired by crawling and climbing of caterpillars. Each robot module is 3D printed in the shape of a caterpillar with feet whose gripping mechanism exhibits variable friction in order to generate a crawling gait; modules can be combined to make multi-limbed devices.

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