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14. ABSTRACT
The 2nd UMD Workshop on Distributed Sensing, Actuation, and Control for Bio-inspired Soft Robotics was held at the University of Maryland, College Park, MD, on October 3, 2016, co-chaired by Derek Paley (U. Maryland) and Carmel Majidi (Carnegie Mellon). The workshop brought together about 35 scientists, mathematicians, and engineers from a range of STEM disciplines (e.g., neurobiology, applied mathematics, and control theory) for discussions on the fundamental challenges of distributed sensing, actuation, and control of hyperelastic continua.

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ABSTRACT

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Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

"Three Advances in Soft Robotics: Foam Actuators, Optically Dynamic Skins, and Optoelectronic Sensing." Robert Shepherd (Cornell)
"Fast Dynamics in Soft Systems." Barry Trimmer (Tufts)
"Soft Robotics at Small Scales." Sarah Bergbreiter (UMD)
"Rubbery Switches for Bio-inspired Logic and Control." Iain Anderson (Univ. of Auckland)
"Shape and Gait Optimization for Active Elastic Curves and Surfaces." L. Mahadevan (Harvard Univ.)
"From Optimal Control to Filaments." PS Krishnaprasad (UMD)
"Modeling the Dynamics of Soft Robots." Oliver O'Reilly (UC-Berkeley)
"Optical Sensing in Transparent Soft Robots." Chris Atkeson (CMU)
"Nanoparticle-based Self-assembling to Integrate Sensing, Actuation and Control for Bio-inspired Soft Robotics." Mingjun Zhang (Ohio State)
"Strechable Ionics: From Transparent Artificial Muscles to Biocompatible Ionic Skin." Cristoph Keplinger (CU-Boulder)
"Active Sensory Skins: 2D Fabrication to 3D Functionality." Rebecca Kramer (Purdue)
"Elephant Trunks and Frog Tongues." David Hu (Georgia Tech)
"Underwater Sensory Systems for Flow Characterization." Eva Kanso (USC)
"Distributed Hydrodynamic Sensing for Disturbance Rejection and Wall Detection in Underwater Robots." Kamran Mohseni (U. Florida)
"Design and Rapid Fabrication for Soft Bioinspired Robots." Mike Tolley (UC-San Diego)

Number of Presentations: 15.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u> <u>Paper</u>

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TOTAL:

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Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Post Doctorates

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Faculty Supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Under Graduate students supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

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The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

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NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

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ONR/ARO Workshop Final Report
Derek Paley, University of Maryland
Carmel Majidi, Carnegie Mellon University
November 2, 2016

The *2nd UMD Workshop on Distributed Sensing, Actuation, and Control for Bio-inspired Soft Robotics* was held at the University of Maryland, College Park, MD, on October 3, 2016, co-chaired by Derek Paley (U. Maryland) and Carmel Majidi (Carnegie Mellon). The workshop brought together about 35 scientists, mathematicians, and engineers from a range of STEM disciplines (e.g., neurobiology, applied mathematics, and control theory) for discussions on the fundamental challenges of distributed sensing, actuation, and control of hyperelastic continua. The workshop lasted one day and included a number of short talks and a social event. The talks were organized into four sessions; Sessions 2-4 included a twenty-minute panel discussion at the end of the talks. In this way, the workshop emphasized working discussions on the cutting-edge open research questions – rather than research presentations on the state-of-the-art. The meeting brought together researchers from engineering and biological perspectives, academia and government. Additional support was provided by the University of Maryland Department of Aerospace Engineering and the Maryland Robotics Center.

In welcoming remarks, Dean Pines of the A. James Clark School of Engineering compared the current workshop to those DARPA organized that led to the Grand Challenges. Opening remarks by ONR program manager Tom McKenna provided an overview of his bioinspired systems program. With soft robotics, there is an opportunity to emulate creatures at the bottom of the ocean. Indeed of the three recent BRC winners, two proposed seastar-inspired robots and one an octopus-inspired robot.

Session 1: Progress on Open Problems in Bio-inspired Soft Robotics

Robert Shepherd (Cornell) presented “Three Advances in Soft Robotics: Foam Actuators, Optically Dynamic Skins, and Optoelectronic Sensing.” He described how liquid phase processing is a step towards reliable, distributed actuation and sensing. Applications include ventricular assist devices, stretchable light guides for strain sensing, and dynamic coloration in elastomeric displays. Dr. McKenna inquired about results for intrinsic (pneumatic) actuation; there were also questions about on-board valves and multiplexing.

Barry Trimmer (Tufts) presented “Fast Dynamics in Soft Systems.” He asked why are soft robots slow? In contrast, fly-catching caterpillars are fast. He described experimental studies of tobacco hornworm caterpillars defense that investigated the hypotheses of ballistic vs. active control. Hydrostatic pressure is greater in small caterpillars than in large ones. The defense mechanism may be an example of thin-walled cylinder buckling. A practical approach for fast crawling may be tendon-activated robots. Shape memory actuators (SMAs) had been used in earlier caterpillar robots but are too slow and inefficient for high performance applications. An audience member questioned whether energetically-costly behaviors were useful for periodic motion or only applicable to infrequent predatory or escape motions.

Sarah Bergbreiter (UMD) presented “Soft robotics at small scales.” Her focus is on high area density and high dynamic range, and material diversity in microfabrication. An example is a jumping mechanism that achieved heights 100X the body size. Other topics included magnetic actuation, skin sensors for tactile sensing, and low-voltage soft actuation. An audience member was interested in the most important sensory information needed for bio-inspired robot operation.

Iain Anderson (U. Auckland) presented “Rubbery switches for bio-inspired logic and control.” The product StrechSense utilizes electroactive polymers for continuous strain sensing. Signal processing permits continuous capacitive sensing to yield local information. For example, applications include smart garments. The question is how to get more information from stretch (and pressure) by coupling strain with control/logic parameters: e.g., relax=on; stretch=off. Closed-loop control is possible in which strain influences operation. He described three oscillators with a closed-loop dynamics, and two electronics-free robots: a caterpillar and a dragonfly. His recent results are based on the use of dielectric elastomer actuators (DEAs), which can be used for gated logic (AND, OR, XOR, etc.).

Session 2: Mechanics & Control of Continuous Bodies

L. Mahadevan (Harvard) presented “Shape and gait optimization for active elastic curves and surfaces.” Active mechanics of soft curves such as exhibited by soft filaments can be modeled using stretch and shear theory with SE(3), the special Euclidean group in three dimensions. For example, active filaments slide in the shape of the letter “S”. He posed an inverse design question pertaining to optimal gaits. Future topics include soft sheets that stretch, shear, and grow. Discussion ensued on the neuromechanics of crawling: for example, is a central-pattern-generator (CPG) needed?

PS Krishnaprasad (UMD) presented “From Optimal Control to Filaments,” also invoking the geometry of regular curves and moving reference frames. Curve evolution and filaments resembles flocking theory in the continuum limit. In this way, filament dynamics and control can be related to allelomimetic behaviour.

*Oliver O’Reill*y (UC-Berkeley) presented “Modeling the Dynamics of Soft Robots,” inspired by plant growth that tends from soft to firm over time. As a simple example, he described a two-mass model that locomotes using slip vs. stick-slip friction. Current activities focus on using rod theory and other tools from continuum mechanics to model the deformation of pneunet actuators, which have unintuitive constituent relationships.

Anette (Peko) Hosoi (MIT) presented open research questions inspired in part by snail locomotion. Complexity in locomotion lies in the material properties of fluid -- passive mechanical solutions can do much of the work. She discussed a fluidic diode developed under the ChemBots program in partnership with Boston Dynamics. A challenge to control soft structures is the disconnect between the mechanics and controls communities. There was a debate about the extent to which bioinspired soft robots depend on a CPG. MJ Wells was quoted for his remarks on how proprioception is used locally in an octopus (J. Exp. Biol., v41, pp. 433-445, 1964). One novel idea is switchable composites: e.g., like an octopus stiffening its arm. Also, flying and swimming motions could harvest energy.

Session #2 Panel Discussion started with a focus on energy exchange in legged locomotion, in particular looking at systems in closed feedback loops. Soft robots are coupled to the environment; it should be possible to control oscillations parametrically, like in insect flight. Rigid foot placement requires policy-based control, which may be inferior to model-based control based on optimal methods. Discussion returned to whether a CPG is required. Is a CPG a phase sensor or a phase dictator? Some organisms outgrow a CPG in youth to become a system of coupled oscillators. (Perhaps a better term is a *de*centralized-pattern-generator.) The panel was asked: What are some pragmatic steps for controlling soft robots? A suggestion was to exploit constraints and/or conserved quantities in systems with an intermediate number of degrees of freedom (DOF), e.g., by locally adapting compliance. A classic example is an inverted pendulum on a cart, with a rigid rod replaced by a flexible rod: low-dimensional models of the dynamics are key. Soft robots have a lot of dissipation and damping, so they may have fewer modes. Other discussion questions were as follows: How might we leverage material properties? Do open-loop and small-scale behaviors lead to emergent behavior at large scales?

Session 3: Actuators, Sensors, & Soft Robot Prototyping

Chris Atkeson (CMU) presented "Optical sensing in transparent soft robots." He started by promoting his build-baymax.org website, based on ongoing collaboration with Disney research. A take-away message was that density doesn't scale (consider Jabba the Hutt). Inflatable robots can be made human sized. Chris aspires to create whole-body vision systems using inexpensive, small cameras available due to the cell phone market.

Mingjun Zhang (Ohio State) presented "Nanoparticle-based Self-assembling to Integrate Sensing, Actuation and Control for Bio-inspired Soft Robotics." Bioinspiration for this work arose from venus flytraps (bistable dynamics) and the sundew flower (nanofibers for sensing).

Cristoph Keplinger (CU-Boulder) described "Stretchable Ionics: From Transparent Artificial Muscles to Biocompatible Ionic Skin." Electrical conductors for soft machines enable transparent artificial muscles. Dielectric elastomers don't heal or scale up; as alternative is electrohydraulic transducers. There were questions on how to handle high-voltage requirements and direct current in conventional electronics.

Rebecca Kramer (Purdue) presented "Active Sensory Skins: 2D Fabrication to 3D Functionality." She discussed adding skins to inert objects to create motion: robotic fabric can be actuated using shape-memory alloy. Multi-function materials, such as active variable-stiffness fibers and liquid metals, can create flexible, stretchable sensing.

Printable electronics enable high yield processing, e.g., using printed thin-film devices. A goal is ink-jet-style cartridges of printable functions. Lastly, she described closed-loop control results from an extended jointed system with a soft, cabled spine.

Session #3 Panel Discussion opened with a question about designing the null space of a high DOF actuator to be fault-tolerant or self-healing. Another question was how to connect the dots between nanoparticle fundamental research and experimental robotics research. An example was given about how, as lidar and radar become cheaper and more available, they have enabled autonomous cars. However, motor control movement has always lagged sensing, because small chips cannot move large things! Cheap actuation is a perennial challenge. Question: is the soft-robotics community unbalanced: i.e., too small? Too fundamental? There is a need for artificial muscles, but amplification is a challenge in actuation because it requires a reservoir of power. Designs for new chemistry for internal combustion can power robots, such as catalytic hydrogen peroxide to produce gas pressure, but those these designs are typically only about 30% efficient. A soft robot toolkit was discussed -- is the instrumentation back-end still too large?

Session 4: Fluid-Structure Interactions

David Hu (Georgia Tech) discussed “Elephant trunks and frog tongues.” Empirical observations of these organisms have yielded insights, such as how a portion of the trunk’s weight comes from letting trunk segments go slack, and how the trunk uses suction-aided grasping. Frog tongues are sticky; they are 10x softer than human tongues and 30x softer than marshmellows. Frog’s saliva is a shear-thinning fluid, like paint; it flows during impact. Frog’s release prey using their eyeballs. Cat tongues have structures as stiff as their claws.

Eva Kanso (USC) presented “Underwater Sensory Systems for Flow Characterization.” Harbor seals follow hydrodynamic signatures, sea turtles return to the islands of their birth, and female copepods follow chemically flavored trails. These inspirations led to her investigation of rheotaxis in fish, which is based on hydrodynamic signals.

Kamran Mohseni (U. Florida) presented “Distributed hydrodynamic sensing for disturbance rejection and wall detection in underwater robots.” He has also worked in the area of lateral-line sensing in biology, using tools from Fourier analysis and potential flow. A question was whether these techniques applied to non-rigid bodies.

Mike Tolley (UC-San Diego) presented “Design and Rapid Fabrication for Soft Bioinspired Robots.” He described autonomous soft systems with functionally graded materials. Untethered rapid integration of soft and rigid components is possible using a portable pneumatic power source. Current 3D printing technology can achieve 4-5 orders of magnitude range of stiffnesses, and even stiffness gradients.

Session #4 Panel Discussion The panel received the question of how to adapt shape for targeted sensing in a way that is unique to soft robots? Also, what is the biggest problem with underwater vehicles that soft robots could solve? Responses included capture, transition from water to land, fish-inspired propulsion, and operation in tidal zones. The panel discussed materials that can act as sensors and actuators. The Google car focuses on sensing (not actuation), but certain tasks are not possible without soft manipulators possibly aided by vision. Question: Do soft robots do more with less?