AFRL-AFOSR-VA-TR-2020-0076

Robotic Fabrics: Multifunctional Fabrics for Reconfigurable and Wearable Soft Systems

REBECCA KRAMER
PURDUE UNIVERSITY

12/20/2019
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB2
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
30-06-2020

2. REPORT TYPE
Final Performance

3. DATES COVERED *(From - To)*
15 Aug 2016 to 14 Aug 2019

4. TITLE AND SUBTITLE
Robotic Fabrics: Multifunctional Fabrics for Reconfigurable and Wearable Soft Systems

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-16-1-0267

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
REBECCA KRAMER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
PURDUE UNIVERSITY
401 SOUTH GRANT ST
WEST LAFAYETTE, IN 47907-2024 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTB2

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2020-0076

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Reconfigurable systems that sense and adapt their position and structural properties will significantly enhance the performance of next-generation machines. This project aimed to address this need by introducing a class of planar soft robots based on fabrics. Robotic fabrics leverage the diverse properties of technical fabrics with integrated functional materials to achieve adaptable, compactable, and manufacturable structures. Robotic fabrics have all of the necessary functions, such as actuation, sensing, and stiffness control, embedded in a single conformable substrate by using responsive materials that reduce system complexity while adding functionality.

15. SUBJECT TERMS
Reconfigurable systems, Planar soft robots, Robotic fabrics, Sensing and actuation, Stiffness control

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UU		LEE, BYUNG
					19b. TELEPHONE NUMBER *(Include area code)* 703-696-8483

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

DISTRIBUTION A: Distribution approved for public release

AFOSR YIP Year 3 Final Report - FA9550-16-1-0267 12/20/2019 Robotic Fabrics: Multifunctional Fabrics for Reconfigurable and Wearable Soft Systems Yale University (subcontract from Purdue University)	
Principal Investigator	Rebecca Kramer-Bottiglio
AFOSR Program Manager	Dr. B. L. Lee

1. RESEARCH OBJECTIVES and RELEVANCE

Reconfigurable systems that sense and adapt their position and structural properties will significantly enhance the performance of next-generation machines. This project aimed to address this need by introducing a class of planar soft robots based on fabrics. Robotic fabrics leverage the diverse properties of technical fabrics with integrated functional materials to achieve adaptable, compactable, and manufacturable structures. Robotic fabrics have all of the necessary functions, such as actuation, sensing, and stiffness control, embedded in a single conformable substrate by using responsive materials that reduce system complexity while adding functionality.

Our approach was comprised of four research tasks: (1) design and fabrication of active variable stiffness fabrics, (2) manufacturing sensors directly into fabrics, (3) control of high deformation planar structures, and (4) demonstration of robotic fabrics.

Representative applications of relevance to the Air Force include: (1) self-deployable airfoils, where robotic fabrics may be utilized in a wing-like structure that self-deploys and folds or wraps during storage, and (2) reactive automatic tourniquets that employ quasi-static sensory-active fabrics capable of sensing traumatic injury and activating a static loading condition.

By treating fabric as the foundation of a robot, it can be transformed from passive equipment to active machinery that will positively impact manufacturability, transportability, and adaptability of previously complex systems.

2. MOST SIGNIFICANT TECHNICAL ACHIEVEMENT(S)

During the third (final) year of this YIP grant, we made the following technical achievements:

1. Introduced enhanced variable stiffness conductive composite by incorporating low-melting-point metallic particles.
2. Developed Joule-heating variable stiffness fibers to use in robotic fabrics.
3. Adapted shape-memory wires into ‘ribbons’ to generate in-plane bending motion for thin-body actuation.
4. Developed fabric strain sensors that maintain the fiber architecture of the fabric and are printed directly into fabrics.
5. Implemented sensing, actuation, and stiffness control into several robotic fabric demonstrations.

3. ACTIVITIES AND ACCOMPLISHMENTS

In the sections below we detail how we designed and adapted existing functional fiber components in order to maintain key properties of fabric (i.e., thinness, conformability, and breathability), and outline their manufacturing processes. We also present an original printable sensory ink and demonstrate closed-loop control based on sensor feedback. Finally, we showcase multiple robotic fabric applications that each demonstrate a new frontier for systems built on a fabric platform (Fig. 1).

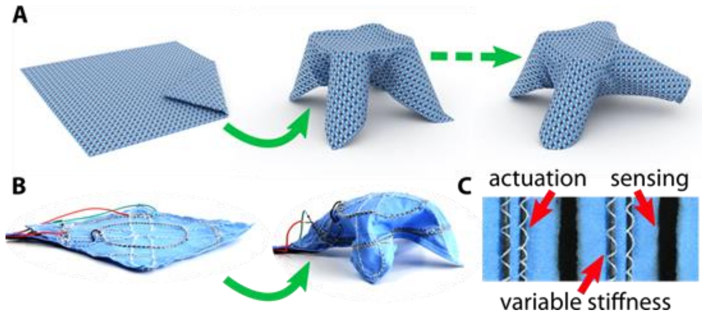

Fig. 1. Robotic fabrics. (**A**) Rendering of a potential robotic fabric capable of locomotion. (**B**) Actualized robotic fabric demonstration. (**C**) Fiber-based robotic components (actuators, structural supports, and sensors) can be combined in a variety of ways to create thin, planar, fabric-based machines.

3.1. Actuation Fibers for Robotic Fabric

We stipulate that a truly robotic fabric must have some source of self-actuation. As of this writing, motion-generating fabrics have made only rare appearances in end-user products[1]. However, as efforts are made to mimic the stranded muscular tissue in living animals, several different fiber-like actuators of varying utility have come to light[2]. Some of the more promising examples include shape-memory polymers, shape-memory alloys, electromechanical twisted carbon nanotube yarns, and supercoiled nylon strands.

We selected Nitinol shape-memory alloy (SMA) wire as our actuating fiber. SMA is electrically conductive and, when programmed to remember a shape, activates with heat. These two traits make electrical control via Joule heating a simple process. SMA is usually shaped into a coil or mesh to allow for high-strain linear contraction. We instead utilize SMA wire to generate bending motion (Fig. 2A), which has typically only been demonstrated using SMA "hinges" cut into large panels[3],[4]. Our method allows the actuator fiber to remain "in-plane" with the fabric substrate (Fig. 2B,C), and allows for reversible antagonistic motion when paired with an actuator on the reverse side of the fabric. Additionally, it allows us to anchor our actuators to fabric by couching – a well-established sewing technique.

One of the biggest challenges when integrating antagonistic wire bending actuators into a highly flexible fabric is that any off-center forces encourage the wire to twist the fabric rather than bend cleanly. This contortion can introduce chaotic actuation or even bending opposite the intended direction if the wire rotates in its couching, or twist on itself. We overcame this challenge by flattening the round SMA wires (Fig. 2D) into ribbons (Fig. 2E), modifying the area moment of inertia such that bending is favored over twisting. Additionally, when affixed to a fabric base, the couching is able to hold a flattened wire tighter to the fabric, preventing the actuator from rotating.

We characterized effectiveness of this flattening treatment by measuring the tendency for an SMA wire to bend out of plane in the presence of an opposing force. Here, we clamped an SMA wire in a pre-buckled configuration as in Fig. 2H, and applied a force to the centerpoint at different incoming angles. At an angle of 0°, in-plane with the bending direction, a wire is expected to experience a snap-through as the beam is deflected (Fig. 2F). Conversely, at an applied force angle of 90°, a wire should twist about the fixed-fixed axis (Fig. 2G). This experiment clearly shows that by increasing the wire aspect ratio (flattening the wires), they become more resistant to out-of-plane forces and favor in-plane deflection (Fig. 2H).

For bi-directional actuation of fabric, SMA wires are used in antagonistic pairs. Each SMA wire must be able to bend backward from its normal actuation trajectory when the opposing actuator is active, and it is

[1] J. Berzowska, M. Coelho, in *Ninth IEEE International Symposium on Wearable Computers (ISWC'05)* (IEEE, Osaka, Japan, 2005; http://ieeexplore.ieee.org/document/1550790/), pp. 82–85.
[2] T. L. Buckner, R. Kramer-Bottiglio, Functional fibers for robotic fabrics. *Multifunctional Materials*. **1**, 012001 (2018).
[3] J. K. Paik, E. Hawkes, R. J. Wood, A novel low-profile shape memory alloy torsional actuator. *Smart Mater. Struct.* **19**, 125014 (2010).
[4] J. K. Paik, R. J. Wood, A bidirectional shape memory alloy folding actuator. *Smart Mater. Struct.* **21**, 065013 (2012).

during to this reverse bending that wires are most susceptible to twisting out of plane. Measurements revealed that the flexural modulus of our SMA wires is consistent regardless of bending direction (E ≈ 66 GPa), however, plastic deformation occurs at different stresses depending on bending direction (Fig. 2I). We surmise that it is this difference in plastic deformation onset that encourages the wire to rotate, avoiding excessive elastic energy buildup. When bending forward in the direction of programmed actuation, plastic deformation occurs at a relatively low stress and is mostly a result of reversible detwinning of the martensitic crystal lattice. In the reverse direction, it is possible to introduce permanent dislocations and microcracks into the wire which interfere with the austenite-martensite transition and adversely affect the programmed actuation. The material flexural strength determines the point at which this occurs, and interestingly, the reverse flexural strength is not constant across SMA aspect ratios (Fig. 2I). We avoid this overstrained regime except for the initial unwrapping and straightening of the wire in preparation for the sewing step, in order to maximize the lifetime of our actuators in robotic fabrics. By also avoiding excessive temperatures, we have continuously used our antagonistic actuators for upwards of 1,000 cycles with no noticeable degradation.

'Activated' (heated) SMA generates force by building up internal material stresses as its crystalline structure transitions from martensite to austenite. Given that stresses in bending are greatest on the outer surface, we would expect that regions farthest from the neutral axis contribute most to the bending force. That is, thicker wires have potential for larger output forces than a thin wire of similar cross-sectional area (Fig. 2J). Indeed, we see that for flat wires, the output force is linearly proportional to the area moment of inertia. However, round wires underperform, reaching a force-output plateau due to actuation forces being directed out of plane.

Given this characterization, we selected an aspect ratio of 2.5 for all further demonstrations, as it provided a reasonable balance of output bending force, system stiffness, and stable in-plane motion.

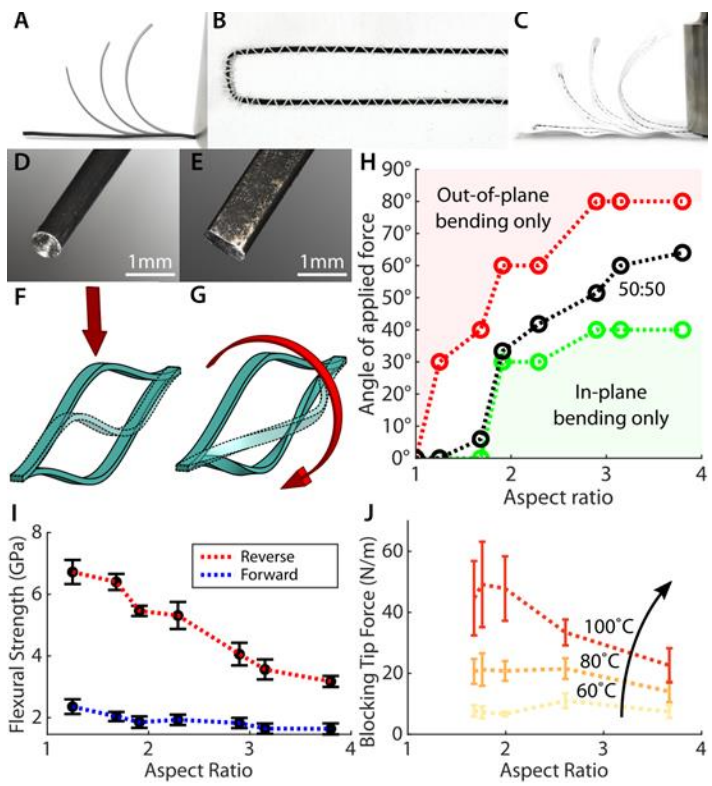

Fig. 2. SMA actuators. (**A**) SMA wire programmed to exhibit bending motion. (**B**) SMA wire sewn into a fabric substrate. (**C**) Sewn SMA wire used to actuate fabric body. (**D**) Initial round SMA wire. (**E**) Flattened SMA ribbon.

(**F**) Round SMA actuators tend to generate higher bending force than flat wires. (**G**) SMA flexural strength is dependent on the direction of bending. Bending against the programmed direction is much more difficult. (**H**) A flat wire will tend to bend and buckle in plane. (**I**) A round wire will tend to twist and bend out of plane. (**J**) Experimental data demonstrating the concepts in (H) and (I).

3.2. Variable Stiffness for Robotic Fabric

Although a fabric might be equipped with actuators, its inherent lack of a supportive structure results in ineffective or chaotic motions. The ability to actively add or remove stiffness on demand, then, becomes very useful in a robotic fabric. By selectively manifesting "bones" or "joints" in a fabric, the direction and degree of actuation can be regulated with higher repeatability and fewer total actuators. In addition, an on-demand support structure allows a robotic fabric to perform move-and-hold operations, as well as sustain loads which would otherwise collapse a typical fabric. Variable stiffness (VS) is possible using many different techniques, but expressions of this concept in fiber-like morphologies are limited. The most successful examples include silicone tubes filled with a low-melting-point material, strands of glass-transition polymer, and segment jamming via tension in an axial wire.

Our 1.59 mm (1/16 inch) diameter VS fibers (Fig. 3A, B, C) are based upon a thermally-responsive epoxy that softens significantly as it undergoes a glass transition at approximately 60 °C (Fig. 3D, E). We employ this epoxy matrix as-is and within a composite that incorporates a low-melting-point metallic alloy filler which melts at 62 °C (Field’s Metal; FM)[5], at a volume ratio of approximately 100:85 (46 vol% FM) (Fig. 3F,G). The fibers are Joule heated via an internal conductive stainless-steel thread (Fig. 3E, F).

We measured the flexural moduli of fibers made from both the neat epoxy matrix and the FM composite over a range of temperatures (Fig. 3H). The addition of FM raises the maximum rigid modulus while lowering the heated (i.e., soft) modulus. Even with the addition of the flexible stainless-steel thread in the fiber, the lower stiffness bound remains below 25 MPa which is soft to the touch and well within the force output capabilities of our SMA actuators. However, the FM composite tends to fail at lower stresses when rigid, which may be due to poor bonding at the interfaces between epoxy and FM particles (Fig. 3I). The fiber formulation can therefore be made to favor higher stiffness using the FM composite or higher strength using the neat epoxy.

Because the response of a thermally-controlled fiber is time-dependent, characterizing the time to completely transition between rigid and soft states is crucial for effective control sequencing in robotic fabrics. We measured the thermal conductivity of the VS composite fiber, and as expected when compared to analytical models, the increased volume fractions of FM lead to increased thermal conductivity (Fig. 3J). We then developed a numeric heating and cooling simulation of the VS fibers under a wide range of material conditions, and compared it to experimental data. Fully cooling from a uniform 65 °C in free convection takes approximately 70 seconds regardless of FM content (Fig. 3K). On the other hand, heating times varied slightly depending on the material composition and whether the steel heating yarn was properly centered in the fiber (Fig. 3L). Notably, the increased thermal conductivity from the FM inclusions smooths the thermal gradient in the fiber, reducing hotspots which could result in premature material degradation and cold spots with incomplete phase transitions (Fig. 3K, L).

[5] T. L. Buckner, M. C. Yuen, S. Y. Kim, R. Kramer-Bottiglio, Enhanced Variable Stiffness and Variable Stretchability Enabled by Phase-Changing Particulate Additives. *Advanced Functional Materials*. **0**, 1903368.

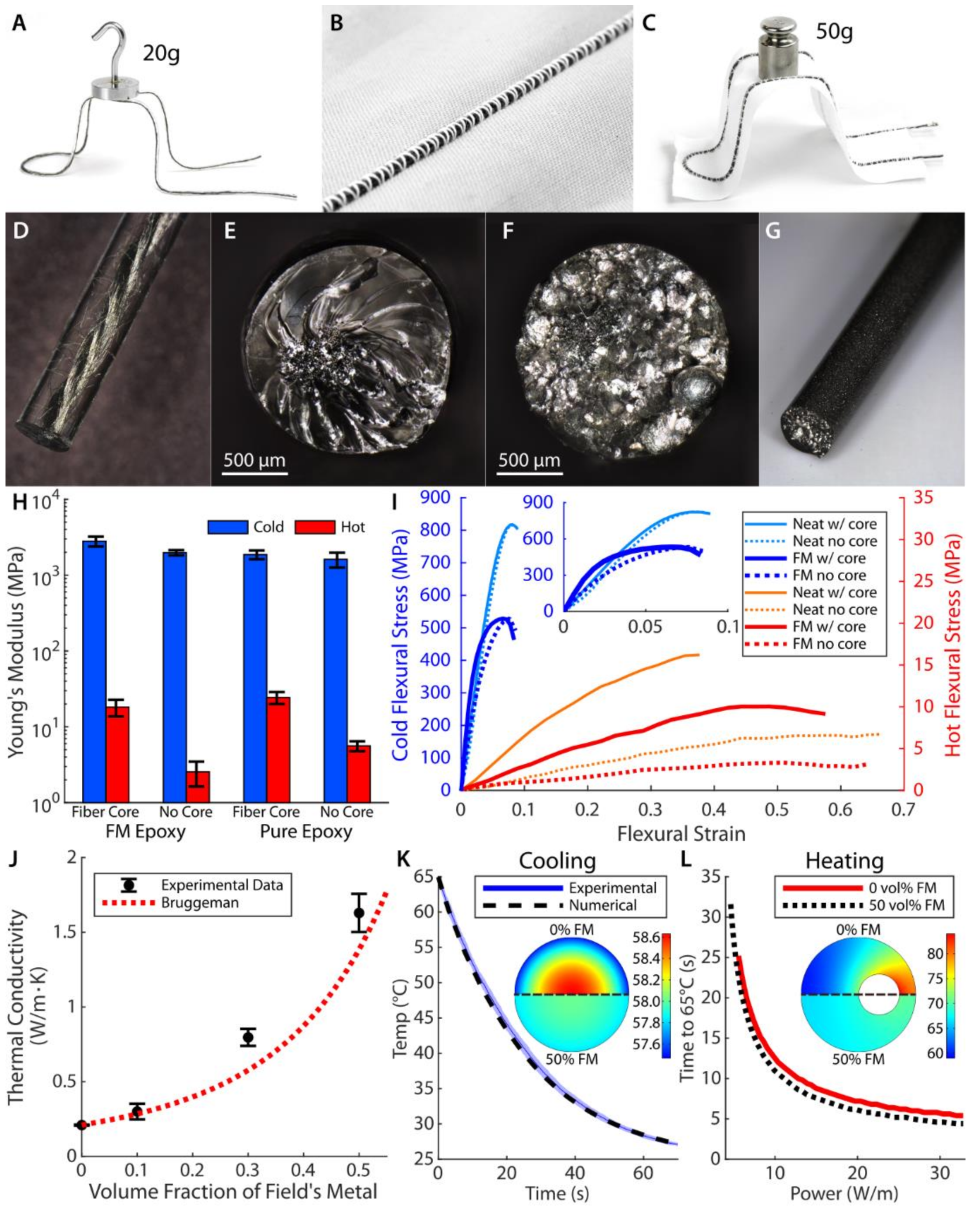

Fig. 3. Variable stiffness fibers. (**A**) A shaped VS fiber supports a (max) 20g load. (**B**) VS fiber sewn onto a fabric substrate. (**C**) Added support from fabric allows VS fiber to support up to 50g before legs begin slipping. (**D**) Neat epoxy VS fiber. (**E**) Neat epoxy cross-section. (**F**) FM composite cross-section. (**G**) FM composite VS fiber. (**H**) Hot and cold flexural modulus for both the neat epoxy and FM composite (46 vol% FM), with and without stainless steel yarn core used for Joule heating. Error bars are standard deviation. (**I**) Failure strains for the VS fibers. (**J**) Measured thermal conductivity of the composite vs. vol% of Field's metal, compared with Bruggeman effective medium theory. Error bars are 95% confidence interval. (**K**) Free convection cooling of VS fibers. Experimental data is for neat epoxy specimens. Numerical simulations for both neat epoxy and FM composite had negligible difference. Inset shows computed cross-sectional thermal gradient for both 0 and 50 vol% FM fibers after 7 s of cooling from 65°C. (**L**) Numerical simulation results for 'worst case' heating scenario, with the heating core center offset to 2/3 of the VS fiber diameter. Inset shows computed cross-sectional thermal gradient after 6 s of heating at 13W/m.

3.3. Sensing for Robotic Fabric

An important part of any robot is the ability to sense changes internally or in the environment, and respond appropriately. To create sensors, we used a self-coagulating, paintable conductive ink which allows a region of fabric to become highly sensitive to small changes in strain while adding negligible stiffness to the fabric[6]. Composed of a polydimethyl-siloxane (PDMS) precursor emulsified in a carbon black nanoparticle/ethanol suspension, this ink can easily permeate and bond to individual filaments of a fabric. This penetration into the fiber weave itself maintains the original porosity of the fabric, and creates an electrically conductive pathway that changes in resistance as the fabric weave is stretched and the gaps present between fibers are enlarged (Fig. 4A, B).

By printing this ink on opposite faces of a fabric, sensors can be used to detect structural bending. Despite some permeation through the cloth, the printed face will be denser with conductive particles, and this small offset from the neutral axis is enough to bias the sensor toward a compression response in one bending direction and extension in the other. The sensor signal is most consistent in extension, so querying the corresponding sensor depending on bend direction leads to repeatable sensor values.

In Figure 4C, we show a section of cloth with these printed sensors and two antagonistic bending SMA actuators attached. The sensor feedback made it possible to control the fabric actuation and hold different curvatures (represented as target sensor signals, Fig. 4D). Of note, without VS elements, the device naturally relaxes into a neutral center position when neither actuator is active due to a balance in opposing spring forces in the SMA wires.

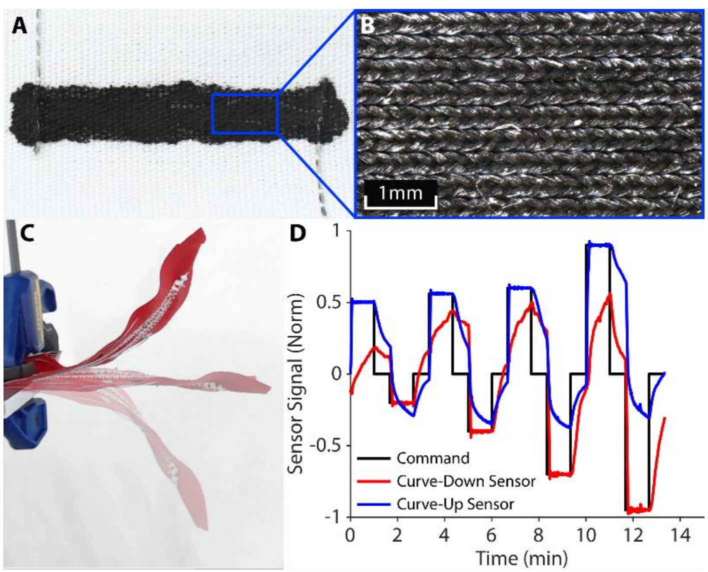

Fig. 4. Conductive ink sensors. (**A**) The carbon-black/PDMS/ethanol emulsion is printed directly onto the fabric. The surface conductivity is sufficient such that printed sensor blocks can be electrically connected by sewing over them with conductive thread. (**B**) A microscope image of ink-coated knitted spandex fabric. (**C**) A simple actuator-sensor device curls up and down, generating a sensor signal dependent on device curvature. (**D**) The curling device

[6] S. Y. Kim, Y. Choo, R. A. Bilodeau, M. C. Yuen, G. Kaufman, D. S. Shah, C. O. Osuji, R. Kramer-Bottiglio, Green Manufacturing of Sensors for Soft Systems using Self-Coagulating Conductive Pickering Emulsions. In review in *Science Robotics*. [unpublished].

follows the control signal by modulating the power output to the SMA actuators. Each sensor is actively used only when the corresponding fabric face is in extension.

3.4. Applications of Robotic Fabric

We present a series of demonstrations that utilize the SMA ribbon actuators, VS fibers, and in-fabric sensors, suggesting a range of possible applications for robotic fabric.

First, we showcase a robotic fabric tourniquet. This device is composed of a fabric sleeve with embedded rows of parallel actuators, VS fibers, and conductive carbon ink traces (Fig. 5A). When the fabric is severed along one of the conductive carbon ink traces, the damage is detected as a broken circuit and an emergency response is triggered at the damage site. The fabric will compress and then hold that position without further power expenditure (Fig. 5B, C, D). This type of responsive active sleeve could potentially be used as a smart garment in military or exploratory environments where automatic emergency measures could counteract life-threatening situations where and medical aid is not immediately available. By altering the arrangement of actuators, sensors, and VS fibers, it is conceivable that other types of assistive wear could also be created, such as augmenting muscular motion, creating dynamic orthostatic pressure clothing, or even simply changing shape to fit different climate conditions.

Second, we demonstrate a shape-changing robotic fabric sheet. The initial form of this device is a flat, square section of cloth (Fig. 5E, G). Upon activation, the device softens its VS frame and lifts itself up into a table-like platform structure. This new shape becomes rigid and load-bearing, as demonstrated by placing weights on the platform. The shape is then returned to its initial configuration via an antagonistic actuator which flattens the device again (Fig. 5F). By choosing not to soften certain VS fibers, such as the central VS ring (Fig. 5H, I), the resulting shape can be controlled. This signifies that more complex shape transformations in future works may be able to rely upon small numbers of actuators and VS elements working in concert to direct motion rather than needing large numbers of specialized actuators for every feature of the transformation. Transforming robotic fabric structures of this type could be used as a self-deploying shelter, super-compactible furniture, or as temporary storage shelf. This shape change ability is an early indication of the potential for extremely adaptable machines with on-demand tool generation.

Last, we demonstrate a self-deploying airplane wing in a fully untethered system. The robotic fabric wings are seated into small slits in the side of the fuselage, wherein all additional circuitry, microcontrollers, and batteries are enclosed. The fabric wings curl to wrap around the fuselage for compact storage (Fig. 5J), and uncurl into a deployed state with wings extended (Fig. 5K, L, M, N). This demonstration shows the potential for robotic fabrics as an adaptable component in a larger machine, and shows how a particular robotic fabric segment or tool might self-stow or move out of the way when not in use. This is a key functionality for use cases when light weight and low storage volumes are highly desired, as in transportation to and from remote locations.

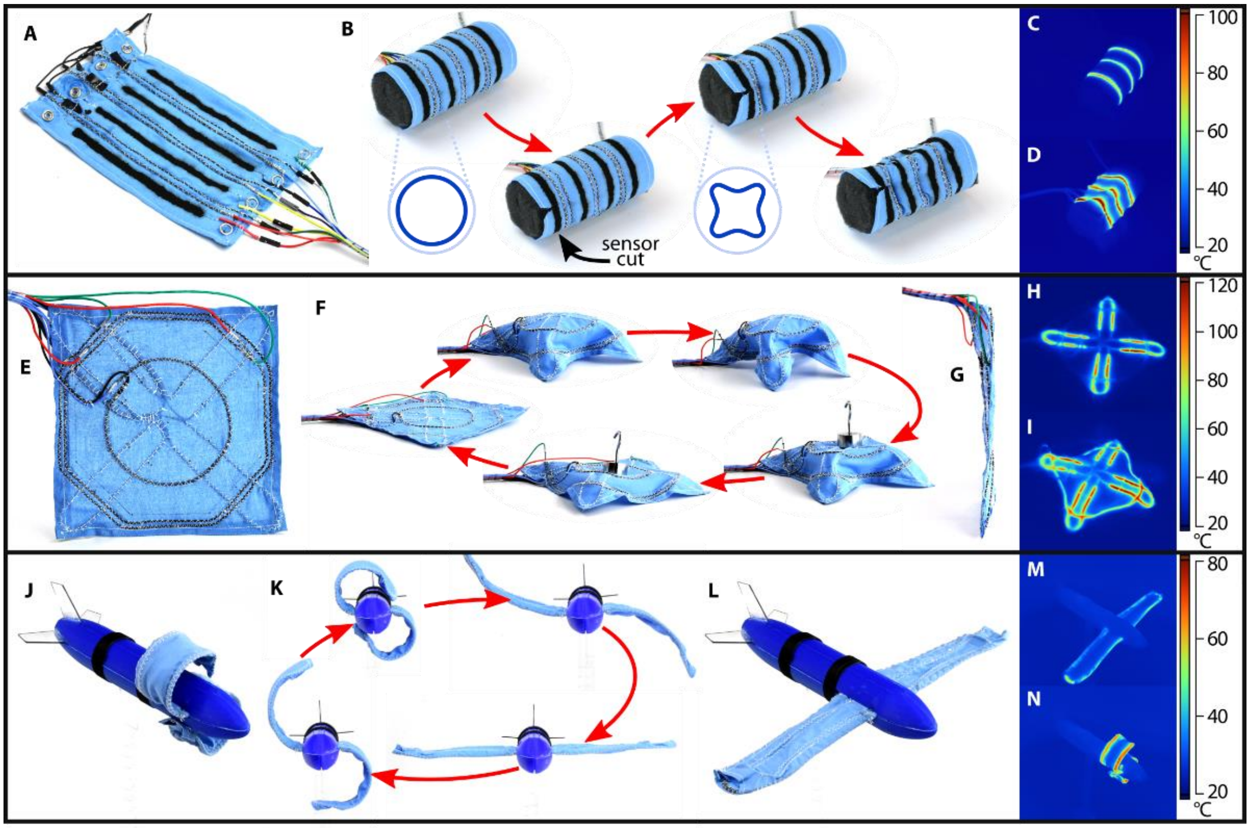

Fig. 5. Robotic fabric demonstrations. (**A**) Robotic fabric tourniquet. (**B**) Tourniquet is buttoned about a foam body. It reacts to a damaged circuit by contracting and holding a tightened pose. (**C**) Thermal image of the tourniquet as VS fibers soften. (**D**) Thermal image of activated SMA actuators constricting. (**E**) Robotic fabric "popup" table. (**F**) From an initial flat state, the table is able to stand up, stiffen into a load-bearing platform, and then collapse under a load as it softens and actuates back into its initial flat configuration. (**G**) Fabric "popup" table is approximately 2mm thick. (**H**) Activation and softening of table "leg" VS fibers. (**I**) Activation of SMA actuator wire, causing table to stand up. (**J**) Robotic fabric wing in self-stowed position. (**K**) Robotic fabric wing curls and uncurls from deployed, open state into a compacted, stowed state. (**L**) Robotic fabric wing in deployed position. (**M**) Activation and softening of wing VS fibers. (**N**) Activation of curling SMA wires.

4. FUTURE OUTLOOK

By treating fabric as the foundation of a robot, it can be enhanced from a passive material to active and wearable machinery that will positively impact the manufacturability, transportability, and adaptability of complex robotic systems. We have developed and presented a set of fabric-compatible components that show the potential to be core building blocks of rudimentary robotic fabrics. SMA actuator ribbons, designed exclusively for bending motion, allow the actuator to remain in the plane of the fabric substrate. VS fibers, capable of a stiffness change of two orders of magnitude, grant their substrate a tunable structure capable of guiding actuation paths and supporting loads. Even basic controls are possible using printed resistance sensors compatible with the open porous nature of most fabrics.

There are still many hurdles to overcome before robotic fabrics reach their full potential. We expect that with time, scientific advances will unveil improved actuation, variable-stiffness, and sensory technologies that are ideal for future robotic fabric developments. In the future, we envision mass-produced rolls of robotic fabric, available for purchase, and then programmed as required to fit varied tasks. Self-reconfiguring machinery made from this material could bend and twist into new shapes as needed, and then collapse for compact storage. It may even allow for consumer clothing that actively adjusts itself and assists the wearer. Such visions call on other challenges such as the development of complex design tools, compact or fiber-form power supplies, and distributed computation and thin-body control. As with most emerging concepts, the architecture of a robotic fabric at its full potential is unknown. The definition of robotic fabrics may very well evolve as new technologies are discovered and new challenges are encountered. We hope that this step toward autonomous robotic fabrics will continue to encourage future advances.

5. PUBLICATIONS RESULTING FROM AWARD

Published

1. Buckner, T. L., White, E. L., Yuen, M. C., Bilodeau, R. A., & Kramer, R. K. **A move-and-hold pneumatic actuator enabled by self-softening variable stiffness materials.** In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 3728-3733, 2017.
2. Buckner, T. L. & Kramer, R. K. **Move-and-Hold Folding Enabled by 3D Printed Self-Softening Variable Stiffness Material.** In Workshop on Folding in Robotics, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2017.
3. Bilodeau, R. A., Miriyev, A., Lipson, H., & Kramer-Bottiglio, R. **All-Soft Material System for Strong Soft Actuators.** In IEEE International Conference on Soft Robotics (RoboSoft), pp. 288–294, 2018. Best Paper Award.
4. Case, J. C., Booth, J., Shah, D. S., Yuen, M. C., & Kramer-Bottiglio, R. **State and Stiffness Estimation using Robotic Fabrics.** In IEEE International Conference on Soft Robotics (RoboSoft), 2018.
5. Booth, J. W., Shah, D., Case, J. C., White, E. L., Yuen, M. C., Cyr-Choiniere, O., & Kramer-Bottiglio, R. **OmniSkins: Robotic skins that turn inanimate objects into multifunctional robots.** Science Robotics, Vol. 3, Issue 22, 2018.
6. Bilodeau, R. A., Yuen, M. C., Case, J. C., Buckner, T. L., & Kramer-Bottiglio, R. **Design for Control of a Soft Bidirectional Bending Actuator.** IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2018.
7. Buckner, T. L. & Kramer-Bottiglio, R. **Functional Fibers for Robotic Fabrics.** Multifunctional Materials, 2018.
8. Bilodeau, R. A., Yuen M. C., & Kramer-Bottiglio, R. **Addressable, Stretchable Heating Silicone Sheets.** Advanced Materials Technologies, Vol. 4, No. 9, p. 1900276, 2019.
9. Buckner, T. L., Yuen, M. C., Kim, S. Y., & Kramer-Bottiglio, R. **Enhanced Variable Stiffness and Variable Stretchability Enabled by Phase-Changing Particulate Additives.** Advanced Functional Materials, Vol. 29, No. 50, p. 1903368, 2019.

In Review

10. Kim, S. Y., Choo, Y., Kaufman, G., Yuen, M. C., Osuji, C. O., Kramer-Bottiglio, R. Green **Manufacturing of Sensors for Soft Systems using Self-Coagulating Conductive Pickering Emulsions.** Science Robotics (in review).

In Preparation

11. Buckner, T. L., Bilodeau, R. A., Kim, S. Y., & Kramer-Bottiglio, R. **Robotic Fabrics: Thin, Planar, Fiber-based Machines.** In preparation.

6. STUDENTS and POSTDOCTORAL RESEARCHER(S)

<table>
<tr><th>Assistance Type</th><th>Number</th><th>Roles / Comments</th></tr>
<tr><td>Postdoctoral</td><td>0</td><td></td></tr>
<tr><td>Graduate</td><td>3</td><td>Adam Bilodeau, working on fabric-inclusive multifunctional robots with reduced system and manufacturing complexity, and closed-loop control of robotic fabrics.
AY 16/17 – supported by alternative funding.
AY 17/18 – fully supported by this YIP grant.
AY 18/19 – fully supported by this YIP grant.

Trevor Buckner, working on variable stiffness materials, functional fibers for robotic fabrics, and robotic fabric demonstrations.
AY 16/17 – partially supported by this YIP grant, partially supported by a Purdue fellowship.
AY 17/18 – fully supported by a Yale fellowship.
AY 18/19 – partially supported by this YIP grant, partially supported by Yale start-up funds.

Dylan Shah, working on integration and control of robotic fabrics.
AY 16/17 - partially supported by this YIP grant, partially supported by a Purdue fellowship.
AY 17/18 – fully supported by a NASA fellowship.
AY 18/19 – fully supported by a NASA fellowship.</td></tr>
<tr><td>Undergraduate</td><td>0</td><td></td></tr>
<tr><td>Other</td><td>0</td><td></td></tr>
</table>

7. ISSUES / CONCERNS

None to report.