AFRL-AFOSR-VA-TR-2018-0340

Distributed Algorithms for Stiffness and Shape Changing Computational Meta-Materials

Nikolaus Correll
REGENTS OF THE UNIVERSITY OF COLORADO

08/28/2018
Final Report

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)* 28-08-2018	**2. REPORT TYPE** Final	**3. DATES COVERED** *(From - To)* 4/1/2015-05/31/2018

4. TITLE AND SUBTITLE Distributed Algorithms for Stiffness and Shape Changing Computational Meta-Materials	**5a. CONTRACT NUMBER** FA9550-15-1-0238
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Nicolaus Correll	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Colorado at Boulder 1111 Engineering Drive 430 UCB Boulder, CO 80301	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research (AFOSR) 801 N Randolph St., Rm. 732 Arlington VA 22203 United States	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution A

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This research has led to novel devices, distributed algorithms and tools for smart composites that can change their shape by controlling their stiffness. The composite consists of variable stiffness actuators based on thermoplastic polymers, nichrome wiring, temperature sensor, and a networked microcontroller. The microcontrollers work in concert to calculate the required stiffness in order to achieve any desired shape. The algorithm for shape change is fully distributed and scales well with the size of the material and the number of elements. The approach has been experimentally validated on a beam of six variable stiffness elements that autonomously achieved a variety of shapes just using electricity and a bending moment.

With distributed computation a critical element of future smart materials that integrate sensing, actuation, computation and communication, this research has also created the foundation for a novel distributed machine learning approach in which the structure of the network is simulating lossy,

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*

Reset

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Distributed Algorithms for Stiffness and Shape Changing Computational Meta-Materials

Final Report – Nikolaus Correll
Associate Professor
University of Colorado at Boulder

Abstract This research has led to novel devices, distributed algorithms and tools for smart composites that can change their shape by controlling their stiffness. The composite consists of variable stiffness actuators based on thermoplastic polymers, nichrome wiring, temperature sensor, and a networked microcontroller. The microcontrollers work in concert to calculate the required stiffness in order to achieve any desired shape. The algorithm for shape change is fully distributed and scales well with the size of the material and the number of elements. The approach has been experimentally validated on a beam of six variable stiffness elements that autonomously achieved a variety of shapes just using electricity and a bending moment. With distributed computation a critical element of future smart materials that integrate sensing, actuation, computation and communication, this research has also created the foundation for a novel distributed machine learning approach in which the structure of the network is simulating lossy, time-delayed communication links, allowing to train a distributed controller using conventional algorithms for training neural networks.

I Introduction

My research group is interested in materials that couple sensing, actuation, computation and communication, which we denote as “Robotic Materials”. This AFOSR effort focusses on a special class on materials that can change their shape. We have made progress on both manufacturing and controlling such composites, leading to two successful PhD thesis defenses by Michael “Andy” McEvoy who graduated in Spring 2017 and Dana Hughes who graduated in Spring 2018. Results from this effort are described in Section II.

Albeit the material implements actuation and computation in a distributed fashion – justifying its appellation as a “material”, sensing of the system’s state is done using external sensors, prompting the investigation of novel sensing technologies that are suitable for material-centric integration by PhD student Dana Hughes. These efforts are described in Section III and have led to a variety of applications ranging from wearables to robotic manipulation, all enabled by novel composite manufacturing techniques.

With the increasing amount of information such sensors create, Hughes has also begun investigating techniques from machine learning to investigate signal processing *inside* the material, which we describe in Section IV. Further directions (Section V) and a list of publications from the performance period conclude the report.

II Shape-changing Materials

Our work is motivated by the shape-changing abilities of animals equipped with muscular hydrostats. These systems do not require skeletons, but double as both structural elements and actuators by varying their stiffness and lengths while maintaining their volume. Examples of such systems in nature are shown in Figure 1

Figure 1. Muscular hydrostats in nature: Octopus tentacles, elephant trunks and mammalian tongue.

In the course of this project, we have developed a variety of variable stiffness elements that are actuated by tendons and allow a beam made of such elements to assume any shape by adjusting both its stiffness and external torque. We have improved our design in the course of last year, which is illustrated in Figure 2. This work has been published in McEvoy's PhD thesis and has been accepted in the prestigious *Soft Robotics* journal.

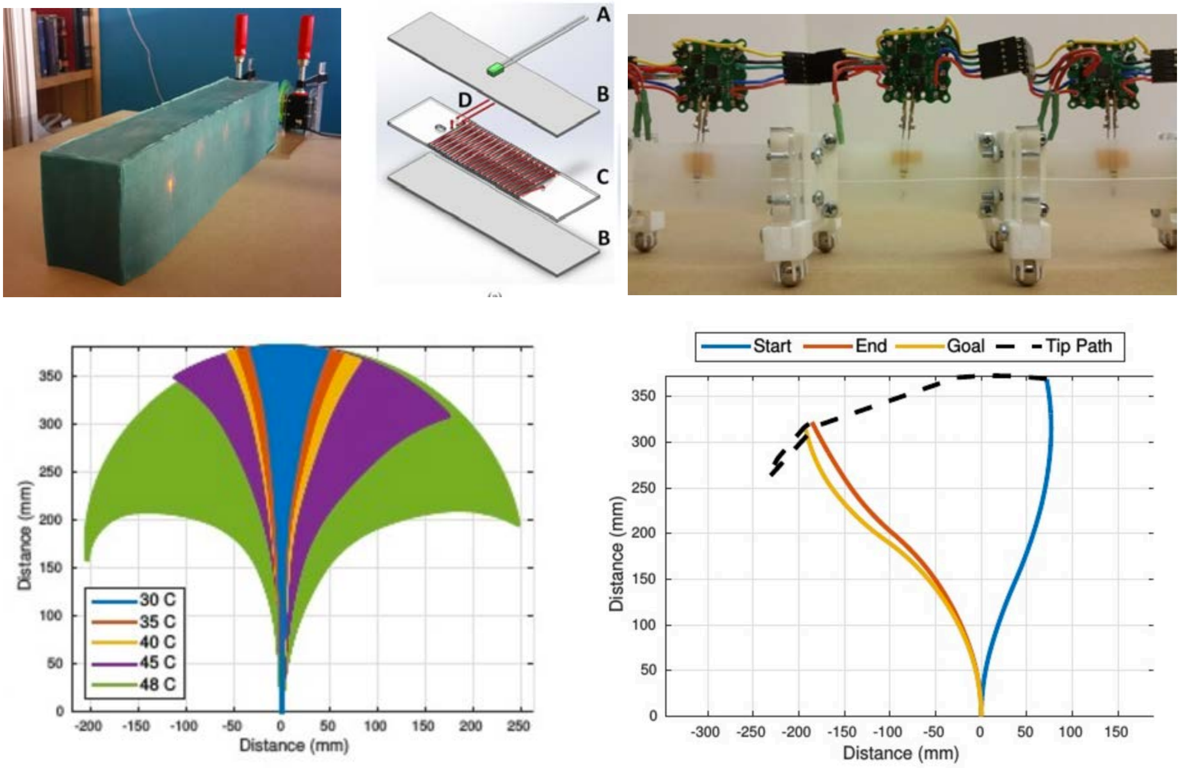


Figure 2. From top-left, clockwise: Shape-changing beam (outside view). Individual variable stiffnes element using a thermistor and nichrome wire to control temperature of polycaprolactone embedded in silicone. A sequence of varbiable stiffness elements with control electronics (inside view). Curvature as a function of temperature at 10N force. Sample trajectory of the beam from a start to a goal position. (McEvoy, 2018)

In addition to refining manufacturing and evaluating the resulting design, we have also developed an algorithm for solving the inverse kinematics of the beam, i.e. how to change each individual element in order to reach a certain desired global state, in a distributed fashion. In a nutshell, our approach operates by treating the N-body system as a k<<N body system in which only k elements in a small window of the overall system can be changed at a time. We then locally solve the inverse kinematics for this problem and move the window on. This approach is illustrated in Figure 3 and has been published at a conference (McEvoy, 2016) where it was awarded with a “Best Paper Award”.

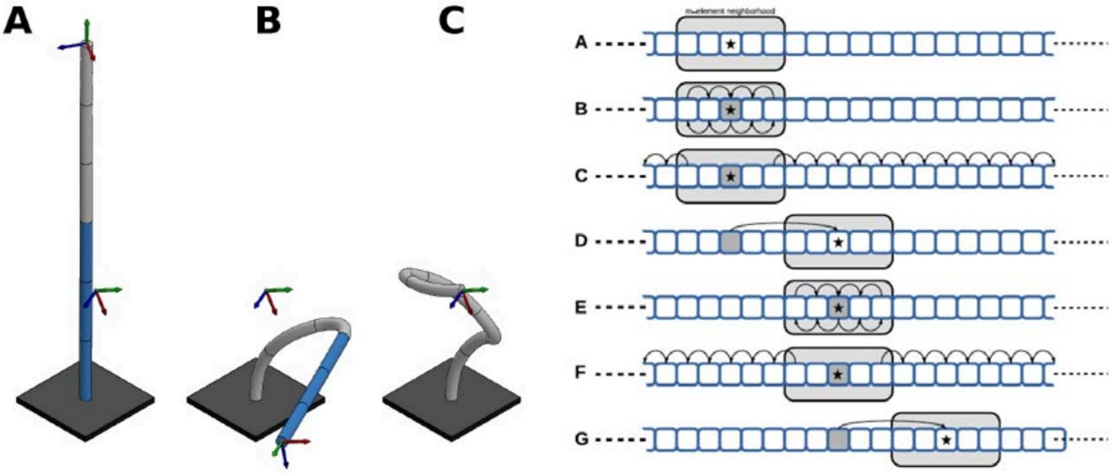


Figure 3. A 6-body system is solved by first calculating a motion that gets the tip as close as possible to the desired goal using only the lower three elements and then the upper three elements. The resulting algorithm results in computation literally traveling throughout the length of the material. (McEvoy, SysInt, 2016)

III Novel sensors for robotic materials

We are interested in composites that embed a large quantity of sensors, possibly with high bandwidth, requiring large amounts of computation and communication. Albeit “curvature” is the obvious quantity a shape-changing material might sense, we are already investigating such sensors in a parallel effort on “Soft Robotics” supported by the National Science Foundation. In this work, we focus instead on proximity and touch sensors, that would make materials interactive with both users and their environment. These efforts have led to two unexpected applications, textile user interfaces and sensors for robotic manipulation. Both have led two preliminary patents and commercialization by Gaugewear Inc. and Robotic Materials Inc., respectively.

Figure 4 shows a novel textile composite that is able to detect the location of a human finger placed anywhere along the strip. The composite consists of conductive textiles that sandwhich a non-conductive layer that serves as dielectric. In a nutshell, the system works as follows: A 900 Mhz signal is sent into the composite which acts as an antenna. The reflected signal is measured. Touching the material anywhere changes the phase of the signal, which can be measured using appropriate electronics. What makes this approach particularly interesting for deployment across large surfaces in a composite material is that all the necessary electronics for analyzing the signal – including basic gesture recognition can be co-located in the material.

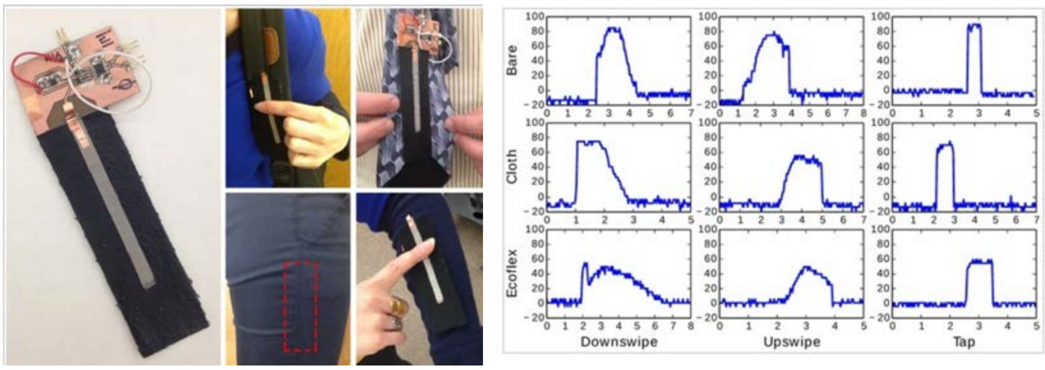


Figure 4. Textile composite that can sense the presence of human fingers (left). Temporal signal for a variety of gestures and cover materials. The gestures are clearly discernible and can be recognized using a simple neural network. (D. Hughes, Sensors, 2017).

We have also investigated integration of conductive fabrics into soft robotics, leading to a soft actuator that can be controlled using human gestures and interact with metals. This is shown in Figure 5. Here, we edged patterns into copper-coated nylon using the exact same photolithography techniques that are used in the manufacturing of printed circuit boards. Interestingly, the fabric is already used as constraint layer in the soft actuator, thereby showing new ways to add multi-functionality to composites that already integrate fabric.

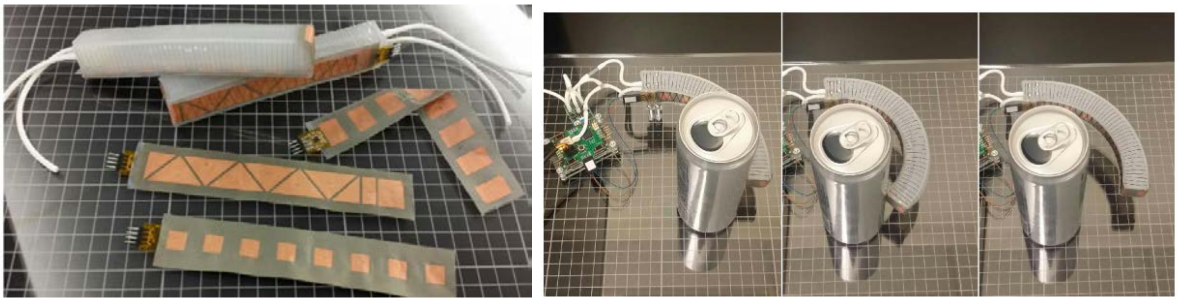


Figure 5. Soft actuators with integrated sensors based on conductive textiles (left). Soft actuators equipped with such sensors have the ability to detect conductive metals in the environment, e.g., (N. Farrow, ICRA, 2017).

Finally, we have investigated integration of infrared proximity sensors into soft rubber materials, enabling them to detect proximity to objects around them and even double as pressure sensors by measuring the deformation of the material. This sensor has been nominated for a “Best Paper Award” at the premier robotic conference (RSS), lead to a patent application, a new collaboration with a prosthetics researcher (Segil, 2017) and is currently commercialized by Robotic Materials Inc. The sensor, in an array of 8x8, is shown in Figure 6, in an application as “robotic skin” as well as a commercial product, based on technology licensed from the university and marketed by “Robotic Materials Inc.”, a company founded by the PI.

The manufacturing of such composites that can sense, communicate information within the material, perform some basic processing of information, and need to have – in the case of a robotic gripper – certain structural properties is non-trivial and described in the manufacturing of multi-functional composite track at the 2017 Int. Conf. on Composite Materials (ICCM) in Xi’An, China. (Correll, ICCM, 2017) This is shown in Figure 7.

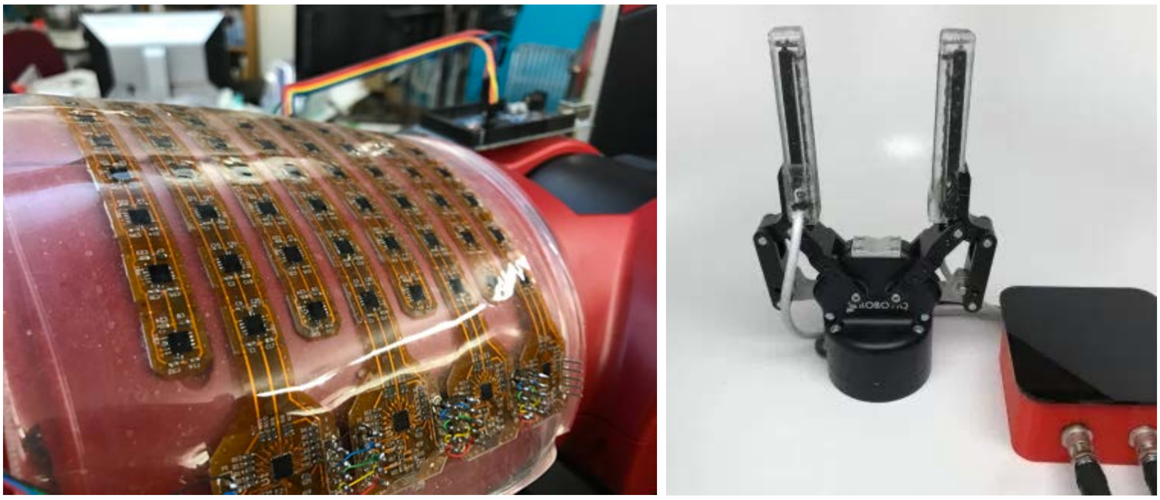


Figure 6. “Robotic Skin” consisting of an array of 64 infrared proximity sensors emedded in polymer (left) and a commercial robotic gripper (right) with a similar array of sensors (right).

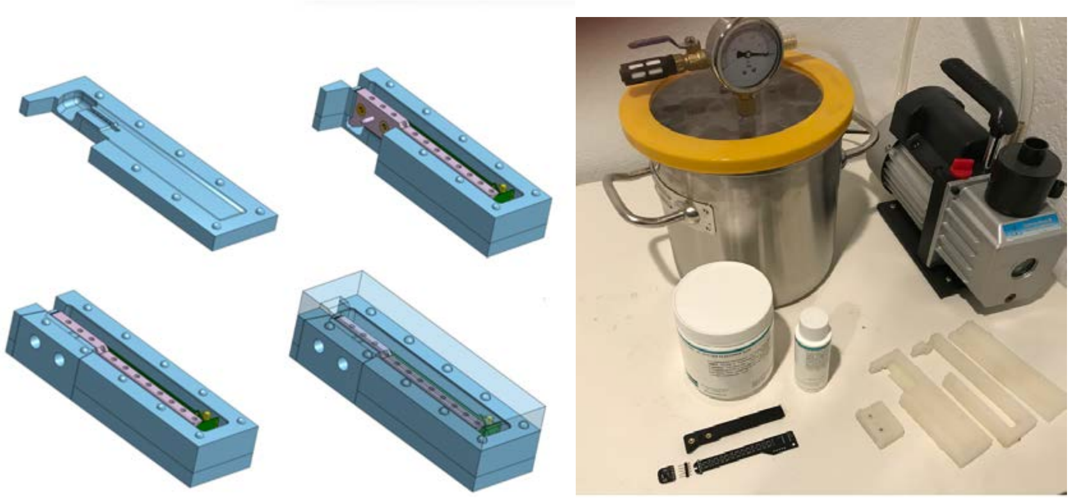


Figure 7. A multi-part mold holds the structural material (3D printed ABS) and the printed circuit boards during overmolding (left). Equipment and materials used during the process (right). (Correll, ICCM, 2017)

IV Signal processing in robotic materials

Our results demonstrate that the computational requirements of robotic materials for signal processing and control are non-trivial. Calculating the inverse kinematics of a shape-changing material has a computational complexity that is cubic with the number of elements (albeit we provided a linear-time approximation), and materials like the robotic skin in Figure 6 create large amounts of data. In order to move on from ad-hoc solutions to these problems, we have begun investigating more general methods inspired by recent breakthroughs in machine learning. It is well known that a neural network is able to approximate any conceivable mathematical function and, with certain modifications, even encode any computer program. Training such networks has recently become much easier, making it possibly feasible to use these technique to train both controllers and signal processing for robotic materials.

We have begun to explore this idea by training neural networks on data sets that were available online and are relevant to the robotic materials context. The key idea is illustrated in Figure 8.

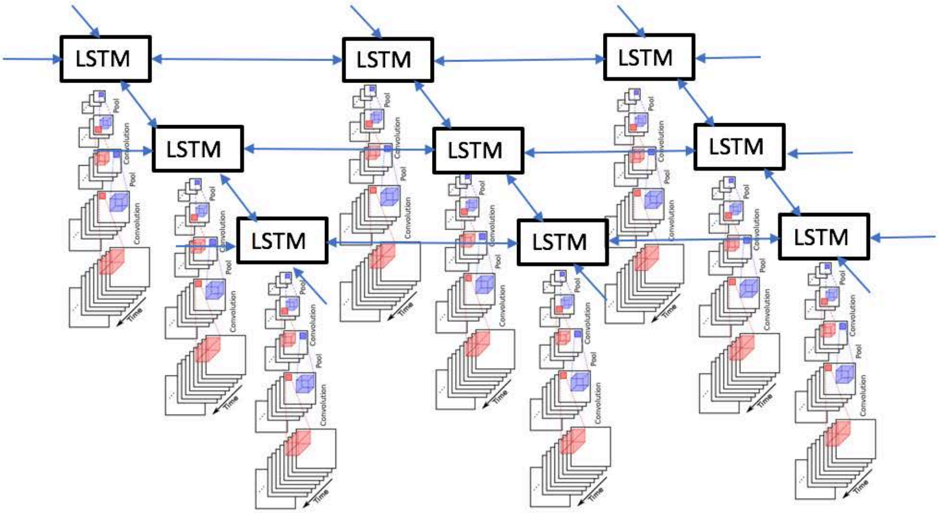
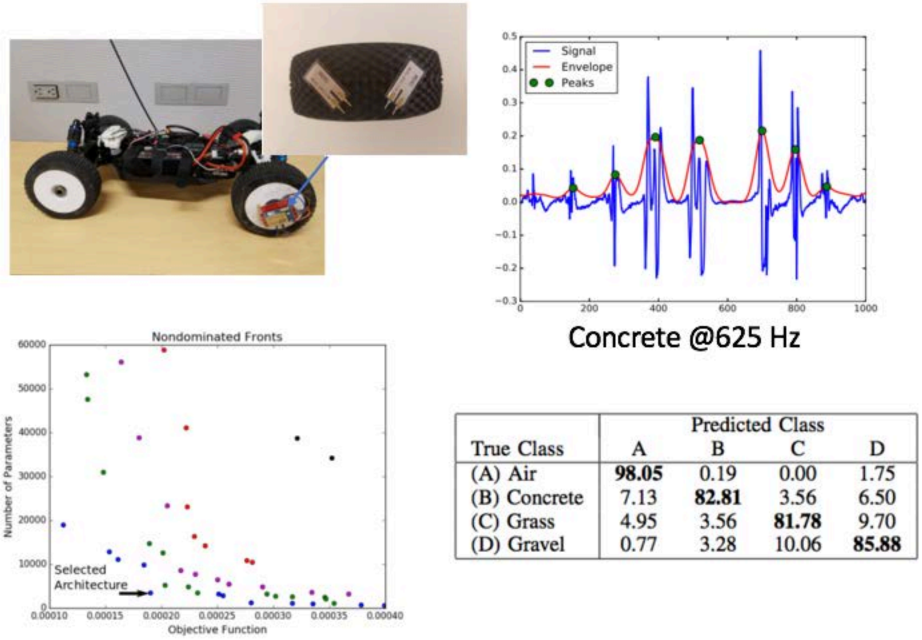


Figure 8. An ensemble of convolutional neural networks whose individual output feeds into a Long-Short Term Memory (LSTM) cell, which communicate with their local neighbors.

One such dataset consists of "social touch" pressure data from human-robot interactions, another consists of inertia measurement units (IMUs) that were distributed across the human body. We have been able to successfully train neural networks for both applications with emphasis on limiting the available computational power and the communication between neighboring computers so that the computation could be performed on computers that are small enough to be co-located with the sensors. These efforts have led to two publications (Hughes, ICRA, 2017) and (Hughes, DARS, 2016), the latter nominated for a "Best Paper Award". An additional case study for distributed machine learning has been the smart skin shown in Figure 6, which has led to a journal publication (Hughes, 2018), as well as a rubber tire with integrated piezo microphones to classify the ground the tire is on. This setup and selected results are shown in Figure 9. Different surfaces (air, concrete, grass, gravel) lead to different spectral information (top right), which can the be classifed using a neural network. Optimal parameter sets for the neural network that trade network size and performance are found using genetic algorithms. This research has been described in (N. Correll, 2017), which has been invited for journal publication in the premier robotics journal Int. Journal of Robotics Research with Dana Hughes as the lead author.



	Predicted Class			
True Class	A	B	C	D
(A) Air	**98.05**	0.19	0.00	1.75
(B) Concrete	7.13	**82.81**	3.56	6.50
(C) Grass	4.95	3.56	**81.78**	9.70
(D) Gravel	0.77	3.28	10.06	**85.88**

Figure 9. Top left: An RC car with microphones and computation embedded in the tire. The inset shows the sensors for comparsion reasons. Different surfaces (air, concrete, grass, gravel) lead to different spectral information (top right), which can the be classifed using a neural network. Optimal parameter sets for the neural network that trade network size and performance are found using genetic algorithms.

V Conclusion

This research project has pioneered a new class of smart composites that tightly integrate sensing, actuation, computation and communication and demonstrated a large variety of application areas from shape-changing airplane wings to smart cloths, smart tires, and smart robotic skins. Distributed computation is critical for adding intelligence to these systems, which includes both signal processing and control, and neural networks provide a powerful tool to not only implement the required computation, but also automatically train distributed algorithm. The latter has emerged to be one of the foci of my research group.

The work on "robotic materials" has also led to considerable visibility in both the robotics and material science communities with a highly-cited review paper in *Science*, a vision paper at the key Sensor Networks conference (Han, 2017), a vision paper at a robotics conference (Correll, 2017), and a workshop sponsored by the Computing Community Consortium (CCC) in Washington, DC. In addition to distributed computation, these events have shown the need for future robotic materials to both communicate and be powered wirelessly, which is the focus of my ongoing AFOSR research effort.

Patent applications

N. Correll. "Measuring distance and contact force during robotic manipulation, US20170297206A1 filed on 4/14/2016.

D. Hughes and N. Correll. “A Robotic Skin for Collision Avoidance and Affective Touch Recognition”, PPA No. 62/690,996 filed on 6/28/2018.

N. Correll and R. Patel. “3D perception using integrated proximity, contact and force sensing”, PPA No. 62/694,889 filed on 07/06/2018.

R. Patel, J. Segil, R. Weir and N. Correll. “Multi-Modal Fingertip Sensor with Proximity, Contact, and Force Localization Capabilities”. PPA No. 62/694,278 filed on 07/06/2018.

Publications (June 1, 2016 – May 31, 2018)

Names in italic denote PhD students supported by the funded effort. R. Patel has been supported by a teaching assistant ship, while AFOSR funds have been used for materials and travel.

M. A. McEvoy, N. Correll. Shape-changing materials using variable stiffness and distributed control. Soft Robotics, 2018

R. Patel, R. Cox, N. Correll. Integrated proximity, contact and force sensing using elastomer-embedded commodity proximity sensors. Autonomous Robots, 42 (7), pp. 1443-1458, 2018.

D. Hughes, D. Lammie, N. Correll. A robotic skin for collision avoidance and affective touch recognition. Robotics & Automation Letters, 3 (3), pp. 1386-1393, 2018.

N. Correll, C. Heckman. Materials that Make Robots Smart. International Symposium on Robotics Research (ISRR), Puerto Varas, Chile, 2017. **Best Paper Award.**

R. Han, N. Correll, K. Pister, P. Dutta. New Directions: Wireless Robotic Materials. 15th ACM Conference on Embedded Networked Sensor Systems (SenSys), Delft, The Netherlands, 2017.

N. Correll. Manufacturing of Multifunctional soft composites with integrated proximity and tactile sensing. 21st International Conference on Composite Materials , Xi'an, China, 2017.

N. Farrow, L. McIntire, N. Correll. Functionalized Textiles for Interactive Soft Robotics. Int. Conf. on Robotics and Automation (ICRA), 2017.

M. A. McEvoy. Shape-changing robotic materials using variable stiffness elements and distributed control. PhD thesis, Department of Computer Science, University of Colorado at Boulder. Committee: N. Correll, K. Maute, C. Heckman, D. Grunwald, 2017.

Jacob Segil, Radhen Patel, Yanyu Xiong, Marie Schmitt, Richard Weir, Nikolaus Correll. Force Sensing Prosthetic Finger Tip using Elastomer-Embedded Commodity Infrared Proximity Sensor. In: Myoelectric Controls Symposium (MEC), New Brunswick, 2017.

D. Hughes, A. Krauthammer, N. Correll. Recognizing Social Touch Gestures using Recurrent and Convolutional Neural Networks. In: Int. Conf. on Robotics and Automation (ICRA), 2017.

D. Hughes, H. Profita, S. Radzihovsky, N. Correll. Intelligent RF-Based Gesture Input Devices Implemented using e-Textiles. In: Sensors, 2017.

D. Hughes, N. Correll. Distributed Convolutional Neural Networks for Human Activity Recognition in Wearable Robotics. Distributed Autonomous Robotic Systems (DARS), London, UK, 2016. **Nominated for Best Paper Award***.*

R. Patel, N. Correll. Integrated force and distance sensing for robotic manipulation using elastomer-embedded commodity proximity sensors. Robotics: Science and Systems, Ann Arbor, MN, 2016. **Nominated for Best Paper and Best Student Paper awards.**

M. A. McEvoy, N. Correll. Distributed Inverse Kinematics for Shape-Changing Robotic Materials. In: 3rd International Conference on System-integrated Intelligence: New Challenges for Product and Production Engineering , Paderborn, Germany, 2016. **Best Paper Award**.