Robotic Materials: From smart polymers to computational metamaterials

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***Abstract*—We describe "robotic materials", a new class of metamaterial that tightly integrate sensing, actuation, computation, communication and power routing in a periodic fashion. Instead of relying on a strict division between mechanism, sensors, and control system, robotic materials allow a unified approach to robot design, customization and manufacturing. Robotic materials shift the complexity of manufacturing to the foundry, which provides functional raw materials in the forms of sheets, rods and bars. Possible functionalization include the ability to sense at high spatial resolution, the ability to change shape and appearance, or to perform distributed computation. We illustrate such materials using three examples: a sensing skin that can sense texture, a bar that can change its shape, and a rubber belt that can move autonomously. We then describe manufacturing challenges of robotic materials and survey recent advances in the field that have the potential to make robotic materials ubiquitous and cheap.**

I. INTRODUCTION

Advances in polymer science, miniaturization of computing, and manufacturing techniques have enabled a new class of robotic devices that embed sensing, computation, actuation and communication at high densities. This embedding can be so tight that the distinction between device and material blurs. This new class of materials has the ability to change its physical properties such as stiffness, density, weight, shape or appearance in response to external stimuli, and is able to adapt and learn. Here, the boundary between the dynamics of the physical system and control algorithms blurs, which allows trade-offs between morphological and silicon-based computation. Such materials shift the burden of integration and manufacturing from the designer to the foundry, enabling a new class of apparently simple robots made from functionalized stock materials such as rods, bars and sheets that can sense, and change their appearance and shape.

The vision of functionalizing materials by embedding networked computation, sensing and actuation has been first articulated by [2] and was motivated by the advent of micro-electromechanical systems (MEMS). This work, summarizing the outcome of a DARPA workshop, has led to a series of influential follow-ups that laid the foundation for the field of sensor networks [31] and amorphous computing [1] that set out to "create the system-architectural, algorithmic, and technological foundations for exploiting programmable materials." This paper describes a series of novel artifacts that we dub as "computational metamaterials" (CMM). The term metamaterials has been coined by Walser in 2000 [30], to describe "macroscopic composites having a manmade, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses to specific excitation" in order to overcome the limitations of classical composite materials. CMMs extend this definition by adding computation to create arbitrary relationships between sensing and actuation. CMMs are therefore subsets of amorphous computers, implemented in a lattice structure sharing power and communication locally.

The ultimate CMM consisting exclusively of mobile sensing, actuation, and computational elements has been introduced by Goldstein as "Programmable Matter" [5] (not to be confused with the term introduced by Toffoli and Margolus [28] to describe physics-inspired computation) and led to the claytronics project, which aims at casting materials into modular robots, with all the energy, structural, and mechanical problems this entails. In contrast, we wish CMMs to take advantage of the properties of the underlying polymer material, which can be both sensed and actuated upon.

This paper illustrates this concept and future challenges using a series of examples that demonstrate high-bandwidth sensing, actuation via feedback control, and distributed computation in an integrated system.

II. TACTILE SENSING IN METAMATERIAL SHEETS

The human skin implements a variety of sensors measuring both static and dynamic information with highly varying bandwidth such as pressure, shear, temperature, and textures [10]. We describe two distinct efforts for producing active polymer sheets with embedded sensing and computation at opposite ends of the perceptive spectrum. On the one hand, texture discrimination requires high temporal resolution with low spatial distribution of sensing sites. On the other hand, shape discrimination requires low temporal resolution with high spatial distribution of sensing sites. We describe the prototypes and fabrication processes of both types of skin.

A. High-bandwidth sensing: texture recognition in skin

Our current understanding of texture sensing requires sampling vibration signals at frequencies in the order of hundreds of Hertz, their spectral analysis, and subsequent classification [4]. Replicating a system such as the human skin with its abilities to identify textures almost anywhere on the body therefore imposes serious engineering challenges that we argue can best be solved by a CMM that samples and processes high-bandwidth information locally and routes resulting high-level information to a central processing unit only when an important event occurs.

We describe such a system in [7], which consists of individual nodes equipped with a microphone, op-amp, and microcontroller that are networked with their 6-neighborhood, leading to a hexagonal lattice (Figure 1). Each microcontroller samples vibration signals recorded by the microphones at 1kHhz and performs a 256-bin Fast Fourier Transform (FFT) of the signal, which is then fed into a logistic regression that has been trained offline to differentiate 15 different textures.

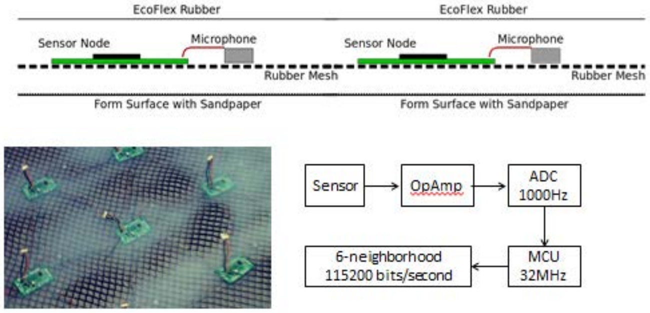

Fig. 1. System overview over a CMM that can identify and localize textures rubbed against it. PCBs and microphones are embedded in flexible rubber (EcoFlex) and suspended on a neoprene mesh.

The signal processing chain is depicted in Figure 2. Note that the signal is modulated by the material itself before it gets sampled and further processed. Knowing the frequency dependent attenuation can therefore inform the necessary discretization of the CMM.

We demonstrate texture recognition at 4Hz as well as triangulation of its localization by using intensity information recorded by at least three nodes at a time in [7]. As all of these operations can happen in parallel, this approachs scalability is only limited by the time it takes information from anywhere in the system to a sink, which scales with the square-root of the number of devices, assuming they are arranged on a disc with a data sink in its center. While the implementation of this particular CMM is bulky at present, future iterations of this system could be implemented on a single silicon wafer that can then be stretched and embedded in a composite as shown in [25], see also Section IV.

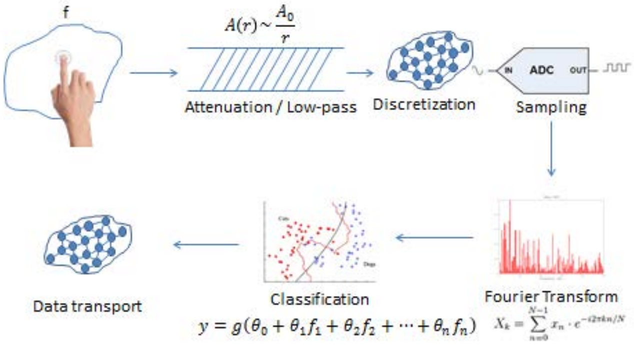

Fig. 2. Signal processing chain ranging from material-based attenuation to discretization, FFT, logistic regression and networking.

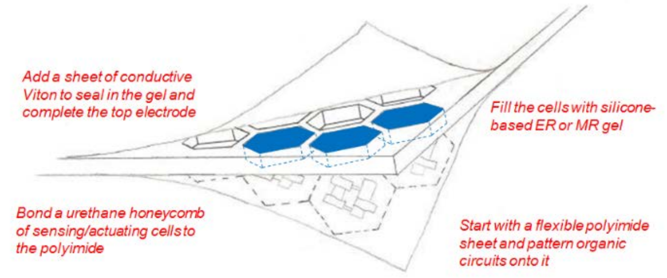

Fig. 3. Cutway visualization of a sheet of pressure-sensitive skin CMM with dielectric gel [29] for sensing and/or actuation.

B. High-density pressure sensing

Intrinsic and extrinsic tactile sensing of force or pressure has been extensively explored for several decades [29, 22, 12]. Our current understanding from human physiology suggests spatial sampling every 2mm to 20 mm can be useful for shape discrimination. We further prototyped a CMM for local sensing and detection of shape patterns based on pressure sensing of hexagonal tactels.

This tactile skin consists of a neuromorphic architecture comprised of multiple layers of neuronal circuitry for computation, a sensing medium for pressure/displacement, and an outer covering, as illustrated in Figure 3. The neuronal circuitry forms a perceptron-based artificial neural network that is interconnected across the substrate of the skin and can be programmed or can learn to perform specific computations. We have fabricated synthetic neural networks from both polymer electronics [21] and conventional silicon electronics to demonstrate skin capabilities. Here, polymer neural networks that can be printed across the skin offer the capability to implement sensing arrays at high densities and include simple pre-processing, whereas stretchable electronics provides an opportunity for compressing information and routing it a to a central location.

III. HIGH-SPEED FEEDBACK CONTROL: SHAPE CHANGING RODS

Shape change of complex morphologies such as the human hand, a bird wing, an airfoil of the future, car chassis or adaptive robotic system requires the simultaneous control of many actuators. In biological systems part of this control is often involuntary, or reactive, and follows a larger pattern

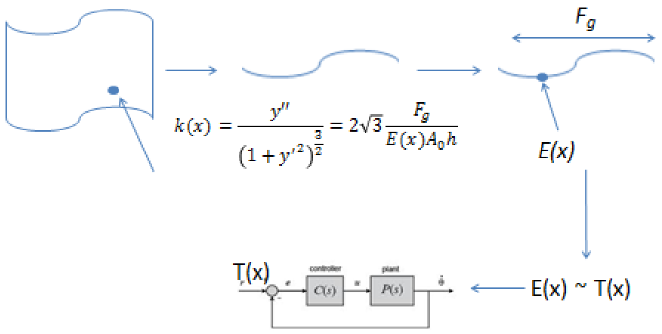

Fig. 5. Global shape change due to local feedback control of stiffness illustrated using the 1D beam equation. Stiffness can be controlled by varying the temperature of a thermoplastic, e.g.

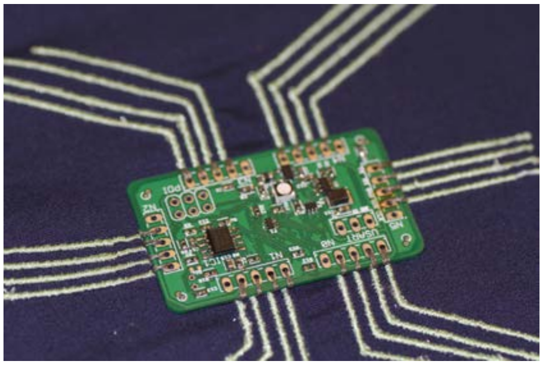

Fig. 7. PCB attached to cloth. Interconnects are provided by conductive thread stitched using an automatic sewing machine.

issued by the brain. CMMs have the potential to mimic these processes and perform local, high-speed control based on global patterns disseminated in the material.

We have been developing a class of CMMs [15] that have the ability to locally change their stiffness and shape (Figure 4) [16]. These properties are related via the beam equation, which expresses the curvature of a beam as a function of its stiffness and bending force (Figure 5). We control stiffness by joule heating and melting a low-melting point polymer (Polycaprolactone), albeit other approaches and materials such as sheet jamming [11] or Fields metal [26] are possible. Each element of the CMM is therefore equipped with a heating coil, a temperature sensor, and a microcontroller to implement a simple feedback controller. Implementing a desired stiffness profile, which can later map into the corresponding shape profile, is therefore equivalent to disseminate a temperature profile into the CMM and locally ensuring that the temperature profile is met. Note that the temperature profile can be provided as a spatial function that can be locally resolved using a coordinate system that is trivial to establish in a grid networking topology.

Actuation is accomplished by applying an external moment using a single pneumatic actuator [8] or tendon actuator [17] extending along the entire length of the beam.

Shape change can also be accomplished by creating CMMs in which each individual element can bend [3]. A ring-shaped CMM consisting of eight elements, each equipped with dedicated sensing, computation and actuation, and networked with their neighbors to the left and right is shown in Figure 6. A forward rolling motion was achieved by evaluating a local photo sensor to determine whether a cell was facing the ground or not. A cell then inflated when it was facing the ground, but one of its neighbors did not. This led to a rolling motion of the mechanism. Other conformations of such an autonomous material are thinkable, leading to snakes, arms [14], or sheets. Other approaches to shape change include folding via built-in shape memory alloys [6].

Local feedback control, illustrated here using a shape-change example, is also relevant for appearance change, which can be achieved by embedding lights, but also passively by injecting liquids with desired optical or thermal properties [20, 19].

IV. MANUFACTURING

The systems shown in Figures 1, 4 and 6 all have been manufactured by a combination of printed circuit board (PCB) populated with off-the-shelf surface mounted devices (SMD), wired interconnects to provide power and communication between CMM elements, and embedding in a polymer material. Manufacturing these systems at scale requires overcoming a series of challenges that are due to the multitude of processes involved, the lack of automation, which is only available for subsets of the process, such as PCB edging and assembly, and finally compatibility of involved polymer materials.

Silicone materials such as EcoFlex do not bond with any other material. Embedding structural materials therefore requires either perforation, e.g., of a flexible circuit as in the system shown in Figure 6, or using a mesh structure as in Figure 1 (Neoprene mesh) that provides sufficient the silicone to form sufficient cross linkages. After assembly of the PCB interconnects via wires (Figure 1) or soldering of flexible PCB (Figure 6)and alignment of parts on a mesh carrier or mold, silicone based materials can be simply poured. Accommodating the pneumatic actuator channels in the system of Figure 6, required a design of a multi-piece mold, into which place holders for the pneumatic channels were inserted during curing [3].

There are multiple possible solutions to automate the PCB interconnection process. In cloth-based wearable systems such as [23], interconnects can realized using conductive thread (Figure 7). While the sewing can be automated for the most part, affixing the thread to the PCB vias requires manual work. Ribbon cables, either from individual strands or flexible PCBs, are readily available in various lengths, but also require manual assembly and add significantly to the stand-off height of the PCB. In case all the required sensing, processing and actuation can be integrated into a single silicone die, interconnects can be designed in a spiral shape, which allows stretching the circuit array over multiple orders of magnitude. For example, [25, 24] describes an array of sensors and piezo-electric actuators that can be screen printed and embedded into a composite. [32] uses a similar method to embed sensing, computation

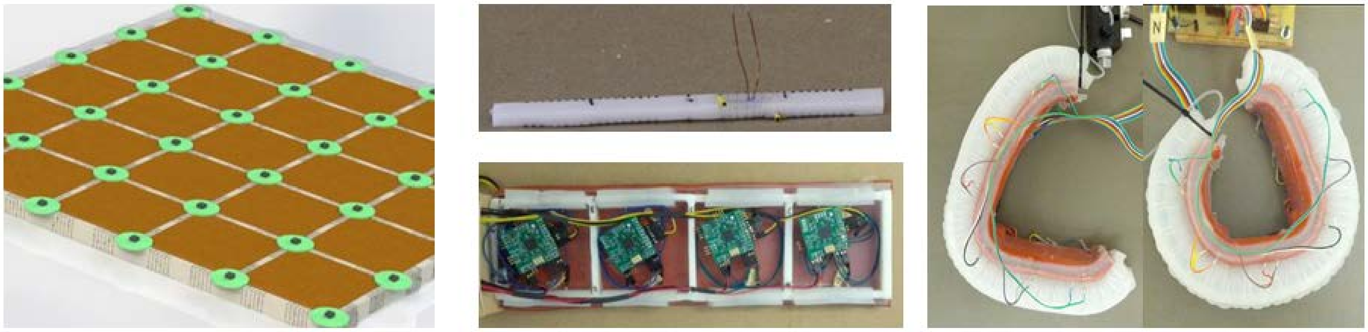

Fig. 4. Concept drawing of a shape-changing CMM with embedded control (green discs). Low-melting point plastic bars with integrated heating coils and temperature sensor (middle, top) are arranged in a lattice and augmented with embedded controllers (middle, bottom). Shape can be changed by an external actuator, here pneumatic (right), and is exclusively determined by the stiffness profile and force.

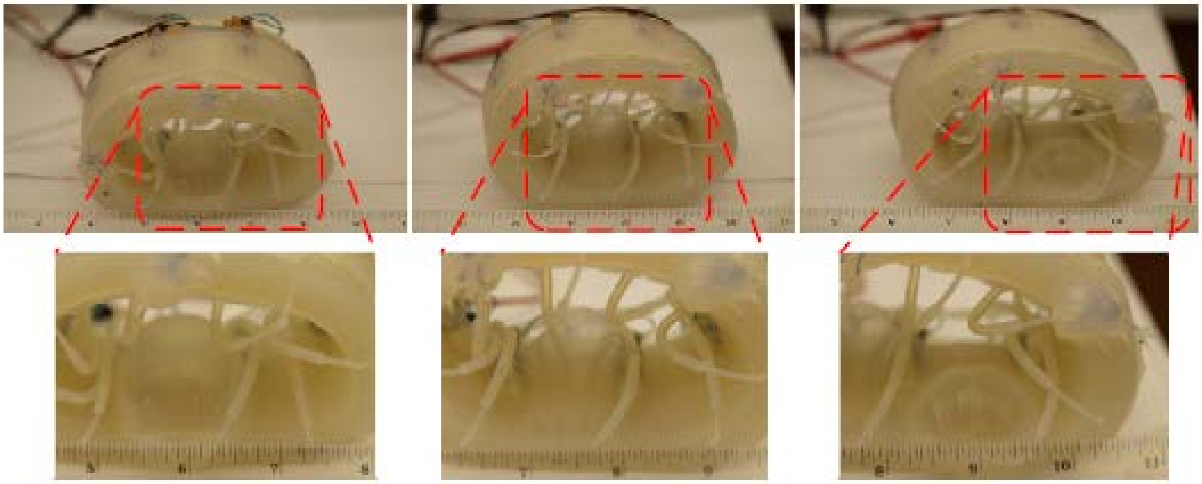

Fig. 6. Pneumatic belt rolling autonomously on a flat surface using distributed

and radio elements into a soft, conformable circuit that can be attached to the skin. Limitations of this approach include the limited number of interconnect wires that can run in parallel and the feasibility of processing complex circuits that require a variety of base materials.

It is also possible to functionalize the carrier polymer, such as ABS plastic, such that a copper solution adheres to the surface. Entire circuits—including the capability of directly mounting SMD devices—created using this technique are known as *Molded Interconnect Devices* (MID) [9]. Electro-mechanical components, PCBs and interconnects can be aligned and integrated using *Shape Deposition Manufacturing* (SDM) [18]. Here, place holders for electro-mechanical parts or interconnects are subtracted from a polymer or metal using a precision mill. These parts can then be embedded in the structure by depositing a polymer material, which can again be precision milled after curing. Finally, 3D printing allows creating structures with embedded conductive parts with the advent of carbon-infused ABS and PLA filaments, which are limiting due to their relatively high resistance of 10kΩ/cm at 1.7mm diameter.

All robotic materials described in this paper implement control using conventional silicon-based electronics. The advent of polymer electronics, semi-conductors made exclusively from polymers, might enable a new generation of all-polymer computational metamaterials [21]. A flexible, organic field effect transistor (OFET) that we manufactured is shown in Figure 8.

Principally, polymer electronics can be manufactured in large sheets [27], but integrating circuits that are more complex than very few transistors or RFID tags, requires to overcome major challenges in material science, processing and manufacturing.

V. DISCUSSION

While the potential of robotic material is tremendous, challenges that need to be overcome and possible avenues to pursue seem to be overwhelming. There are two observations that are helpful to navigate this problem: first, an introspection which tools are actually available to the extended robotics community, and second, an analysis of which of the many

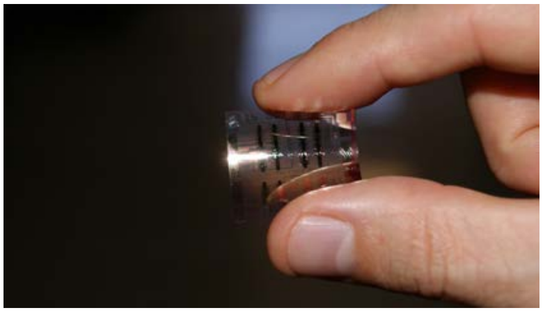

Fig. 8. Complete, four-neuron Synthetic Neural Network made of Organic Field Effect Transistors (OFETs) and Organic Memristive Read Only Memories (OM-ROMs) printed onto flexible substrate.

applications are of high enough value and can be feasibly implemented with existing technology.

The skin shown in Figure 1 consists of a microcontroller (MCU), MEMS microphone, an operational amplifier (OpAmp) and some passive components. Although MCU, OpAmp and microphone can be mass-produced from silicon using lithographic processes, those processes are not compatible with each other and make it hard to combine both MEMS structures and high-density logic on the same wafer. Implementing the proposed skin in stretchable silicon as [24], e.g., therefore requires fundamental interdisciplinary research to advance both processing techniques and find solutions to compromises that need to be made. Implementing such a design in polymer electronics is even farther out as, albeit constant progress is being made, the field still needs to overcome very basic challenges like finding orthogonal solvents that allow stacking up multiple layers of polymer, improving yield, scaling down size, and increasing efficiency to only name a few.

Although exciting, the value proposition of such a skin is currently questionable as robots and prosthetic devices that could actually benefit from such a system are not ubiquitously deployed. We therefore need to identify applications where robotic materials can provide better solutions than existing systems. In terms of high-bandwidth sensing, such applications are likely to find in Non-destructive evaluation such as detecting cracks in airplane wings or other high-value systems. In terms of shape-change, simple systems that can change the aero-dynamical properties of cars or planes with a minimum of turbulence and at lower cost than traditional hinge-based systems are a promising direction.

Both polymer electronics and flexible silicon electronics have distinct advantages. In a nutshell, these are the ability to be simply printed vs. high efficiency/speed. We therefore believe future robotic materials to combine these techniques efficiently and use polymer electronics to implement simple, local feedback control or collect and pre-process data at high spatial resolution, which can then be processed in bulk on high-speed silicon architectures using conventional networking techniques [13].

VI. CONCLUSION

We have demonstrated a series of highly-integrated CMMs that provide significant capabilities, which are difficult to realize using conventional, centralized approaches. This is illustrated using high-bandwidth sensing and local feedback control. Implementing these systems in a hierarchical, centralized fashion would require expensive wiring and quickly reach the limitations of a central processing unit both in terms of available analog-digital converters and processing power.

Although all of the systems here are achieved using off-the-shelf components and manual processing, their assembly into systems is tedious and requires advanced manufacturing techniques. Albeit MID, SDM and screen printing are promising technologies, realizing any of the systems presented here, will require significant advances in these technologies to be feasible.

If successful, these techniques can enable a new class of “robotic materials” that will lead to a paradigm shift in robotic design and lead to novel robotic systems with unprecedented, animal-like dexterity, agility, sensitivity, and adaptivity. These systems will pose novel challenges in programming, requiring to synthesize low-level code from a description of high-level, emergent behavior of the overall structure provided by the designer.

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