ROBOTIC MATERIALS WITH CONTROLLABLE STIFFNESS

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Abstract

We present an approach to control the local stiffness of a composite polymer material by using sensing, actuation, computation and communication embedded in a periodic fashion. We call this class of materials “Robotic Materials”. Initial stiffness is achieved by a polycaprolactone (PCL) grid. Each PCL bar is equipped with a dedicated heating element, thermistor and networked microcontroller that can drive the bar to a desired temperature/stiffness. We present experimental results using a 4x1 grid that can assume different global conformations under the influence of gravity by simply changing the local stiffness in individual parts. We also show how the conformation changes as a function of the temporal order of stiffness transitions while keeping the external force constant. We also explore the potential of such a material to change its configuration upon application of arbitrary forces from built-in actuators using Finite Element Simulation.

1 Introduction

We wish to investigate the computational and systems level challenges of a new class of composite materials that tightly embed sensing, computation, and actuation. We achieve this by embedding conventional smart materials with traditional electronic components; thereby augmenting the smart material with sensing, computation, and actuation abilities in a homogeneous, periodic, and amorphous manner. We call this class of materials ”Robotic Materials” (RM).

Traditionally, conventional smart materials are limited to a specific type of external stimulus such as heat, electric current or magnetic fields which induces a radical change in their physical properties such as form, size, stiffness or color among others. While these capabilities have enabled a large number of novel devices, design of polymers with specific capabilities is a hard problem and highly dependent on the specific application, environment and overall system design. A possible approach to increase the functionality of a polymer material is to pair it with appropriate actuators, sensors, and computation. This will allow us to couple material properties to arbitrary stimuli via programmable logic. Using communication between devices allows us to implement any desired spatio-temporal dynamics supported by the material’s properties by literally programming the embedded computational devices.

In this paper, we present a RM with the ability to actively change its stiffness in a localizable fashion. By this, we mean that the material can assume different stiffnesses in arbitrary locations to change its resistance to deformation at different locations in a programmable manner, under distributed computational control. Applications for such materials range from versatile orthopedic casts to the aerodynamic surfaces of cars, boats, and airplanes, that can change their shape while in motion. Figure 1 contains examples of both actuated and static structures which we believe could be implemented with such a material.

Fig. 1: Applications for a programmable stiffness Robotic Material range from furniture whose function can be changed by its users to shape-changing boats, cars and airplanes.
Although integration of sensing and actuation into smart structures for the purpose of structural health monitoring, shape-change and vibration control have been proposed in the past (Section 1.1), these approaches increase the functionality of existing materials by inserting sensing, computation and actuation only at strategic locations, which require expert knowledge about the application.

The RMs proposed in this paper are true composite materials. Amorphous and periodic, their function is independent of the size or shape and the end user is able to determine their final functionality based on the material’s embedded properties, which the user can program.

While this paper relies on off-the-shelf electronics, advances in electronics miniaturization and manufacturing techniques will ultimately lead to smart materials with a high material resolution for actuation and sensing capabilities.

1.1 Related Work

Robotic Materials result from a fusion of Materials Science with Computer Science. In particular, the RM presented in this work has its roots in the amorphous computing paradigm [1], which has been originally motivated by the material science community [2]. So far, including sensors and computation into materials at high density has found considerable interest for structural health monitoring [3, 4]. High bandwidth sensing and large data requirements has motivated local computation early on [5], and has been demonstrated within a (wireless) network in bridge [6] or airplane wing [7, 8] monitoring applications, among others. There is also an understanding that such smart materials pose considerable systems and networking challenges [9], and [10] considers communication and power distribution via optical fibers.

Variable stiffness materials have received attention for both vibration control and as the basis for morphable airplane wings, see [11–14] for extensive reviews of the field. Designing materials that exhibit variable stiffness based on exclusively passive effects is a hard problem [15], and being able to arbitrarily change stiffness is desirable. For example [16, 17] construct a variable stiffness material by exploiting the temperature-dependent variable shear modulus of polymers sandwiched between metal bars. The dynamical material properties as a function of temperature of the underlying polymer material used in [16, 17] and in this prototype RM have been well studied in [18, 19]. This paper integrates a similar approach as shown in [17] into a networked system at miniature scale, which motivates additional challenges in distributed computation and networking, which we would like to study in the future.

How to actuate shape-changing materials is a recurrent challenge and shape memory polymers (SMP) and embedded pneumatic channels offer promising directions [20, 21].

2 Materials and Methods

We choose polycaprolactone (PCL) as the primary material component providing the stiffness in this application. PCL's low melting point near 60 °C, along with is widely variable stiffness profile preceding melting provides the variable stiffness of the presented computational smart material. The material properties for PCL described in [22] show that, when heated, the material can deform under loads that are a few orders of magnitude smaller than those required at room temperature.

2.1 Polymer Actuator and Sensor

The core functionality of the prototype variable stiffness composite polymer is provided by PCL bars with embedded sensing and actuation. We manufacture PCL bars by heating the PCL and molding it in a laser-cut, acrylic multi-part mold, we then embed the thermistors and Nichrome wire. Figure 2 shows an overview of the process used to manufacture this atomic component of the composite material.

After melting an appropriate amount of PCL (Polymorph, TOL-10951, Sparkfun Electronics) in a hot water bath (Figure 2a), the molten PCL is pressed into a mold to form solid bars (Figure 2b). The bars have a rectangular cross section of 1.25 cm × 0.5 cm and are made in 30.5 cm lengths, resulting in four bars at a time (15.25 cm per bar).

Once the solid PCL bars have been removed from the mold, they are measured and marked for the installation of the Nichrome wire. Nichrome wire (36 gauge, NW36100, Jacobs Online) is then wrapped around the PCL bar at 3 revolutions per centimeter over a 2.5 cm length. This led to an overall resistance of each wire of approximately 28 Ω and a resulting current of approximately 430 mA at 12 V. The thermistors (NTSD1WF104FPB40, Murata Electronics, Digikey)
(a) PCL pellets are melted in a hot water bath.

(b) The molten PCL is pressed into a mold to make $12.5 \times 5.0 \text{mm}$ bars. Bars are cut into $152.4 \text{mm}$ lengths when removed from the mold.

(c) Each bar is marked and wrapped with Nichrome wire at 1 revolution per $3.2\text{mm}$. A thermistor is embedded into the center of the Nichrome wire wrap.

Fig. 2: Process for manufacturing atomic polymer sensor/actuator composites of the variable stiffness material.

are embedded in the center of this wrap (Figure 2c).

Each actuator segment is encased in approximately 4 mm thick silicone rubber (Ecoflex 00-30, Smooth-On) (Figure 3). We do this to contain any actuator segment that is heated to melting. The molten PCL stays inside the silicone cavity and roughly retains the rectangular cross section of the undeformed solid bar.

2.2 Manufacturing of the 4x1 Variable Stiffness Composite Material

The polymer sensor/actuator segments can now be assembled into arbitrary tessellations. In this paper, we chose a simple grid in which only longitudinal elements are active, whereas latitudinal elements are passive PCL elements of the same size as the active ones (Figure 3). The different segments can now be welded together using a heat gun. Finally, we attach the whole assembly to the silicone foam sheet (McMaster-Carr, 87485K71). Non-actuated PCL segments are not encased in silicone rubber since they are not heated.

Enclosing the composite material into a silicone foam sheet not only protects the internal components, but also provides additional stiffness to the material when molten, limiting both the maximal stretch and bend radius that the material will support without use of excessive force.

2.3 Computational Hardware

The board utilizes an ATxmega128A3U microcontroller unit (MCU). The ATxmega128A3U can be run at up to 32 MHz and is equipped with 128 Kbytes of flash memory. This computational power allows for non-trivial computation and signal processing and exceeds the computational requirements of the functionality presented in this paper. We selected this chip, however, as it is equipped with seven hardware serial ports (USARTs), which allow asynchronous communication at 115 kbps with up to seven other MCUs. This feature allows us to use this platform also in three-dimensional composite materials in which each computational element might have up to six neighbors. In this paper, each board has the capability of communicating with up to four neighbors via a two-wire serial port, and thereby with every board in the system via hop-to-hop communication [23]. Each board also provides connections to share common power and ground. An overview of the custom board is shown in Figure 4.

Each board is equipped with a combined red, green, blue (RGB) light emitting diode (LED) to communicate different status messages. When the boards are not sending debugging information to a computer via the serial output, the LED flashes sequences alerting an observer which wire is active and whether or not the set temperature has been reached.

Each board is also equipped with a Hall effect sensor (Allegro Microsystems, A1393SEHLT, Digikey) as a means to detect magnetic fields as an example external stimuli. In this paper, the Hall effect sensor is used to turn on and off the different nichrome heating elements via an external magnet.
The 12 V power supply is supplied to each board using a simple power bus. A dual N-channel MOSFET (Vishay Siliconic, Si7904BDN, e.g.) is used to turn the heating elements on and off.

It is worth noting that the integration presented here is far from the technical limits that are achievable with off-the-shelf electronic components and established manufacturing techniques. A version of the Atmel Xmega (128A3) is available as 5x5mm^2 ball-grid array package, whereas dual MOSFETs such as the Si7904BDN that can switch loads up to 17.8W are available in 3.3x3.3mm^2 packagings. These dimensions make board sizes smaller than 1cm^2 on flexible circuit board realistic, but are not needed for the experiments presented in this paper.

2.4 Temperature Control Logic

The temperature controller was prototyped using an Arduino Mega ADK that can drive up to eight N-channel MOSFETs (Vishay Siliconix, IRF510PBF, Digikey) and thermistors (Murata). The thermistors are monitored using a voltage divider and the analog in pins of the microcontroller. Current through the Nichrome wires is controlled by the MOSFETs that are connected to digital out pins. As the architecture of the Atmel Mega and Xmega series are very similar, transferring controllers from the Arduino to the embedded control board is straightforward.

The temperature controller is programmed to hold the temperature of the Nichrome wrapped PCL bar at a designated set point with +/-0.5 °C hysteresis.

We have found for this prototype that a simple on-off controller is sufficient to reach and hold a desired set temperature as fast as possible, without the need to develop a rate dependant PID controller. Currently In future work we expect to develop a more advanced temperature control mechanism.

The time to reach 50°C was recorded for eight different segments and average and standard deviation are shown in Figure 5. Differences between different bars can be explained by slight differences in manufacturing, in particular the length and geometry of the heating wire. At this temperature, the PCL bars are completely melted. As shown, all bars reach this set temperature between 3 and 4 minutes when starting at room temperature. The temperature curves do not
Fig. 5: Average step-response for heating a polymer sensor/actuator element to 50 °C when starting at room temperature and cool-off.

show much overshoot and all of the temperatures settle to within ±0.5° of the set temperature within 30 seconds of reaching it.

2.5 Arbitrary Stimuli for Smart Materials

In order to demonstrate the RM’s capability to react to arbitrary stimuli, we have implemented code that allows switching the heating element on and off by activating the Hall effect sensor. The first pass of a magnet turns the first wire on, the second pass turns wire two on, the third pass turns both wires on, and the fourth pass turns both wires off. With each pass, the RGB LED flashes blue as an indication that the pass has been registered. This simple user interface not only allows for easy experimentation, but also demonstrates the ability of RMs to tie arbitrary sensors to actuation via programmable logic.

3 Experiment

We wish to show that the proposed variable stiffness composite polymer material can implement arbitrary spatio/temporal stiffness patterns. In the absence of mechanical actuation, we demonstrate conformation changes of the material under the influence of gravity. We constructed a test-rig that allows us to mount the composite polymer in the classical cantilever beam setup, where one end of the beam is fixed to the wall and the other end can move freely. This setup is shown in Figure 6a.

3.1 Experimental Results

In a first series of experiments, we demonstrate the ability of the RM to assume spatio-temporally varying temperature profiles. We heat each element to 50 °C, which causes rapid deformation of the beam due to gravity. Once each element has reached a stable confirmation, we allowed it to cool and heated the next element as shown in Figures 6b through 6e. It is worth noting that each of the images were taken with the material in a stable configuration in which all elements have been cooled down and are therefore completely stiff. The last figure in this series shows the results when activating all of the elements, which lets the entire beam follow gravity and stretch out. After manually restoring the initial configuration and cooling, the experiment can be repeated.

The second series of experiments is designed specifically for the calibration of our finite element model. In each test we heat both segments of a given cell to 50°C and record the vertical (Z-axis) and horizontal (X-axis) displacements. We also measure the angle that results from the 4x1 beam’s hinge-like deformation. Table 1 shows the results collected from our experiments and the values that we are able to obtain from our correlated model and Figure 7 shows each of these measurements.

![Figure 7: The experimental measurements taken in order to correlate our FEM for simulation purposes.](image)

Table 1: Correlation of experimental and simulation results for the 4x1 test beam. The values are defined in Figure 7.

<table>
<thead>
<tr>
<th>Test Case</th>
<th>ΔZ (mm)</th>
<th>ΔX (mm)</th>
<th>α (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1</td>
<td>-23.5</td>
<td>-24.3</td>
<td>69°</td>
</tr>
<tr>
<td>Cell 2</td>
<td>-15.9</td>
<td>-12.8</td>
<td>57°</td>
</tr>
<tr>
<td>Cell 3</td>
<td>-7.4</td>
<td>-3.9</td>
<td>32°</td>
</tr>
<tr>
<td>Cell 4</td>
<td>-3.9</td>
<td>0.0</td>
<td>3°</td>
</tr>
</tbody>
</table>
(a) Initial configuration: the 4x1 test beam with all of the cells inactive, i.e. all of the PCL bars are at room temperature.

(b) Initially the 4th cell is activated to 50 °C and the others are left at room temperature.

(c) The 4th cell is allowed to cool and the 3rd cell is activated to 50 °C.

(d) Next the 3rd cell is allowed to cool and the 2nd cell is activated to 50 °C.

(e) Lastly, the 2nd cell is allowed to cool and the 1st cell is activated to 50 °C. This geometry is only possible to achieve with distributed local control schemes.

(f) Compare with all of the elements activated, demonstrating the conformation that arises with global simultaneous activation of all elements.

Fig. 6: This sequence of images shows the 4x1 test beam curling up and stretching out under gravity load and spatio-temporal variation of its stiffness profile.
4 Simulation

We are also interested how a variable stiffness composite material could behave using forces other than gravity. For this we use a finite element model that has been correlated to our experimental results.

4.1 Finite Element Model

In order to study more complex geometries and loading configurations, we implement a model of the variable stiffness composite polymer material in *NX.Nastran*. The PCL bars in the 4x1 test beam are modeled with CHEXA(8) elements while non-structural mass is used to account for the silicon rubber encasements as well as the silicon foam sheet. The boundary conditions of the test beam are modeled at the base of the structure by fixing all of the degrees of freedom. An overview of the finite element model used is shown in Figure 9.

We use the material properties for PCL found in [22], that is a Young’s modulus of 190 MPa and a maximum tensile strength of 14.2 MPa. Initial estimates for the stiffness of the PCL at different temperatures are made using [22]; we then correlate these values to our experimental results using four different test cases, namely, fully activating both segments of each cell. Because of the large displacements observed in experimentation, we use *NX.Nastran*’s solution 106 for nonlinear static analysis.

4.2 Identification of System Properties

In order to explore other properties of the proposed variable stiffness RM, we first calibrated our *NX.Nastran* model to match our experimental results. Figure 8 shows the test cases we used in *NX.Nastran* to evaluate correspondence with our physical setup.

For this paper, we have simply manually tuned the Young’s modulus in the simulator until we found sufficient quantitative agreement with the experimental data. The resulting material properties that we used for PCL in our FEA are shown in Table 2.

Table 2: A summary of the PCL material properties used in our FEA of the 4x1 test beam.

<table>
<thead>
<tr>
<th>Property</th>
<th>T = 20°C</th>
<th>T = 50°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>density</td>
<td>5531.7</td>
<td>5531.7</td>
</tr>
<tr>
<td>E (MPa)</td>
<td>190.0</td>
<td>2.2</td>
</tr>
<tr>
<td>ν</td>
<td>0.33</td>
<td>0.33</td>
</tr>
</tbody>
</table>

4.3 Simulation Results

We are interested in evaluating the possible conformations a variable stiffness RM could assume when using both arbitrary forces and varying stiffnesses under uniformly applied forces. We explore this using our calibrated *NX.Nastran* FEM. Figure 10a shows the *NX.Nastran* model with a force that is slightly offset from the RM’s centerline.

Figure 10a shows a simulation in which both segments in cell 3 are heated. Results demonstrate the expected hinge-like bending that was seen in the experimental test under the force of gravity.

In Figure 10c we show a simulation in which cells 2, 3, and 4 are set to 75 %, 50 % and 25 % of the room temperature stiffness, respectively. The segments in cell 1 are left inactive. This result suggests that a variable stiffness gradient approach is suitable to assume specific bending radii. Evaluating the temperatures that correspond to these stiffnesses in our prototype variable stiffness RM is a part of our future work.

Note that for these simulations we are only interested in the deformations and do not model the restorative forces that would be needed to transition between the possible curvatures.

5 Discussion

We have demonstrated a variable stiffness robotic material that can achieve a large number of possible conformations under constant force simply by changing the stiffness of individual elements and the order in which these stiffness changes are made. This is a high-dimensional planning problem — our 4x1 beam can be heated in $2^4 = 16$ different ways, not including intermediate temperatures. Finding optimal policies that achieve a desired profile by switching the order of stiffness change operations, is a challenging research problem for larger systems and is part of our future work.

In this paper, whereas mechanical actuation is limited to passive effects due to gravity, although it is thinkable to introduce other forms of actuation such as pneumatics [21], hydraulics, or shape memory polymers (SMP) to create arbitrary forces within the material such as we have explored in simulation.

Although the variability of stiffness in PCL is sufficiently large to enable applications such as shown in Figure 1, its rate of change on the order of minutes may be limiting for dynamic applications where rapid
stiffness changes are required. While this could be improved by choosing nichrome wires with lower resistance, resulting in higher power output, future manufacturing technologies might enable integration of heating wire at much higher densities, thereby improving the distribution of heat within the material. Similarly, alternate polymers may support much steeper temperature/stiffness curves, thereby allowing the material to reach a desired stiffness point with a much smaller temperature variation. Finally, active cooling mechanisms could be explored for rapidly stiffening the material into new conformations.

In our prototype, we have only demonstrated activation of individual cells. Any system that requires multiple cells to keep an exact temperature simultaneously, such as the one simulated in Figure 10c, requires the coordinated action of multiple elements. This is because each element heats up slightly differently, therefore communication between the elements is necessary to share progress on heating and adapt current locally in order to reach a desired melting temperature at exactly the same time.

For both stiffness change and actuation, power distribution in the material poses a major challenge. Future robotic materials will therefore require intelligent power management systems that will manage where power is consumed in the system and how this power is routed in order to ensure that the maximum carrying capacity of conduits is not exceeded.

Simulation results are based on data for homogeneous PCL and in this study do not capture the subtleties of heat wire geometry, wiring and thermistor
placement. While this approach is sufficient to obtain approximate agreement with our experimental result, in the future we wish to quantify the actual material properties of the resulting composite experimentally in order to better understand the impact of embedding sensing and actuation.

In addition to materials that can change their curvature, results in [24] show that periodic materials with geometries that allow for drastic shape changes with positive or negative Poisson ratios could make particularly interesting targets for selective stiffness changes using local sensing, actuation and computation. Instead of simply uniformly folding or expanding as in [24], such materials could be compressed and expanded into a large number of possible irregular shapes using techniques developed in the proposed work.

6 Conclusion

We have presented a prototype robotic material that can selectively and locally change its stiffness profile. Distributed computation allows parts of the material to be independent of each other, making it scalable and robust to failures. Applications for such a material range from orthopedic casts, to conformable furniture and dynamic airfoils or hydrofoils. While this paper focuses on a PCL based material, the distributed sensing, control and the computational methods and tools used in this work can be combined with arbitrary sensors, including microphones, magnetometers, pressure or light sensors, e.g., arbitrary smart materials including shape memory alloy, electrorheological fluids or electroactive polymers, e.g., and complex algorithms that take full advantage of the embedded computer’s memory and neighbor-to-neighbor communication.

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