Cyber-physical Materials: Computational Meta-Materials

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Background and Motivation. Computational Meta-Materials (CMMs) are cyber-physical systems that gain their properties from their structure and embedded sensing, actuation, computation, and control (SAC^2). CMMs are a new class of bio-inspired materials that allow unprecedented multi-functionality through their ability to be programmed. This feature enables arbitrary spatio-temporal behaviors that could be used in such applications as camouflage and morphable or reconfigurable surfaces and structures.

Figure 1: CMMs are inspired from biological systems such as the cuttlefish, the manta ray, and the sea cucumber. Cuttlefish can rapidly change the color of their skin for camouflage, manta rays move through the water by flexing their fins, and sea cucumbers can essentially liquefy themselves to maneuver through small openings.

CMMs result from a synthesis of Materials Science and Computer Science. CMMs combine materials whose behavior is governed by complex dynamic systems of equations with SAC^2 at discrete locations throughout the material. For these materials to become viable, the theoretical framework that encompasses both the material properties and the computational properties must be developed. These materials have their roots in the amorphous computing paradigm, which I will use to investigate the system architectural, algorithmic, and technological foundations for exploiting programmable materials.

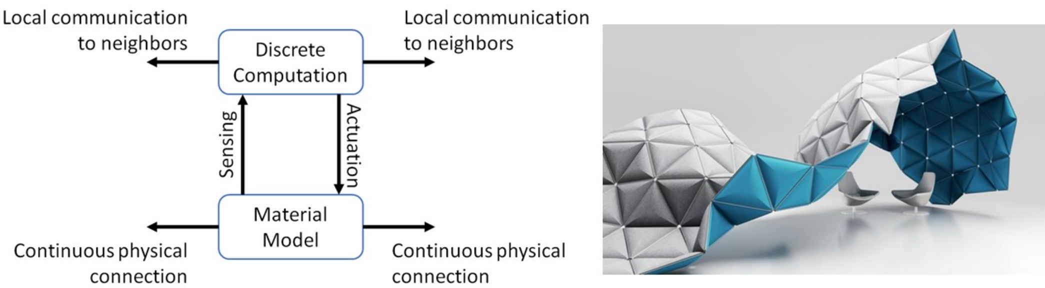

Figure 2: The diagram on the left shows the cyber-physical model of CMMs. In my vision, SAC^2 will be distributed throughout a material and will locally control key material attributes so that the materials can become an interactive part of our environment. The picture on the right shows a concept of this vision, reconfigurable structures.

Current Research My main research thrust is to develop a principled formal approach for the design of morphable CMMs. I will use the amorphous medium abstraction to study the behavior of the continuous physical models of the materials as they are coupled with discrete computational nodes.

As a motivating experiment, I am investigating the ability to change the shape of a simple beam (Figure 3). The shape of the beam is related to the applied moments and the stiffness through the equation $v''(x,t)E(x,t)I = M(x,t)(1 + v'(x)^2)^{1.5}$. I use nichrome heaters to change the stiffness of a thermoplastic bar by varying the temperature, $E(x,t) = f(T(x,t))$, which is controlled by a combination of local feedback control and local communication to enforce desired sequencing. I then apply external actuation forces to the bar to induce a desired shape change.

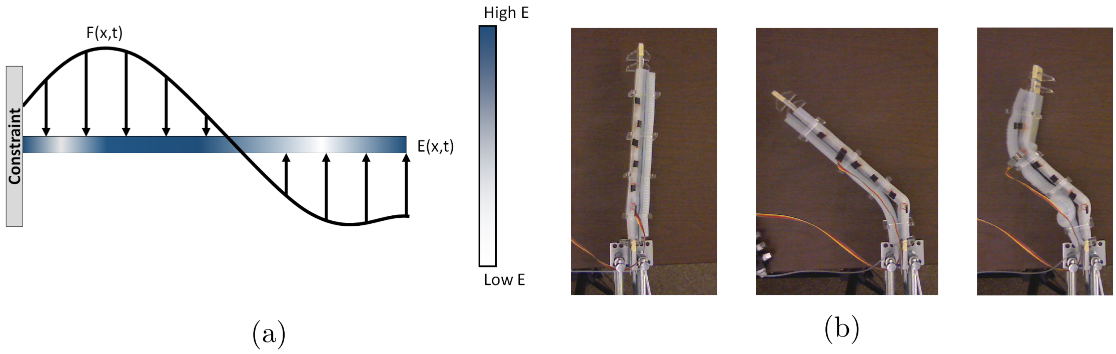

Figure 3: An example of a morphable CMM. (a) shows the physical model for the bar. A change in shape is brought about by the coupled stiffness and applied force functions, both of which vary with time and along the length of the bar. (b) shows the bar changing shape under a set of chosen stiffness and force profiles implemented by a distributed control law.

The proposed morphing CMMs offer several areas for exploration within the cyber-physical systems domain. One of the main challenges will be developing the distributed controllers needed to achieve arbitrary shape changes that encompass both the continuous material and the discrete computational elements.

Another topic of interest will be the power management issues that arise from embedding computation and actuation into a material. Determining a control sequence that allows the desired shape change to occur without overloading the systems resources will be of critical importance.

In any CCM there will be a trade-off between computational density and communication speed. More computational power may mean less communication is need with neighboring elements to determine a control plan, or vise-versa. The interplay between the embedded information network, the embedded power network, and the distributed algorithms that will be used to control the materials are tightly coupled and offer many new and exciting challenges.

Potential Impact. Computational meta-materials are enabled by advances in polymer sciences, miniaturization of computing elements, and manufacturing capabilities, and have the potential to become ubiquitous in aerospace, civil engineering, robotics and everyday objects whose surfaces and structural elements will become multi-functional. By tightly integrating computation, communication, sensing and actuation inside the material at high density and in large numbers, CMMs are the ultimate cyber-physical system, posing unprecedented challenges in distributed control and global-to-local programming that the CPS community has the ability to address.