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DEVELOPMENT OF ACTIVE-CELLS FOR MACROSCOPICALLY DEFORMABLE STRUCTURES

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ABSTRACT

In this paper we describe extensions and improvements upon prior work on “active cells”--small contractile electromechanical elements used in large numbers to create actuated composite structures. Each element (cell) consists of square fiberglass end-pieces encapsulating a bias spring within two telescoping tubes, actuated using two contractile shape memory coils, and occupying approx. 1cm^3 when fully contracted. The end-pieces contain conductive interfaces to nearby cells, thus allowing channeling of power through a connected network of cells to provide actuation far from the source of electrical current. Prior work developed the conceptual structure of such a cell as well as preliminary prototypes. This paper describes the attachment of cells to each other and to rapid-prototyped cell interconnects -- as well as improved fabrication techniques for the shape-memory coils -- resulting in robust actuation for each cell, and the creation of considerably more complex chained and networked composite structures. A detailed exploration of appropriate interconnect mechanisms, powering schemes to provide network-level structural deformations, and examples of multi-cell structures are presented.

INTRODUCTION

This paper explores the development of an existing concept prototyped in our prior work [1] to create contractile electromechanical cells that are able to interface with one another to create complex load-bearing structures. The project was inspired by the complex structures found in nature that use relatively simple electrochemical cells to create large swaths of highly articulable macroscopic tissues. Specific examples of such structures include peristaltic motion of the gastrointestinal tract, rhythmic activation of cardiac muscle, and many others.

A careful look at a complex tissue such as from the human heart shows the principal action of the structure comes from cells that are simultaneously structural and contractile. The mobility of the entire structure occurs through structured activation of these cells by nearby pacemaker cells.

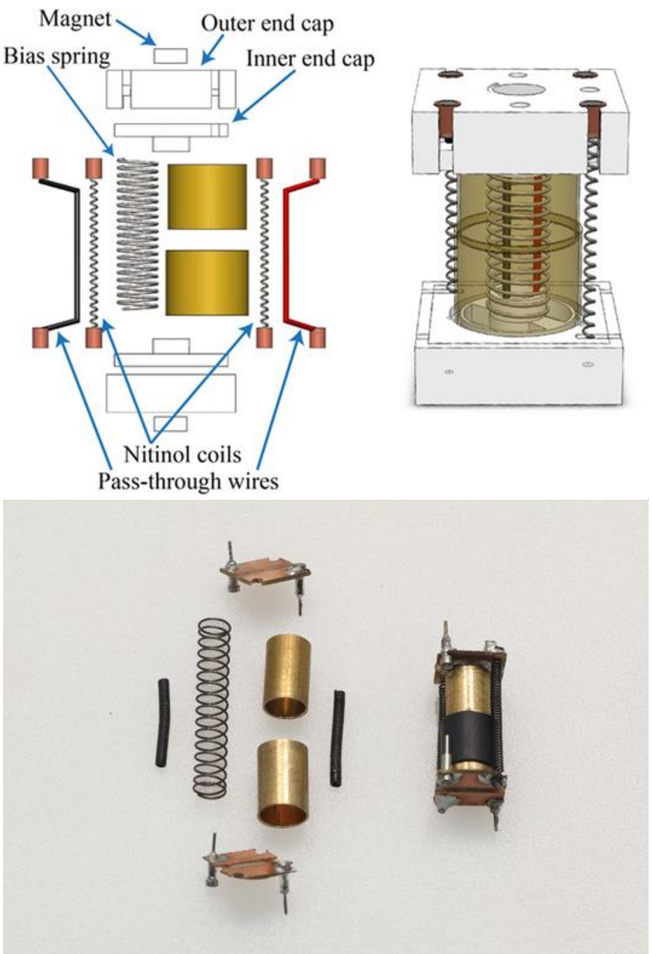

Fig. 1 Improvements to Active Cells in scaling, fabrication and performance (top: original prototype, bottom: new active cell).

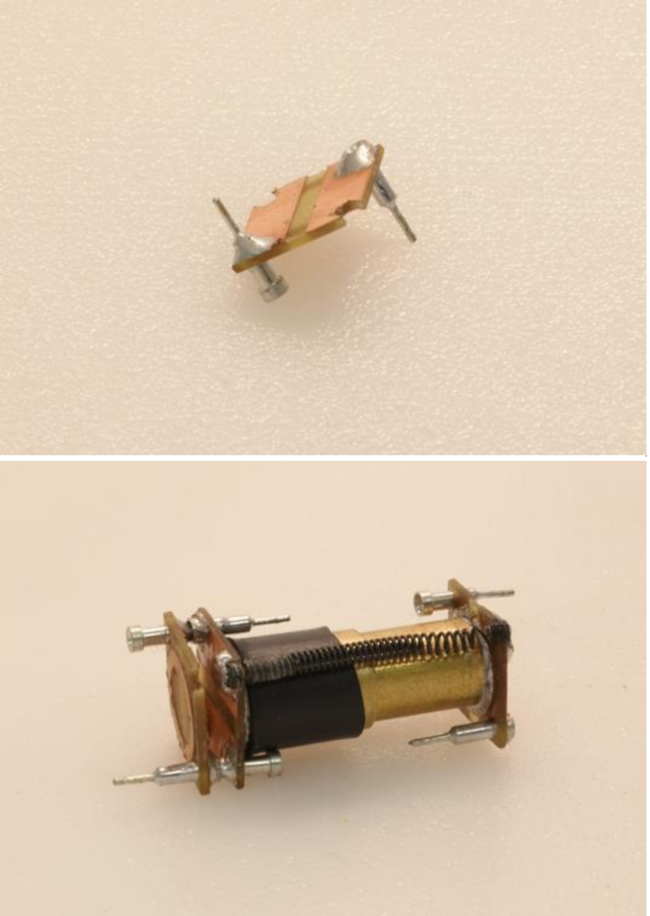

Fig. 2 Pin connections (top) to improve inter-cell contact. Lower contact resistance causes less heat buildup at the end-caps. Adjacent cells are also held close to each other (bottom), enabling compact assembly.

Our initial efforts engineered a simple rapidly prototyped cell that used shape-memory alloy (SMA) as the contractile element that was activated by resistive heating from an off-board power signal.

Related work:

The concept of creating actuated materials is not new. Existing work has focused on creating reconfigurable robotic modules [2,3], foldable or deformable composite structures [4,5], and rigid structure through magnetically joining “pebbles” [6]. An important related inspiration is in the study of variable geometry trusses and adaptive structures, which explore many of the concepts our work implements [7,8].

Almost all of the previous approaches were motivated by the allowable form-factors for a particular compositing process. Explored processes include laminar compositing of shape memory materials with epoxies, silicates, and other metals [9,10], Nitinol reinforced concrete [11], and flexible rods with low-count shape memory fiber [12,13].

More recent work more closely related to our approach has been the encasing of a Nitinol braid into a tube or solid sphere [14] and the creation of a cellular material where the pressure in each chamber affects the bulk material properties [15]. Our previous work considers the packing of cells for connectivity [16,17], neglecting any specific cell design, and our other work presented previously at this conference uses a similar approach of considering “cells of materials” for conductive pathways [18].

One of the key differences between this work and previous approaches to “smart materials” methods is the simplicity of the cells’ *designs*, as well as their *assembly*; the proposed designs use easily fabricated fiberglass cells with Nitinol coils to create contractions of the cell. We take a design-oriented approach, where the user can design the active element and choose any the assembly architecture to better tune the overall structural and deformation properties.

CELL DEVELOPMENT

The choice of actuation using Nitinol requires the corresponding selection of a biasing mechanism that allows the contracted cell to return to its rest position. The selection of such a biasing spring is a non-trivial exercise, requiring the evaluation of the austenitic and martensitic phase change that brings about the effective stroke of the cell, alongside the stiffness of the biasing spring. The procedure for determining the rest length and stiffness of this bias spring is detailed in our prior work [19].

Structural changes:

To scale down the cells (previous cells were approximately 1 in square in cross section, with rest length of about 1.5 in.), we used 1 cm^2 fiberglass boards as end-caps to the cells, allowing the incorporation of connectors as well as the brass tubing on one board. We further reduced the wiring for a second power channel through the cells: while this reduced the operational bandwidth of any series of cells, it further scaled down the cell size and simplified fabrication methods. The rest of length of a cell is approximately 1.75 cm. A fully contracted cell is approximately 1cm long.

Inter-cell connections:

An important consideration in the feasibility of multicellular structures is the inter-cell interfacing mechanism. Initial testing with magnetic latching methods illustrated the difficulty of having four points of contact between adjacent cells, since any backlash during motion would weaken or break inter-cell contact. To solve this problem, we used a pair of electrical pins on each face of the cell to establish reliable contact between cells (Fig. 2).

MULTI-CELL STRUCTURES

The feasibility of using Active Cells to create large-scale structures depends largely on the ability to connect cells in large numbers. We tested the scalability of such connections using rapidly prototyped “nodes” that connected to a variable number of cells. The cells and nodes thus formed a network of edges and vertices respectively, where every node (and cell connections terminating at that node) is internally connected to maintain a particular potential given the distribution of power sources in the network.

Interconnecting nodes:

Nodes in this multi-cell network are designed to be common points of contact for several cells. While electrically a node is a single-potential location in the large circuit that is the cell network, a node must also appropriately transmit the mechanical deformations that occur through cells contracting. Each node contains a cell-coupler that mimics the end-cap of the cell, and is thus easily connected and disconnected from adjacent cells. During normal operation, the connection force threshold is lower than expected, allowing the node to maintain low connection resistance and keeping interfacial power dissipation low. Additionally, the cell-couplers branching out from a node meet at a pin joint in the center of the node, allowing free relative rotations about this center.

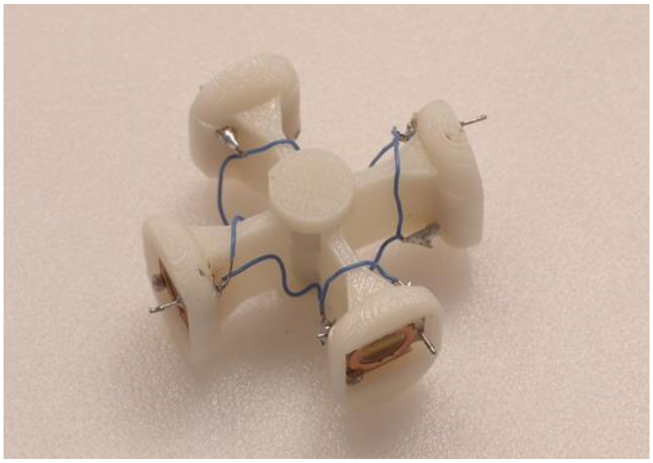

Fig. 3 Single interconnecting node in active cell network.

Fig. 5 Simple active cell network: square grid. Four nodes connect four links (cells). Activation of cells involves setting a potential difference between any pair of nodes. Inset shows alternative starting state.

Fig. 6 Triangular active cell network: demonstrates the use of the pin joint (node) in the network to create planar structures.

Fig. 4 Mechanical mates between cells and nodes. Multiple links (cells) can meet at a node. Each node mechanically acts as a pin joint.

Effectively, simply connecting cells and nodes together creates a kinematically mobile series-parallel network of resistances. Each cell in this network has a known resistance and each node allows several such resistances to be electrically connected while simultaneously allowing rotations at each of the connections.

Simple articulated structures:

In order to demonstrate these multi-cellular structures, we first connected four Active cells in a square grid using four nodes (Fig. 5). This structure is structurally simple and has predictable performance when the cells are activated. To activate a given cell, an electrical potential difference is applied at the two adjacent nodes to that cell. Naturally, such a potential difference causes current to flow in two parallel paths, with 75% of the input current flowing through the selected cell and 25% of the input current flowing through the remaining three cells. By keeping the voltage difference on for a small amount of time, the

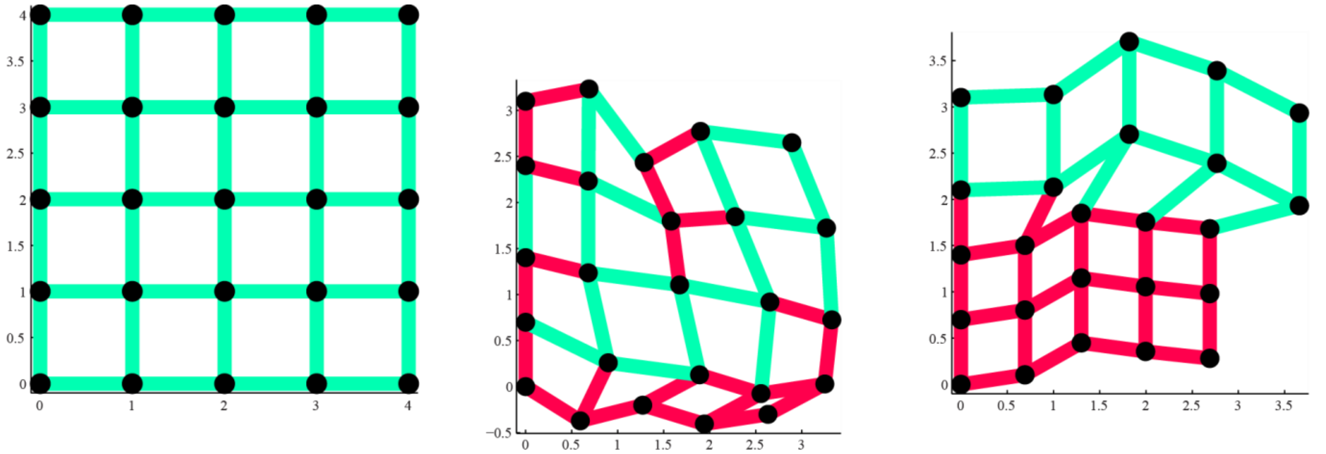

Fig. 7 A network of cells in the nominal state (Left) and two different activation schemes (Center and Right). In each configuration, the cells that are active are shown in red and the cells that are inactive are shown in green.

selected cell is activated and the cell contracts, while the remaining cells do not.

A second simple structure uses three cells and three nodes arranged in a triangle (Fig. 6). Activated as the square-grid, this structure demonstrates the possibility to tile large surfaces with polygons, modifying the local geometry and stiffness by selectively activating cells.

In the absence of boundary constraints on the cell structures, the entire structure deforms as any local deformations take place. If the structure's external boundary is fixed, any local deformations cannot deform the structure, but instead translates to local stiffness changes. Both global deformations and selective stiffness changes are thus realizable goals for active cell structures.

INCREASING STRUCTURAL SCALE

The practical success of building simple structures using Active Cells begs several questions about scalability. Among these, an important first step is to investigate the control large networks of cells. Simulations into the structural deformations of a network of nodes and contractile links show the importance of physically grounding nodes in a large structure. Fixed and selectively-mobile nodes create widely varying structural response to cell activation.

Simulations:

While this paper has focused primarily on the building blocks that will be used to form larger structures (see Fig. 5 and 6), we have conducted preliminary experiments to assess both these building blocks as well as larger ensembles of cells arranged in a plane.

In Fig. 7, we show the results of three simulations in which we solve for the position of cells in a rectangular grid. Here, we assume that the cells on the left of the structure are still allowed to move along the Y-axis, but their position along the X-axis is fixed. The configuration of the structure is determine by finding a static equilibrium that minimizes the stored elastic energy over all cells. The cells that are in their relaxed state (Martensitic Nitinol elements) are shown in green, while the cell in their contracted state (Austenitic Nitinol elements) are shown in red.

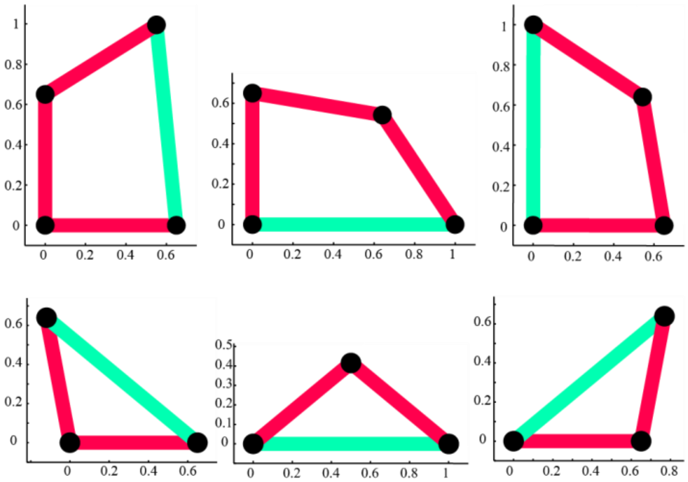

Fig. 8 Two potential basic building blocks of larger structure: (Top) square lattice of cells and (Bottom) triangular lattice of cells in three different configurations of active/inactive cells. In each configuration, the cells that are active are shown in red and the cells that are inactive are shown in green.

The network of cells in Fig. 7 is shown with cells connected on a rectangular grid, however other basic geometric elements are also possible. In Fig. 8 we demonstrate through simulation multiple configurations of two different potential building blocks for structures made of active cells. The number of potential open space deformations is $\binom{n}{k}$, where n is the number of sides and k is the number of actuated sides. Here, as previously, the inactive cells are shown in green and the contracted cells are shown in red

In the literature, most variable geometry trusses are designed with links that are rigid linear actuators, and as such, determining the position and orientation of the points on the truss is an extremely difficult and computationally intensive problem of solving the highly parallel inverse kinematics. On the other hand the analysis of the shape of the structures we propose is a much simpler process, though still somewhat computationally expensive, of finding the minimum energy configuration of the ensemble of cells. Thus, our simulations assumed we start at a known configuration of the system and we perform a minimization of the stored elastic energy of the system to solve for the current configuration of the ensemble.

Hardware implementation:

This simulation framework for determining the configuration of deformed structures of actives cells will provide methods for both determining structure given control inputs, as well as for validation of models. We are currently in the process of fabricating a sufficient number of cells and interconnects to perform larger scale testing of structure made of these active cells. The planned hardware implementations will also provide a test bed for further research into control systems appropriate for controlling both the stiffnesses and deformation of the structures as a whole, as well as for localized stiffness and deformation control.

CONCLUSION

We describe the design of improved Active Cells: electromechanical contractile elements able to be connected to each other and to rapidly-prototyped attachment nodes to create large-scale structures. We describe preliminary efforts at creating these macrostructures targeted towards one of two major applications: large-scale external deformations of the global structure through activation of internal cells, and stiffness changes in the structure using selective cell activation when fixed boundary conditions exist in the structure. By establishing the feasibility of studying modular macrostructures using Active Cells, this paper opens up the possibility of further research into important mathematical and engineering problems associated with such macrostructures.

ACKNOWLEDGMENTS

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