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Active cells for redundant and configurable articulated structures

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Abstract

The proposed research effort explores the development of *active cells*—simple contractile electro-mechanical units that can be used as the material basis for larger articulable structures. Each cell, which might be considered a 'muscle unit,' consists of a contractile Nitinol Shape Memory Alloy (SMA) core with conductive terminals. Large numbers of these cells might be combined and externally powered to change phase, contracting to either articulate with a large strain or increase the stiffness of the ensemble, depending on the cell design. Unlike traditional work in modular robotics, the approach presented here focuses on cells that have a simplistic design and function, are inexpensive to fabricate, and are eventually scalable to sub-millimeter sizes, working toward our vision of articulated and robotic structures that can be custom-fabricated from large numbers of general cell units, similar to biological structures. In this paper, we present the design of the active cells and demonstrate their usage with three articulated structures built with them.

Keywords: active structures, modular robot, shape-memory alloy

(Some figures may appear in colour only in the online journal)

1. Introduction

The focus of this paper is in the creation of a class of articulated structures from simple 'robotic' cells. While the approach has elements similar to work in modular robotics, the described work greatly differs in the simplicity of the cells and their ability to scale in terms of size of construction. These cells (shown in figure 1) are intentionally simplistic such that they are easy to fabricate (with a very small number of parts) and also hold the promise that the principal concept can be scaled to be much smaller in size (eventually submillimeter scale). The long-term goal of the project is the development of electromechanical composite materials made of a large number of tiny contractile engineered cells that serve as the building blocks for larger articulated or variablestiffness structures (e.g. figure 2). This cell-based approach, which has been largely overlooked in engineered systems, is ubiquitous in biology—groups of similar cells form tissues, groups of tissues form organs, and groups of organs form complex organisms.

There has been a fairly large amount of research in modular and reconfigurable robots, the majority of which rely on 'units' that are self-contained robots themselves, complete with their own suite of actuators (generally for mobility), sensors, and control electronics, resulting in systems with fundamental lower limits on the sizes that can be achieved. Alternatively, we are working toward a much simpler concept of electromechanical units that we call 'active cells,' inspired by biological systems wherein essentially all multicellular organisms are comprised of specialized cells that together form complex systems. As a specific example of where many similar specialized cells are co-located, the human heart is comprised of only two active-cell types (myocardiocytes and cardiac pacemaker cells) within the extracellular matrix [1],



Figure 1. An exploded view of the assembly of an active cell (left) and a fully assembled cell (right). Each Nitinol coil and pass-through wire, with their copper terminals, are prepared previously to assembly. Then, the brass tubing is attached to the inner end-cap piece and the magnets are attached to the outer end-cap piece with cyanoacrylate. The final step is simple assembly of the constituent pieces.

(through Joule heating for Nitinol), and the lack of required complicated complementary structures (in contrast to common Lorentz force actuators, for example, which generally require bearings, magnets, and a physical or electronic means of commutation between coils). As with the biological muscle cells, these simple and largely homogeneous cells are simultaneously structural and contractile, but unlike most modular robots, are neither self-assembling nor selfreconfiguring.

Nearly all existing approaches to modular robots can be classified as either being very general purpose (with the necessary attendant complexity) or simple but mostly passive components. In terms of the former, there have been a number of very impressive projects involving highly capable generalpurpose modular robots, including CKBots [7] and SMORES [8]. Additionally, much of the theoretical consideration for modular and cellular robotics was presented by Fukuda and Ueyama [9], which parlays into the expanding field of cooperative and distributed robotics (e.g. [10, 11]). Thorough reviews of the work in the area prior to 2009 are found in [12, 13].



Figure 2. Potential applications—muscle contraction in the heart (left), peristaltic locomotion in earthworms (center), and whole aircraft deformation (right).

with skeletal muscle generally comprised of a single myocyte type within an extracellular matrix.

In a previous work, we studied the design of the conductive surfaces of contractile cells utilized in large groups to create large conductive structures [2], experimentally demonstrating purely conductive structures consisting of hundreds of cells with passive cell-to-cell contacts [3], and designing methods of creating active cells with parallel bias elements [4, 5]. In this paper, we extend that work by exploring the development of the contractile aspect of the cell, investigating the implementation of active material actuator elements (Nitinol Shape Memory Alloy (SMA)) and antagonist passive springs, implemented in modular cell blocks that are reconfigurable. While Nitinol has limitations in terms of thermodynamic inefficiencies and achievable bandwidth, it has relatively good achievable strain and is more durable than other material actuators [6]. Material actuators are generally desirable due to their potential to be utilized at very small scales, simple powering schemes On the spectrum of the simpler modular robot projects, roBlocks [14] (later commercialized as Cubelets by Modular Robotics LLC), are single-function blocks but are not particularly simple in terms of design. A related approach to simple, crystalline-based robots that achieved volume change through linear actuators in all directions was developed by Rus and Vona [15]. Recent examples of simple modules that are mostly passive, e.g. they only deal with latching and unlatching, are given by Moses and Chirikjian [16], Gilpin *et al* [17], and Tolley *et al* [18]. Perhaps the most impressive, more general-purpose modular robot to date is called 'Mill-Moteins' [19]—this seems to be the first effort that has achieved scales on the order of 1 cm per module and has actuation, rather than just latching.

Unlike these and other related work, we are working toward very simple modular 'cells' that are both structural and contractile, with an eye toward eventual miniaturization and easy mass production. We begin this paper with a description of the design of the Nitinol-based contractile element of the cell (section 2), followed by a description of the design of the mechanical cell housing and electrical interconnects (section 3). Next, we present several proof-of-concept experimental demonstrations of a small groups of cells, arranged in various configurations as active structures: a parallel platform, an inchworm robot, and a rolling structure (section 4). We conclude with a discussion on the contributions and limitations of the current approach and identify the next steps for future work (section 5).

2. Cell contractile element

The choice of SMA Nitinol as the primary method of actuation, coupled with the goal of a minimalist approach to engineering the structure of the active cells, sets forth specific design challenges. Nitinol has fundamental limitation in terms of thermodynamic efficiency [20]; however several efforts in both miniaturization [21–23] and micro-machining or laser etching [24–26] has shown Nitinol to be feasible for making scalable actuators, as opposed to magnetic or electrostatic actuation methods that have fundamental challenges at very small scales. The choice of Nitinol also drives many of the design decisions, such as the mechanical design of the cell, spring selection for a return force for the one-way SMA spring coils, and cell interconnects and mating, which are addressed in the following.

2.1. SMA-Nitinol

The desired eventual scale of the actuator cells (<10 mm) places strict limits on the complexity of the actuation mechanism, making an active-material actuator attractive (as opposed to a small electric motor, for instance). Our current concept exploits the shape memory effect of nickel-titanium (NiTi) SMAs. SMAs have the distinct advantage of being highly compact and requiring little overhead in terms of drive electronics. The direct electrical interfacing and ease of integration make them apropos for this application. NiTi, the most widely available SMA, can exert high forces and sustain large stresses when the ends of a NiTi wire are constrained and transitioned from the martensitic to austenitic phase [27]. Conversely, many other active material actuators, such as electro-active polymers and piezoelectric cells, allow either limited stresses or very low achievable strains, making them less suitable. NiTi is durable, inexpensive, and can achieve large strains when heated.

NiTi SMAs have their own inherent limitations, however. The mechanism by which they actuate stems from a phase change phenomenon in which the crystalline lattice of the metal transitions from austenitic structure to martensitic structure on cooling. Heating causes the crystalline domains to transition to the more compact austenitic lattice form, inducing a strain in the material. In commercial NiTi SMAs, this strain is currently limited to approximately 4% for straight drawn wire in tension for repeatable, non-deteriorating cycling of the shape memory effect. Additionally, SMA is a unidirectional actuator—an external restoring stress must be applied to strain it to its detwinned state. The SMA must then be heated to revert back to the more-dense austenitic lattice (see figure 3). Despite these limitations, however, we believe it is the most reasonable option for the proposed work because it provides the potential for miniaturization (although the engineering challenges of miniaturization are not addressed in this paper).

Another engineering challenge with using Nitinol is creating reliable electrical and mechanical connections [28]. Nitinol manufacturing involves heat treatment in an oxygen atmosphere, leaving a thick oxide layer that acts as a passivation layer and makes it difficult to create reliable conductive connections using basic solders. Designers often resort to a combination of either abrasives or etchants, specialized fluxes (like Indalloy Flux #2 or #3, Indium Corporation, 2013), and subsequent soldering to make a strong mechanical and electrical connection. Another common solution is a mechanical crimp that scrapes and penetrates the oxide layer to provide the connection.

In our design, we created our own custom Nitinol coils (shown as the black 'springs' on the outside of the cells in figure 1) by creating a close winding of 0.3 mm diameter Flexinol wire around 1 mm diameter music wire. By making coils, rather than using the manufacturer-provided straight drawn wire, we are able to trade off the stress and strain capabilities of the Nitinol. The coil on the music wire was clamped at both ends during heat treatment. To set the memory shape, the coil was heated with a butane torch and quenched in cold water. Although using a torch to bring the Nitinol to a temperature through visual inspection of color change is much less precise than other techniques involving highly controlled ovens, this method did provide the ability to easily create long lengths of coil, and we still achieved high repeatability in spring properties across batches of coils (see section 2.2 for a discussion on return spring optimization).

We cut the coil to the appropriate length, leaving four extra coils at each end of the length, and pot soldered the Nitinol inside a small piece of copper tubing as shown in figure 4. This method is advantageous because the Nitinol coil exits the terminal at an angle consistent with the spring pitch and helps avoid stress concentration and permanent plastic deformation from occurring near the terminals. The process of manufacturing straight-drawn Nitinol wires into spring coils provides several design parameters for choosing the two spring stiffnesses for the austenitic and martensitic phases, K_a and K_m , respectively. The ideal model of a wound spring specifies the spring constant as a function of the material properties and the geometry, namely

$$K = \frac{Gd^4}{8 N D^3},\tag{1}$$

where K is the spring constant in N/m, G is the shear modulus of the material, d is the diameter of the Nitinol wire, N is the number of turns in the coil, and D is the mean diameter of the coil. This ideal is valid for both compression and extension, assuming the coil is not at a hard-stop if in compression; it has not been extended past the point of allowable detwinning and



Figure 3. Nitinol SMA activation cycle.



Figure 4. Bonding Nitinol coil to copper electrode through a potsolder technique in copper tubing. The photo shows a completed soldered electrode (left) and a tube and coil prepared for bonding (right).

entered the region of permanent plastic deformation, and buckling has not occurred (if in compression). Thus, the spring design can be separated into aspects that are materialdependent, G_a and G_m being the austenitic and martensitic shear moduli into aspects that are geometric, namely the wire diameter, coil diameter, and number of turns. Usually the material properties are fixed given a specific forming and annealing process, but the remaining parameters allowed us to generate Nitinol springs with a wide range of stiffness properties given the geometries of the cell design described previously. After the properties of the Nitinol spring were identified, the bias spring selection remained to complete a two-way Nitinol actuator.

2.2. Bias/return spring selection

One of the most critical aspects of the active-cell design was choosing a bias/return spring that maximizes the recoverable strain of the cell. Most designs have relied upon tension



Figure 5. Choosing the return spring for parallel spring configuration. The Austenite and Martensite stiffness curves (bottom) represent 3 different Nitinol pieces created in two different batches of forming and annealing. Spring properties were consistent despite crude annealing techniques.

springs for the return spring. Here, we chose to use a spring that is in parallel with the Nitinol springs to make the design more compact and approximately cubic when in the compressed state, whereas the parallel design is much longer and thinner to achieve the same strain. While devices with the bias spring in parallel with the Nitinol spring are kinematically identical to the series design, the parallel spring presented two other design challenges: (1) the diameters of the return spring coils needed to be fairly large compared to the length of the return spring to prevent buckling and (2) we had to find a spring manufacturer that made appropriately designed springs. Because the spring is in parallel with the Nitinol coils, this became a problem of first identifying the forcedisplacement curves for our Nitinol coils for both the austenitic and martensitic phases, then choosing a spring with a force-displacement profile such that the equilibrium positions maximized the cell displacement.

Figure 5 illustrates the process of finding a bias spring that provided the maximum recoverable strain of the active cell. In figure 5 (top), the bias return spring has a stiffness of K_s and a rest length of ℓ_0 . The Nitinol coil has an apparent stiffness in extension of K_M when in the martensitic phase and stiffness of K_A when in the austenitic phase, with a memory length of L_0 . Figure 5 (top left) illustrates that typically the rest length of the return spring is longer than the memory rest length of the Nitinol coil. This ensures that the Nitinol coil is always in tension, while the return spring is always in compression. As the ends of the Nitinol coil and the return spring are fixed, as shown in figure 5 (top right), the length of the two together will achieve a static equilibrium somewhere

between L_0 and ℓ_0 . When the Nitinol is in the martensitic state, the return spring will detwin the Nitinol coil and the static equilibrium will be nearer to ℓ_0 . However, when the Nitinol coil is in the austenitic state, the static equilibrium will be closer to L_0 .

This static equilibrium can be seen pictorially in figure 5 (bottom). Here, the extension of zero on the x axis indicates the memory rest length of the Nitinol, ℓ_0 . The red curve indicates the spring stiffness curve of the Nitinol coil as it is tensioned while in the austenitic phase. The gray curve indicates the apparent spring stiffness curve of the Nitinol coil as it is tensioned while in the martensitic phase. We say 'apparent' spring stiffness in this case because as the martensitic coil is extended, it is actually detwinning after a short period of initial elastic deformation, rather than just elastically deforming. This can be seen in the plot as we periodically relaxed the martensitic Nitinol coil and it returned to a zero force state, but at a different extension offset. The blue line indicates the spring stiffness of the return spring as it is compressed from its rest length. In these particular experimentally determined curves in figure 5 (bottom), the rest length of the return spring was 34 mm longer than the memory rest length of the Nitinol coil, $\ell_0 - L_0 = 34$ mm. In this pictorial formulation, the static equilibrium for both the martenstic and austenitic phases of the Nitinol coil can be determined by the points at which the return spring stiffness curve intersects each of the martensitic and austenitic coil spring stiffness curves. In this design methodology, the recoverable strain of the active cell will be determined by the total travel between the equilibrium points for the cold (martensitic) and hot (austenitic) configurations. The optimization of these coils for the maximum allowable strain, using linear springs, was accomplished by determining the maximum allowable return spring length that would not buckle and then optimizing the stroke length over all possible stiffnesses of commercially available springs with this desired length.

Ideally, one would use a constant force spring with magnitude near the point where unrecoverable plastic deformation begins to occur while in the martensitic phase. However, constant force springs on the scale of the active cells described in this paper (and even smaller moving forward) are not readily available. The next best spring selection then becomes the spring with the longest rest length and spring constant requisite to intersect the martensitic forcedisplacement curve near the point where unrecoverable plastic deformation begins. An important consideration when choosing springs is the spring buckling thresholds, which will determine the maximum rest length achievable as a function of both the spring diameter and the amount of compression that will occur. Figure 5 shows a repetition of the extension and release on an Instron testing system (Model 5542, Instron Corporation, Norwood, MA, USA) for both the austenitic and martensitic phases of the coil. A simple characterization done prior to the experiments shown in figure 5 was a destructive test, in which we continued the extension and release procedure until the coil began to exhibit permanent plastic deformation (at ~ 15 mm of extension). For this reason, we limited the range of motion caused by the bias spring to cause 9–10 mm of travel.

In the experiments described later, we operated the Nitinol coils by transitioning between the fully martensitic and fully austenitic phases, but more precise control can be achieved by characterizing the Nitinol actuation hysteresis and controlling the volume fraction of martensite and austenite in the coils.

3. Cell structure

3.1. Mechanical structure

The goal is to provide a structural framework that is as simple as possible and also provides (1) physical structure to each cell and (2) electrical and mechanical connection points between adjacent cells. The preliminary design, shown in figure 1, is characterized by a low number of parts, a single pre-assembly step, and a straightforward final assembly. Each cell is made up of only two Nitinol coils, two pass-through wires, two telescoping brass tubes, a bias spring, a magnet, and an inner and an outer end cap. The ends of the Nitinol coils and the pass-through wires are prepared as shown in figure 4, such that the pot-soldered copper tubing serves as both the electrical connection between cells and the mechanical connection within the cell. Each end cap is composed of an inner and outer piece. The inner pieces are attached to the telescoping tubes and have channels for the pass-through wires to be routed through the center of the tubes. The inner end cap has also an alignment feature to keep the bias spring centered within the telescoping tubes. The magnet is glued to the outer end cap with cyanoacrylate and the pass-through wires are attached to the end cap via press fit; the inner and outer end caps are fitted together. The final step is to manually compress the entire cell and insert the Nitinol coils into the press-fit features on opposing corners of the cell.

Here the parts were made with a three-dimensional (3D) printer to facilitate rapid iteration and modification in the early stages of this effort. However, all of the parts could have easily been constructed as molded (hard polyurethane) or machined (nylon or PTFE) pieces, which include the tubes that constrain the motion to a single degree of freedom. Here we used telescoping brass tubes that are manufactured to be used as close-fitting bearing surfaces.

Nitinol formed as extension springs with the memory shape set to the fully compressed configuration is a unidirectional actuator. Ohmic heating of the Nitinol and the transition to the austenitic lattice will return the coil to the fully compressed configuration. But subsequent cooling does not generally alter the shape of the Nitinol spring, barring the use of two-way shape memory effect (TWSME). The TWSME involves a fairly complicated training process and one of the directions of the two-way effect tends to degrade fairly quickly over repeated cycling [20]. For this reason, we



Figure 6. An illustration of the controller and conductive pathway for a linearly connected group of cells. (ChA = Power Channel A, ChB = Power Channel B, R_N = Effective resistance of a Nitinol coil).

have utilized the one-way shape memory effect and chosen a bias/return spring to extend the cell upon cooling.

3.2. Cell interconnects, power distribution, and control

Each end cap contains four of the pot-soldered terminals, two for the pass-through connections and two for the Nitinol connections. A magnet attached to the face of each end cap draws the four terminals together. The two pass-through terminals on each end are spring-loaded to prevent the case wherein manufacturing inaccuracies would prevent four planar contacts from being made robustly. Because of the four conductive pathways through each cell, we were able to create simple circuits for the ohmic heating of the Nitinol coils.

We created two channels where an end cap connects the conductive pathways that are on opposite corners of the cells, as shown in an example circuit for a linearly connected group of cells in figure 6. In this manner, we could set up cyclic patterns for the activation and relaxation of the active cells. Cells could be created with a single conductive pathway, but the choice of multiple pathways adds additional functionality with minimal added complexity. Other potential measures of minimal added complexity could involve simple passive electronics that makes the activation of active cells dependent on the direction of current flow or the frequency of electrical oscillation. This could allow the 'addressing' of individual cells, despite the single pathway and without the need from microcontrollers or localized intelligence.

4. Experimental implementation of groups of cells

To demonstrate the versatility of the cell concept to be used in a variety of active structures, three distinct devices created from groups of cells were implemented: a parallel platform made of three cells, a mobile inchworm made of four cells, and a pentagonal rolling robot made of five cells. In each of the configurations, the cells were actuated externally via a tether of wires, with power switching appropriately to effectuate the necessary sequence of actuation for a particular structure. The equations and principles governing the motion of the each of the active structures are presented according to

 Table 1. Active Cell Mechanical Properties

Property	Value
Active cell mass	17.775 +/- 0.548 g
Maximum tensile force	20.65 N
Uncontracted length	40.64 mm
Contracted length	30.48 mm
Tensile stiffness (martensitic Nitinol coils)	0.53 N mm^{-1}
Tensile stiffness (austenitic Nitiniol coils)	3.61 N mm^{-1}
Compressive stiffness	0.11 N mm^{-1}



Figure 7. Two configurations of the parallel robot platforms with legs composed of active cells. (Top) the nominal configuration with vertical normal. (Bottom) a tipped configuration with two activated cells.

the geometry. The mechanical and physical properties for the experiment are found in table 1.

4.1. Parallel robot platform made of three active cells

The first active structure created is a simple parallel platform composed of three active cells. In the language of parallel mechanisms, the platform can be described as a '3-PS' structure with one of the legs fixed and the other two allowed to slide across the surface of the ground. This allows the platform to be tipped, tilted, and lowered by activating the three cells that form the legs. Though the cells described in this paper were optimized for maximum displacement, the cells could alternatively be optimized for maximum variability in stiffness such that the stiffness of the platform could be modulated.

Figure 7 represents two different configurations of the platform, both the nominal structure with all the cells in the uncontracted state (top) as well as a configuration with two cells contracted (bottom). Sequences of platforms of cells could be chained together to create longer active structure



Figure 8. The nominal configuration (left) and the parallel robot platforms with each of the legs actuated individually (three figures on the right: blue dot indicates actuating cell).

with larger workspaces, such as non-modular solutions shown in [29, 30]. Additionally, combinations of platforms in sequence and parallel could be combined to form other variable geometry trusses.

The position, P, and normal vector, N, of the center of the triangular platform, as shown in figure 7, is given as

$$P = \frac{P_1 + P_2 + P_3}{3}$$
$$N = (P_2 - P_1) \times (P_3 - P_1)$$
(2)

where

$$P_{1} = (0,0, q_{1}),$$

$$P_{2} = (L_{12}, 0, q_{2}),$$

$$P_{3} = (L_{13} \cos (\alpha), L_{13} \sin (\alpha), q_{3}),$$

$$L_{ij} = \sqrt{L^{2} - (q_{i} - q_{j})^{2}},$$

and

$$\alpha = \cos^{-1} \left(\frac{L_{23}^2 - L_{13}^2 - L_{12}^2}{2L_{13}L_{12}} \right).$$
(3)

Here, P_1 , P_2 , and P_3 are the positions of the points where each leg attaches to the platform with respect to some coordinate system. The quantities q_1 , q_2 , and q_3 are the generalized coordinates describing the length of each leg, and L_{ij} is the length between the *i*th and *j*th leg on the platform. The angle α is the angle of the size of the platform connecting leg 1 and leg 3 from the horizontal.

Figure 8 shows the experimental platform in the nominal configuration (left) and three different achievable configurations with each of the cells contracted individually, either in the fully relaxed or fully contracted state. More precise control of the platform height and orientation can be achieved by feedback control of the Nitinol temperature or change in resistance [31–33].

4.2. Mobile inchworm made of four active cells

As a second experimental demonstration, a mobile inchworm was set up to demonstrate the performance of ensembles of active cells in series. Four cells were arranged in a line, as shown in figure 9, with the magnetic end caps providing an intrinsic polarity and alignment to the structure. Power was



Figure 9. Linear chain of four cells, demonstrating successful 'peristaltic' locomotion.



Figure 10. Linear chain of four cells, demonstrating successful electrical connections. Example showing 'peristaltic' locomotion.

switched to the cell network for a period of time (2 s), allowing the cells to contract fully, and then turned it off for 4 s, allowing the cells to relax (figure 10).

Since actuation of the active cells is from the shape memory effect, and the contraction of Nitinol is omnidirectional, it is necessary for complete actuation of the modular



Figure 11. The three configurations of the pentagonal structure of active cells use to roll the structure clockwise. (Left) the unactivated structure. (Center) two cells activated to move the center of mass left, but remaining to the right of the point of contact with the ground. (Right) two cells activate to move the center of mass to the right.

robot that cellular actuation be externally directed. To achieve this, a small metallic bristle was added to the end caps of the cells, all aligned in one direction when the cells are assembled end to end. This bristle provides an anisotropic frictional contact with the ground [27], allowing the group to inch forward in a peristaltic-like locomotion [28]; thus the entire motion occurs in the direction allowed by the bristle. Overall, this setup caused the group of four cells to contract and relax, all in one direction because of their aligned bristles in contact with the ground (made of a rough foam to increase friction). The group of cells forming this modular robot thus moves like an earthworm steadily forward.

The motile performance of the setup is evaluated simply as the rate of motion of the front (head) of the robot, and this was observed to be approximately 60 mm min^{-1} (about 6.5 mm motion forward in each full contraction and relaxation stroke). Although our experimental setup used direct powering of the cells, it is possible to optimize the use of the two power channels to provide faster locomotion.

4.3. Pentagonal rolling module made of five active cells

The final active structure is a circular deformable robot, with similarities to other non-modular examples [34–36]. The structure is actuated to roll forward by changing either the center of mass or the shape of the perimeter of the rolling structure. Figure 11 shows the pentagon robot in three distinct shapes used to roll the structure forward (top) and the accompanying changes in perimeter shape and center of mass (bottom). The center of mass (\bar{x} , \bar{y}) is calculated, assuming the center piece and the cells can be represented as point masses, as

$$\bar{x} = \frac{\sum_{i=1}^{5} m x_i}{M + \sum_{i=1}^{5} m}, \ \bar{y} = \frac{\sum_{i=1}^{5} m y_i}{M + \sum_{i=1}^{5} m}.$$
 (4)

where M is the mass of the center piece, m are the masses of

the active cells, and (x_i, y_i) is the position of the *i*th cell. The origin is defined at the middle of the center piece. When a cell is activated, the distance of the modeled point mass from the origin is decreased, thus affecting the overall center of mass of the entire structure and the shape of the enclosing membrane.

Figure 12 shows the experimental structure made of the active cells in the same three states as shown in figure 11 at three different stages of rolling forward. Though more complex control schemes with appropriate gaiting patterns could be used to provide continuous forward rolling motion, the approach taken in these experiments was to effectuate rolling in discrete steps using only the three shape changes shown in figure 12.

5. Conclusions and future work

In this paper, we have presented the design and prototype of 'active cells' and their use in implementing three simple modular active structures, with each cell being both loadbearing and contractile. Unlike traditional modular robotics, the approach presented here focuses on cells that have a simplistic design and function, are inexpensive to fabricate, and are eventually scalable to sub-millimeter sizes. By using shape-memory alloy (SMA) with a minimum amount of engineered structure necessary to provide cell-to-cell transmission of power and control, the approach works toward our vision of actuated structures that can be custom-fabricated from large numbers of general cell units, similar to biological structures.

One key problem remaining relates to the fabrication, modeling, and control of much more complicated articulated structures. This may involve both dimensional reductions from a large number of cell positions and orientations to lower dimensional representations of the overall structure shape, as well as better control algorithms to precisely control cell lengths and stiffnesses. Furthermore, structures that are not just chains of the cells but also have more material adhering between cells (akin to biological structures with an extracellular matrix) will require additional consideration in the mechanics of how cells interact.

The cells presented in this paper have clearly identifiable design improvements to improve further experimental use. The current cell design, while showing a large repeatable strain and having the desired level of mechanical simplicity, requires the connector caps of the cells to be modified in order to allow for lateral connections in addition to the linear connections, thus allowing truly 3D structures to be built. Efforts are currently underway to further miniaturize the cells to volumes 1 cm³ and smaller. Eventually, as in more complex biological systems, wherein a number of specialized cell types combine to make complex multicellular organisms, we intend to create additional types of active cells with complementary functions. Sensor cells that respond to external stimuli, controller cells that modulate signals as they are transmitted, as well as additional actuator cells that provide other simple



Figure 12. The pentagon roller making three steps to the left. The cells which are activated to proceed to the next step are indicated (blue dot) in each phase.

single-degree-of-freedom motions, such as shear or bending, will be created.

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