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Simple, Scalable Active Cells for Articulated Robot 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 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 towards our vision of robot structures that can be custom-fabricated from large numbers of general cell units, similar to biological structures.**

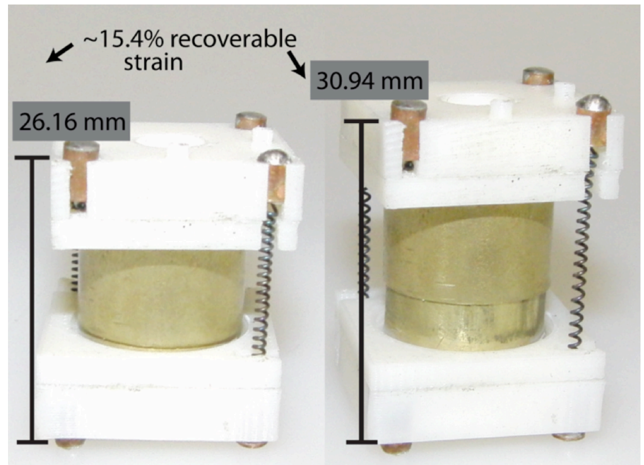

Fig 1. The repeatable motion of an active cell through ohmic heating of the Nitinol shape-memory alloy (SMA).

I. Introduction

The focus of this paper is a class of cellular robotics that are differentiated from existing work in re-configurable and self-replicating robotics by the simplicity of the cells and their ability to scale in terms of size of construction and method of actuation. These cells (shown in Fig. 1) are intentionally simplistic in their design and construction such that they are easy to fabricate (with a very small number of parts) and also hold the promise that the principle concept can be scaled to be much smaller in size (eventually sub-millimeter 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 variable-stiffness structures (e.g. Fig. 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 a system with fundamental lower limits on the sizes that can be achieved. Alternatively, we are working towards a much simpler concept of electromechanical units that we call '*active cells*', inspired by biological systems where essentially all multicellular organisms are comprised of specialized cells which together form complex systems. As a specific example 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], with skeletal muscle generally comprised of a single myocyte type within an extracellular matrix.

In previous work, we studied the design of the conductive surfaces of contractile cells utilized in large groups to create large conductive structures [2], as well as experimentally demonstrating purely conductive structures consisting of hundreds of cells with passive cell-to-cell contacts [3]. 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 better achievable strain and is more durable than other material actuators [4]. Material actuators are generally desirable due to their potential to be utilized at very small scale, simple powering schemes (through Joule heating for Nitinol), and lack of required complicated complementary structures (in

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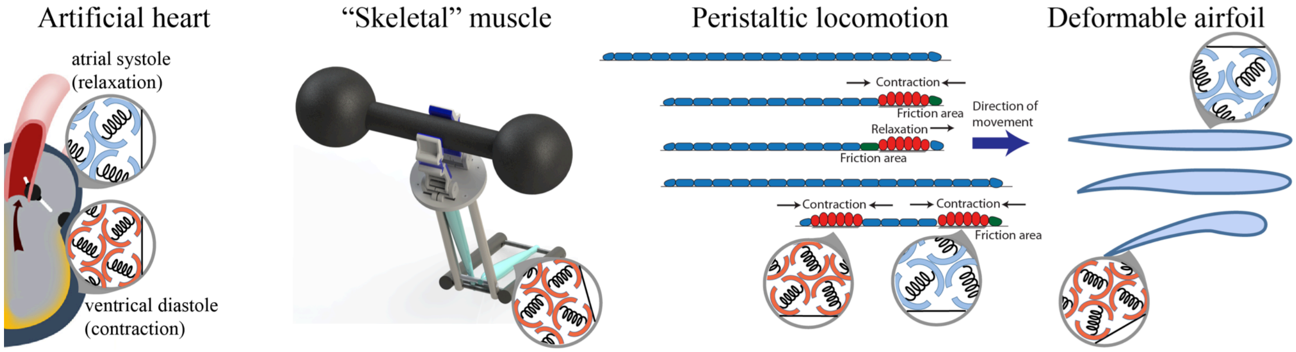

Fig. 2. Potential applications – muscle contraction in the heart and arm (left and left-center), peristaltic locomotion in earthworms (right-center), and whole aircraft deformation (right).

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 self-reconfiguring.

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 general purpose modular robots, including CKBots [5] and SMORES [6]. Additionally, much of the theoretical consideration for modular and cellular robotics was presented by Fukuda and Ueyama [7], which parlays into the expanding field of cooperative and distributed robotics (e.g. [8], [9]). Thorough reviews of the work in the area prior to 2009 are found in [10], [11].

On the spectrum of the simpler modular robot projects, roBlocks [12] (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 [13]. Recent example of simple modules that are mostly passive, e.g. they only deal with latching and unlatching, are given by Moses and Chirikjian [14], Gilpin et al. [15], and Tolley et al. [16]. Perhaps the most impressive more general purpose modular robot to date is called Milli-Moteins [17] – this seems to be the first effort that has achieved scales on the order of 1cm per module and has actuation, rather than just latching.

Unlike those and other related work, we are working towards very simple modular "cells" that are both structural and contractile, with an eye towards 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 II), followed by a description of the design of the mechanical cell housing and electrical interconnects (section III). Next we present a proof-of-concept experimental demonstration of a small group of cells, arranged as a linear chain performing a peristaltic-like locomotion pattern (section IV). We finish with a discussion of the contributions and limitations of the current approach and identify the next steps for future work (section V).

II. Cell Contractile Element

The choice of shape-memory alloy 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 [18], however efforts to miniaturize [19], [20], [21] and give microstructure [22], [23], [24] to Nitinol makes it a feasible method of actuation for scaling, as opposed to magnetic or electrostatic actuation methods which 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.

A. *Shape memory alloy – 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) Shape Memory Alloys (SMA). 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 makes them apropos for this application. NiTi, the most widely-available SMA can develop high stresses (approx. 100 MPa in the martensitic phase and 560 MPa in the austenitic phase) in wires of less than 0.5 mm thickness [25]. 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 shape memory alloys 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

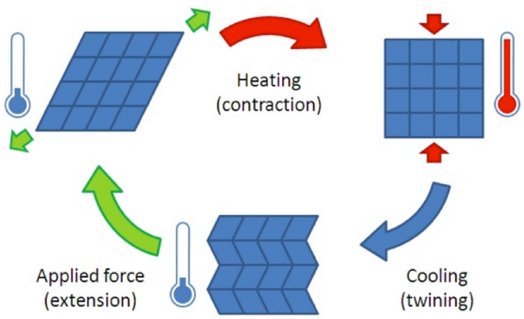

Fig. 3. Nitinol SMA activation cycle

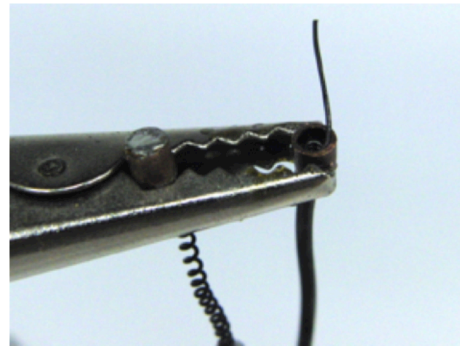
Fig. 4. Bonding Nitinol coil to copper electrode through a pot-solder technique in copper tubing. Left: completed electrode and Right: tube and coil read for bonding.

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 the more-dense austenitic lattice (see Fig. 3). Despite these limitations, however, we believe it is the most reasonable option for the proposed work because it provides the potential for miniaturization (though the engineering challenges of miniaturization are not addressed in this paper).

Another engineering challenge with using Nitinol is creating reliable electrical and mechanical connections [26]. Nitinol forms a thick oxide layer that makes it difficult to create reliable connections with basic solders. Designers often resort to a combination of either abrasives or etchant, 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 create our own custom Nitinol coils (shown as the black "springs" on the outside of the cells in Fig. 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 memory shape was set by fixing the ends of the Nitinol onto the music wire, heating with a butane torch, and quenching in cold water. Though 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 II.B. for a discussion of return spring optimization).

We cut the coil to the appropriate length, leaving 4 extra loops at each end of the length, and pot solder the Nitinol inside a small piece of copper tubing as shown in Fig. 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.

B. Bias/Return spring selection

One of the most critical aspects of the active cell design is choosing a bias/return spring that maximizes the recoverable strain of the cell. Most designs have relied upon tension spring for the return spring. Here, we chose to do a spring that is in parallel with the Nitinol springs to make the design more compact and approximately a cube when in the compressed state. This choice had two effects: (1) the diameter of the return spring coils need to be fairly large compared to the length of the return spring 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 becomes a problem of first identifying the force displacement 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 maximize the cell displacement.

Fig. 5 illustrates the process of finding a bias spring that provides the maximum recoverable strain of the active cell. 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 force displacement 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.

In this design, the Nitinol springs will always be acting as tension spring, whereas the return spring will always be in compression. In Fig. 5 (top) we see that given a phase state of the Nitinol coils, the length of the coil will be determined by the static equilibrium between the bias spring and the Nitinol coils. The extremes of these static equilibria are represented in Fig. 5 (bottom) by the points where the linear spring force displacement line crosses the Austenitic and Martensitic force displacement curves. The recoverable strain of the active cell will be determined by the total travel

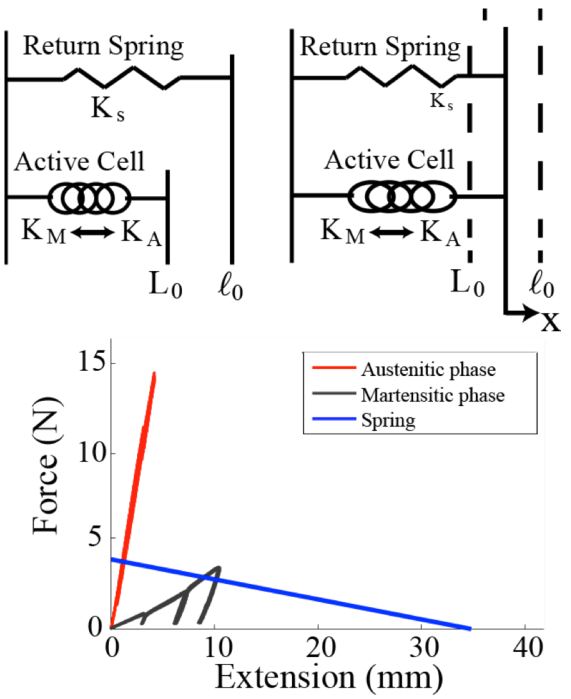

Fig. 5. Choosing the return spring for parallel spring configuration. The Austenite and Martensite stiffness curves (bottom) represent 3 different Nitinol pieces created in two different batches of forming and annealing. Spring properties were consistent despite crude annealing techniques.

between the equilibrium points for the cold (Martensitic) and hot (Austenitic) configurations. In the experiments described later, we operate 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.

III. Cell Structure

A. Mechanical Structure

The goal is to provide a structural framework that is as simple as possible that also provides (1) physical structure to each cell and (2) provides electrical and mechanical connection points between adjacent cells. The preliminary design, shown in Fig. 6, is characterized by a low number of parts, a single pre-assembly step, and straightforward final assembly. Each cell is made up only of two Nitinol coils, two pass-through wires, two telescoping brass tubes, a bias spring, a pair of magnets, and a pair of inner and outer end caps. The ends of the Nitinol coils and the pass-through wires are prepared as shown in Fig. 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 also has 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 and the inner and outer end caps are

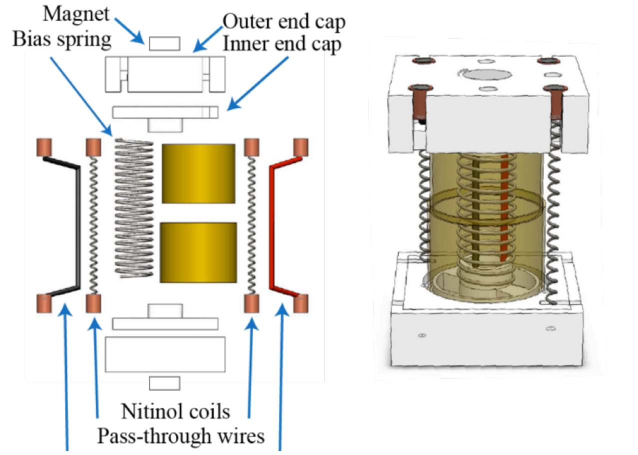

Fig. 6. An exploded view of the assembly of an active cell (left) and a fully assembled cell (right). Each Nitinol coil and pass-through wire, with their copper terminals, are prepared previously to assembly. Then, the brass tubing is attached to the inner end cap piece and the magnets are attached to the outer end cap piece with CA glue. The final step is simple assembly of the constituent pieces.

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.

Herein, the parts have been made with a 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 extensions 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 [18]. For this reason, we utilize the one-way shape memory effect and choose a

TABLE I. 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
Tensile stiffness (austenitic Nitiniol coils)	3.61 N/mm
Compressive stiffness	0.11 N/mm

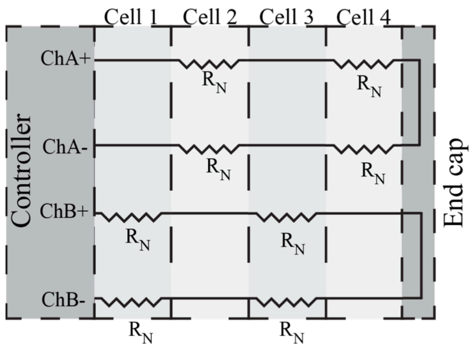

Fig. 7. An illustration of the controller and conductive pathway for a linearly connected group of cells.

bias/return spring to extend the cell upon cooling. A characterization of the mechanical characteristic of each cell is given in Table I. There are some variation in the uncontracted and contracted length based on slight variations in the length of the Nitinol coils and lengths of the brass tubes, where the table gives average values.

B. 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 outer face of each end cap draws the four terminals of two adjacent cells together. The two pass-through terminals on each end are spring loaded to prevent the case where manufacturing inaccuracies would prevent four planar contacts from being made robustly. Because of the 4 conductive pathways through each cell, we are able to create simple circuits for the ohmic heating of the Nitinol coils.

For the experiments shown later, we create two channels where an end cap connects the conductive pathways that are on opposite corners of the cells, as shown in Fig. 7. In this manner, we are able to set up cyclic patterns for the

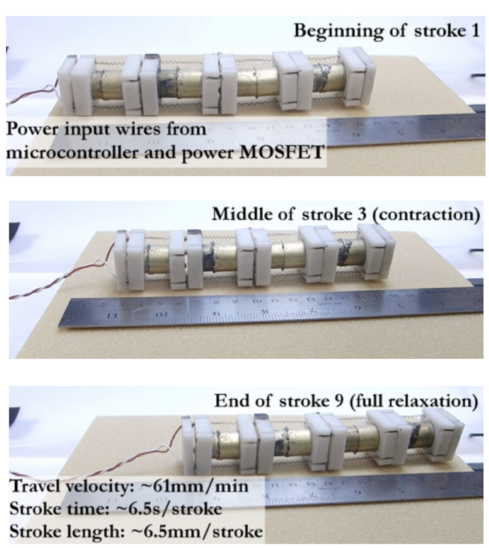

Fig. 8. Linear chain of four cells, demonstrating successful electrical connections. Example showing "peristalsis-like" locomotion.

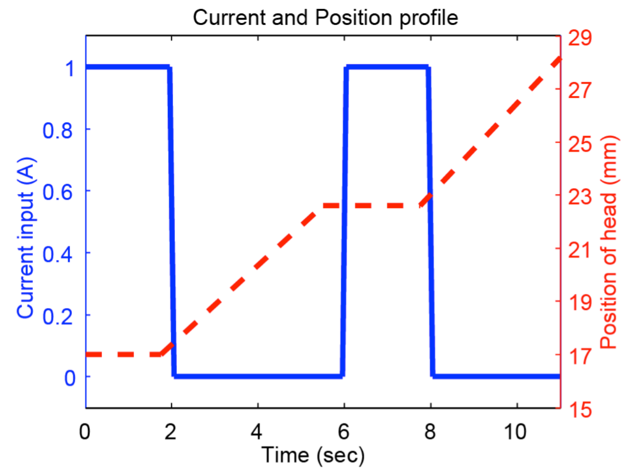

Fig. 9. The switched current input to the system (top) and the position of the head of the robot (bottom) during the course of two successive motion cycles.

activation and relaxation of the active cells. Cells could be created with a single conductive pathway, but the choice of multiple pathways added additional functionality with minimal added complexity. Other 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.

IV. Experimental Implementation of Groups of Cells

A simple experimental implementation was set up to demonstrate the function of the cells and the performance of ensembles of active cells. Four cells were fabricated, each approximately 2.5 cm long when contracted. The cells are arranged in a line, with the magnetic end-caps providing an intrinsic polarity and alignment to the structure (Fig. 8).

The microcontroller (PIC16F690) switched power to cell network for a period of time (2s), allowing the cells to contract fully, and then turned it off for 4s, allowing the cells to relax (Fig. 8). Power MOSFETs (IRF540) provided the necessary current (1A) to the network of cells when the microcontroller directed. The current input to the system as well as the position of the head of the robot is shown on Fig. 9.

Since actuation of the active cells is from the shape memory effect, and the contraction of Nitinol alone would not cause a motion necessary to move the chain of cells forward, it is necessary to introduce an asymmetry in the cells' contact with the ground. In this manner, a contraction of the cells will cause motion in a single forward direction.. 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 peristalsis-like locomotion [28] thus the entire motion occurs in the direction allowed by the bristle. Overall, this setup causes 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 60mm/min (about 6.5mm 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.

V. Conclusions and Future Work

In this paper, we presented the design and prototype of a "active cell" modular robot that is both load bearing 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 towards our vision of robot structures that can be custom-fabricated from large numbers of general cell units, similar to biological structures.

There are a number of immediate directions for future work on the topics presented in this paper. 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 will be modified in order to allow for lateral connections in addition to the linear connections, allowing truly three-dimensional structures to be built. Eventually, as in more complex biological systems, where 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, as well as controller cells that modulate signals as they are transmitted will be created, as well as additional actuator cells that provide other simple single degree of freedom motions, such as shear or bending.

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