Amoebots

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1 Introduction

The compliant nature of soft robots allows them to delicately interact with their environment. This property makes soft robots well suited for tasks such as manipulation and traversing difficult terrain. For years researchers have striven to design locomotive systems viable for use in search-and-rescue robots[1]. Whole skin locomotion is one such mode of locomotion[2].

Whole skin locomotion (WSL) is inspired by the movement of an amoeba, whose locomotion heavily depends pseudopods and cytoplasmic streaming. In this process, endoplasm flows into the developing pseudopod causing to grow forward away from the cell body. At the same time rear facing pseudopods are retracted into the cell. This motion allows amoebas to move effectively through its environment. In whole skin locomotion robots, an inverting torus is often used to mimic the effects of cytoplasmic streaming[2]. As the torus inverts the entire exterior facing membrane moves in the same direction and returns though the center.

WSL has several advantages compared to other common locomotive mechanisms such as two-anchor and wheeled locomotion. In two-anchor locomotion a robot uses anisotropic friction to move forward in by extending and contracting its body. In this system the forward pushing ability is limited by the difference in the coefficient of friction in the forward and backward direction.[1] This limits their viability in (cluttered) environment. Wheeled locomotion faces a similar limitation in that the friction force on the bottom half of the wheel has to be larger than the force on the top half. Most wheeled solutions simply prevent the top half from contacting the environment altogether, so this solution has limited utility in highly confined spaces. WSL does not face such limitations. "Since the entire skin is used for locomotion, the robot can move as long as any surface of the robot is in contact with the environment, be it the ground, walls or obstacles on the side, or the ceiling."[2]. This property would make the robot well suited for traversing tight spaces such as collapsed buildings or humane gastrointestinal tract[2].

There are two common models for WSL, solid concentric tube (CST) and a fluid filled torus (FFT). CST uses a flexible membrane wrapped around a solid core for structure. A FFT is a toroidal membrane filled with fluid such as air or water. The internal pressure of the fluid allows the membrane to retain its toroidal shape. Most computational analyses uses the CST model because it is much simpler when compared to FFT[2]. However, most physical experiments use a FFT because they are significantly easier to fabricate and are commercially available.

Several robots have been developed to explore the applications and viability of WSL. [3] shows a FFT filled with faro-fluid that can be manipulated using magnetic fields magnetic fields. In [5] a FFT was successfully driven using ionic polymer metal composites (IMPC). [2] shows an example of a shape memory alloy (SMA) actuated torus. The structure of this prototype is unique, its structure is supported by bend tape springs. While most WSL robots can be classified as soft, traditional WSL robots have been developed. [5] shows a snake like robot utilizes WSL. The robot is actuated by traditional DC motors.

In this paper we will describe the design and testing of a FFT actuated by shape memory alloy contractile rings.

1.1 Nitinol Coil Actuators

The drive system is actuated using Nitinol (NiTi) coil actuators.In straight wire, Nitinol can contract up to 7%. Longer stroke lengths can be achieve by annealing the wire in a coil[]. NiTi coil actuators can deform between 200% and 1600% depending on the coil geometry[6]. The force and stroke of a SMA coil actuator is depended on 4 factors, wire diameter, spring diameter, pitch angle and number of active coils[7].

The proposed drive system uses a series of SMA contractile rings. These rings to invert the torus by compressing the rear end and causing the liquid inside to flow forward. Each contractile ring is attached to the torus by four brackets evenly spaced around the torus membrane. An experiment was designed to determine how the bracket geometry effects the efficiency of the contractile ring. We hypothesized that longer brackets will invert the torus more effectively because the force on the end of the bracket will create a moment and actively push the torus inward. The experimental setup can be seen in figure 1. Two ropes are wrapped around opposing half of the torus. This is sketched in figure 2. When these ropes are pulled they roughly simulate a contractile ring. A similar mechanism is used to close drawstring bags. An instron machine was used to pull the ropes and measure the force needed to contract the torus. The pulley system allows the linear motion of the instron machine to pull both ropes and contract the torus.

1.2 Experimental Materials

Two sizes of FFT were used, each one can be purchased commercially under the product name water worm. The first FFT has an outer circumference of about 150mm and a length of 125mm. The size is smaller and only has an outer circumference of 110mm and a length of 100mm. The

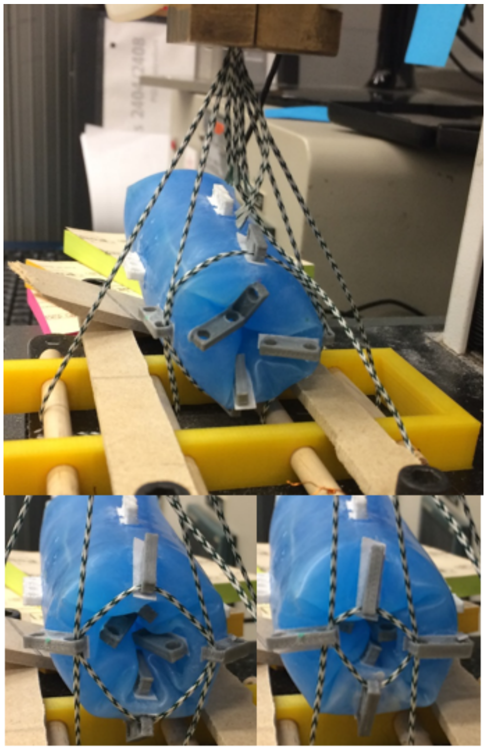

Fig. 1. Test setup to evaluate the contractile force used to invert a FFT.

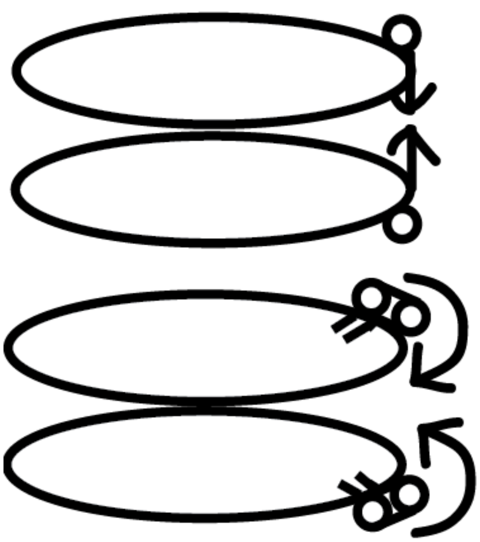

Fig. 2. (Top) With a point bracket the contractile force is pointed toward the rotational axis of the torus. (Bottom) With and elongated bracket, the lever are creates a moment that partly pushed the torus inward.

membrane materials are unknown, however it is believed to be a variant of vinyl. Four types of brackets were tested, point brackets hold a single contractile ring. Double brackets hold two contractile rings, they are defined by the center distance between the two rings (ie, a 0.25in double bracket separates the two rings by 0.25in. Figure 1 shows double brackets on a large FFT.

1.3 Experimental Procedure

1.3.1 Pulley Calibration

The use of the pulley adds an additional source of friction that needs to be accounted for during analyses. A simple procedure was developed to measure the friction of the pulley system. In this procedure we first measured the spring constant of a tension spring in a typical tensile test. We then measured the same spring again though the pulley system. Any increase in force required to extend the spring was attributed to friction in the pulley system. The coefficient of friction of the pulley system was determined to be 2.7.

1.3.2 Testing Procedure

Double brackets were spaced evenly so that the distance between rings is consistent between brackets. Single brackets were spaced so that the distance between each successive row increased by 0.125in. Double brackets were not tested on the smaller torus due to difficulties adhering them to the torus in each test, the small and large tori were contracted 50mm and 80mm respectively. Tests were repeated 5 times and the average force was taken for all tests. Figure 1 shows the force contracting plots of the double bracket tests for the larger torus. The results support the hypotheses that longer brackets invert the torus more effectively. As the brackets got longer the height of the first maxima decreased. However, not all longer brackets were found to be suitable for inversion. The 0.25in brackets frequently failed to enter the torus during contraction. This greatly increased the chance of jamming the torus. These results are promising, however, more research is needed to further investigate the interactions between elongated brackets and the toroidal membrane. Despite the apparent correlation between bracket length and inversion efficacy, the point brackets on the smaller torus required the smallest force to invert. It is hard to draw conclusions comparing the two tori because they were from different manufacturers and the material composition is unknown. We found the contractile force requirements measured during testing were conservative. Later in the design processed SMA contractile rings only capable of pulling 0.3N were able to reliably invert the torus. A more accurate test will be the subject of future research. For the rest of the design processes 0.3N was used as the minimum inversion force.

2 Contractile Ring Design

The contractile rings were fabricated by bending a linear SMA coil actuator around the outside of the torus. The stress strain curves de-twinning of NiTi is shown in the figure (x). The blue shows the stress needed to distort the wire in the Martensitic phase and the red in the Austenite phase. The curve of the martensitic phase is distinctly nonlinear. It has four parts, a linear phase as the Austenite phase experiences elastic deformation, a plaque caused by shear induced detwinning of the austenite phase into martensitic, and a second linear steeper phase where the martensitic experiences elastic deformation. The distance between points on the martensitic and austenite curve is the effective stoke of the actuator. [7] SMAs actuators are unidirectional and require an external stress to transition back to the martensitic phase.

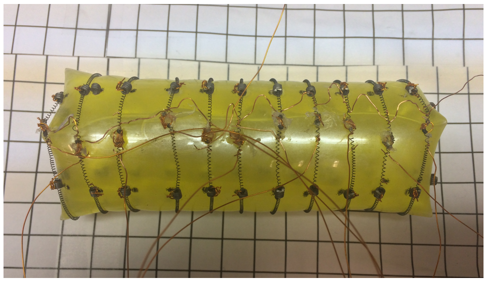

Fig. 3. Operational prototype of toroidal drive system.

For this robot uses the rotation of the torus to expand the rings on the front end. As a result it is vital to minimize the force required to de-twinned the actuator. We chose to limit the deformation of the actuator to 4% strain. This elongates the coil to the end of the plaque and allows it to have the largest stroke per deformation force.

2.1 Actuator Design

The coil actuator has to have a length 110mm equivalent to the outer circumference of the torus at 4% strain. Additionally additional should have a minimum length of 30mm. This gives the actuator a minimum desired stroke of 266%. The actuator must also have a minimum actuation force that exceeds 0.30N. Using these parameters and the framework described in [7] the coil actuator was designed. The resulting actuator is uses 0.15mm NiTi wire, has a diameter of 0.9mm and 150 active coils. It has a minimum length of 22mm, has a pull force of 0.59N and requires 25N to elongate.

3 Prototype

The final prototype is pictured in figure 3. It has 11 contractile rings spaced 9mm apart. Each ring is attached to the toridal membrane with 4 point brackets constructed out of a small coil of spring wire. Testing showed elongated brackets are more effective at inverting the torus however they could only be fabricated using thermoplastic and could be melted by the heat generated by the contractile ring. The water inside the torus acts as an effective heat sink, and prevents the contractile ring form melting the toriodal membrane. However, before the prototype is tested, it is chilled to about 35 degrees Fahrenheit as an added precaution.

4 Prototype Testing

Figure 4 shows prototype testing. Contractile rings were activated using a current of 0.4 amps. The prototype successfully rolled forward 50mm before actuator wire melted though the torus membrane.

5 Future Work

Prototype testing was limited due to incompatibility between the torus and contractile rings. When used at full power the contractile rings could easily melt though the membrane. This prevented us from fully assessing the capabilities of the prototype. Future work will focus on increasing heat dissipation. Current methods being investigate are passive evaporate cooling and ”space blankets” to absorb and reflect heat away from the membrane.

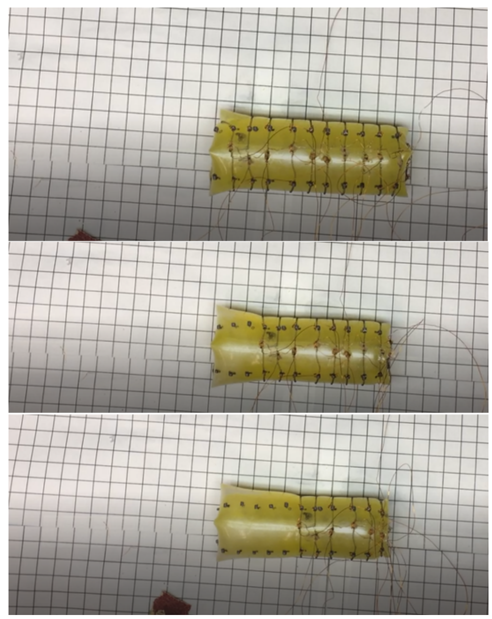

Fig. 4. Testing of toroial drive system.