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Actuation Mechanisms for Biologically Inspired Everting Toroidal Robots

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***Abstract*—Inspired by the pseudopod mobility mechanism found in amoebas, we propose a toroidal robot which can fold in on itself to generate the same overall motion of the amoeba. One of the advantages of such a robot is its ability to squeeze under obstacles and through holes smaller than its nominal diameter. These abilities make it particularly well suited for unstructured and highly constrained environments such as medical and search and rescue applications. We present several actuation mechanisms which are being investigated towards the development of an everting toroidal robot. For smaller scale applications, we present contracting ring actuators made up of shape memory alloy rings or electroactive polymer rings that create a differential stress and drive the motion. For larger scale applications, we present a tape spring mechanism which uses a membrane composed of treads arranged in a circular pattern. Another large scale mechanism uses a snake-like robot that can be formed into a torus which can ascend and descend cylindrical structures. We also present a chemical actuation method which utilizes chemically induced swelling in cross-linked polymers to produce forward motion. Finally, we describe a novel torus shaped actuator being developed which uses shape memory alloy rings to generate an everting motion.**

I. Introduction

An amoeba is composed of a liquid endoplasm which is free to flow inside a gel-like outer ectoplasm. The pseudopod mobility mechanism uses a process called cytoplasmic streaming, shown in Fig. 1, in which the endoplasm flows toward the front of the pseudopod where it turns into the gel-like ectoplasm, extending the pseudopod. At the same time, the ectoplasm at the back end of the cell turns back into the liquid endoplasm. The net effect of the endoplasm-ectoplasm transformations is the forward motion of the amoeba [1].

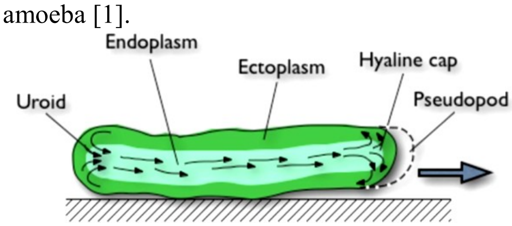

Fig.1. Cytoplasmic streaming in amoebas.

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II. Everting Toroidal Robots

Inspired by cytoplasmic streaming in amoebas, we present a locomotion mechanism in which a toroid shaped membrane folds in on itself to generate the same overall motion used by amoebas. The mechanism is similar, in principle, to the popular water wiggler toys. Toroidal robots using this principle would be capable of squeezing under obstacles and through holes smaller than their nominal diameter as shown in Fig. 2. These abilities make toroidal robots particularly well suited for the unstructured and highly constrained environments found in medical and search and rescue applications [2].

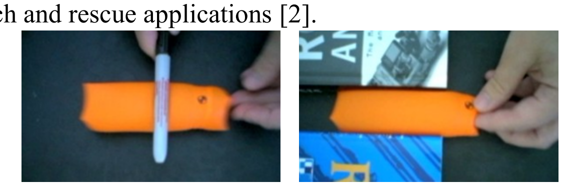

Fig.2. Fluid filled toroid model demonstrating the ability to squeeze under obstacles and through holes.

III. Actuation Mechanisms

A. Contracting Ring Actuators

One of the actuation mechanisms that can be used is contracting ring actuators. In this method, shape memory alloy (SMA) rings or electroactive polymer rings are used to compress one end of the toroid. The differential stress in the membrane causes it to fold in on itself while creating forward motion [3]. Fig. 3 shows two experiments in which active tension cords were used to investigate the feasibility of using contracting ring actuators. In the first experiment, the tension cords were activated sequentially, resulting in forward motion of the toroidal model. In the second experiment, the everting toroid successfully squeezed through a square hole with less than half on the model's cross-sectional area. These results demonstrate that, for small scale applications, contracting ring actuators are a feasible mechanism for propulsion as well as for squeezing through a hole.

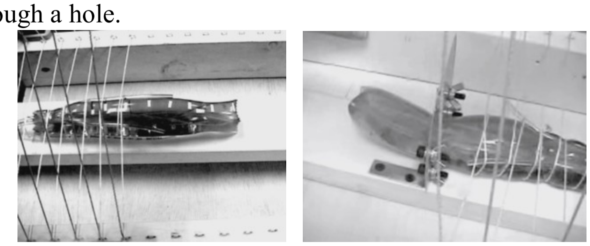

Fig.3. Everting toroid using contracting rings actuators for propulsion, and for traversing a hole.

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B. Larger Scale Mechanisms

For larger scale applications, other mechanisms are being considered. The first mechanism uses a statically stable tape-spring mechanism which is fully compliant yet can maintain its shape without an internal structure [4]. The second mechanism uses a snake like robot that is wrapped around a cylindrical structure into the shape of a torus. Each segment of the robot behaves as a universal joint. A nutating motion between the segments is converted into an everting motion in the whole body, allowing the robot to climb up and down the cylindrical structure [5].

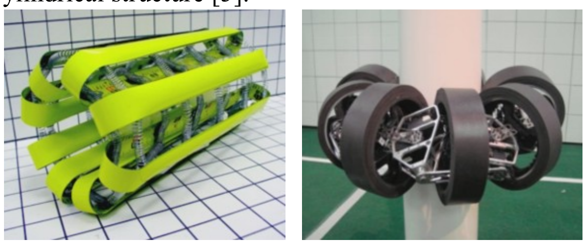

Fig.4. Statically stable tape-spring mechanism, and snake-like robot formed into a torus.

C. Chemically Induced Swelling

A propulsion force can also be generated using a chemically induced actuation method. It is well known that swelling occurs in cross-linked polymers upon absorbing a solvent [6], [7]. If the membrane of a toroidal robot is made of a cross-linked polymer, it will swell when exposed to a solvent. If solvent is only applied to one end, the swelling creates a differential stress in the membrane, causing the membrane to rotate and generates forward motion.

Fig. 5 shows an experiment in which this mechanism was successfully demonstrated using a fluid filled toroid model. Hexane, the solvent, was brushed onto a membrane made up of polydimethylsiloxane (PDMS). The result was a forward motion of 7.62cm in two seconds. Unfortunately, we found that this mechanism is not easily repeatable. To better study the swelling effect, another experiment was performed in which only a strip of PDMS was exposed to hexane. However, no observable change was seen in the strip, demonstrating that chemically induced swelling is difficult to recreate even under controlled conditions.

Because of these results, a better understanding is needed of the relationship between swelling and the amount of solvent, absorption time, and stress in the membrane. Other combinations of polymers and solvents should also be investigated to find a combination which is more repeatable.

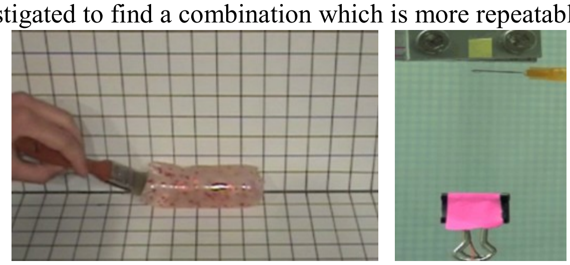

Fig.5. Chemically induced swelling being demonstrated with a fluid filled toroid model, and hexane being applied to a strip of PDMS.

D. Torus Shaped actuator

We are also developing a torus shaped actuator which uses SMA wires arranged in a circular patter along the entire length of the torus [8]. Fig. 6 shows a cutaway of the actuator and a circular cross-section with, in this case, eight SMA rings. The two red vectors represent SMA wires that are being actuated while the blue vectors represent wires not being actuated. By actuating the wires sequentially, the torus actuator generates an everting motion. Fig. 6 also shows a quarter segment of a prototype actuator that has been built and successfully rotated by actuating individual SMA wires.

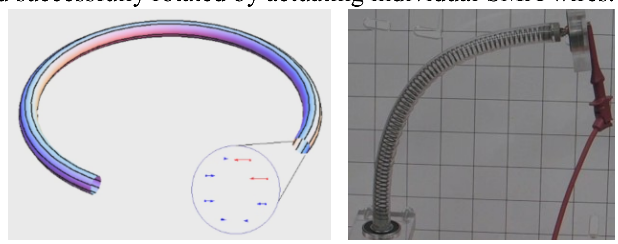

Fig. 6. Cross-section of the torus shaped actuator, and a prototype quarter segment.

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