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Electroelastomer rolls and their application for biomimetic walking robots

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ABSTRACT

Electroelastomers (also called dielectric elastomer artificial muscles) have been shown to exhibit up to 380% electrically-driven strain. Their elastic energy density and power output compare favorably with natural muscles. A variety of actuator configurations have been developed for a variety of important applications including linear actuation, fluidic control, and flat panel speakers. In particular, spring rolls are compact, have a potentially high electroelastomer-to-structure weight ratio, and can be configured to actuate in several ways, including axial extension, bending, and as multiple degree-of-freedom actuators. They combine load bearing, actuation, and sensing functions. Simulation and robot fabrication have produced six-legged robots, using a spring roll as each of the robots' legs, that can run and clear obstacle.

Keywords: Electroelastomer; dielectric elastomer actuator; strain sensor; biologically-inspired robot; artificial muscle

1. INTRODUCTION

New high-performance actuator materials capable of converting electrical energy to mechanical energy or vice versa are needed for a wide range of demanding applications such as mini- and microrobots, biomorphic robots, prosthetic devices, and heel-strike generators. Diverse candidate materials are under investigation. Most of these materials excel in some measures of performance (such as energy density or strain) but are unsatisfactory in others (such as efficiency and speed of response). Electroactive polymers are more attractive in this regard.[2] Conducting polymers such as polypyrrole and polyaniline have high actuation pressure and energy density, but their response speed and coupling efficiency are rather low.[3] Poly(vinylidene fluoride-trifluoroethylene) copolymer is an important actuator polymer.[4] It exhibits reasonably high strain (4%) and elastic energy density (0.3 J/g), though the strain is still not high enough for certain applications where high stroke is essential.

At SRI, we have discovered electroelastomers (electroactive elastomers) that may revolutionize actuator materials. Specifically, acrylic copolymer elastomers not only achieve the high and reversible electromechanical strain (380% in area) that is possible only with elastomers[5] but also have extraordinarily high specific elastic energy density (3.4 J/g), stress (up to 8 MPa), and electromechanical coupling efficiency (60–90%). The remarkable performance is obtained when the elastomer films are appropriately prestrained. We have developed a set of actuator configurations including the "spring roll" which is multifunctional and reproduce such important functions of natural muscles as motors, sensors, brakes, and springs.[7] They represent an important step in the development of synthetic muscles. Animation, simulation, and fabrication of small walking robots using a spring roll as each of the robot's six legs produced "synthetic bugs" that exhibit lifelike motion.

2. METHODS AND RESULTS

2.1 Spring Roll for Actuation

Figure 1 illustrates a simple one degree-of-freedom (1-DOF) spring roll. When the roll was free standing, the compressed spring held the acrylic films in tension. There were about 20 layers stacked in the roll. In general, the spring rolls are compact, have a favorable form factor, and lend themselves to multiple-layer fabrication which is critical for high power output.

Figure 1. A spring roll with axial extension strain. It was fabricated by rolling two prestrained about a compressed central spring.

When a high voltage was applied, in the range of 1-6 kV, the acrylic films expanded. As a result, the roll extended in length as the central spring's compression was partially released. The strain increases linearly with the square of applied electric field, similar to that for electroelastomer thin films and confirms that the

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operation mechanism remains a largely electrostatic effect.[8] The electroelastomer film may be characterized as a dielectric between two compliant electrodes of a capacitor. The polymer film enhances the effect as a result of higher breakdown electric field and dielectric constant. The highest strain achieved is 12 mm, or 26% of active (i.e., electroded) length, in a spring roll 65 mm long with 45 mm active length. This number compares favorably with natural muscle strains in animal legs, which are typically 4–15%. The spring rolls were able to operate at up to 10 Hz. At frequencies higher than 5 Hz, the strain declines significantly.

In the spring roll design, the stiffness of the roll is the sum of the stiffness of the central spring and the rolled polymer films. Spring rolls with 20 layers of acrylic films rolled together, as shown in Table 1, could lift a 0.5 kg weight (about 50 times the roll's weight) and exert an 8 mm stroke; the maximum force was 15 N. When 35 layers were rolled around a stiffer spring, the force of the resulting spring roll was increased to 21 N. The maximum strain was 23%, more or less unchanged from that of the spring rolls with only 20 layers of acrylic films.

2.2 Spring Roll as Strain Sensor

It has been shown that electroelastomers also function in reverse, converting a mechanical motion into an electrical signal, as in heel-strike generators.[9] This phenomenon may be exploited for strain sensing. Candidate parameters to sense the mechanical deformation of electroelastomers include capacitance in the electroelastomers, resistance of the compliant electrodes, and resistance of the electroelastomers. Figure 2 displays the capacitance change of a spring roll upon axial tension and compression. Each data set is a continuous loop of either tension and relaxation or compression and relaxation. As can be seen from the graph, the capacitance increases linearly with the length of the spring roll. The linearity and hysteresis (repeatability) are very good. The offset near-zero stroke stems from experimental problems and, to a lesser degree, the fact that the spring rolls do exhibit some creep (long-term hysteresis). While creep does not affect the accuracy of the displacement measurement, it does make measurements of force based solely on capacitance inaccurate.

2.3 Spring Roll as Multifunctional Robot Leg

We investigated the significance and feasibility of developing a small, legged robot with spring rolls as legs. Conventionally, a robot leg or locomotion is achieved by the use of leg structure to support the robot weight, actuator, and strain sensor. A rather sophisticated central control is required to coordinate the actuator and sensor functions. Using spring rolls as the leg structure, we combine actuation, sensing, and elastic (spring dynamics) and viscoelastic (compliance/damping function) properties in the leg. Significant savings in weight and component count are an obvious benefit; however, there are others. Studies of the elastic and damping properties of natural muscles indicate that these passive structural properties are important to leg performance, in addition to the force-stroke properties provided by natural muscle as an actuator. Therefore, a spring roll leg may enable agile locomotion like that of animals in unstructured environments.

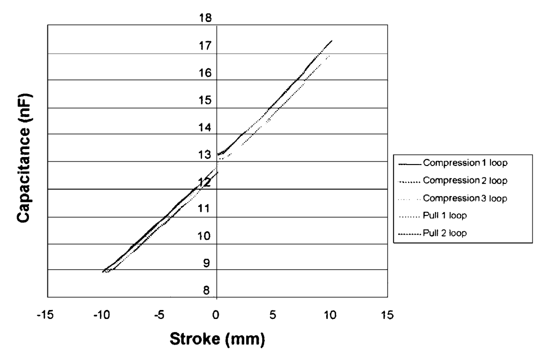

Figure 2. Capacitance change of a spring roll with tension and compression.

As actuator, spring rolls outperform most existing actuator technologies for small-size and large-strain applications. An electromagnetic actuator or motor is heavy and becomes energy inefficient at small sizes and slow speeds. As sensors, the spring rolls are suitable to sense a wide range of strokes (1–100% of leg length), which is critical to the robot mission.

The obstacle clearance capability of the robot is 7 mm at 10 mm leg strain and 390 g robot weight. It increases with strain rate. When a dynamic gait (10 Hz) is allowed, obstacle clearance linearly increases with strain rate. Obstacle clearance appears to vary by the inverse of the square root of the mass. Quadrupling the robot mass would cut the clearance in half.

We fabricated a proof-of-principle robot based on the simulation, using a spring roll as each of the robot's six legs. The robot is about 7.5 in. long and 5 in. wide. Each spring roll leg is a linear actuator with 3–6 mm strain at 1–10 Hz frequency. The speed was as high as 2.7 in/s. Nonetheless, there is much room for improvement considering the maximum strain of 12 mm that the spring rolls can output.

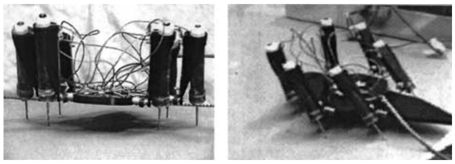

Figure 3. Front (left) and side (right) views of a walking robot with spring rolls as legs.

2.4 Multi-DOF Spring Roll

We also demonstrated a 3-DOF spring roll, shown in Figure 4. In this spring roll, electrodes are patterned on four sides, each connected through the copper wires. The common electrode is connected through a copper wire placed on the opposite end of the roll. The patterned electrodes allow each individual side to be actuated, which could cause the roll to bend in any direction. When all four sides were activated, the roll extended in axial length. Through slight modification, 1-DOF bending and 2-DOF bending spring rolls could also be fabricated. The right-hand panel of Figure 4 shows an animated robot with 1-DOF bending rolls as each of its six legs. With 2- or 3-DOF bending, the robot would be able to move in any direction without turning. These multi-DOF spring rolls provide even more exciting possibilities for mobile robotics and compliant grasping.

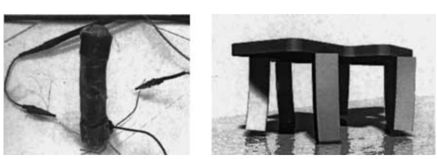

Figure 4. Left: A 3-DOF spring roll. Right: A legged robot using multi-DOF spring rolls as each of its 6 legs.

3. CONCLUSIONS

Electroelastomers based on a dielectric elastomer between compliant electrodes show great promise for actuation. The spring rolls are easy to fabricate, compact, multifunctional, and mechanically robust. For load-bearing, they can support up to 50 times their own weight. The strain (26%), response speed (5 Hz), and strain sensing are useful properties for component devices. Furthermore, the multifunctionality gives promises for artificial muscles to enable biologically inspired robots. The design concept has also been expanded for the fabrication of rolls with 2- or 3-DOF actuation, allowing for application to other types of biomimetic robots, such as snakes or worms, as well as many other electromechanical devices.

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