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Digital fabrication of “smart” structures and mechanisms - creative applications in art and design

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Abstract

This paper describes the design and fabrication of novel “soft” structures and mechanisms employing “smart” shape-changing materials. These structures and mechanisms incorporate shape memory alloy (SMA) micro-actuators, enabling them to exhibit lifelike movement when stimulated by the application of electric current. Fabricated by 3D printing in a soft elastomer material, their design includes internal channels into which the SMA actuators are easily mounted. Other design features allow flexibility of movement and facilitate cooling of the SMA actuators.

A tentacle-like active structure is described, which incorporates an antagonistic pair of SMA micro-actuators, allowing it to exhibit two-way motion. Results are presented for the speed and range of motion of the tentacle-like structure.

The paper goes on to describe a creative arts application for smart active structures and mechanisms which exploits the technologies under investigation: an interactive puppet which exhibits lifelike, expressive movement. This research in digital fabrication and smart materials has implications for the fields of interactive and robotic art and design, soft robotics and physical computing.

Introduction

Smart materials are materials which change their physical properties in response to external stimuli. In this paper we report results from an interdisciplinary research project investigating how smart materials technologies, together with 3D printing, might be creatively exploited within art and design applications.

We describe the design, prototyping and testing of a tentacle-like active structure which is fabricated by 3D printing in a soft elastomer material. The tentacle structure is actuated by shape-memory alloy “artificial muscles”. We go on describe a purpose-built flex sensor based interface which allows the tentacle-like structure to be controlled like a puppet.

We begin this paper by briefly reviewing relevant research by others working in the field of smart materials and soft robotic technologies.

Smart materials and soft robotics

The term “Soft robotics” refers to robotic devices that are fabricated from soft, flexible, materials, instead of the hard plastics and metals traditionally used in robotics [2, 3, 4, 5, 8]. Researchers working in this field have identified that a robot made from soft materials may mimic more closely the functions of a living organism such as an octopus or jellyfish. In addition, for robotic devices which are to function in close proximity to the human body, soft materials may be more desirable since they may be more comfortable than hard metals or plastics and also less likely to cause injury. Research groups active in this area include, for example, the Biomimetic Devices Laboratory, Tufts University, USA, and the Soft Robotics Group, Bristol Robotics Laboratory, UK.

Gilbertson [1] describes how a finger- or tentacle-like active structure can be fabricated from silicone rubber catheter tubing. Actuation is provided by shape-memory alloy (SMA) “Muscle Wire” threaded through three channels running along the length of the tubing. When electric current is passed through the Muscle Wire it contracts (typically by 4-5 %) and this causes the tubular structure to bend. The structure can bend in three different directions, depending on which Muscle Wire is powered. Gilbertson describes the actuated structure as exhibiting smooth, life-like movements.

Trimmer [2], Kate *et al.*[3] and Lin *et al.* [4] report recent research into the development of biomimetic soft-bodied robots, at Tufts University, USA. They describe Caterpillar-like crawling [2, 3] and rolling [4] robots which have been fabricated by molding silicone rubber in 3D printed molds. These soft-bodied robots incorporate SMA helical coil actuators which are either bonded to the inside of the body cavity of the robot [2, 3] or mounted in lumina molded into the structure of the robot’s body [4]. When heated electrically, the SMA coil actuators employed in [2, 3, 4] provide significantly greater contraction when compared to the Muscle Wire actuators described previously, thus giving greater movement. In [2, 3] the crawling action of a caterpillar-like “Softbot” is achieved by SMA coil actuators which sequentially compress the robot’s body segments. These then re-extend, either passively, through the recoil action of the elastic body wall, or actively, by actuating adjacent SMA coils. In 2008, the “Softbot” was exhibited at the Museum of Modern Art in New York, in the exhibition entitled “Design and the Elastic Mind.” In [4] a caterpillar-like robot performs an impressive “ballistic rolling” action. This is achieved by rapidly contracting of a pair of SMA coils mounted within longitudinal lumina in the lower (ventral) portion of the robot’s body. Wedge-shaped notches are removed from the lower portion of the robot’s body to aid flexing when the SMA coils contract. The SMA coils are segmented half way along their length, so that anterior and posterior sections of the robot can be actuated independently, when rolling and when crawling. The authors of [4] suggest that the design of the rolling robot could be modified to give it dorsal-ventral symmetry - it could then perform a ballistic roll in both dorsal and ventral directions, and actively recover its initial state.

In [5] Rossiter *et al.* describe electroactive polymer actuator technologies and fabrication techniques for applications in soft robotics. Electroactive polymer (EAP) actuators include dielectric elastomer actuators, which expand in area and contract in thickness with the application of a high voltage [6] and ionic polymer metal composites, which bend when stimulated by a relatively low voltage [7]. Rossiter *et al.* describe a number of soft robots and actuators based upon ionic polymer metal composites including anguilliform swimming robots and artificial cilia [5]. In [8] Rossiter *et al.* describe the fabrication by 3D printing of a dielectric elastomer actuator for soft robotics. The structure of a double membrane actuator was fabricated by photopolymer jetting (Objet Geometries Limited, Israel) in rigid and soft elastomeric materials. Compliant electrodes were applied to the structure by spraying or painting by hand.

Rossiter *et el.* point to the future possibility of 3D printing complete soft robots and soft-smart devices [8]. The paradigm of *Printable Robots*, in which complete robots, including sensors, actuators, control systems and power supply may be fabricated by multi-material inkjet printing technologies, was proposed by Daigle [9].

We will now describe the design, fabrication and testing of the tentacle-like active structure.

Digital fabrication of a tentacle-like active structure

The design of the tentacle-like active structure is illustrated in Figure 1. The tentacle design comprises an elongate structure which is fabricated in a soft elastomer material. The active length of the structure is 55 mm. Like the robot caterpillar described in [4], the tentacle structure incorporates longitudinal lumina accommodating SMA coil actuators and cables, and notches are removed from the sides of the structure to aid flexibility. However, whilst in [4] the robot caterpillar is fabricated by casting silicone elastomer materials in 3D printed plastic molds, the tentacle-like structure is fabricated by 3D printing directly in a soft elastomer material (Fullcure 930 material, Objet Geometries Limited, Israel [10]). This eliminates the molding stage. The ability to print structures and mechanisms directly in a soft, rubber-like material means that features which might otherwise be difficult to mold may more easily be incorporated into a design. Direct printing of soft structures also speeds up design iterations since modifications can be made to the design of the structure itself without also needing to also re-design tooling (i.e. molds). Once the soft structure has been 3D printed, the support resin is carefully removed from the internal lumina. If required, the structure can then be coloured by dyeing with ordinary fabric dye [11].

The SMA coil actuators (Biometal Micro-helix BMF 150, Toki Corporation, Japan) are mounted within lumina running down the left and right side of the tentacle. These operate antagonistically as follows: When electric current passes through the left hand NiTi coil it contracts, causing the tentacle to bend to the left. Similarly, when current passes through the right hand coil it contracts which causes the tentacle to bend to the right. The range of movement of the tentacle-like active structure is illustrated in Figure 2.

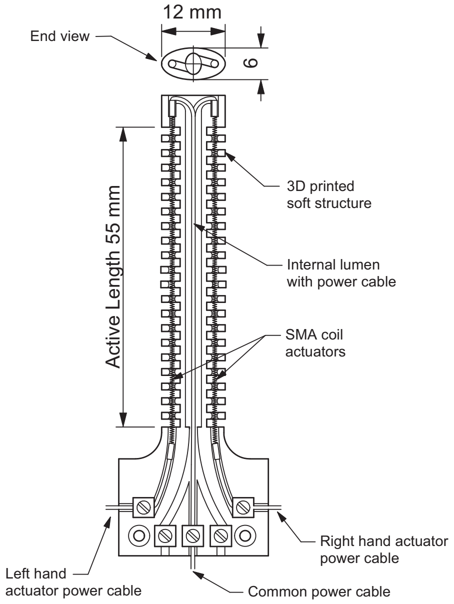


Figure 1. Tentacle-like active structure.

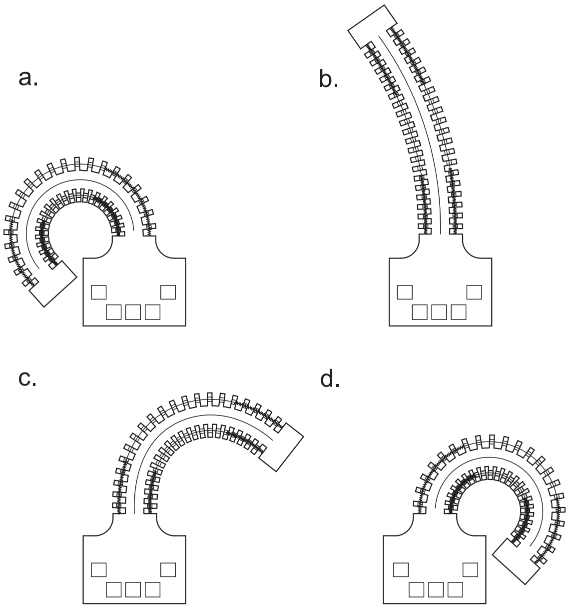


Figure 2. Range of movement of tentacle-like active structure.

In order to investigate the speed of movement of the tentacle, we recorded the time taken for it to bend approximately 180 degrees, as shown in Figure 4. Results of this investigation are presented in the table in figure 4 which includes values for actuation voltage and time.

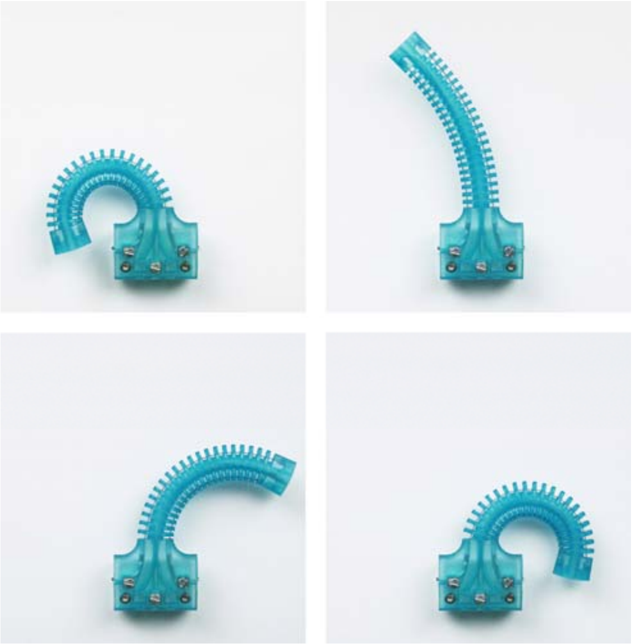
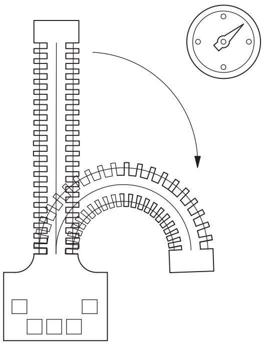


Figure 3.Working prototype of the tentacle-like active structure.



Actuation Voltage (V)	Time (S)
2.5	5.3
3	3.4
3.5	2.6
4	2.1
4.5	1.5

Figure 4. Approximate time for the tentacle to bend through 180 degrees.

Design concept: tentacle-like smart puppet

Having designed and fabricated a working tentacle-like active structure, we went on to develop a flex sensor based analogous interface, in order that the tentacle might be controlled like a puppet. The interface takes the form of a flexible "wand" which incorporates a pair of resistive flex sensors (Spectra Symbol, Salt Lake City, USA) which are mounted in opposing directions, as shown in Figure 5. The external structure of the control wand is fabricated by 3D printing in the same Objet Fullcure 930 material as the tentacle. When the control wand is bent to the left, the resistance of one of the flex sensors increases, and when bent to the right, the resistance of the other flex sensor increases. Movement of the tentacle-like "smart puppet" is controlled by the wand, via custom electronics and software. This comprises: an analog signal conditioning stage, Arduino microcontroller prototyping board, dual MOSFET driver circuit and custom open-loop control software. In operation, bending the wand to the left causes the tentacle to move the left, and bending the wand to the right causes the tentacle to move to the right

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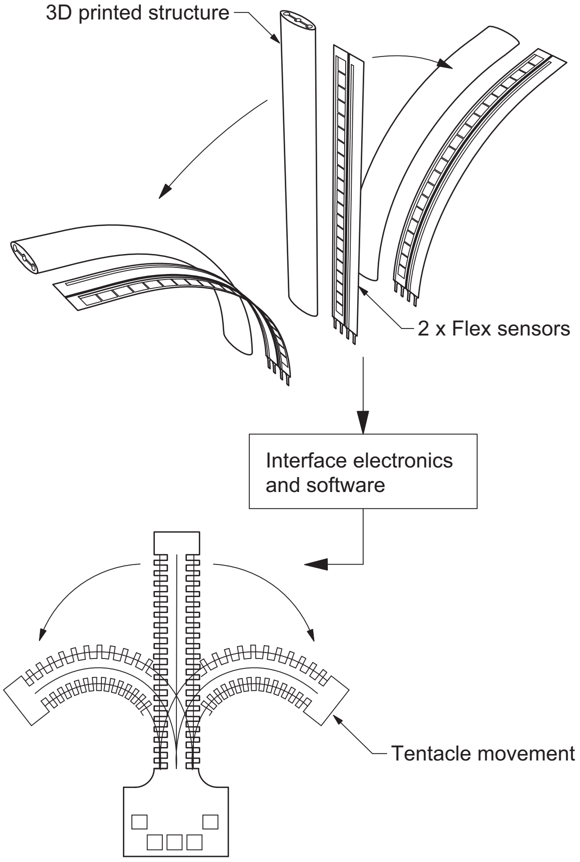

Figure 5. Design concept: tentacle-like "Smart Puppet" with flex sensor based analogous interface.

Conclusions

In this paper we have described the design, prototyping and testing of a tentacle-like active structure and an analogous "smart puppet" control interface.

SMA-actuated soft robots developed previously by others have been fabricated by casting silicone elastomer materials in 3D printed moulds [2, 3, 4]. In the present paper, we have demonstrated that structures for SMA-actuated smart devices can be 3D printed directly in a soft elastomer material. This eliminates the molding stage, making it quicker and easier to fabricate soft structures and mechanisms which, after the removal of support resin, can be made smart simply by inserting SMA actuators and flex sensors.

Design can be a highly iterative process. The ability to 3D print directly in an elastomer material means that any modifications which may be needed to "fine-tune" a design only need to be made to the structures or mechanisms themselves – redesign of molds is no-longer necessary. Significantly, the research presented in this paper points towards the future possibility of *Printable Robots*, as predicted by Daigle [9], and to the printing of soft robots and soft-smart devices proposed by Rossiter et al. [8].

Potential applications within the visual arts and design are wide ranging, including interactive artworks, "smart puppets" for animation, animatronics and performance, and product designs that automatically can change shape to alter their appearance or to enable different functions.

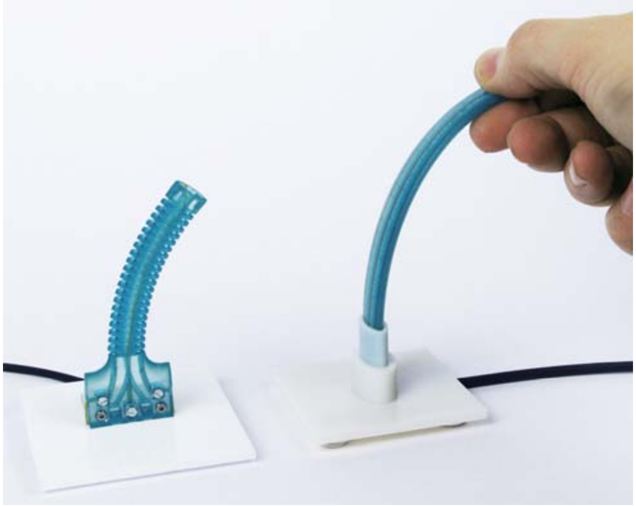

Figure 6.Working prototype "Smart Puppet" with flex sensor based analogous control interface.

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Author Biography

Peter Walters holds the position of RCUK Fellow in Rapid Prototyping, within the Centre for Fine Print Research, University of the West of England. His research focuses on novel applications for 3D printing and smart materials within the creative arts and design. Peter is also a visiting researcher at Bristol Robotics Laboratory, where he is a member of the soft Robotics Group.

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