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Three-Dimensional Fabrication of Smart Actuators: Design Applications

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Abstract

This paper describes the design and digital fabrication of a series of "smart" devices which exhibit changes in shape and/or surface texture in response to external stimuli. Such stimuli include changes in temperature, pressure, or the application of electric current.

Smart shape-changing devices which exhibit dynamic visual and tactile characteristics may in future be incorporated into the design of interactive products and systems, providing a new multi-sensory dimension in the communication of information to product users.

Working devices employing shape memory alloy, electroactive polymer and bio-actuation technologies are presented. These have been fabricated through a combination of laser cutting, photopolymer jetting (3D printing system by Objet Geometries Ltd), and vacuum casting of silicone rubber. Here the use of soft, compliant materials has enabled the realization of devices with novel tactile qualities. Possible functional and aesthetic applications for such devices will include product interfaces which respond to users and/or changes in their environment.

The paper reports on an interdisciplinary investigation which brings together design, smart materials and digital fabrication technologies. Implications of the research are identified within the area of multi-sensory product interface design.

Introduction

Research reported in this paper investigates how developments in digital fabrication techniques, together with advances in smart materials technologies, can be applied in the design and production of smart devices which change their physical properties in response to external stimuli. This research has involved the design, realization and testing of actuator devices which exhibit changes in their shape and/or surface texture in response to changes in temperature, pressure or with the application of electric current.

In the design of physical product interfaces, Norman [1] points to the use of shape as means of identification, for example, to help product users to distinguish between different switches and controls. Chamberlain et al. [2] describe the design and testing of an identification system incorporating visual and tactile cues for use in safety-critical medical product applications, to help prevent user error.

The possibility of developing devices which can exhibit *dynamic* visual and tactile cues, such as change*s* in shape or surface texture, through the use of smart materials technologies, presents exciting opportunities for product interface design [3, 4] and research by others in this and related areas includes, for example: Horev's investigation of communication through shape-change in objects and tangible interface design [5]; April Tsui's DynamicTextures [6]; and work by the digital jeweller and researcher Jayne Wallace [7]. Examples of applications for smart actuator technologies within physical interface design include: "Blossom", a digital jewellery piece by Jayne Wallace which exhibits meaningful and expressive gestural movement [7]; a temperature-responsive drinking cup designed by April Tsui, which projects "thorn-like" spines from its outer surface to indicate that its contents might be too hot to hold [6]; a Braille display device proposed by Rossiter et al. [8]; a wearable tactile display developed by Koo et al. [9]; haptic displays described by Ashley [14]; a bi-stable visual and tactile indicator, which may be employed to warn that a product has changed from a safe to a dangerous state [3, 4].

This paper demonstrates a series of smart shape-changing actuator designs based around a bi-stable "pop-out" spike mechanism. The structure and function of this mechanism is first introduced, and then the authors go on to describe the different methods by which actuation was achieved, using shape memory alloy (Nitinol), ionic polymer metal composite (IPMC), dielectric elastomer and bio-actuation technologies.

Design and fabrication of pop-out spikes

The actuators described here employ a bi-stable mechanism which comprises a spike which is made in a soft, flexible, elastomer material, and which "snaps" between retracted and deployed states (Figure 1). The spike "pops out" when a small force is applied to the stem on the rear of the component. Pulling on the stem returns the spike to its retracted position.

The pop-out spikes were made in RTV silicone rubber, by vacuum casting, in moulds which were designed in 3D CAD software and produced in photopolymer resin using the Eden350V™ 3D printing system by Objet Geometries Ltd. The moulds were made in the Objet Fullcure® 720 material, a rigid, transparent photopolymer. Using moulds made by this method, pop-out spikes were produced in a range of sizes, from 15 mm outside diameter (min. wall thickness 1mm typ.) down to 4 mm outside diameter (min. wall thickness 0.25mm typ.).

Some of the larger sized spikes were also produced by 3D printing them directly in the Objet TangoPlus Fullcure® 930 photopolymer elastomer material. This method enables components to be produced in soft materials without the moulding stage. However, the wall thickness of some of the smaller spikes was in places less than the 0.6 mm minimum stated by the manufacturer of the 3D printing system [10].

Therefore, for consistency, spikes made by vacuum casting silicone rubber were used for all of the versions of the actuators described here.

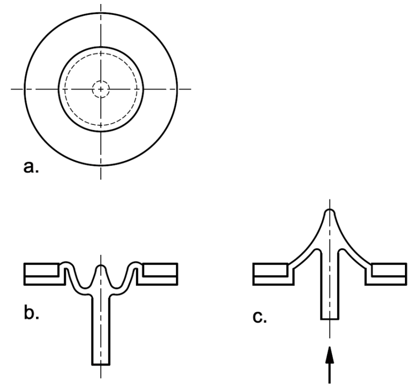

Figure 1. *Pop-out spike: (a) plan view, (b) retracted position, (c) deployed position*

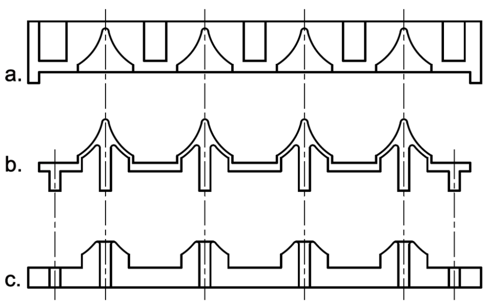

Figure 2. *Moulding pop-out spikes: (a) female mould, (b) moulded part, (c) male mould*

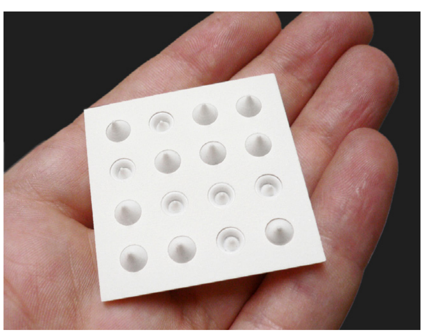

Figure 3. *6mm diameter pop-out spikes made by vacuum casting silicone rubber are attached to a frame that is laser-cut from rigid plastic.*

Actuation of pop-out spikes:

Shape memory alloy actuation

Shape memory alloy actuation [11, 12] was successfully demonstrated using Nitinol wire as follows. In the schematic drawing shown in figure 4, a lever is formed from 0.750 mm diameter Nitinol wire (Mondo-Tronics Inc.). The lever is mounted underneath the pop-out spike and has a small plastic "hammer" attached which makes contact with the underside of the spike. When the spike is retracted, the lever is bent out of its normally straight position. When heated to its transition temperature, which in this case was 55-75 deg C, the Nitinol wire lever straightens, and the hammer pushes on the underside of the spike, causing it to pop out. For demonstration purposes, the Nitinol wire may be heated electrically, for example, with power from a 6V lantern battery, or with a hot-air gun. Once the Nitinol wire has cooled, the spike may be returned to its retracted position by hand. The mounting rings and the hammer component were fabricated in Objet Fullcure® 720 material by 3D printing.

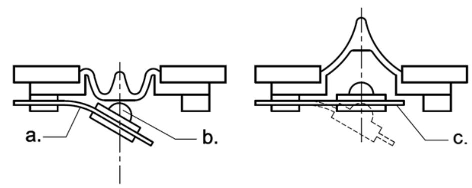

Figure 4. *Schematic drawing showing Nitinol lever-actuated spike. When the spike is retracted, the Nitinol lever is bent (a). The hammer (b) is in contact with the underside of the spike. When the Nitinol is heated it straightens (c) and the spike is popped out.*

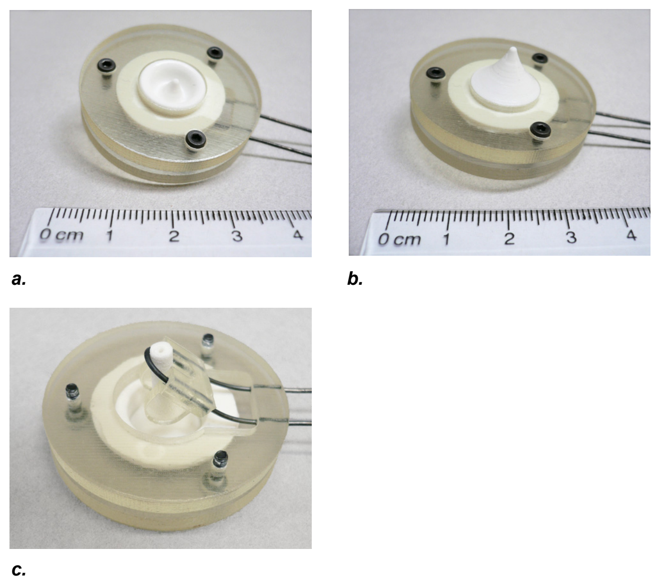

Figure 5. *Nitinol lever-actuated spike (a) retracted, (b) deployed, and (c) underside view showing Nitinol lever arrangement with spike in its retracted position.*

Ionic polymer metal composite actuation

The pop-out spikes were also actuated using an ionic polymer metal composite (IPMC) bending actuator [13, 14]. The actuator was made from Nafion 1110, with a dry thickness 254 µm, 5 times electro-less plated with gold.

The bending actuator is mounted beneath the stem on the underside of the pop-out spike as shown in figure 6. To stiffen the stem of the spike, it was sheathed in a short length of rigid plastic tubing. When a voltage of approx. 2.5v DC is applied across the upper and lower surfaces of the actuator, it bends upwards (figure

6 b), pushing against the stem on the underside of the spike with just enough force to cause it to pop out.

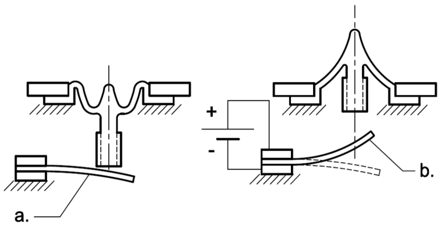

Figure 6. *IPMC bending actuator mounted beneath a pop-out spike. The actuator in relaxed position (a) and actuated position (b).*

a. *b.*

Figure 7. *Pop-out spike with IPMC actuation (a) retracted, and (b) deployed, where the dashed line indicates the shape of the IPMC bending actuator in its previously relaxed position.*

Dielectric elastomer actuation

Dielectric elastomer actuation [14] was demonstrated using a balanced dual diaphragm actuator, functionally equivalent to the Universal Muscle Actuator (UMA) manufactured by Artificial Muscle Inc. The two diaphragms of this actuator were fabricated from acrylic polymer tape, approx. 2.5x linear pre-strained, and coated with silver grease on their upper and lower surfaces to create conductive electrodes. The dual diaphragm actuator was mounted beneath the pop-out spike as shown in figure 8. Again, the stem on the underside of the spike was stiffened by sheathing it in short length of rigid plastic tube.

When a voltage of 3000V DC was applied to the electrodes of the upper diaphragm, its thickness is compressed and its surface area increases. Due to the pre-strain force in the lower diaphragm, the actuator then provides a linear stroke in the upwards direction, which was sufficient to cause the spike to pop out.

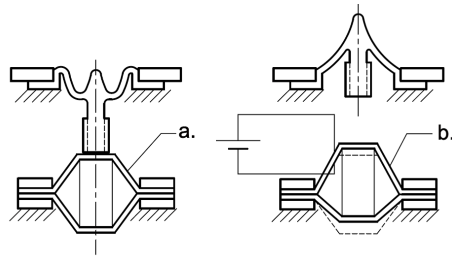

Figure 8. *Pop-out spike with dielectric elastomer actuation: (a) balanced dual diaphragm actuator mounted beneath the retracted pop-out spike and (b) in its actuated state, with the pop-out spike deployed.*

Figure 9. *Balanced dual diaphragm actuator with pop-out spike in retracted and deployed positions.*

Bio-actuation

In related research [3, 4], bio-actuation was demonstrated, where gas produced by a live biological material - live baker's yeast - was found to provide sufficient pressure to cause a bistable silicone rubber structure to pop out. Also, increasing the ambient temperature above room temperature was found to reduce the time taken for the spike actuator to pop out.

In figure 10, a mixture of baker's yeast, sugar and water is contained in a sealed capsule mounted beneath a pop-out spike, which is in its retracted position. The live yeast generates carbon dioxide gas, which causes an increase in pressure beneath the spike structure, and when sufficient pressure is accumulated, the spike pops out.

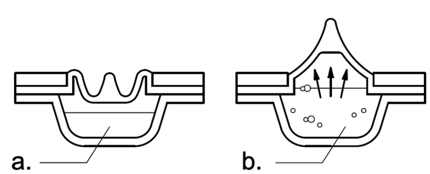

Figure 10. *Bio-actuation of a pop-out spike: (a) a mixture of baker's yeast, sugar and water (b) the build up of gas generated by the live yeast causes the spike to pop out.*

Summary and future research

3D fabrication technologies, including photopolymer jetting (Objet Geometries Ltd) laser cutting and vacuum casting techniques have been effectively applied in the production of "pop-out" spike actuators, which employ shape memory alloy, electro-active polymer and bio-actuation technologies.

The different actuation technologies under investigation each have advantages and disadvantages, and these must be taken into account when considering their suitability for any particular application. Nitinol shape memory alloy actuators have the advantage that they can be actuated in response to heat from their surroundings, or alternatively, by heating them electrically, with a moderate operating voltage. However, Whiteley [12] identifies that the time taken for the actuator to cool down in order to be reversed means that the overall cycle time for this type of actuator is extended. The advantages of IPMC actuators include their large deflection and relatively low operating voltage [13, 14]. However they are capable of providing a relatively low actuation force [13]. Also, to operate most effectively, they must be kept wet, and so require encapsulation if they are to be used in dry conditions [13, 14]. Dielectric elastomer actuators can provide higher actuation forces, whilst requiring relatively high voltages for their operation [14]. Lastly, bio-actuation, demonstrated using live baker's yeast, has the advantage that yeast is a cheap and readily available bio-material - a small amount of yeast, mixed with sugar and water, can produce gas which can be harnessed to do useful work. A disadvantage of the arrangement described above is that actuation can only occur once, after which the spent yeast must be removed and replaced with fresh.

So far actuation has been demonstrated in only one direction – the spikes pop-out, but are returned to their retracted position by hand. Future research will seek to define an appropriate two-way actuation system through which the spikes might also be retracted. Ongoing research continues to explore applications for shape-changing actuators as visual and tactile indicators, and investigates further ways to exploit digital fabrication technologies in the production of smart actuated devices.

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