

# 3D printing and fabrication of “smart” responsive devices: a comparative investigation

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## Abstract

*This paper describes methods for the three-dimensional fabrication of smart actuators and responsive devices incorporating functional parts in elastomeric materials. The paper focuses on the fabrication of a bi-stable device which exhibits a dramatic change in shape when subjected to an external pressure load.*

*Two different fabrication methods are described. In the first method, parts are fabricated by casting the elastomer material in moulds produced by 3D printing. In the second method, parts are fabricated directly by 3D printing in a printable elastomer material. Experimental results are presented for devices fabricated by both methods, comparing their response under a pressure load. The effect of changing part geometry (wall thickness) is also investigated.*

*In addition, a working device with two-way actuation is demonstrated, in which a pair of shape memory alloy actuators are employed to bring about changes in the device's shape.*

*Possible applications for such devices include visual and tactile indicators and displays for interactive products. Other areas where they may be employed include robotics and interactive art and design applications.*

## Introduction

Three-dimensional shape and surface texture may be employed to communicate information to the users of products and systems. For example, some Victorian bottles had conspicuous surface textures on their outside surfaces, which served as a warning that their contents could be harmful if consumed. Norman recommends that levers and switches should be designed to “look and feel different”, to help prevent user error through misidentification, particularly when safety is a priority - for example, controls for aircraft or nuclear power stations [1]. Research led by Chamberlain at Sheffield Hallam University involved the development and testing of a visual and tactile identification system for medical connectors which are used in drug delivery systems, to help prevent misconnection errors which can be potentially fatal [2, 3].

A number of design studies have explored how changes in shape and texture may be exploited as a means of communication. For example: Tsui's study of ‘Dynamic Textures’, which includes a temperature-responsive cup with spines which rise from its outer surface, to warn that the cup may be too hot to hold [4]; Horev's investigation of shape change within interaction design [5]; a digital jewellery piece by Wallace entitled ‘Blossom’, which displays an expressive movement, opening like a flower when it receives a signal from a remote location [6]. Other relevant examples include a wearable tactile display by Koo et al. [7] braille displays by Johnson and Orlosky [8] and Rossiter et al. [9]; a

tactile feedback device by the TiNi Alloy Co. [10] haptic displays reported by Ashley [11]; and visual and tactile indicator devices described in [12, 13].

Research in other related areas includes the “Softbot” developed by Trimmer, Kaplin and colleagues at Tufts University, which is a caterpillar-like robot made from silicone rubber, with movement provided by shape memory alloy spring actuators [14, 15]; a bistable jumping structure by Santer and Pellegrino [16] employing shape memory alloy spring actuators, and which demonstrates principles which may be employed in structural elements for “binary robotics systems” [21]; a dual diaphragm electroactive polymer actuator by Rossiter et al. which was fabricated by photopolymer 3D printing and is capable of providing two-way actuation for soft robotic applications [17].

Research described in this paper investigates methods for the fabrication of a pressure-responsive bi-stable device. This device changes shape in response to an externally-applied pneumatic pressure load. Devices are fabricated by two different methods, using different materials. Their response to a pneumatic pressure load is observed and compared. Lastly, a device employing shape memory alloy actuators is demonstrated. Here two-way actuation is achieved using a pair of shape memory alloy spring actuators acting in opposite directions to one another.

## Anemone Indicator

The anemone visual and tactile indicator, which is shown in figs. 1 to 3, comprises an array of spikes radiating from the outer surface of a hemispherical diaphragm. The device is made from a soft elastomer material, and the structure can be inverted, as shown in fig 1a so that the spikes are retracted, nesting within the inverted hemisphere. The anemone indicator is a bistable structure, since it is stable in both retracted and deployed states. When retracted, applying a force or pressure load onto the underside of the anemone indicator causes it to “pop-out” i.e to revert to its deployed state fig 1b. The device is called the anemone indicator because in form and action it is in some ways reminiscent of the sea anemone, which turns parts of its body inside out to feed.

The anemone indicator was first presented in [12] where prototypes were fabricated by vacuum casting silicone and polyurethane elastomer materials, using moulds made by stereolithography. In [13] a bistable “pop-out” spike of a different design was presented, which was fabricated by vacuum casting silicone rubber in 3D printed moulds (in Objet Geometries Ltd Fullcure® 720 resin), and also by 3D printing directly in a photopolymer elastomer material (Objet Geometries Ltd Fullcure® 930 resin). However, in [13] tests were not carried out to compare the functional performance of devices made by the two fabrication methods - working actuated devices were only presented using the vacuum cast silicone rubber versions of the pop-out spikes.

In the present investigation, anemone indicators were fabricated by vacuum casting silicone rubber in moulds produced by 3D printing using the Objet Eden 350 V photopolymer 3D printer and Fullcure® 720 resin (Objet Geometries Ltd, Rehovot, Israel). The silicone rubber was RTV 139 with 5% C148 catalyst (Alchemie Ltd, Kineton, Warwick, UK) which had a hardness of 30 +/- 3 Shore A [18]. Anemone indicators were also fabricated by 3D printing directly in the Objet Fullcure® 930 photopolymer resin, with “rubber-like” properties, having a hardness of 27 Shore A [20].

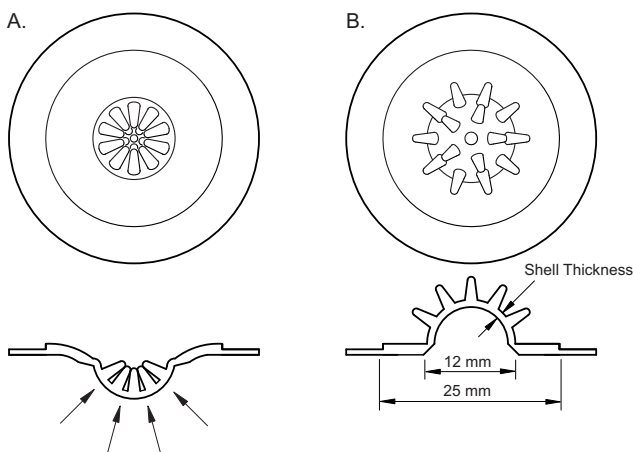


Figure 1. Anemone indicator shown (a) retracted and (b) deployed



Figure 2. Anemone indicators in silicone rubber, within an aluminium frame



Figure 3. Anemone indicator in 3D printed photopolymer

## Comparison of “pop-out” pressures for pneumatic actuation

Using the apparatus shown in fig. 4, anemone indicators fabricated by both methods were tested to compare their response to a pneumatic pressure load. In the tests, an anemone indicator was connected via tubes to a medical syringe driver pump, and in parallel to a digital manometer with record facility. At the beginning of the test the indicator was in its retracted state. At the start, the volume of air in the system was approx. 61 ml. The pneumatic pressure acting on the underside of the indicator was gradually increased by advancing the syringe driver pump (flow rate 100 ml/hr) until the indicator “popped out”. Once the indicator was fully deployed, the syringe driver pump was turned off. The maximum pressure recorded by the manometer prior to the indicator popping out was logged (i.e. approximately the “pop-out pressure”). The effect of changing the geometry of the component i.e. the wall thickness of the indicator’s hemispherical shell was also investigated, and the combined results of these tests are shown in fig 5. Three samples of each type were tested. The lines on the graph represent the average (mean) value for indicators made from silicone rubber and “rubber-like” photopolymer material.

As can be seen from the graph, the anemone indicators made by 3D printing in the Objet Geometries “rubber-like” photopolymer material were found to pop out at a lower pressure than those made from silicone rubber. This reflects the fact that the Objet Fullcure 930 photopolymer resin has a slightly lower Shore A hardness value than the silicone rubber used in this investigation. Also evident from the graph is that increasing the component wall thickness has the effect of raising the pressure at which the indicators pop-out.

A significant difference in the dynamic response of the silicone and photopolymer indicators was observed. It was found that once the critical pressure was reached, the silicone indicators popped out quickly, whereas the photopolymer indicators appeared to “creep” out much more slowly. This difference in dynamic response was recorded using a pressure transducer attached to a data logger (sample rate: 10 readings per second). The increase in pressure on the underside of the indicator was again provided by the syringe driver pump. As can be seen for the graph in fig. 6, once the maximum pressure is reached, the time taken for the 3D printed photopolymer indicator to “snap through” (i.e. the time taken for the pressure to drop from maximum to minimum) is approx 13.2 seconds, whereas the silicone version of the indicator takes approx 1.1 seconds to snap through.

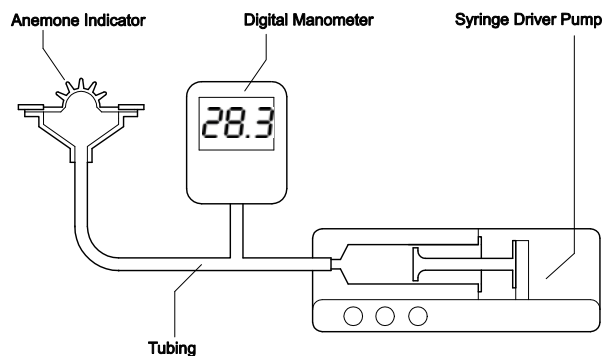
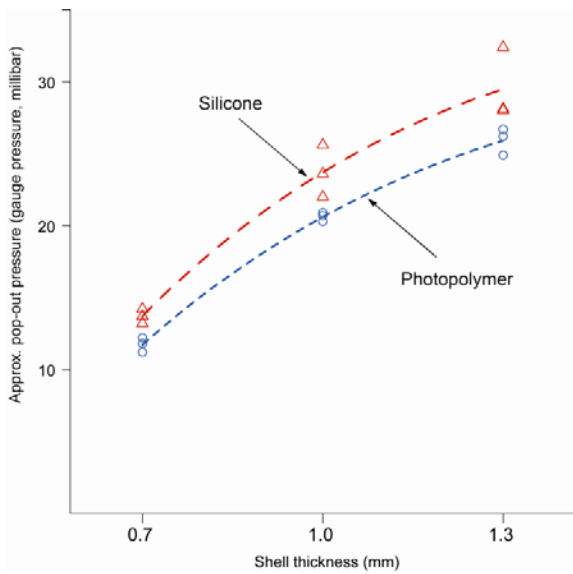
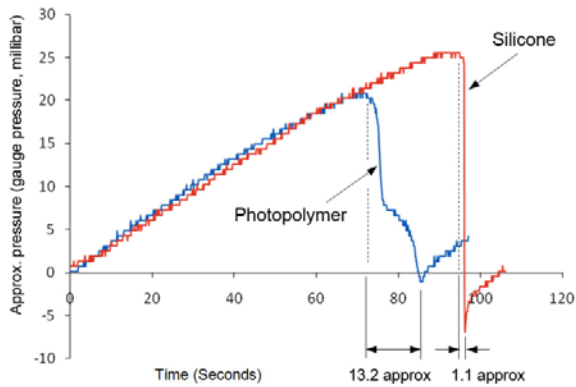


Figure 4. Pressure testing apparatus



**Figure 5.** Pressure testing results: Approximate “pop-out” pressure (gauge pressure) for silicone and photopolymer anemone indicators



**Figure 6.** Pressure testing results: typical “snap-through” times for silicone and photopolymer anemone indicators, shell thickness 1.0 mm

## Two-way actuation of the anemone Indicator

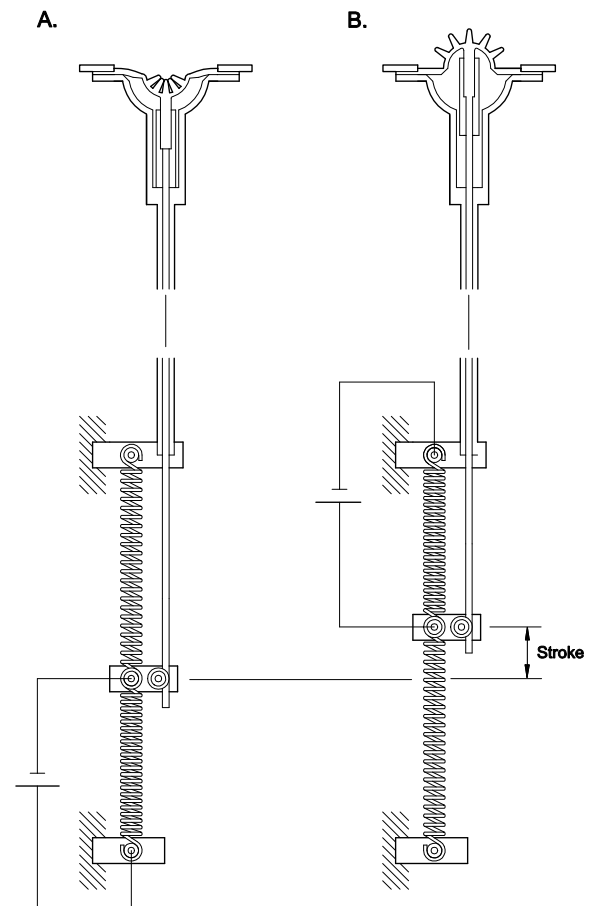
Two-way actuation of the anemone indicator device was accomplished using a pair of NiTiNol shape memory alloy (SMA) spring actuators, which contract in length when heated.

NiTiNol is a “smart” shape memory material which, when configured appropriately, may be employed to provide two-way actuation. Gilbertson describes actuation using SMA “muscle wires”, with various mechanisms for providing a bias force to help return the SMA wire to its original length once cooled, including spring, gravity, magnetic and reverse bias configurations, and also the “opposing wire bias” configuration, in which two SMA wires act in opposing directions [19]. Tactile and Braille display devices employing NiTiNol actuation have been developed by the TiNi Alloy Co [8, 10]. At the Deployable Structures Laboratory, University of Cambridge, Santer and Pellegrino employed NiTiNol springs actuate a bistable jumping structure. The nitinol

springs provided the actuation force and stroke required for the structure to “snap through” from one stable state to the other - one spring actuator was employed to trigger the jump, and two were used to reset the structure in readiness for the next jump [16].

For the anemone indicator, a pair of SMA spring actuators were configured to act in opposite directions, as shown in fig 7. The SMA actuators were heated electrically, using power from a 6v lantern battery. A flexible “bowden cable” was used to transmit the linear movement of the spring actuators to a stem on the underside of the anemone indicator. When the lower spring is heated, the indicator is retracted (fig. 7a), and when the upper spring is heated, the indicator is deployed (fig. 7b). Anemone indicators in silicone rubber and “rubber-like” photopolymer materials were actuated by in this way.

However, it should be noted that with this particular arrangement, if neither of the two SMA springs is heated, then the pair come to rest at approximately the mid-stroke position. This results in the indicator being positioned between its fully retracted and fully deployed states. In order for the indicator to remain fully retracted or fully deployed, it is necessary to continue to apply sufficient electrical power to one or other of the SMA actuators, to enable it to hold its position.



**Figure 7.** Two-way actuation of the anemone indicator using shape memory alloy springs shown (A) retracted and (B) deployed

## Summary and conclusions

Pressure-responsive anemone indicator devices were fabricated by vacuum casting silicone rubber in 3D printed moulds, and also by 3D printing the devices directly in a “rubber-like” photopolymer material (Objet Geometries Ltd Fullcure® 930). The response of these devices under a pneumatic pressure load was compared. It was observed that once the maximum pressure was reached, the devices fabricated in the “rubber-like” photopolymer took significantly longer to snap through than devices made in silicone rubber. It may be concluded that the photopolymer material has a significantly greater damping effect than the silicone rubber which was used in this investigation. Strongly viscoelastic behavior has been reported previously in an elastomeric photopolymer material printed using the Objet Geometries 3D printing system [17]. Two-way actuation of the anemone indicator was demonstrated using a pair of shape memory alloy springs configured to act in opposite directions to one another, in order to pull or push the indicator between its retracted or deployed states. However, this particular configuration is to some extent unsatisfactory, since power is required to hold the indicator in either state. This negates the bistability of the anemone indicator structure itself.

In relation to robotic systems comprising multiple bistable structural elements, Santer and Pellegrino [16] have pointed to the advantage that power is not required to hold such a structure any of its stable states. Similarly, for the anemone indicator, it would clearly be advantageous if power was not needed to hold the device in its retracted or deployed states.

Therefore, ongoing research is directed towards the development of an improved method of actuation for the anemone indicator. For example, a small electrically-powered bi-directional pump could provide an increase or decrease in pneumatic pressure, which would cause the indicator to snap between retracted and deployed states. Additionally, the author continues to explore possible future applications for smart, responsive devices within art, design and robotics.

## References

- [1] D. A. Norman, “The Design of Everyday Things” (MIT Press, 1998) pp. 92 - 95
- [2] P. Chamberlain, P. Gardner, R. Lawton, “Shape of Things to Come”, in R. Michel (ed.) “Design Research Now” (Birkhäuser, Basel, Switzerland, 2007) pp. 99 – 116
- [3] P. Walters, P. Chamberlain, M. Press “In Touch: An investigation of the benefits of tactile cues in safety-critical product applications” in *Techné: Design Wisdom*, Proc. of 5th European Academy of Design Conference, Barcelona University, Spain, 28 – 30 April 2003
- [4] A. Tsui, “Dynamic Textures”, Art Centre College of Design, Pasadena, US (2004)  
[www.dynamictextures.com/Thesis/Welcome.html](http://www.dynamictextures.com/Thesis/Welcome.html)  
accessed 11 May 2009
- [5] O. Horev, “Talking to the hand – the interactive potential of shape change behavior in objects and tangible interfaces” Proc. of European Workshop on the Design and Semantics of Form and Movement DeSForM 2006, Eindhoven, Netherlands, 26- 27 October 2006.
- [6] J. Wallace, “Blossom”, in J. Wallace, “Emotionally charged: A practice-centred enquiry of digital jewellery and personal emotional significance” PhD Thesis, Sheffield Hallam University, UK (2007)
- [7] I. M. Koo, K. Jung, J. C. Koo, J.-D. Nam, Y. K. Lee, H. R. Choi, “Development of Soft-Actuator-Based Wearable Tactile Display” *IEEE Transactions on Robotics*, Volume 24, Issue 3, June 2008 pp. 549 – 558.
- [8] D. Johnson and S. Orlosky, Braille display device, described in R. G. Gilbertson, “Muscle Wires Project Book” (Mondo-tronics Inc. San Rafael, CA, 2000) p 1-9.
- [9] J. Rossiter, B. Stoimenov, T. Mukai, “A Self-switching Bistable Artificial Muscle Actuator” Proc. of SICE-ICASE International Joint Conference, SICE-ICCAS 2006, Busan, Korea.18-21 Oct 2006
- [10] TiNi Alloy Co. tactile feedback device, described in R. G. Gilbertson, “Muscle Wires Project Book” (Mondo-tronics Inc. San Rafael, CA, 2000) p 1-13.
- [11] S. Ashley, “Artificial Muscles” in *Scientific American* (October 2003) pp 52 – 59.
- [12] P. J. Walters, “Knowledge in the making: Prototyping and human centred design practice” PhD Thesis, Sheffield Hallam University, UK (2005).
- [13] P. Walters, J. Rossiter (2008) “Three-Dimensional Fabrication of Smart Actuators: Design Applications” Proc. of IS&T International Conference on Digital Fabrication Technologies, Pittsburgh, Pennsylvania, 6-11 September 2008.
- [14] “Enter the softbot [soft-bodied robots]” *Computing and Control Engineering* Volume 18 Issue 2 (2007) p 18 – 21.
- [15] B. A. Trimmer, A. E. Takesian, B. M. Sweet, C. B. Roger, D. C. Hake, & D. J. Rogers (2006) “Caterpillar locomotion: a new model for soft-bodied climbing and burrowing robots” in Proc. of 7th International Symposium on Technology and the Mine Problem, Monterey, CA: Mine Warfare Association, 2 – 5 May 2006.
- [16] M. J. Santer and S. Pellegrino (2004) “An asymmetrically-bistable monolithic energy-storing structure” in Proc. of the 45th AIAA/ASME/ASCE/AHS/ASC Conference on Structures, Structural Dynamics, and Materials, Palm Springs, California, April. 19-22 2004.
- [17] J. Rossiter, P. Walters and B. Stoimenov (2009) “Printing 3D dielectric elastomer actuators for soft robotics” in Proc. of 11<sup>th</sup> SPIE Electroactive Polymers and Devices (EAPAD) conference, San Diego, California, March 2009.
- [18] Email correspondence with Alchemie Limited, Warwick, UK, 20th February 2009.
- [19] R. G. Gilbertson, “Muscle Wires Project Book” (Mondo-tronics Inc. San Rafael, CA, 2000) p 2-14.
- [20] [www.objet.com/Materials/Tango\\_Materials/](http://www.objet.com/Materials/Tango_Materials/) (accessed 22 June 2009)
- [21] G. S. Chirikjian (1994) “A binary paradigm for robotic manipulators” Proc. of IEEE International Conference on Robotics and Automation, 8-13 May 1994 pp 3063-3069.

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## Author Biography

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