A Compact Bidirectional Bistable Electrothermal Switch

Pavan Kumar Challa, Abhishek Meena, A. Narayana Reddy

Abstract

In this paper, a novel design of electrothermally actuated microelectromechanical systems (MEMS) switch is presented. The MEMS switches have an applications in power relays, optical circuits, radio frequency devices, and biomedical devices. The electrothemal actuation is chosen for actuating compliant switch as it can generate large forces compare to other actuations. In our design, a curved beam is provided between two in-plane bidirectional electrothermal actuators. Applying appropriate polarity of voltage to the terminals, the bidirectional actuator can move in two opposite directions. There are two states for the switch as the curved beam exhibits two stable configurations; let them be ON and OFF states. Since both the electrothermal actuators can move in opposite direction, they can push the curved beam from ON state to OFF state and vice versa. It can be noted that it does not need any power supply whether it is in either ON or OFF. Novelty in the present design is that actuators along with curved beam is a single piece compliant mechanism. The proposed design can fit in the space of 650 μm × 100 μm.

Keywords: Electrothermal actuation, MEMS switch, Bistable beam, Bidirectional actuator, Snap-through

1. Introduction

Microelectromechanical systems (MEMS) switches have applications in power relays [1]-[2], optical circuits [3]-[4], radio frequency (RF) devices [5]-[6], and biomedical devices [7]. MEMS switches have an advantage over solid-state switches as they consume less power [8]. Furthermore, losses are minimum during OFF state in MEMS switches as they work based on physical contact.

Any switch by definition should have two states, i.e., ON and OFF states. This can be achieved using actuations like electrothermal, electromagnetic and piezoelectric actuations. For example, a bimetal strip can act as switch as it undergoes bending with elevated temparatures. If elevated temperature is considered as ON state in bimetal strip then room temperature is OFF state. Since realizing two layer of composite material is difficult in microfabriation, a single material electrothermal U-shaped actuator is developed [9]. The U-shaped actuator undergoes deformation similar to bimetal strip but works based on temperature gradient. Any actuator with and without voltage applications considered as two states of switch. However, the drawback of such a switch is that it requires a power supply in at least one of the states. Therefore, providing bistable element can overcome this difficulty.

The bistable switches are developed based on bimaterial thermal expansion [3], [10], pseudo-rigid body model based compliant mechanism [11]-[12], snap-through assisted by residual stresses [13]-[14] and snap-through assisted by curved beams [2], [15]. In all these bistable switches, actuator pushes the bistable element from one state to other. In other words, actuator and bistable element are two disconnected pieces and switch action takes place through physical contact during actuation. Few designs of bistable switches are also proposed with straight beams [16]. However, the working principle of these switches is neither shown through simulations nor experiments. Similar to other switches, the bistable switches based on straight beams are also having separate actuator and switching element. The switches that are proposed based on biomaterial and residual stresses are difficult to fabricate. Natural choice is to go for curved beam switches and pseudo-rigid body model based switches. The design that is proposed in this work is based on curved beams. To the best of authors' knowledge all bistable switches consists of two separate parts, i.e., disconnected parts of

P. K. Challa
Mechanical Engineering, IIT Guwahati, , E-mail: challapavan69@gmail.com

A. Meena
Mechanical Engineering, IIT Guwahati, , E-mail: abhijeph@gmail.com

A. N. Reddy
Mechanical Engineering, IIT Guwahati, , E-mail:annem@iitg.ernet.in.

actuator and bistable element, as found in the literature. In the proposed design the switch and bistable element are integrated into a single piece.

Doubly curved beam is considered as bistable element in the present design which is adopted from [15]. Clearly, the residual stresses are not required as stress free doubly curved beam can exhibit bistable snap-through. An in-plane bidirectional electrothermal actuator is adopted from [16] as two directional motion is necessary with reference to the state of stress free configuration. The novelty in the present design is to integrate these elements such that it is a single piece yet acts as bistable actuator.

2. Concept of design and working principle

A bistable curved beam is fixed between two in-plane bidirectional actuators as shown in initial configuration of Fig. (1). There are three terminals for each electrothermal actuator as shown in Fig. (1). Furthermore, the terminals of actuators are anchored mechanically to the substrate. As mentioned, the electrothermal actuator is adopted from [17] which can move in two directions from mean (stress free) position with application of voltage. Voltage distribution and mechanical deformations are shown in Fig. (2). Clearly, upward motion can be obtained by applying voltage to bottom terminal and grounding others and similarly downward motion can be obtained by applying voltage to top terminal. This bidirectional motion is utilized to move curved beam from one stable position to other stable position. Schematic diagram of working principle of bistable electrothermal actuator is shown in Fig. (3). Detailed snap-through analysis of curved beam and electrothermal analysis are required to decide dimensions. These analysis are presented in the next section.

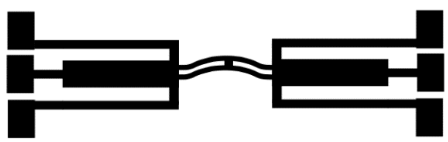

Figure 1: Schematic diagram of bistable switch

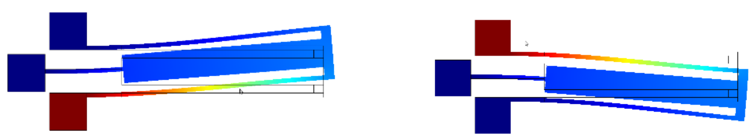

Figure 2: Deformed configurations of in-plane bidirectional electrothermal actuator with voltage distribution (a) upward deflection obtained by applying voltage to bottom terminal and grounding top and central terminals (b) downward deflection obtained by applying voltage to top terminal and grounding bottom and central terminal.

3. Design of bistable curved beams

The objective is to obtain a geometry of beam such that it exhibit bistable snap-though, i.e., force-displacement curve should intersect zero force axis at non-zero displacement. At first stage the single curved beams are considered. It has been observed that many geometries are undergoing snap-through but they are not bistable as force-displacement do not intersect with force zero axis other than origin. For example, two geometries of curved beams are simulated in ABAQUS finite element analysis software package and also prototypes are made using laser cutting process on acrylic sheet. First beam made with geometry of 70 mm width, 4 mm deep, 0.5 mm in-plane thickness and 2 mm out of plane thickness is shown in Fig. (4). It is important to note the radius of curvature of first beam is 155 mm which can be computed based on width and depth. The second beam is made of geometry of 80 mm width, 1 mm in-plane thickness and other dimensions are same as that of first beam. The radius of curvature of second beam is 202 mm which can be computed based on width and depth. The prototype of second beam geometry is shown in Fig. (5). First beam can be manually actuated and the snap-through phenomena be felt but it doesn’t exhibit bistable behaviour. On the other hand, the second beam does not undergo deformation, if the beam is pushed forcefully then it fails. Stress computation using finite element analysis also shows that the second beam geometry exceeds yield stress before reaching snap-through. Therefore, the finite element analysis should be carried out not only for snap-through behaviour but also for stresses. Final deformed state and load displacement curve are shown for first and second beams in Figs. (6) and (7), respectively.

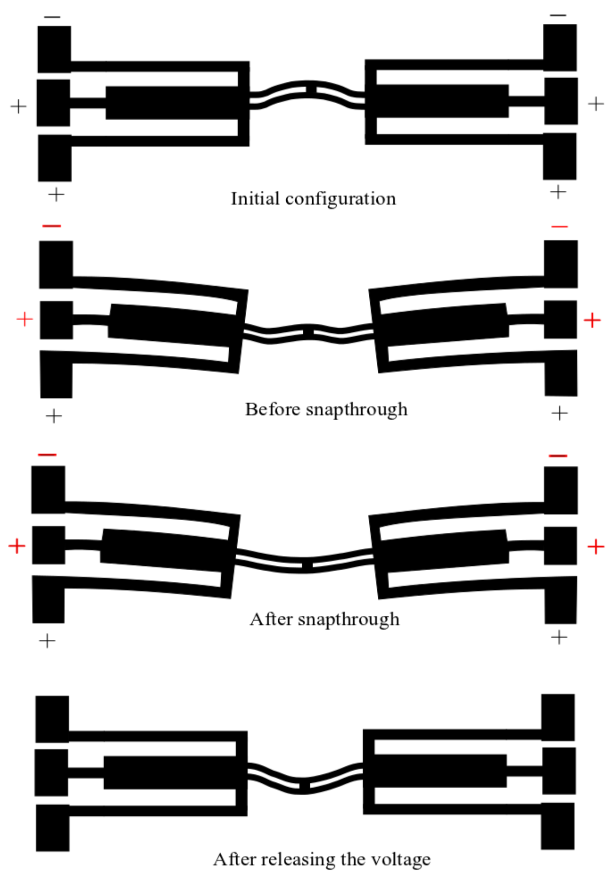

Figure 3: schematic diagram of working principle of bistable actuator.

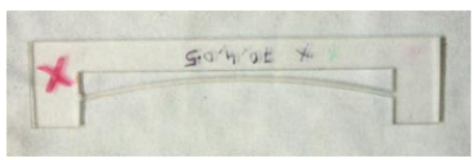

Figure 4: Prototype of arch beam with 70 mm width, 4 mm deep, 2 mm out-of-plane thickness, 0.5 mm in-plane thickness and 155 mm radius of curvature

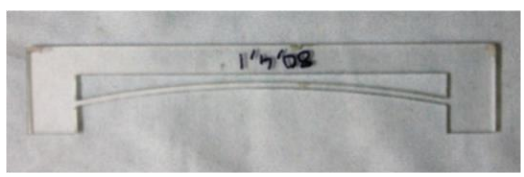

Figure 5: Prototype of arch beam with 80 mm width, 4 mm deep, 2 mm out-of-plane thickness, 1 mm in-plane thickness and 202 mm radius of curvature

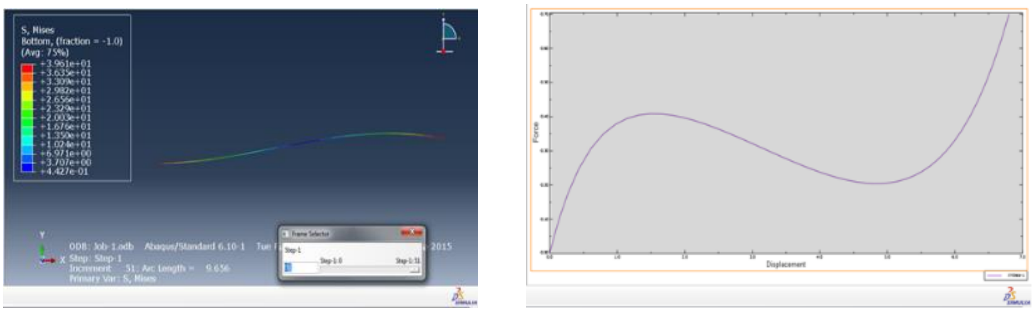

Figure 6: Simulations on arch beam with 70 mm radius of curvature, 4 mm deep, 2 mm out-of-plane thickness and 0.5 mm in-plane thickness for concentrated load at middle of the beam: (a) deformation accounting symmetry of beam (b) force-displacement curve for middle position of beam

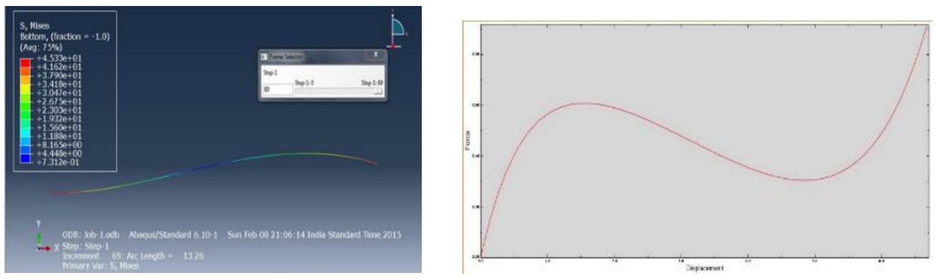

Figure 7: Simulations on arch beam with 80 mm radius of curvature, 4 mm deep, 2 mm out-of-plane thickness and 1 mm in-plane thickness for concentrated load at middle of the beam: (a) deformation accounting symmetry of beam (b) force-displacement curve for middle position of beam

The curved beam geometry (see Fig. (8)) is proposed such that the force-displacement curve intersect with zero force line. The proposed geometry is obtained using trial and error method. It can be noted that 72.66 mm radius of curvature of arch with 15 mm straight line segments on both ends. Joining of straight line and arch are smoothened by 25 mm fillet radius circle. Since the force-displacement curve is intersecting with force zero axis, the beam is expected to undergo bistable state. Though the beam is snapping it is flipping back to original state through the asymmetric mode as explained in [2]. The reason to consider clamped end boundary conditions is that the beam should stay in the same state after removal of voltage to the actuator. In fact, it is easy to obtain bistable behaviour with pin ended boundary conditions. Though the pin ended boundary conditions can be realised using flexure hinges, the actuator cannot transfer moment. Hence, providing flexure hinges between actuator and beam to obtain bistable behaviour is not useful. On the other hand, it is difficult to obtain a single beam that exhibit bistable behaviour. As discussed in [2], [15], the difficulty can be overcome by connecting two curved beams with a stiffener.

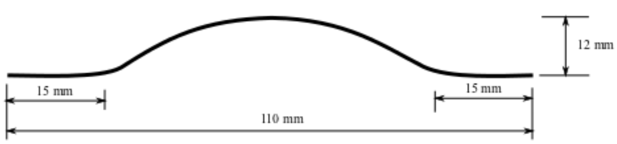

Figure 8: Doubly curved beam with stiffener at middle and the geometry of beam with 75 mm radius of curvature, 8 mm deep, 80 mm width,

Two curved beams connected by a stiffener can avoid the asymmetric mode of snap-through [15] and thereby obtain the bistable behaviour. Initially the beam is designed on macro scale size to verify the computational result with experiment. Several geometry of beams are considered for trial and error approach for checking snap-through and also to maintain stress within failure stress. A geometry beam shown in Fig. (9) is simulated for bistable behaviour and made on laser cutting machine to verify experimentally. The geometry of prototype is 80 mm width, 8 mm deep, 0.5 mm beam thickness, 15 mm straight beams connected to the end of circular curved beam and 1 mm stiffener is connected to both beams in the middle. In addition, 25 mm fillet is provided between arch and straight part of beam to avoid sharp corners. The radius of curvature of both beams is 104 mm which can be calculated based on width and depth. Undeformed and deformed configurations are shown in Fig. (10). Force-deflection curve intersects zero force axis as shown in Fig. (11) at mid-point of the beam. Hence, the bistable behaviour is expected for this geometry. Note that the load is also applied at mid-point vertically downward direction.

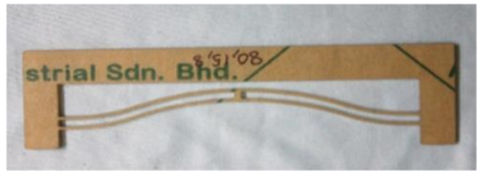

Figure 9: Prototype of doubly curved beam with stiffener at middle

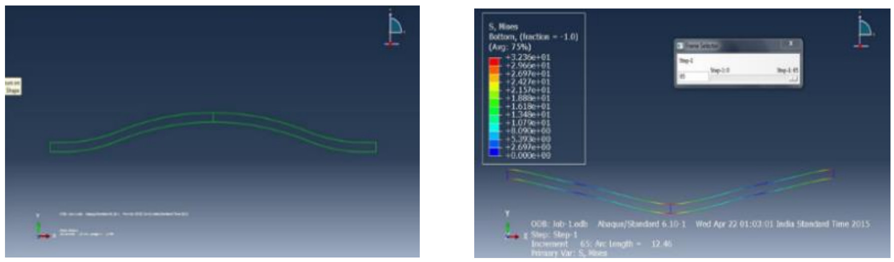

Figure 10: Snap-through analysis on curved beam using ABAQUS finite element analysis software package (a) undeformed configuration (b) deformation after snap-through

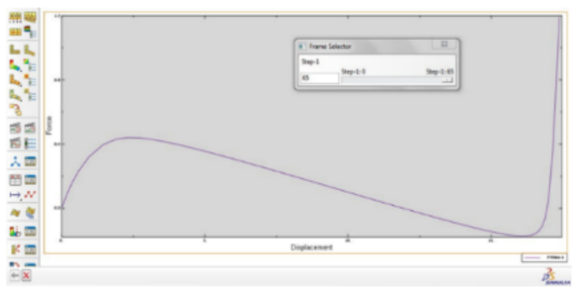

Figure 11: Force-deflection curved for doubly curved beam at mid-point

Experiments are also conducted on prototype to verify the snap-through behavior using gravity weight as shown in Fig. (12). Loads are incrementally added to find the approximate force for which the beam undergoes snap-through. The load is observed to be 0.45 N. The bistable state is shown in Fig. (12) by removing applied loads. In conclusion, the doubly curved beam can serve the purpose as it undergoes bistable state.

Figure 12: Snap-through behavior of doubly curved beam (a) deformation under action of load (b) deformation after removal of load, i.e., second stable state

The main task is to get dimensions of the doubly curved beam for micro-swich that exhibits bistable behavior. Accounting fabrication limit, the in-plane thickness of beam is assumed to be 2 µm. Other dimensions are scaled down based on macroscale beam. The micro-beam width of arch 320 µm, horizontal extension 60 µm, depth of beam 32 µm, out-of-plane thickness is 8 µm. Geometric nonlinear analysis on micro-beam is carried out using ABAQUS finite element analysis software package. Force-deflection curve (Fig. (13)) shows that the micro-beam exhibit bistable snap-through behavior and critical load for the beam is 180 µN. Note that silicon mechanical properties are assumed for micro-beam while carrying out analysis. Thus, doubly curved beam with above mentioned geometry is a candidate for the bistable switch. Now, the question remains to see the size of electrothermal actuators such that they apply sufficient moment to push the beam from one stable state to the other stable state. The reaction moment that is developed under action of critical load is 9.9×10^{-3} N·µm. We assume that the electrothermal actuator generate moment 9.9×10^{-3} N·µm and hence it moves from one stable state to other stable state. The dimensions of electrothermal actuator are presented in the next section.

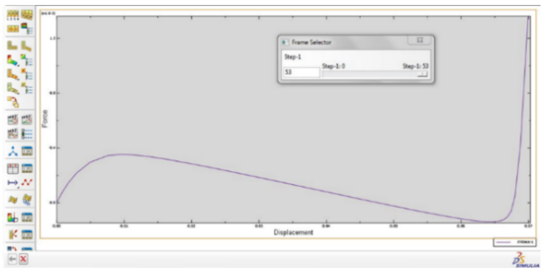

Figure 13: Force-displacement curve for micro-beam

4. The in-plane bidirectional electrothermal actuator

The geometry of the actuator is adopted from [17]. The critical moment which was obtained in the case of micro scale silicon curved beam has been considered as the requirement. The dimensions of the actuator are shown in the Fig. (14). In this case also thin beams are considered to be 2 µm as there is limit imposed by microfabrication. COMSOL Multiphysics finite element analysis package is used to find required voltage to provide sufficient moment which can cause bistability.

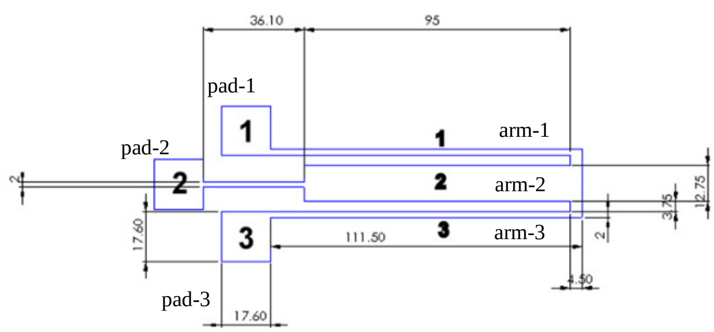

Figure 14: In-plane bidirectional electrothermal actuator with dimensions.

4.1 Working of Actuator:

First positive voltage is applied to pad-1 while grounding pod-2 and pod-3 as shown in Fig. (15a). Using conservation of current (i.e., Kirchhoff law of current), easy to see the current in arm-1 is equal to current in arm-2 and arm-3. Clearly, sum of cross-section area of arm-2 and arm-3 is more arm-1, the current density is more in arm-1 compare to other (see Fig. (16a)). Therefore, due to Joule heating arm-1 is hotter than others. Furthermore, arm-1 expands more than arm-2 and arm-3 thereby bending take place as shown in Fig. (17a). The bending of two actuators can create moment on doubly curved beam and hence the beam moves from one stable position to other as stated. Now voltage will be removed and arms revert back to their original positions, but curved beam remain in same state as it is bistable. If voltage application is interchanged between pod-1 and pad-3, i.e., positive voltage to pad-3 and grounding pad-1, the actuator bends in opposite direction. It should be noted that pad-2 is always grounded. The voltage distribution, current distribution and deformed configuration are shown in Figs. (15b), (16b) and (17b), respectively. Since actuator bends in opposite direction, the curved beam is also pushed to original state. Voltage is calculated to generate the moment by trial and error. The following electrical, thermal and mechanical properties are considered for actuator in simulations.

Electrical resistivity = 4.2×10^{-4} Ω-m, thermal conductivity = 100 W/mK, coefficient of thermal expansion $\alpha = 3 \times 10^{-6}$ K^{-1}, Young's modulus = 150 GPa, Poisson's ratio = 0.3, and density $\rho = 2.329 \times 10^{3}$ kg/m^3. Considering convection is important in electrothermal simulation as pointed out in [18]. Therefore, the convective heat transfer coefficient is considered to be 20 W/m^2K. It is found that 16 V are required to generate sufficient moment for these parameters. It should be noted that all pads are fixed for mechanical analysis, pads temperatures are assumed to be 300 K, i.e., room temperature for thermal analysis and all arms are assumed to be electrically insulated in electrical analysis.

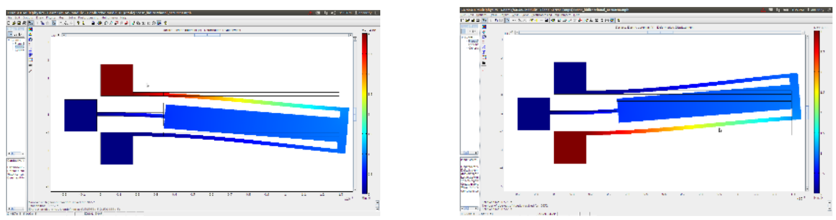

Figure 15: Voltage distribution in in-plane bidiredtional electrothermal actuator (a) voltage applied at pad-1 while grounded other pads (b) voltage applied at pad-3 while grounded other pads

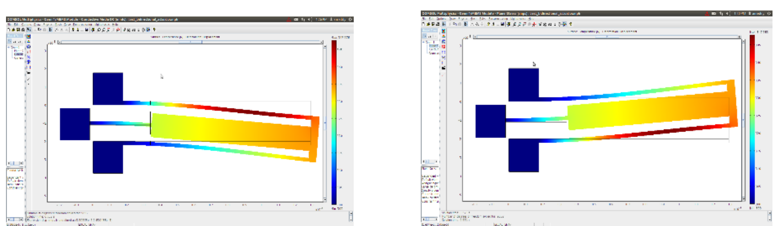

Figure 16: Current density distribution in in-plane bidiredtional electrothermal actuator (a) voltage applied at pad-1 while grounded other pads (b) voltage applied at pad-3 while grounded other pads

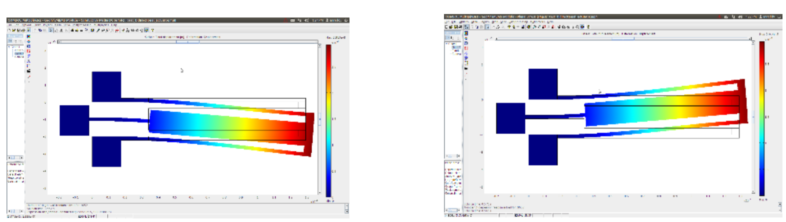

Figure 17: Deformation of in-plane bidiredtional electrothermal actuator (a) voltage applied at pad-1 while grounded other pads (b) voltage applied at pad-3 while grounded other pads

5. Conclusion

A novel design is proposed for electrothermal micro-swich such that it acts as actuator as well as switch. In other words, single piece bistable electrothermal swich is porposed. Geometric nonlinear analysis are carried out on single curved beams and doubly curved beams using ABAQUS finite element software pakage. Prototypes are made on 2 mm thick acrylic sheet using laser cutting machine to verify geometric nonlinear analysis. Experiments demonstrated that doubly curved beam can undergo bistable snap-through behavior. Scaled down doubly curved beam is proposed and analyzed for bistable analysis. The electrothermal actuator dimensions are also proposed to move bistable beam from one state to other state. Two bidirectional actuators and curved beam put together as shown in Fig. (1) leads to working design. The voltage required to actuate the actuator was found to be 16 V.

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