A Switchable Dual-Mode Actuator Enabled by Bistable Structure

Bo Li,* Lei Jiang, Wentao Ma, Yakun Zhang, Wenjie Sun, and Guimin Chen*

Soft actuators are favored due to their flexibility and adaptability, but are limited to single actuation mode. Herein, a novel soft actuator with a dual-kinestate performance is proposed. By subtly integrating a bistable compliant mechanism with artificial muscles, the soft actuator is capable of switching between binary motion and continuous motion with accurate output. Functions of overcoming external interference and regulating the snapping time are realized with programmed voltages. Two applications utilizing the switchable kinestate are illustrated, including a mechanical encryption display system with one actuator and an amplitude modulation system with two actuators in parallel. This novel soft actuator exhibits potential applications for the multi-mode actuation of soft robots.

1. Introduction

A soft bistable actuator utilizing electroactive polymer is a new type of mechatronic device that is self-actuated with two predefined positions.[1] Unlike the conventional soft actuator that is composed of intrinsic soft materials, this type of soft bistable actuator integrates a compliant structure for mechanical motion output and voltage-activated artificial muscle materials for fast actuation. Benefiting from both soft and compliant elements, the soft bistable actuator features large stroke, fast response, and high transient power density. These advantages are favored by new soft robots with unprecedented performances in grasping,[2] swimming,[3] and running.[4] To name a few, by several bistable actuators in connections, a digital-like discretization in a continuous working space is achieved, which, for the first time, links the mechanical system to binary robotics.[5]

However, there are challenging issues in actuation considering the integration of both active materials and mechanical structures. For the dielectric elastomer (DE) artificial muscle-based bistable actuator, previous studies have well established a coupled field theory for DE,[6] but there is a lack of theoretical guidance linking the strain in the material to the motion in the mechanical structure. Consequently, to trigger the bistable motion, high-level pulse voltage, at the risk of electrical breakdown, was applied on the DE for sufficient acceleration to induce a moment in a shuttle mass on the tip of the actuator structure.[5,7] This method was obtained after a sophisticated match between the flexible mechanical frames and the hyper-elasticity DE by extensive experimental combinations. In addition, other positions, except for the two terminates of the stable states, are not maintainable as they are unstable states in snapping, which means a continuous motion is sacrificed.

To address this challenge, in this article, we present a new type of soft bistable actuator capable of two types of actuation modes: binary/continuous motion that is switchable on-demand upon a voltage. We employ two types of artificial muscles, where the DE is responsible for continuous motion actuation covering the entire half-workspace (from a stable position to the flat state) and the twisting and coiled polymer fibers (TCPFs) for binary motion actuation that can overcome external interference. Through programmed voltage actuation, we achieve an accurate motion output with high repeated precision in the dual-mode actuation, without causing electrical breakdown. Utilizing this voltage-adjustable performance, we demonstrate two applications in 1) an electromechanically encrypted display with one actuator and 2) an amplitude modulation system with two actuators in parallel.

2. Experimental Results and Application

2.1. Design of the Soft Bistable Actuator

Figure 1 is the schematic illustration of the bistable actuator. In the principle design, Figure 1a, we use two kinds of electroactive artificial muscles: a piece of DE and two TCPFs, each of which is responsible for one type of actuation mode. TCPFs are used to control the binary motion due to their large force in one degree of
freedom displacement output. DE has a fast response with large in-plane expansion, so we can utilize its stable electromechanical response to control the continuous motion of the actuator. In Figure 1b, by prestretching DE to a moderate level, we program the stored energy $\Delta E_{\text{total}}$ in the actuator and the assembled actuator bends in its beams to reach a self-stabilized equilibrium state, a stable state. Due to the symmetric design of the structures, two stable states are obtained. The two motions are switchable on-demand.

Figure 1. Illustration of the principle of bimodal switching in the soft bistable actuator. a) The actuator is composed of a piece of DE, two TCPFs, and a compliant structure. b) With a prestretch on DE, the assembled actuator bends to reach an equilibrium state, a stable state. Due to the symmetry of the structures, two stable states are obtained. c) The total energy landscape has two local minimums, corresponding to the stable states and denoted by the bending angles $\theta_{\text{eq}}$ and $-\theta_{\text{eq}}$. The local peak represents the energy barrier that the bistable motion should overcome when snapping the unstable state. When powered by DE only, the actuator can be operated in a continuous motion, in either direction or , by the deployment of the beams in the mechanical structure. When powered selectively by TCPF, the landscape of the energy is altered to lower the energy barrier to enable a reversible binary motion . The two motions are switchable on-demand.
maximum peak. The valleys are the stable states \( \Theta_2 \) and \( \Theta_3 \) as denoted by the bending angles \( \theta_{eq} \) and \( -\theta_{eq} \). The peak represents the energy barrier that the binary motion should overcome when snapping through the unstable state \( \Theta_1 \). Through applying different voltage and pre-stretch, we can manipulate the height of the energy barrier and the shape of the landscape (Figure 1c) so that a dual-mode motion in actuation is attained. For example, when powered by DE only, the actuator operates in a continuous motion, following the path of either \( \Theta_1 \rightarrow \Theta_3 \) or \( \Theta_2 \rightarrow \Theta_3 \), in terms of a bending deployment as DE expanding under a voltage. When powered alternatively by TCPFs with linear contraction, the landscape of the energy is altered to lower the energy barrier \( \Delta E_{TCPF} \) to enable a binary motion following \( \Theta_1 \leftrightarrow \Theta_3 \). The two motions are switchable when different kinds of artificial muscles are powered. Note that, unlike previous only DE-based bistable actuators,[10] here, we enable the binary motion with two TCPFs, whose voltage is below 20 V in a safe and available range in most mechatronics.

### 2.2. Actuation Mode of Continuous Motion

We next verified the proposed scheme by experiments and theoretical study. The materials and fabrication of the actuator are described in the Experimental Section as well as in the Supporting Information. To obtain the relationship between the bending angle and the voltage, we applied a series of triangle waves of voltage (0–5500 V) on DE, with a rise and declining rate of 366.6 V s\(^{-1}\), while the TCPF was powered off. The actuator’s bending angles in 15 cycles were recorded (Figure 2a). It is well acknowledged that some DE-based actuators using VHB films have a strong time-dependent performance resulting from the viscoelastic deformation in DE.[11] To improve the precision of such a soft actuator, either feed-forward programming or hysteresis compensation has been proposed.[12] Here, we present another control-free methodology through the mechanical design for attainable high precision in the same material. Figure 2b illustrates the repeatability of the actuator in 15 loading-unloading cycles, and the curves are identical. The insert of Figure 2b is the bending angles at the maximum voltage level, which are overlapped, showing good repeatability. The detailed data are collected in Figure 2c at the listed voltage levels, and their standard deviations are analyzed. The maximum standard deviation is 0.34\(^\circ\), which suggests a high precision in repeated positioning (accuracy within 97.95–99.78%). We attribute the advances to the design of the actuator using compliant beams that restrict the deformation of DE within its stable electromechanical coupling that exhibiting a quasi-linear actuation strain range.

The experimental results at 0, 500, 1500, 2500, 3500, 4500, and 5500 V are compared (Figure 2d) with finite element method (FEM) simulation, displaying an ideal coincidence (Movies S1 and S2, Supporting Information). In the FEM study, ABAQUS (ABAQUS 2017) was used to simulate the stable state and continuous motion process under the high voltage of the actuator.[13] We used the subroutine UHYPYER to describe the electromechanical model of DE. Voltage was programmed in the simulation using the subroutine UDFLD, which is time-dependent. (The details of the FEM and experimental setup are described in the Supporting Information.)

### 2.3. Actuation Mode of Binary Motion

To characterize the bistable behavior, a binary motion between the two stable states was measured when the actuator was powered by two TCPFs alternatively. A voltage of 17 V (current of 0.105 A) was applied on one TCPF for quick actuation and powered off when the actuator was fully flattened to induce a consequent snap toward the other stable state. With the same actuation and control strategy on TCPF of the other side, the actuator snapped back, completing one actuation period (Movie S3, Supporting Information). The actuator snapped reversibly in 15 cycles between two stable states. Because TCPF has a training cycle, we started the recording from the second cycle. The cycles of the actuation are plotted in Figure 3a.

During the snapping, the actuator self-stabilized after a short-damping oscillation because of structural compliance. The peak and stable positions (+ and − for each side) are marked to characterize the damping time in Figure 3b. Mechanical bistable mechanism favors a constant displacement defined by its stable states, but when integrated with DE for actuation, its accuracy has seldom been reported. In Figure 3c, even after 15 cycles, the actuator is able to maintain its accuracy in deflection displacement with a standard deviation less than 1.06\(^\circ\) (i.e., accuracy over 97.3%). In an actuation period, five boundary positions are highlighted as the stable positions for the terminates in binary actuation mode and unstable equilibrium positions during the snapping (Figure 3d), which validate the proposed scheme.

During these experiments, we found that by regulating the voltage form in one type of active material, the TCPF, we can manage to realize dual-motion as well. However, in this case, we failed to stabilize the actuator when it is close to its energy maximum point (the fully flattened state), as a sudden snapping would occur, which means the continuous deformation was unable to cover the whole workspace. But using DE to generate continuous motion is a different scheme. DE gradually expands under the action of voltage to eliminate the force generated by its prestretching, and the internal stress of the actuator gradually disappears until the actuator is fully flattened. Under this scheme, all the angles from a stable position to the flat state are attainable (Figure 2), covering the entire workspace (between one energy minimum state and another minimum state). Therefore, we use two types of actuation materials, for switchable motion performance.

Moreover, when the actuator is under the bistable actuation mode, TCPF can generate a greater output force under an increasing voltage to afford an external load, offering an improved block force at a stable state. This feature enables the actuator to resist external interference, which is hardly achieved in only DE-based bistable actuators. To illustrate this ability, we placed a block as a barrier in the snapping path of the actuator, and the actuator could not snap under the same voltage in the previous bistable actuation. However, when the voltage on the TCPF was increased, the block force at the end of the actuator was improved. Consequently, the barrier was swept away and the actuator was able to snap in a cleaned path. In addition, this increased voltage level will not affect the stable state position of the actuator.
The snapping time of the actuator changes with the voltage powered on TCPF. The higher voltage on TCPF promotes speed, but will cause thermal failure. When DE is actuated, it expands and amplifies the bending angle in the structure. Meanwhile, the required deformation from TCPF is reduced, which accelerates the snapping between two stable states. Figure 4a illustrates the process of the binary actuation mode with a fixed voltage U2 on TCPF and an increasing voltage U1 on DE. Two snapping times

**Figure 2.** The actuation mode of continuous motion under triangle wave voltage. a) The voltage form and the tip bending angle. b) The voltage versus angle in 15 loading–unloading cycles. c) The actuator’s repeated positioning accuracy at each voltage. d) The processes of actuator bending in FEM and experiment, showing good consistency.
are defined in Figure 4b, which are asymmetric due to the intended mismatching of TCPF by the two sides of the actuator so that direction-identified bistable actuation performance is attainable. With the increase of U1, the snapping time $\Delta T_1$ declines and then rises, while the $\Delta T_2$ decreases monotonously (Figure 4c). This result offers an extending application of the bistable actuator whose snapping performance can be electrically adjusted.

2.4. An Electromechanical Encryption Display System

The bending angle of the actuator is only related to the level of voltage, either positive or negative, and two stable states determine the bending direction of the actuator. Taking advantage of these features, we illustrated an electromechanical encryption display system with two sets of encryption rules (Figure 5a,b) to demonstrate the function of the switchable actuation mode in the...
actuator. In the electromechanical encryption display system, the actuator was activated by an input voltage, and then it bent to reflect a laser light to a different location area. We first defined the encryption algorithm (Figure 5c), that is, the relationship between the voltage and the displayed letter. In the encryption algorithm, the positive voltage is programmed by one set of user-defined rules, the negative voltage is in another set of rules, and the sign of the voltage determines which set of rules shall be used. When the electromechanical encryption display system receives the voltage signal, an SCM (Arduino MEGA2560) identifies whether the voltage signal is positive or negative. If the voltage is positive, SCM powers on the left TCPF. The laser light is reflected to the half-space with platform 1 through the bending of the actuator. If the voltage is negative, the actuator will be switched to platform 2. Then the value of the input voltage determines the bending angle of the actuator, which can be interpreted by each set of rules. The bending angle and the bending direction of the actuator together decode the incoming information. We name such a display platform as an electromechanical encryption display system, and its performance is demonstrated in Figure 5d and Movie S4, Supporting Information.

2.5. Amplitude Modulation Utilizing Two Actuators

Figure 6 presents another illustrative example of a motion amplitude modulation with two soft actuators in a parallel
configuration. Binary actuation mode is first selected for composing the initial configuration of the platform, and the actuators then work in continuous actuation mode for amplitude output. We fixed two actuators in parallel and used two connecting rods to link the ends of the two actuators. The displacement output in the X direction consists of two factors: 1) the bending angle of the actuator and 2) the angle between the connecting rods. Each actuator has two stable states, denoted as Left and Right, so the amplitude modulation mechanism (AMM) has four configurations: Left–Left, Right–Right, Left–Right, and Right–Left (Figure 6). As the Left–Left and Right–Right configurations are symmetrical, their displacement in the X direction is the same, so only three configurations are illustrated. By selecting different configurations, we modulate the output displacement of the hinge in the same input voltage signal form. When the AMM is in the configuration of Left–Right, the angle between the connecting rods decreases as the voltage increases and the displacement of the hinge increases, resulting in the largest amplitude (Movie S5, Supporting Information). In the configuration of Left–Left, the angle between the connecting rods does not change with voltage changes, so its amplitude of motion is the medium (Movie S6, Supporting Information). In the configuration of Right–Left, the angle increases as the voltage increases, so its amplitude of motion is the smallest (Movie S7, Supporting Information). As the range of amplitude is related to the distance between the two actuators and the link length, different

![Diagram of actuator configurations](image)

Figure 5. Demonstration of the switching capability of the soft actuator as an electromechanical encryption display system. a) The experimental setup when the reflected laser light is regulated by the actuator’s motion. b) The platform with the actuator. c) The encryption algorithm. In step 1, the sign of the input voltage determines the direction of binary motion; in step 2, the actuator is switched to the continuous motion, and the value of the input voltage determines the bending angle of the actuator, which is listed in the encryption algorithm Table. d) The results of the coding and display when the actuator is switched.
modulation performances are programmable and deliverable by adjusting the parallel connection of D and L in Figure 6.

3. Conclusions

A new soft bistable actuator is designed by coupling two artificial muscles (TCPF and DE) and a flexural structure for switchable dual-mode actuations: binary motion and continuous motion. Through the applied voltage, we manipulate the energy curve by tuning the energy barrier for the actuation strategy. The actuator design is studied by FEM, which guides the fabrication. Experimental results verify the design purpose and high repeated position accuracy (>97%) in either motion mode powered by a specific artificial muscle. Applications are illustrated that utilize the switchable actuation mode in a single actuator for an electro-mechanical encryption display system, as well as an amplitude modulator with two soft actuators in parallel. The study reveals that through mechanical design of a compliant structure, a new type of soft actuator, with dual kinestates and a high precision motion, shall offer new insight into developing high-performance soft robots.

Figure 6. An amplitude modulation platform utilizing two actuators in different configurations. Two actuators are connected in parallel for three configurations, and each configuration has an output amplitude. The binary actuation mode of the actuator is used to determine the configuration, and the continuous motion of the actuator is used to modulate displacement.
4. Experimental Section

Materials: The materials for fabricating the bistable soft actuator are as follows: DEs (VHB 4910, 3M company), carbon electrodes (ELASTOSIL 3162/AB, Wacker), nylon fishline (#6, Transparent strand, Ø0.38 mm, NORTH VIKINGS), silver-plated line (140D, SANMAU), polyethylene terephthalate (PET) (0.3 mm), and polymethyl methacrylate (PMMA) (2 and 5 mm). A laser cutting machine (CMA-6040, GD HAN’S YUEMING LASER GROUP) was used to cut PET and PMMA into the desired shape. Elements of the actuator before the assembling are shown in Figure S7, Supporting Information. The fabrication processes of the TCPF and the DE are listed in the Supporting Information.

Methods for Bending Motion Characterization: To control the bistable soft actuator, we used the high-voltage amplifier (AMP-20820, Matsusada) and DC voltage source (HLR-3660D, Henghui) to realize the continuous motion and the binary motion, respectively. We used two laser displacement sensors (LK-C80, KEYENCE) to record the deformation of the actuator. All other control and recording were done through a DAQ card (USB-6363, NI) on a PC by MATLAB. The Supporting Information contains detailed methods.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords

artificial muscles, bistable actuators, deployable structures, soft robots

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