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An Electrostatic Linear Film Actuator with Passive Phase Switching

Junsoo Kim[1], Claudia Sanchez[2], Seongju Byeon[3], Concepción A Monje[2], Amy K. Han[3], and Herbert Shea[1,*]

I. INTRODUCTION

Artificial muscles for soft robots and human interactive machines must deliver not only high force and fast dynamics, but also large stroke, often tens of percent strain, while remaining mechanically compliant. Many existing actuators trade compactness, stretchability, and efficiency: motor driven transmissions and pneumatics add rigid mass, SMAs are inefficient and slow, and electrostatic DEAs and HASEL actuators couple contraction to lateral expansion, complicating dense stacking for high force output[1-3]. In contrast, sliding electrostatic film actuators enable compact multilayer integration without lateral expansion and provide large stroke, approaching 40% contraction, by generating shear forces between ultrathin (≈50–150 µm) slider and stator electrode films[4-6]. However, in multi-stack configurations, force additivity degrades under curvature or electrode misalignment because uneven electrode overlap causes individual layers to generate weakened or oppositely directed electrostatic forces.

Here we introduce an electrostatic linear film actuator that performs passive phase switching mechanically through patterned brush contacts between slider and stator films. As the slider moves, each stator electrode is locally assigned HV or ground at the correct position, maintaining force direction despite bending, and stretch, and enabling operation from a single DC source. In a proof of concept, the actuator autonomously switched four stator phases and reached 280 mm/s, validating fast, sensor-free phase switching.

II. PASSIVE PHASE SWITCHING ELECTROSTATIC FILM ACTUATOR

A. *Design of the Actuator*

The actuator is built from a thin slider film and a segmented stator film (Fig. 1(i)). Force-generating electrodes (FGEs) are patterned on each film and insulated by a dielectric layer. The stator is divided into electrically independent sections separated by compliant PDMS joints to introduce in-plane stretchability while maintaining a predominantly planar electrode geometry. Within each stator section, 4-phase FGEs are routed to local brush electrodes via bus lines (phases A-D). The slider film remains flexible but largely non-stretchable to efficiently transmit tensile load; it integrates 2-phase FGEs and longitudinal brush rails connected to an external DC high-voltage source and ground.

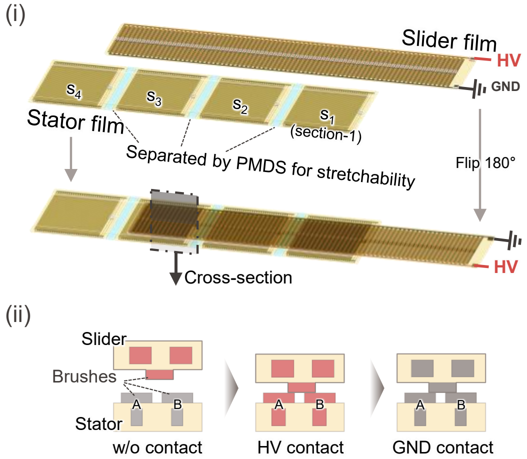

Fig. 1. Architecture and passive phase switching mechanism of the actuator: (i) 3D rendering of the slider and stator films, showing segmented stator sections that enhance stretchability; (ii) brush contact assigns local HV or ground to stator electrodes as the slider moves, enabling autonomous passive phase switching.

B. *Working Principle*

Passive phase switching is achieved through brush contact between the stator and slider (Fig. 1(ii)). When a stator brush touches the slider HV or GND rail, the corresponding stator phase charges to HV or GND; when contact is lost, the phase becomes electrically floating. Because polarity is assigned locally at the brush interface, passive phase switching is governed by geometry and contact. A representative passive phase switching sequence is shown in Fig. 2. As the slider translates, successive brush contacts transfer charge and autonomously switch stator phase polarities (e.g., passive phase switching of B and D, followed by A and C). This preserves the direction of the net electrostatic shear force under constant DC excitation, without multi-phase timing or external position sensing. The mechanism is analogous to brush passive switching in DC motors, but implemented in compliant, ultrathin electrode films.

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[1] J. Kim, and H. Shea are with the Ecole Polytechnique Fédérale de Lausanne (EPFL), Soft Transducers Lab (LMTS), 71b rue de la Maladière, 2002 Neuchâtel, Switzerland.

[2] C. Sanchez, and C. A. Monje is with the Department of Systems Engineering and Automation, Universidad Carlos III de Madrid, 28911 Leganés, Madrid, Spain.

[3] S. Byeon and A. K. Han are with the Department of Mechanical Engineering, Seoul National University, Seoul 08826, Republic of Korea.

* Corresponding author (e-mail: herbert.shea@epfl.ch).

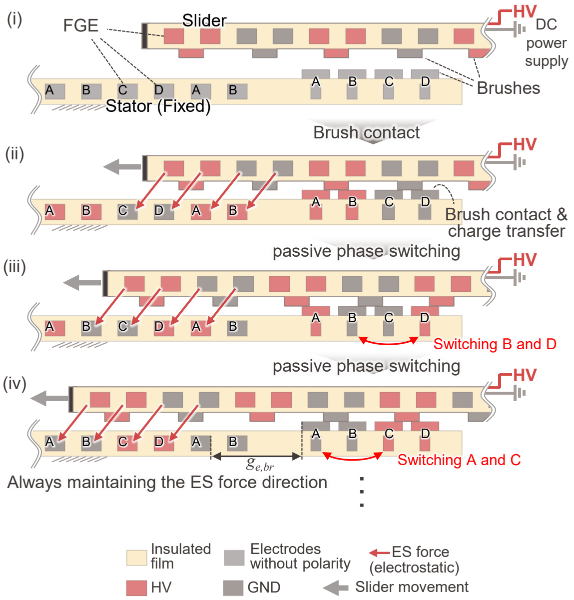

Fig. 2. Passive phase switching sequence of the electrostatic film actuator: (i–iv) as the slider translates, successive brush contacts transfer charge and autonomously switch stator electrode polarities, ensuring that the electrostatic shear force remains in a constant direction under DC high-voltage excitation.

III. PROTOTYPE CHARACTERIZATION AND DEMONSTRATION

A proof-of-concept actuator with a single, non-stretchable stator section was fabricated using commercial flexible printed-circuit processes (Fig. 3(i)). The stator and slider films included force-generating electrodes and brushes. The actuator was immersed in dielectric liquid (silicone oil) and driven by applying 700 V DC only to the slider film. Optical images highlight the brush contact region during motion. Kinematic measurements show 39 mm travel in 300 ms (average 100 mm/s) with a peak speed of 280 mm/s (Fig. 3(ii)). As a demonstration, in 1.5 cSt silicone oil, the actuator achieved ~27 mm reversible motion under 1 kV DC while lifting a 5 g mass, reaching maximum contraction in ~0.3 s and relaxing after voltage removal, demonstrating fast, repeatable, large-stroke motion via passive phase switching with DC input (Fig. 3(iii)).

IV. DISCUSSION

Passive phase switching decouples force generation from precise global timing and alignment, and is expected to enable multilayer stacks that better preserve additive force under stretching or bending. Furthermore, because operation requires only a single HV node and ground, power electronics can be substantially simplified relative to the multi-phase AC drivers required by conventional electrostatic film actuators, while passive phase switching remains sensor-free.

V. CONCLUSION

We presented an electrostatic linear film artificial muscle with passive phase switching that uses patterned brush contacts to mechanically switch stator phases under DC high voltage. A proof-of-concept prototype achieved autonomous phase switching and a peak speed of 280 mm/s at 700 V in dielectric liquid. By maintaining a constant shear-force direction without multi-phase driving or position sensing, the proposed architecture provides a scalable route toward high-stroke, misalignment-tolerant electrostatic artificial muscles.

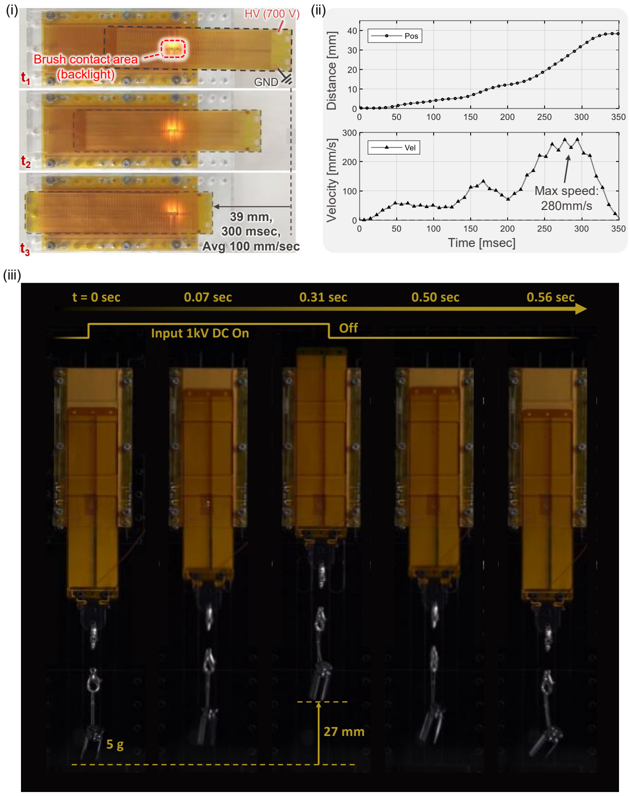

Fig. 3. Experimental validation of passive phase switching . (i) Fabricated stator, slider films, and optical images of motion under 700 V DC in dielectric liquid. (ii) Measured displacement and velocity showing a maximum speed of 280 mm/s. (iii) Demonstration of lifting a 5 g weight in 1.5 cSt silicone oil.

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