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Thin-film Programmable Robotic Damper Enabled by a Stick-Slip-Free Electrostatic Clutch

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***Abstract*—Electrostatic (ES) clutches are promising candidates for wearable and assistive robotics due to their thin, lightweight, and low-power characteristics. However, conventional ES clutches typically suffer from mechanical instability caused by the stick-slip phenomenon, restricting their operation to simple binary (locked or free) modes. In this work, we present a Stick-slip-free Variable Electrostatic (SV-ES) clutch that functions as a high-performance programmable robotic damper. By utilizing a PVC-gel friction layer, the device achieves stable and continuous sliding even under high shear stress (29 N/cm² at 100 V). We demonstrate that this stability allows for precise closed-loop modulation of kinetic friction and motor-free position control. The versatility of the SV-ES clutch is validated through three robotic applications: active motion assistance for a robotic arm, high-fidelity haptic rendering, and programmable impact damping for a robotic leg.**

Index Terms— electrostatic clutch, thin-film, stick-slip, damper

I. INTRODUCTION

CONTROLLING mechanical impedance is essential for safe and adaptive human-robot interaction [1, 2]. While clutches and brakes offer a way to modulate coupling, traditional designs are often too bulky for wearable systems. ES clutches provide a thin-film alternative, yet their widespread adoption in robotics is hindered by stick-slip vibrations, which lead to jerky motion and unintended disengagement during sliding [3-5]. Most existing ES clutches are thus limited to acting as static brakes.

In response, we present a stick–slip–free variable electrostatic (SV-ES) clutch, acting as a high-performance friction modulator. By incorporating polyvinyl chloride (PVC) gel as the frictional layer, the device achieves high force capacity and enables continuous sliding friction control without the instability of stick–slip. The SV-ES clutch generates a frictional stress of 29 N/cm^2 at 100 V. Crucially, the PVC-gel facilitates a dual mechanism for stick-slip suppression: it effectively eliminates the discrepancy between static and kinetic friction while simultaneously shifting the sliding response from velocity-weakening to velocity-strengthening as the plasticizer content increases. These attributes allow the SV-ES clutch to maintain precise friction control even under high shear stresses up to 22.5 N/cm^2, functioning effectively as a programmable robotic damper. This integrated capability—delivering both high and controllable kinetic friction—moves beyond conventional binary operation and opens new possibilities for advanced robotic systems and haptic interfaces.

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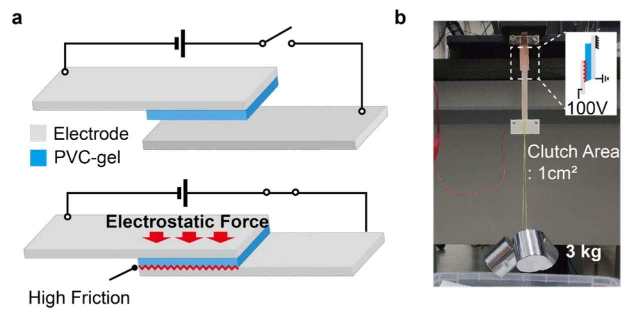

Fig. 1. (a) Schematic of the SV-ES clutch. (b) An SV-ES clutch supporting a static load of 3 kg at 100 V with 1 cm^2 overlap area.

II. RESULTS AND DISCUSSION

The SV-ES clutch, as shown in Fig. 1(a), consists of two electrodes with a PVC (Polyvinyl chloride)-gel layer. When a voltage is applied, the PVC-gel adheres to the opposing electrode due to electrostatic attraction, restricting the

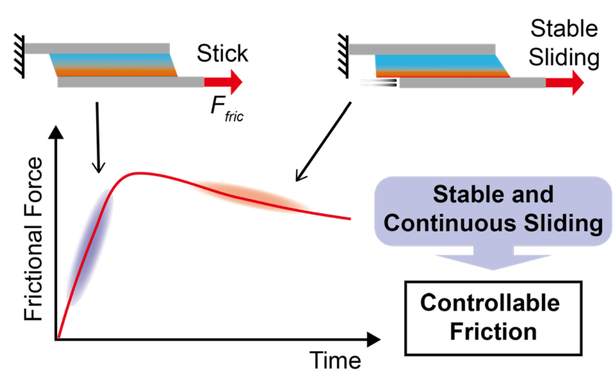

Fig. 2. The SV-ES clutch enables stable and continuous sliding, allowing for precise and controllable kinetic friction modulation.

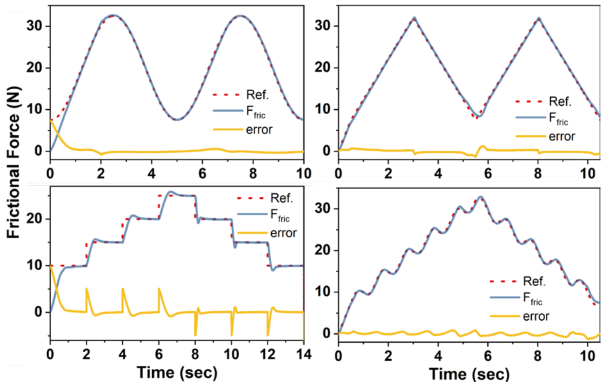

Fig. 3. Kinetic friction tracking performance of SV-ES clutch for various reference profiles, including sinusoidal, pyramid, stepwise (up and down), and pyramid–sinusoidal combinations

relative motion between the electrodes through a strong frictional force. As illustrated in Fig. 1(b), the SV-ES clutch generates a sufficient frictional force to hold a weight of 3 kg when 100 V is applied over an overlap area of 1 cm².

However, conventional ES clutches typically exhibit the stick-slip phenomenon once sliding begins. During sliding, this stick-slip effect causes the film to repeatedly adhere and detach, generating unwanted vibrations. Furthermore, if the film detaches completely, it can lead to mechanical failure, such as dropping the held object.

In contrast, the PVC-gel used in the SV-ES clutch enables stable and continuous sliding, thanks to the negligible disparity between its static and kinetic friction and its velocity-strengthening characteristics. As shown in Fig. 2, stable sliding behavior of SV-ES clutch allows for real-time feedback control of the kinetic friction. Fig. 3 shows the results of controlling kinetic friction by pulling the clutch at a constant speed (1 mm/s) using a motorized stage while feeding back the frictional force via a load cell. Using a gain-scheduled PID controller, we achieved accurate tracking of various force profiles (sinusoidal, stepwise, etc.) with high fidelity.

Fig. 4 demonstrates the potential of the proposed device as a thin-film programmable damper utilizing these unique properties. In Fig. 4(a), a robotic arm holding fragile eggs was programmed to descend. Fig. 4(b) illustrates a haptic glove utilizing the SV-ES clutch. By modulating the frictional force of the SV-ES clutch, the system renders virtual mechanical impedance. Finally, in Fig. 4(c), the SV-ES clutch acts as a variable damper in a robotic leg model to absorb impact energy during landing. These results demonstrate the diverse potential of the SV-ES clutch for robotic applications, maintaining a thin form factor while leveraging its stable sliding characteristics.

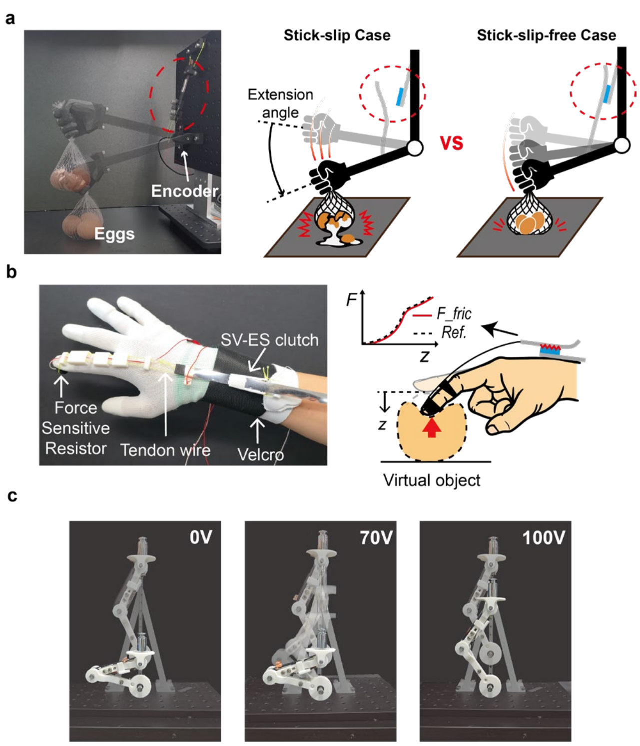

Fig. 4. (a) Experimental setup of a robotic arm for active motion assistance, featuring an SV-ES clutch mounted at the biceps. (b) Wearable kinesthetic haptic glove employing a tendon-driven SV-ES clutch. (c) Schematic of the robotic leg integrated with a belt-pulley mechanism and the SV-ES clutch to function as a programmable damper.

III. Conclusion

We have developed a thin-film programmable robotic damper that overcomes the fundamental limitation of stick-slip in electrostatic clutches. By achieving stable, high-force kinetic friction, this device moves beyond binary switching to enable continuous impedance modulation. The demonstrated applications in motion assistance, haptics, and impact damping suggest that the SV-ES clutch can serve as a core component for the next generation of safe, compliant, and energy-efficient robotic systems.

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