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STEM: Soft Tactile Electromagnetic Actuator for Virtual Environment Interactions

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I. Introduction

With the advancement of virtual reality (VR), research into wearable haptic devices simulating tactile interactions for immersive experiences continues.[1] As humans interact with the physical world through haptics, wearable feedback devices enhance VR immersion and interaction. Providing tactile feedback enables users to manipulate 3D virtual objects, reducing cognitive effort and visual dependence. Wearability critically influences VR immersiveness, as rigid, bulky devices not only pose safety threats but disrupt cognitive connections due to high impedance.[2] Thus, compact vibrotactile actuators like LRAs and coin motors are often used. They provide strong vibrations for interaction notifications. For less dynamic feedback, small motors and linear actuators render spatial surfaces and bumps by producing fingertip indentation forces.[3] Servo motors in thimble structures also deliver pressing sensations.[4-5] While effective, these offer only single-mode feedback, prompting interest in multi-DoF devices using multiple actuators for pressure, vibration, and shear stimuli.[6-7] However, this approach enlarges the system, reducing usability.

Soft materials are increasingly used to create compliant, lightweight haptic actuators. They enable conformal finger contact crucial for effective feedback. Dielectric and electrostatic actuators offer fast responses and high energy density under high voltage (~kV),[8-9] while pneumatic actuators provide strong force (~N) but limited bandwidth and bulky compressors.[10-11] Despite innovations, soft actuation faces challenges of weak output, robustness, and feasibility.

Alternatively, soft materials can serve passively as casing or energy storage. Yu et al. and Li et al. proposed miniaturized electromagnetic actuators using flexible films for vibration at resonance frequency with minimal power input.[12-13]

This study proposes a soft tactile electromagnetic (STEM) actuator worn on the finger, delivering not just vibration but also force, impulse, and arbitrary feedback. Using soft materials for energy storage and encasing enables out-of-plane deformation and enhanced wearability. The hardware aims to render realistic haptic interactions like pressing a button or grasping an object in VR environments. (Fig. 1)

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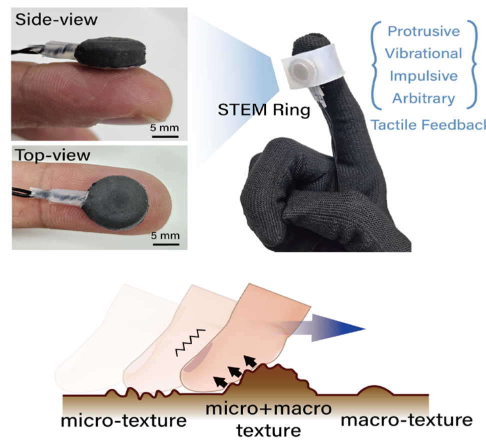
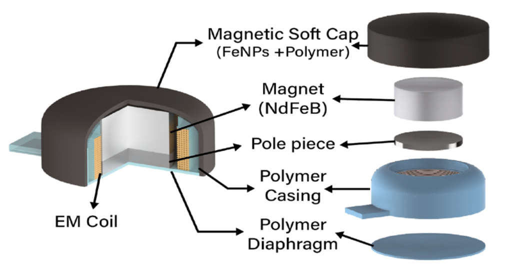


(a)



(b)

Figure 1 (a) Photograph of the soft tactile electromagnetic (STEM) actuator, designed to provide multimodal tactile feedback with enhanced wearability (b) Structural diagram of the STEM actuator.

II. System Description

The proposed actuator consists of an electromagnetic copper coil embedded in a polymer casing, a permanent magnet with a pole piece, and a magnetic soft cap, as shown in Fig. 1b. The magnet is suspended inside the EM coil by a polymer diaphragm, allowing controlled motion. When the coil is activated, the magnet experiences longitudinal displacement via Lorentz force (Fig. 1b).

The elastomer structure allows the magnet to protrude, enabling various haptic feedback modes like impulsive (tapping) and protrusive (pressure) forces. The elastic diaphragm also boosts dynamic performance by using resonance for strong vibrational feedback.

A key design feature is the magnetic reinforcements —specifically the magnetic soft cap (a polymer composite with iron nanoparticles) and the pole piece—which guide

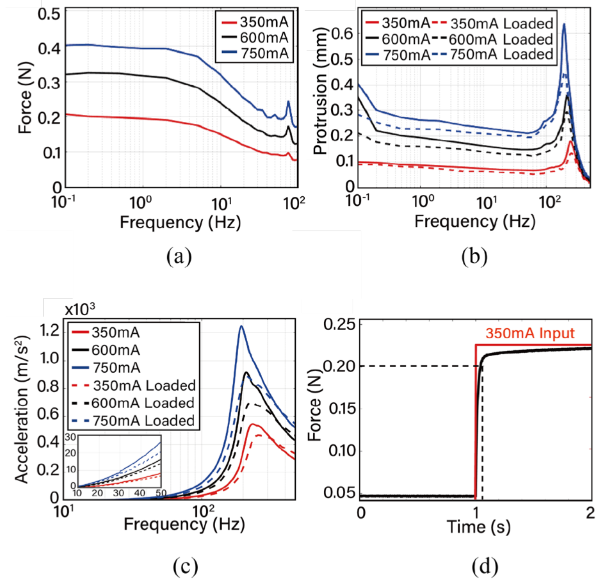


Figure 2 Output performance of the actuator at input current amplitudes of 350, 600, and 750 mA for varying input signal frequencies: (a) Force response, (b) protrusion response showing resonance, and (c) acceleration response. (d) Step input response demonstrating the actuator's high dynamic performance with a low response time.

magnetic flux lines perpendicular to the coil wires, minimizing leakage. This nearly closed magnetic loop improves force output and efficiency.

III. Haptic Actuator Output Performance

The actuator's response to sinusoidal current inputs of 350 mA, 600 mA, and 750 mA was measured across various frequencies. For force output, it produced a maximum of 0.4 N at 0.1 Hz with 750 mA input, far exceeding the fingertip's perceivable normal force (~0.01 N static, ~0.005 N vibrational) . The actuator demonstrated a 25 Hz bandwidth (Fig. 6a). For protrusion output, it achieved a maximum displacement of 0.4 mm at 0.1 Hz under near-static actuation and a peak of 0.63 mm at resonance in the free state (Fig. 6b). With preload, a slight performance drop and a resonance shift from 240 Hz at 350 mA to 190 Hz at 750 mA were observed, attributed to mechanical nonlinearities. For acceleration output, sinusoidal inputs up to 500 Hz were applied, with RMS results shown in Fig. 6c. The actuator consistently exceeded 10 m/s² above 30 Hz, peaking at ~1250 m/s² at resonance with 750 mA input under free state.2 km/h, and 4 km/h conditions was 95.0%, 95.3%, and 96.0%, respectively.

IV. Conclusion & Discussion

In this study, we developed a STEM actuator capable of delivering multimodal tactile feedback. By incorporating magnetic reinforcements, such as the soft magnetic cap and the ferromagnetic pole piece, we effectively amplified the output force by minimizing magnetic flux leakage. The actuator's performance was evaluated by measuring output force, protrusive displacement, and acceleration over a wide frequency range. Its ability to generate diverse feedback—including force, vibration, and impulse signals—demonstrates its versatility in comparison to traditional vibrotactile actuators. Furthermore, the integration of soft materials not only enhances wearability but also ensures sufficient force output for effective haptic rendering.

Despite strong performance, the actuator has limitations. Heat generation during prolonged use may require thermal management for user comfort. While it delivers predefined signals, further research is needed to evaluate its adaptability to real-time, user-driven feedback.

Future work will leverage the STEM actuator to deliver realistic, dynamic haptic feedback, enhancing VR immersion. Its multimodal capabilities could simulate sensations of pressing soft or rigid objects and render textures like rough or smooth surfaces with bumps, contributing to a richer, more intuitive VR experience bridging vision and touch.

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