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Scaling Electropermanent Magnet Controlled Magnetic Soft Actuators for Tactile Unit Cell*

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I. Background/State-of-the-Art

Soft haptic actuators are increasingly vital for applications in virtual reality, robotics, and assistive devices such as refreshable braille displays [1], [2]. Magnetic soft materials enable untethered, energy-efficient, and rapid actuation [3]. Our prior works have leveraged magnetic elastomers for tactile feedback using force-driven actuation with soft magnetic particles [4] and torque-driven actuation with hard magnetic particles [5], yet scaling such systems while preserving functionality remains a key challenge. This work investigates how proportional scaling affects actuator performance in composite elastomer-based torque-mode systems controlled by electropermanent magnets (EPMs).

II. Implementation

As illustrated in Fig. 1 exploded view, each tactile unit cell (taxel) consists of a composite elastomer mounted on a thin Kapton holder with a circular aperture, placed atop an EPM frame. The EPM comprises two AlNiCo-5 magnets connected by soft iron cores; one magnet is wound with a coil to enable magnetic state switching. The side view in Fig. 1 shows how the composite elastomer is embedded with two rectangular out-out-plane anisotropic magnetic elastomers with opposing magnetization directions, which deflect the composite upward due to the toque on the magnetizations when experiencing a uniform magnetic field from the EPM frame. As seen in the Fig. 1 top view, when both AlNiCo magnets have parallel magnetizations, the EPM is in the "ON" state, and when they have antiparallel magnetizations the EMP is in the "OFF" state.

To study scaling, devices were fabricated at the previous baseline size [5] as well as +33% and -33% sizes. All geometric features, including the size of magnetic regions, elastomer thickness and aperture size, were scaled proportionally. The number of coil turns was held constant (240 turns), while the wire gauge was adjusted to maintain current density. Dimensions are summarized in Table I. The fabrication processes for each scaled version are identical, ensuring that any observed differences in performance are assumed to be due to the scaling effects and not fabrication.

III. Results and Discussion

COMSOL simulations were conducted to evaluate deflection under a 20 mT field as a function of magnetic elastomer width for each scaled thickness and aperture size. Fig. 2a reports diminishing gain in deflection as the width of the magnetic elastomer increases for a given aperture size. For fabricated sizes, the simulated deflections were 1.26 mm, 0.95 mm, and 0.63 mm (circled in red in Fig. 2a) for +33%, baseline, and -33% scales, respectively, indicating that the deflection scales proportionally with size.

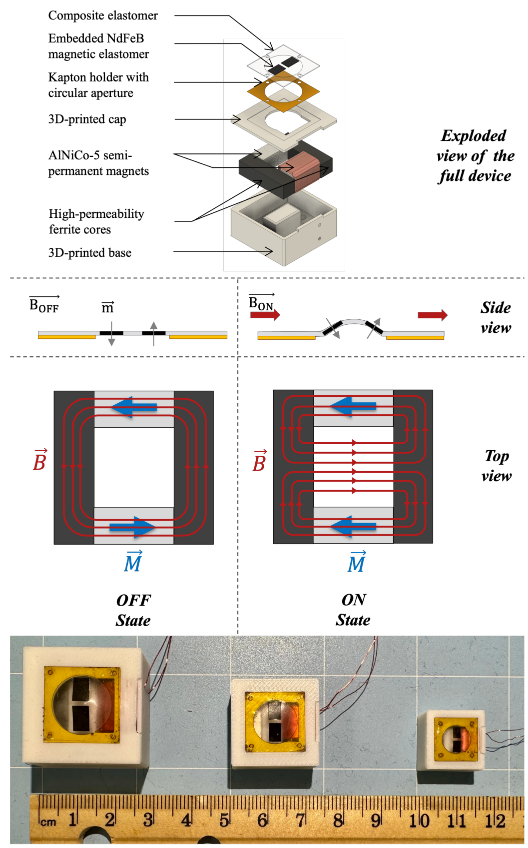

Fig. 1. (Left) Exploded view showing components of the device: composite elastomer on the holder atop EPM frame held together by 3D-printed base. (Right) Side view of the composite elastomer and magnetization direction and top view of the EPM frame showing actuation modes and magnetic flux density configurations within the EPM during the ON and OFF states, (Bottom) the size comparison of the fabricated taxels.

The fabricated taxels of three different scales (pictured in Fig. 1 (bottom) were supplied with a 5 ms pulsed current to flip the magnetization direction of the coiled AlNiCo. For magnetization switching, the current pulse needed to produce a field greater than the coercive field, $H_c = 620$ Oe, of the AlNiCo. For a solenoid, the current required to produce the coercive field is given by

$$I = \frac{H_c L}{N}, \quad (1)$$

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TABLE I

SCALED DEVICE DIMENSIONS AND PARAMETERS.

Parameter	Unit	Baseline	+33%	-33%
Magnet Square Cross Section	mm	4.8	6.35	3.18
Magnet Length	mm	10	13.23	6.63
Gap Between the Magnets	mm	7	9.26	4.64
Fe Core Length	mm	18.2	24.08	12.06
Coil Size	AWG	33	30	36
Total Number of Turns	turns	240	240	240
Coil Resistance	Ω	3.80	2.38	4.90
Coil Inductance	mH	0.327	0.490	0.201
Elastomer Thickness	µm	170	225	113
Width of Magnetic Elastomer	mm	3	3.97	1.99
Length of Magnetic Elastomer	mm	4.5	5.95	2.98
Size of the Aperture	mm	11	14.55	7.29

where L is the length of the magnet and N is the total number of turns in the coil. In our design, since the number of turns is kept constant by changing the wire gauge, the current required to flip the AlNiCo magnetization scales proportionally with size. However, as the wire gauge decreases, the resistive power consumed by the coil scales according to:

$$P = I^2 R = I^2 \frac{\rho l}{A}. \tag{2}$$

Since I scales linearly with size and R scales inversely with size, the result is that power and energy consumption scale down linearly as the device dimensions are reduced. Thus, though the +33% size consumed 2.64 J of energy for switching, the baseline size consumed 1.98 J, and the -33% size consumed only 1.59 J. Furthermore, for each size, deflection was measured optically by focusing a calibrated microscope at the elastomer surface during ON and OFF states. Deflections are plotted in Fig. 2a with error bars. The experimentally measured deflections share the same general trend as the simulated values but are smaller in magnitude, likely because the 2D simulations overestimated the deflection due to the assumption that the geometry extended infinitely in the third dimension.

To meet braille standards (minimum 0.5 mm vertical deflection and 1.5 mm aperture), deflections as a function of Young's Modulus were also simulated, in Fig. 2b, for each size scale down to the requirement of the braille aperture size. Curve fitting of the deflection matches a power relation, whereby extrapolation suggests that an elastomer Young's modulus of 0.75 kPa would would be necessary to meet the requirements for braille. Such devices are conceivable given that materials like block copolymer oleogel have demonstrated Young's Moduli as low as 0.3 kPa [6].

IV. CONCLUSION

This work illustrates the scaling trends of electropermanent magnet-controlled magnetic soft actuators for use in energy-efficient tactile unit cells. Torque-driven composite elastomer actuators were fabricated at three scales: baseline, +33%, and -33%. As desired, the EPM produces a scale-invariant flux density and requires less power to do so as the device size decreases. COMSOL simulations and experimental results confirm that deflection scales proportionally,

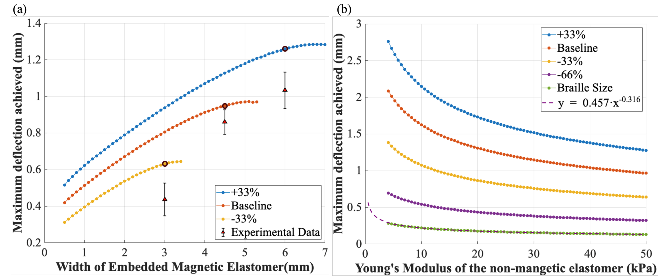

Fig. 2. COMSOL simulation of (a) deflection as a function of width of the magnetic elastomer, with the size of the aperture and thickness of each scale fixed. Circled data points show simulated data at experimentally fabricated scales, while circles with error bars show experimental deflections of the actual fabricated devices. (b) deflection as a function of Young's modulus for scales extending down to braille size with 1.5 mm aperture. The target deflection (0.5 mm) is met at 0.75 kPa modulus.

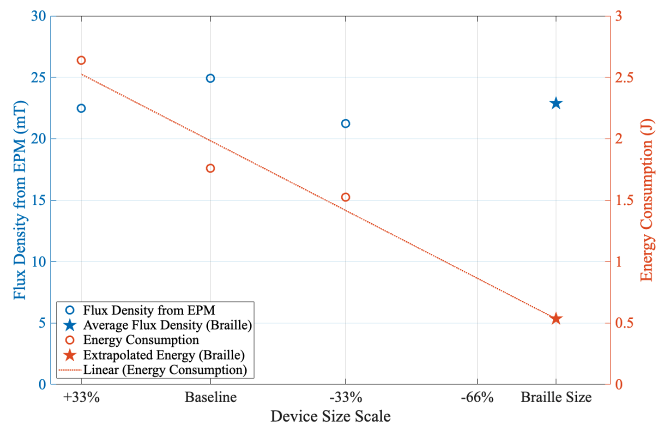

Fig. 3. Summary of measured EPM flux density and energy consumption values as a function of device size. The flux density produced by the EPM was found to be approximately the same for all sizes, while the energy consumption decreased linearly with size. An extrapolation out to the braille size suggests that it would consume only 0.53 J for switching.

and a minimum braille-suitable deflection of 0.5 mm can be achieved by reducing the elastomer modulus to 0.75 kPa. This study informs the size and material constraints necessary for miniaturized, refreshable braille displays and other haptic applications.

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