Applications of Switchable Permanent Magnetic Actuators in Shape Change and Tactile Display

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Figure 1: Applications of a power-efficient switchable permanent magnetic actuator. From left to right: A 5 mm pitch linear tactile display; A self-actuated keyboard; A mobile device tactile display; A haptically augmented steering wheel.

ABSTRACT

Systems realizing shape change and tactile display remain hindered by the power, cost, and size limitations of current actuation technology. We describe and evaluate a novel use of switchable permanent magnets as a bistable actuator for haptic feedback which draws power only when switching states. Because of their efficiency, low cost, and small size, these actuators show promise in realizing tactile display within mobile, wearable, and embedded systems. We present several applications demonstrating potential uses in the mobile, automotive, and desktop computing domains, and perform a technical evaluation of the actuators used in these systems.

Author Keywords

tactile; display; haptic; shape change; low-power; low-cost; magnet; magnetic; actuator; low coercivity; mobile;

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation: Haptic I/O

INTRODUCTION

Implementations of shape change and tactile display offer promising interactions in the mobile, wearable, and embedded domains. However, engineering such systems has remained a challenge due to the power consumption of existing actuation methods, such as motors [2, 7, 8], SMA's [16], and pneumatics [5, 6]. Given a small, low-cost, low-power actuator, we could drastically expand the design possibilities for dynamic physical interactions across the variety of devices and form factors in use today.

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We explore the use of bi-stable permanent magnet actuators for tactile display. The switchable magnets are comprised of a low-corecivity permanent magnet surrounded by a solenoid coil. By briefly pulsing a high current through the wire, the low coercivity magnet can be permanently remagnetized in the opposite direciton. After power is disconnected, the magnet remains in the new state, making the actuator more power efficient than an equivalent electromagnet by orders of magnitude depending on the frequency of switching.

ACTUATOR DESIGN

Permanent magnet actuators have been used across a range of configurations and domains [3, 4, 10, 11, 12, 13, 15, 18, 17, 20, 19]. Our design places a strong NdFeB magnet coaxially above the AlNiCo switching magnet (see Figure 2). The switching magnet is anchored, while a pin connected to the top of the NdFeB magnet and threaded through a fixed surface constrains its motion to the axial dimension. A spacer sets a minimum separation between the two magnets, as the field from the NdFeB magnet increases the current required to coerce the AlNiCo magnet when in close proximity.

In this configuration, when the two magnets are aligned in the same direction along the axial dimension, the NdFeB is pulled down to the bottom layer. Similarly, when the magnets are aligned oppositely, the NdFeB magnet is repelled to the top layer, actuating the pin. The range of motion for the actuator was chosen to be 1.5mm, allowing for visible shape change while maintaining a relatively high output force in the actuated state (the static output force decreases as the NdFeB magnet travels further from the switching magnet). Prior psychophysiological results show that users can detect a protrusion as little as .2 mm in depth on their fingertips [9].

The actuator has a simple drive circuit. A power MOSFET h-bridge, controlled by logic-level signals, regulates current flow through the coil. To prevent large current draws from a power supply, a large capacitor is charged to the supply

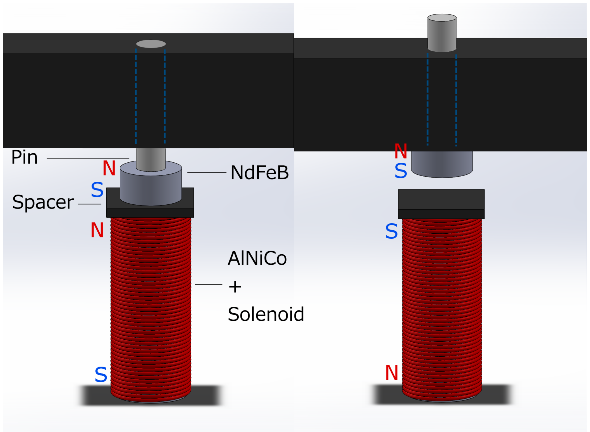

Figure 2: The actuator in its attracting and repelling states.

voltage and then discharged over the coil during a switching pulse, as described by Knaian [10]. A custom pcb was designed to drive an array of our actuators using 100 uF capacitors, MPQ8039 half-bridges, flyback diodes, bootstrap capacitors, and an Arduino Mega 2560 microcontroller.

The physical dimensions of the actuator can be chosen based on the application. Larger permanent magnets can provide greater force output. The gauge of the wire used to wrap the AlNiCo magnet can be increased as well to reduce the operating voltage.

Finally, the actuator is easily augmented with input capabilities. For recognition of simple taps, a pushbutton switch can be used as the spacer between the two magnets. We instead utilize force-sensing resistors for more sophisticated recognition, allowing us to detect even if the user is pressing down on the actuator in its clamped state.

TECHNICAL EVALUATION

Table 1 shows technical specifications of our implementation of the actuator. Forces were calculated using the FEMM finite element analysis package, then verified empirically [14].

	Switchable Permanent Magnet
Power (W)	.01 f **
Force (N) (Min Travel)	.43 (Attraction), .16 (Repulsion)
Force (N) (Max Travel)	.10 (Attraction), .07 (Repulsion)
Height (mm)	13.08 (at max travel, not including pin)
Diameter (mm)	4
Maximum Travel (mm)	1.59
Travel Type	Bi-stable
Back-drivability	Yes
Maximum Switching Frequency (Hz)	140
Cost (quantity = 1000)	$3.49

** f is the switching frequency

Table 1: Technical details for the implemented switchable permanent magnet actuator.

APPLICATIONS

We prototyped three example applications of the switchable permanent magnetic actuator, shown in Figure 1.

Tactile Display on Mobile Devices

Ten actuators were assembled on the side of a mobile device to replicate the interactions of Jang et al.'s Haptic Edge Display at a lower power consumption [9]. The display allows for information presentation and dynamic physical controls to enrich mobile interactions. The display has a pitch of 5 mm and a travel of 1.5mm. Each actuator is individually addressable, allowing the creation of expressive waveforms, context-dependent buttons, rich haptic notifications, physical scrollbars, and other dynamic physical elements.

Haptic Augmentations for Input Devices

Actuators were added to the keys on a small keyboard, enabling keys to type themselves. As with Bailly et al.'s Métamorphe, the device has a number of uses as an instructional interface [1]. In an unfamiliar application, it can demonstrate corresponding keyboard shortcuts to assist in learning. Users can also "set" keys down for command sequences or physically play back macros. Built-in force-sensing resistors enable the keyboard to recognize touch inputs on keys that are already clamped down.

Information Display in an Automobile

A Thrustmaster T80 RS controller was used to prototype a tactile display built into a car steering wheel. Actuators lining the sides of the wheel can haptically display speed, navigational instructions, etc., or form context-dependent buttons. This allows the driver to receive and respond to notifications without diverting their visual attention from the road.

LIMITATIONS

Despite its efficiency, the switchable permanent magnetic actuator has a number of trade-offs with conventional actuation methods in tactile display. Firstly, as a bi-stable actuator, it has only two discrete positional states. In addition, as multiple actuators in close proximity produce interference, a minimum separation between actuators on the order of centimeters is required for proper functionality, increasing the dimensions and/or limiting the resolution of a tactile display. Finally, because the magnetic field weakens with increasing distance, a longer travel equates to a weaker output force in the repelling state. As a result, designing systems with significant visual as well as tactile shape change becomes less feasible.

CONCLUSION

Switchable permanent magnet actuators can be used for low-cost, power efficient tactile display. Despite limitations in force, travel, and resolution compared to conventional methods, they have the potential to facilitate dynamic physical change in mobile, wearable, and embedded devices. It is our vision that utilizing such efficient actuators will aid us in realizing novel interactions throughout the physical world.

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