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Elaboration and Test of High Energy Density Magnetic Micro-Actuators for Tactile Display Applications

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Abstract

This study reports the elaboration and characterization of a 4x4 MEMS elastomeric membrane array with 2 mm resolution, driven by magnetic micro-actuation. The device is to be used for tactile display interfaces providing sensations to the skin in Human-Computer Interactions.

The magnetic micro-actuators include an elastomeric PDMS diaphragm that holds a samarium-cobalt micro-magnet and a miniature Copper coil. The device was first optimized using finite element analysis for different coil-magnet configurations. Magnetic micro-actuators were micro-fabricated and their performances were experimentally evaluated. Each micro-actuator provides forces around 4mN for 800mA RMS driving currents (power dissipation about 100mW).

Keywords: MEMS; Micro-actuators; Microsystems; Magnetism; Magnetic actuation; Tactile display

1. Introduction

Many applications in the fields of Virtual Reality and Human-Computer Interaction have recently heightened the need for tactile devices aiming at the reproduction of tactile sensations [1,2,3]. The requirements for tactile display devices are imposed by physiology, ergonomics and handheld compatibility. The minimal bandwidth is between DC and 300 Hz, for exerted pressures above 60 mN/cm² [4]. The power consumption of such active surfaces should not be higher than a few W/cm².

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Our ultimate purpose is to develop micro-actuator arrays with millimeter resolution providing high forces (a few mN) and displacements (a few 10 μ m) for tactile display applications. Magnetic actuation offers large forces and displacements, and is well adapted to the problem. The literature contains recent examples of miniaturized magnetic actuation schemes, based on solenoids or planar coils.

We propose an optimization of coil-magnet interaction to increase its actuation efficiency for 2x2 mm² micro-actuators. The proposed actuation, which has been used for many years in solenoid-based macroscopic devices, was adapted in this work to millimeter-sized systems, based on hybrid assembling of conventionally fabricated and MEMS processed components.

2. Device concept and elaboration

Each micro-actuator is made of the association of a magnet and a coil, with soft ferromagnetic materials shaped for guiding the magnetic flux across the air-gap, thereby making a magnetically efficient design. It allows resolution improvement down to 1 mm, with appropriate coil design optimization and micro-fabrication (Fig. 1).

The membrane arrays were elaborated using both microfabrication techniques and conventional assembling. A 80 μ m thick PDMS layer was spin-coated on the top side of a Silicon substrate in order to design the elastomeric membranes. Then, a Silicon etching is achieved through an Aluminum mask, delimiting the membrane shapes. This process uses ICP (Induction Coupled Plasma) in order to provide highly anisotropic, vertical etching (Fig. 2).

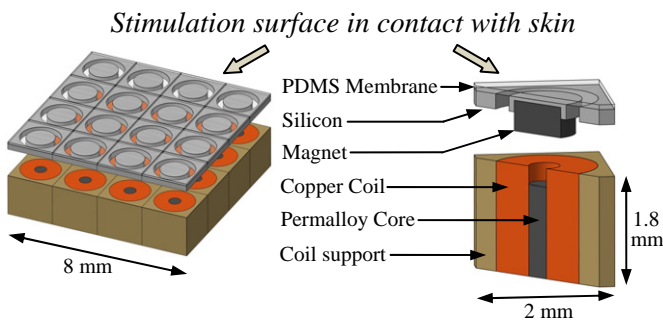


Fig. 1: Global scheme of a micro-actuator array and close-up on the micro-actuator structure.

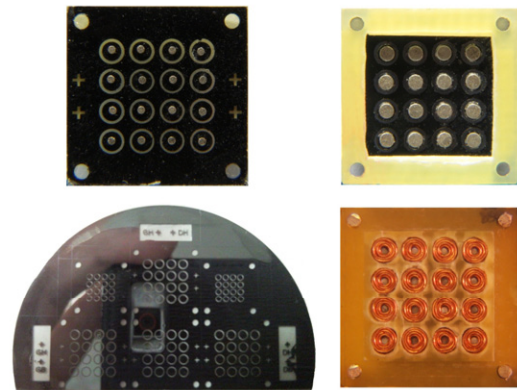


Fig. 2: **Up Left:** Active surface of the tactile device; **Down Left:** Silicon substrate with processed membranes; **Up Right:** Bottom view of a membrane array; **Down Right:** Actuation coil array.

A conventionally assembled actuation mechanism was set underneath these membrane arrays. Planar coils as designed in the literature cannot generate enough forces to fulfill the specifications of our application. Solenoids are only efficient when long magnets are inserted into coils, which lead to friction issues and increases crosstalk between neighboring actuators. Permalloy-core coils can solve this problem.

We made Finite Element Method (FEM) simulations in order to compare different coil configurations (Fig. 3). Design 1 corresponds to a solenoid coil, in which the magnet can be inserted. Design 2 shows a coil with a nickel-iron (Permalloy) core in its center, that can guide and concentrate the magnetic flux provided by the coil. Design 3 has an additional Permalloy part, aiming at the improvement of the previous design.

The magnetic force applied on an elemental volume of magnet by the magnetic field is given by the formula [5]:

$$d\vec{F}_{magn} = (\vec{M} \cdot \text{grad}) (\vec{B}) \cdot dV \quad (1)$$

Where M represents the permanent magnetization of the magnet and B is the magnetic field provided by the actuation coil. The FEM simulations were used for the determination of the magnetic vector field and the integration

of formula (1), resulting in the generated actuation force. Figure 3 shows the forces generated by each design, as a function of actuation distance.

The current micro-actuators are equipped with the second coil design; we set the coil-magnet distance to $400\mu\text{m}$ to keep enough air-gap for deflections. For this distance, each micro-actuator can provide around 4mN forces for 100mW power consumption. Future prototypes could benefit from Design 3, providing higher forces (around 10mN) with decreased air-gap.

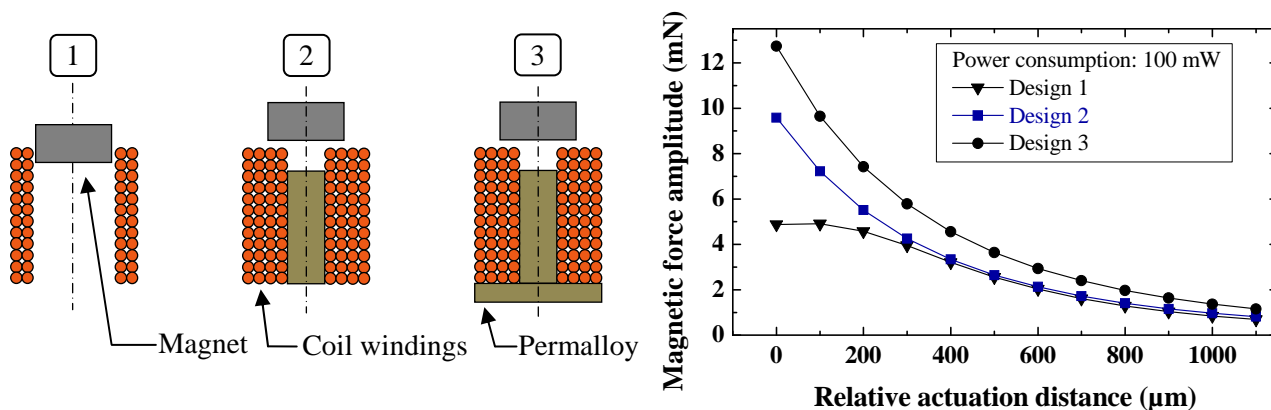


Fig. 3: Various coil-magnet configurations and magnetic forces they can provide.

3. Experimental results

Full device characterizations were made using a Laser interferometry Polytec OVF-505 vibrometer, allowing to determine the dynamic deflection of the micro-actuators. First tests, without any load on the micro-actuators, showed the linearity of the membrane deflection with the driving current, up to 800 mA RMS per actuator. The active area can provide 80 mN/cm^2 overall pressure for this driving current, on the DC-350 Hz bandwidth. Moreover, the membrane resonance is set around 670 Hz ; it allows a rather regular frequency response below 350 Hz .

We made other tests with a load on the active area, in order to simulate the presence of a finger on it. These tests showed a residual vibration in spite of the load (fig. 4), which is suitable for tactile applications. The actuation linearity with input current is verified again.

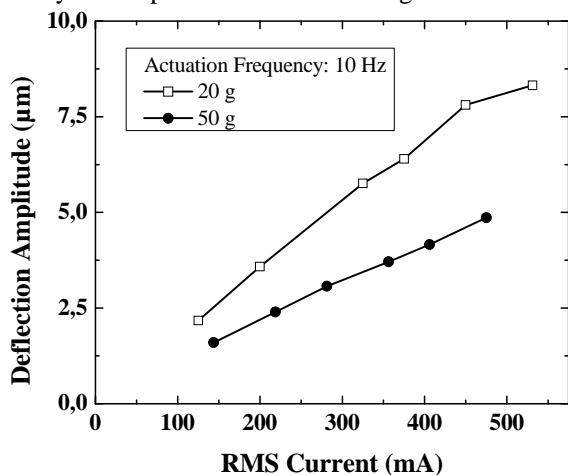


Fig. 4: Linearity of deflection amplitude with input current when load is applied on the active area.

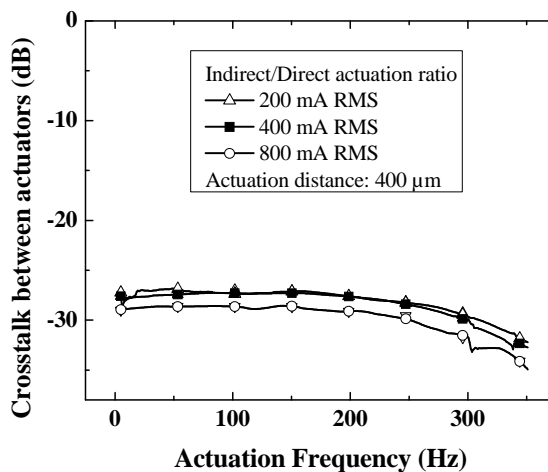


Fig. 5: Micro-actuator array Crosstalk ratio, between indirect and direct actuations.

The crosstalk between neighboring micro-actuators was also characterized. The crosstalk level between micro-actuators is very low (Fig.5); it shows that each micro-actuator can be individually driven without exciting neighboring ones, with a -25/-30 dB ratio.

4. Conclusion

This micro-actuator array shows the capabilities of magnetic actuation for MEMS purposes. Its hybrid elaboration benefits from microfabrication techniques and conventional assembling.

This device was designed for tactile display devices, aiming at providing vibrations to the skin. This device can exert up to 80 mN/cm² pressures on its active area, for a power consumption of 100 mW per actuator, on the DC-350 Hz bandwidth. Each micro-actuator can be individually driven with a low crosstalk level between magnetic actuators.

The lightness and compactness of this device allow its integration in handheld tactile display devices. Its performances meet the guidelines for this application in terms of exerted pressures and bandwidth and stands out for its assets about resolution improvement and MEMS techniques compatibility.

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