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Optimization of the force and power consumption of a microfabricated magnetic actuator

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ABSTRACT

The force (F) and the power consumption (P) of a magnetic actuator are modeled, measured and optimized in the context of developing micro-actuators for large arrays, such as in portable tactile displays for the visually impaired. We present a novel analytical approach complemented with finite element simulation (FEM) and experiment validation, showing that the optimization process can be performed considering a single figure of merit $F/\sqrt{P}$. The magnetic actuator is a disc-shaped permanent magnet displaced by planar microcoil. Numerous design parameters are evaluated, including the width and separation of the coil traces, the trace thickness, number of turns and the maximum and minimum radius of the coil. We obtained experimental values of $F/\sqrt{P}$ ranging from 2 to 12 mN/$\sqrt{\text{W}}$ using up to 2-layer coils of both microfabricated and commercial printed circuit board (PCB) technologies. This performance can be further improved by a factor of two by adopting a 6-layer technology. The method can be applied to a wide range of electromagnetic actuators.

1. Introduction

Electromagnetic-based microactuators combine both high non-contact forces and large actuation strokes [1]. By using permanent magnets, high energy densities can be achieved. Such devices have been demonstrated for a wide range of applications, including lab-on-a-chip valves arrays [2], micromirrors arrays [3] and tactile displays [4,5]. While much research has focused on single microdevices or small arrays of magnetic actuators, electromagnetic (EM) actuation scales well to very large arrays of microdevices by using arrays of microfabricated planar coils driving arrays of small permanent magnets.

Haptic interfaces are central to assistive devices for blind and visually impaired people. Tactile displays generally consist of an array of independent vertical actuators, called taxels (the haptic counterparts of pixels). Several psychophysics strategies have been explored to provide graphical information through tactile displays, using static stimuli (shapes), vibrational stimuli (textures), or both [6,7]. Meanwhile, advances in the use of different actuation technologies in haptic devices have been recently reviewed [8,9], including the use of piezoelectric, electromagnetic, pneumatic and shape memory alloys. EM-based devices continue to be a promising option due to their bandwidth, scaling and portability characteristics. Several EM-based tactile display prototypes have been reported using 3D wire-wound inductors or similar technologies to attract or repel a small permanent magnet. The focus has been on small arrays (less than 100 taxels) generating vibration stimuli (from 20 to 200 Hz) rather than static taxel displacement [4,10,11]. For those dynamic devices, actuation forces of 13 mN using 400 mW power per taxel [4] and 9 mN at 100 mW per taxel [10] were reported, with positive results on psychophysics tests. However, to display maps or other complex graphical information, larger tactile areas are needed (thousands of taxels, covering the area of a page).

Scaling up EM tactile displays to thousands of taxels and to areas of order 20 cm × 20 cm adds important challenges for integration and power consumption. From an integration perspective, going to thousands to taxels implies an array of planar coils, as wire-wound solutions with high-permeability magnetic cores are not manufacturable for such high taxels count. From a power consumption and heat dissipation perspective for a portable device, the

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average power per taxel must be well below 100 mW. The goal of this paper is to provide a model to allow optimizing an EM taxel for large arrays of mm-scale taxels.

In the framework of the Blindpad project,[2] we are developing a tablet-sized 3000 taxel portable tactile display. Pitch size has been set in the range from 4 to 8 mm. In 2004, Hale et al. recommended a threshold pressure for stimuli in fingertips of 60 mN/cm^2, regardless the working taxel frequency [6]. However, more recent works have reported that the perception force threshold varies according to working frequency, sensing area, and surface shape [12–16]. Taking into account a pin diameter pin of 2.5 mm for our device, the required force should be of 3 mN or higher, or 10 mN for a pin with a 4 mm × 4 mm area. Considering a typical 100 Wh laptop battery and a proposed autonomy of 2.5 h, the available average power is 40 mW/taxel. Power consumption can be also improved by incorporating a latching system that holds both taxel states, up and down. In this case, the coil is actuated only for switching, and there is no power consumption as long as the displayed image is not refreshed. Both force and power consumptions are key design drivers, as is scalability and integration aspects.

Analytical models to optimize the performance of coils or magnets for magnetic actuators with no presence of ferromagnetic materials are available in literature [5,17–19]. If the actuator does include a ferromagnetic material, the optimization could be better performed by using iterative algorithms like genetic algorithms [20,21]. These systems are much more complex to solved because of the non-linearity of the equations. However, none of the referred works present a simultaneous optimization of the power consumption and the magnetic force generated by a planar coil on a movable permanent magnet. For example, Fuestel et al. presented in [17] a polynomial analysis of the magnetic force as function of some of the design parameters, but using a fixed value of power. Kruussing presented in [19,22] a study focused on the magnetic domains orientation and its influence in the force calculation, but without extending the analysis to the influence of the applied power.

Given our goal of a portable large-area tactile display based on EM microactuator, here we present the optimization of a magnetic microactuator, consisting of a planar microcoil and a magnetic disc suspended over the center of the coil, with no other magnetic elements. The taxel that is modeled was designed to be readily scalable to large arrays. A novel analytical approach was implemented, complemented with finite element simulation (FEM) and experimental studies. The influence of all key design parameters is analyzed in terms of force and power, comparing: analytical calculations, FEM simulations and measurements. Planar coils were fabricated in different designs using two fabrication technologies, and the magnetic force and power consumption were measured and compared with our model.

As a result of this analysis, a planar coil design is proposed to achieve the taxel requirements for a large array. The method can be applied to a wide range of electromagnetic actuators involving permanent magnets and planar coils, whenever a reduction of the power consumption is required, e.g. valves arrays [2] and micromirrors arrays [3].

2. Magnetic system modeling

The vertical actuator considered in this work consists of a disc-shaped permanent magnet bonded to an elastomer membrane and centered over a planar coil, as represented schematically in Fig. 1. When an electrical current is applied, the magnet is vertically attracted or repulsed due to the interaction with the induced

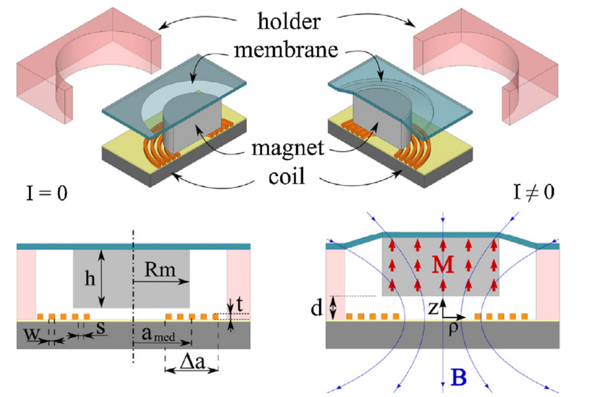

Fig. 1. Schematic of the magnetic system. A permanent magnet is suspended by an elastomer film over a planar coil, being attracted or repulsed when a current is passed through the coil. The parameters under analysis are indicated in the diagram: the magnet radius *Rm* and height *h*, the coil external dimensions a_{med} and Δa and the individual trace width *w*, separation *s* and thickness *t*.

magnetic field. In this case it is possible to describe the system behavior by separately modeling the magnetic interaction between the magnet and the coil on one hand, and the elastic deformation of the elastomer membrane on the other.

The focus of the model presented in this section is to provide an analytical tool to precisely estimate the magnetic force *F* between the magnet and the coil and the power consumption *P*. Given the size of the magnet, this model can be used to design the coil that maximize the actuator performance tacking into consideration the figure of merit $F/\sqrt{P}$. As pointed out later on, this ratio is independent of the electrical current and it allows to compare and optimize different coil designs. Being the actuation force and power the more challenging taxel constrains, the restoring force and the deflection of the membrane can be then tuned to a desired value by choosing the diameter, thickness and elastic properties of the elastomer [18].

Let us consider a permanent magnet of magnetization $\boldsymbol{M}$ and volume *V*, and a differential volume inside it with magnetic moment $\boldsymbol{m} = \boldsymbol{M}\,dV$. The force $\boldsymbol{f}$ acting on $\boldsymbol{M}$ due to an external magnetic field $\boldsymbol{B}$ can be expressed as [23],

$$\boldsymbol{f} = (\boldsymbol{m}\cdot\nabla)\boldsymbol{B} = \nabla(\boldsymbol{m}\cdot\boldsymbol{B}) \tag{1}$$

The second form of Eq. (1) is valid for regions where $\nabla\times\boldsymbol{B} = 0$, i.e. no electrical currents or time-dependent electrical fields are present, which is the case inside the magnetic volume. The total magnetic force is obtained by integrating Eq. (1) over the magnet volume,

$$F_i = \sum_V f_i = \int_V \partial_i(\boldsymbol{M}\cdot\boldsymbol{B}(\boldsymbol{r}))\,dV \tag{2}$$

where *I* depends on the chosen coordinates system. Now using the divergence theorem, Eq. (2) can be transformed into a surface integral,

$$F_i = \oint_S (\boldsymbol{M}\cdot\boldsymbol{B}(\boldsymbol{r}))(\hat{\imath}\cdot\hat{n})\,dS. \tag{3}$$

The permanent magnet we consider is homogeneously and vertically magnetized ($\boldsymbol{M} = M\hat{z}$). Then by symmetry, no lateral force is expected if the magnet is located concentric with the planar coil. Only the vertical component of the force remains and can be calculated from Eq. (3),

$$F_z = M\left[\int_{top} B_z(\boldsymbol{r})dS - \int_{bottom} B_z(\boldsymbol{r})dS\right] \tag{4}$$

with the two surface integrals calculated over the top and bottom surfaces of permanent magnet.

[2] https://www.blindpad.eu