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Design and control of a low profile electromagnetic actuator for foldable pop-up mechanisms

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ABSTRACT

Thin foldable origami mechanisms bring miniaturization and reconfiguration of complex structures allowing large volumetric change, low cost and versatility. Many applications require small robots with multiple capabilities including movement, sensing and communication. One of the major design constraints in these systems is miniaturization, in particular actuator down-scaling. To meet the challenges, researchers have focused both on investigating designs that use high power to size ratio actuators as well as defining novel fabrication methods that aid reduced size component integration.

This paper presents a novel approach for designing and controlling a low profile electromagnetic (EM) actuation system that can provide high speeds and easy control. Additionally, the system can be embedded in miniaturized foldable mechanisms. We report here the modelling of the low-profile EM actuator and the design methodology; further, the fabrication of a 3-cm wide, 1.4 mm thick prototype and real case scenario testing were executed. Our extensive test results verify the position control performance and validate the thermo-mechanical model in terms of expected steady state temperature and dependency by actuation frequency.

1. Introduction

Robots are now used in everyday life, not only for repetitive and tiring tasks, but for diverse human interaction applications. One of the major design constraints of robotics systems is miniaturization. Many applications require small robots with multiple capabilities such as moving, sensing and communicating. In other cases, switching from a compact, folded configuration to a 3D one is desired. Moreover, a variety of goals can be reached through space reduction design; an example is efficient robot locomotion and cooperation in complex environments [1–3]. To face the miniaturization challenge, researchers focus on investigating designs that use high power to size ratio actuators as well as defining novel fabrication methods that aid reduced size component integration. In some studies, compact robots were obtained by closely integrating sensors and actuators within robot body [4,5]. Others focused on fabrication; using novel manufacturing methods, such as layer-by-layer technique [6], allows embedding thin actuators and sensors into flat systems [6,7]. The use of shape memory materials eases system miniaturization [8,9] but they have the drawback of low actuation speed and control complexity.

While simple folding geometries are easy to miniaturize using Smart Composite Microstructure (SCM), shrinking complex 3D mechanisms remains challenging. A successful approach to face this challenge is to employ origami-inspired folding design for assembling and reconfiguration. The folded state can be used to either ease manufacturing [10] or to reduce mechanism size to lower cost of transportation [11]. The challenge we face in this system is designing an actuation scheme that can be embedded in the miniaturized foldable mechanisms while providing high speeds and easy control. The actuator is one of the most difficult components to scale down while maintaining its functionality.

In this work, we present a low profile electromagnetic (EM) actuator designed for embedding in a foldable structure for high performing self-contained shape-shifting devices. The miniaturization (under cm scale) of EM systems is broadly investigated and interesting from an energetic point of view [12–14]. The main advantages of the system we propose are its wide range of motion and the simple manufacturing method which is not usual for EM systems [15]. The main challenge we face is the overall design limitation to keep the system as thin as possible while guaranteeing desired actuation performance. Examples of similar system designs are found in literature for voice coil systems [16]. Most

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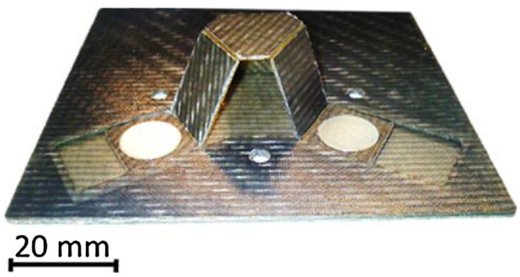

Fig. 1. Pop-up, origami inspired, low profile mechanism presented by the authors in [22].

of the miniature EM systems investigated though use only the vertical component in coaxial magnet-coil interaction giving very small strokes [17,18]. Other systems however, use more efficient methods to move magnets on a surface achieving wider strokes. Nevertheless, the assembly results in quite complex and bulky (over 10 cm) structures [19–21].

Previous work from Salerno et al. [22] introduced a foldable system where the EM actuation is integrated using layered low-profile manufacturing technique. The system was composed of a permanent magnet constrained in a rail and moved by interaction with a coil pair (Fig. 1). The copper multilayer coils are etched onto a flexible Pyralux substrate and embedded in a carbon fiber structure. The investigated design is challenging due to the multidisciplinary approach required for reducing the size and improving the thermal behavior of the system while keeping the desired actuation characteristics.

In this paper, we present a design framework to define the actuator parameter values to reach a desired performance. This framework specifically delineates the coils features to achieve set forces while keeping the systems temperature under a specific limit so allowing continuous actuation. Furthermore, we integrate sensors on top of the structure but maintain a thickness of less than 1.7 mm. We use sensory feedback as control methodology for the proposed actuator.

The major contributions of the presented work are:

– The mm-scale novel planar EM actuator design.
– The thermo-mechanical model of the actuator.
– The design framework of the EM actuator with respect to the required thermomechanical performance.
– The actuator position control based on sensory feedback.

2. Analytical methods for the planar EM actuator

The linear EM actuator considered in this work is made from multiple functional layers: the coil layer is used to generate the magnetic field needed for actuation; the permanent magnet is assembled on the moving part of the actuator; the rail layers constrain the motion of the moving part and the structural layer provides the mechanical stability. Fig. 2 shows the stacked system in (a) and the different layers composing the system in (b). The actuator was fabricated using traditional PCB process to obtain the planar coils, using Smart Composite Microstructure manufacturing technique for the actuator body. The process is described in detail in the authors' previous works [22].

At the base of the design methodology for the proposed low profile EM actuator are the mathematical models that describe electromagnetic interactions and temperature variations of the system. First, we present a model to calculate the magnetic force between the coil system and the permanent magnet (Eq. (3)) and then a model for the transient and steady-state temperature of the system at different input powers (Eq. (8)). These models are used to design the coils. In the following Sections, we describe the physical assumptions we make and the analytical definitions used.

2.1. Magnetic force model

The magnetic force model is derived from the interaction between the magnetic field produced by the thin coils and the permanent magnet. The permanent magnet, with specific magnetization, is modeled as a coil driven by an equivalent current. The magnetic field is derived from the Biot-Savard law [23] which gives the magnetic field produced by a wire driven by a current I at position r:

$$B\left(\vec{r}\right) = \frac{\mu_0}{4\pi}\int\left(\frac{I\vec{dl}\times\vec{r}}{\vec{r}^3}\right) \qquad (1)$$

Where μ_0 is the magnetic permeability in vacuum and dl is the wire element. We use (1) with the Archimedean spiral parametrization of the coils and we obtain the magnetic field. The final equation to compute the magnetic field of the thin coil is reported in (2).

$$B_x\left(\vec{r}\right) = \frac{\mu_0 I}{4\pi}\int\frac{z\left(i_r+\frac{\omega\theta}{2\pi}\right)\cos\left(\theta\right)}{\left(x-\left(i_r+\frac{\omega\theta}{2\pi}\right)\cos\left(\theta\right)\right)^2+\left(y-\left(i_r+\frac{\omega\theta}{2\pi}\right)\sin\left(\theta\right)\right)^2+z^2}$$

$$B_y\left(\vec{r}\right) = \frac{\mu_0 I}{4\pi}\int\frac{z\left(i_r+\frac{\omega\theta}{2\pi}\right)\sin\left(\theta\right)}{\left(x-\left(i_r+\frac{\omega\theta}{2\pi}\right)\cos\left(\theta\right)\right)^2+\left(y-\left(i_r+\frac{\omega\theta}{2\pi}\right)\sin\left(\theta\right)\right)^2+z^2}$$

$$B_z\left(\vec{r}\right) = \frac{\mu_0 I}{4\pi}\int\frac{z\left(i_r+\frac{\omega\theta}{2\pi}\right)\left(x\cos\left(\theta\right)-y\sin\left(\theta\right)\right)+\left(i_r+\frac{\omega\theta}{2\pi}\right)^2}{\left(x-\left(i_r+\frac{\omega\theta}{2\pi}\right)\cos\left(\theta\right)\right)^2+\left(y-\left(i_r+\frac{\omega\theta}{2\pi}\right)\sin\left(\theta\right)\right)^2+z^2} \qquad (2)$$

In this study we are concerned with the force along the x axis that drives the slider inside the rail (Fig. 3). The component on the Z axis could be used in a further study to take into consideration the friction between the rail and the magnet (Fig. 3). To calculate the magnetic forces we model the permanent magnet as a coil of the same shape with equivalent surface current density [23,25]. We discretize the magnet surface into surface elements (a_n) and define the surface current density as a cross product between the magnetization M and the vector normal to each surface element a_n. Only the radial surface S of the cylinder is taken into consideration,

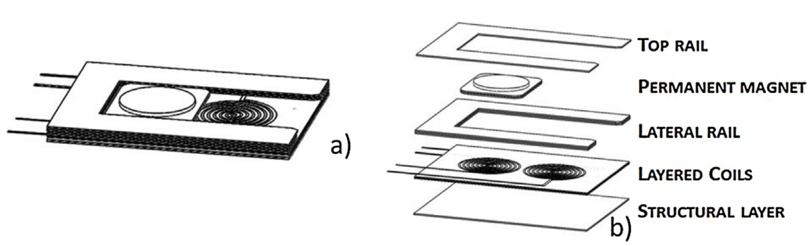

Fig. 2. Construction of the actuator. The stacked layers give an overall thickness of less than 3 mm (a). The exploded view of the actuator shows the carbon fiber structure with the rail, the coils and the slider with an embedded permanent magnet (b).