Novel concept of a series linear electromagnetic array artificial muscle

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Abstract. We propose an electromagnetic artificial muscle (EMAM) actuator whose smallest functional unit/cell consists of an electromagnet created by a solenoidal coil. These cells are coaxially arrayed, being separated by a spring. When actuated by means of an electrical current, the fiber formed by these cells arrayed in parallel collapses, as the gap created by the spring closes in relation to the strength of the current. Fibers are designed to be joined, forming a muscle-like structure. The system is fully customizable in terms of displacement and actuation force, as the stroke can be enlarged by adding more cells to the fiber, while the force can be adjusted with the thickness of the bundle. A mathematical model to describe the operation of a functional unit of the EMAM is given. It predicts the relation between the applied current and the displacement, and is in agreement with the experiment. This novel concept of an EMAM carries the benefits of a linear solenoid array actuator, such as high stroke and uniformity of motion, into the micro domain. It is moreover extended with the capability of precise displacement in micro domain but also fast actuation.

1. Introduction
As modern day robotics, prosthetics and positioning technologies make increasingly higher demands on the properties of actuators such as large stroke, constant force and low power consumption, classical solenoid-based actuators have been discarded so far [1,3].

Concepts of arraying single solenoid actuators to meet these requirements are emerging and pointing to a common architecture that arranges single actuators to a fiber that bypasses the typical disadvantages of classical solenoid-based electromagnetic actuation such as low stroke and uneven force distribution on the stroke length. Challenges are conquered by operating a multitude of similar actuators simultaneously in a chain-like arrangement within their efficiency maximum to overcome the limitations of both possible displacement and uniformity of actuation in terms of maximum force and acceleration.

Obata [1] presents a macroscopic “Muscle Motion Solenoid Actuator” that consists of several identical macroscopic solenoidal actuators arrayed to a fiber to enlarge the total stroke. The number of turns of the solenoidal actuators is adjusted along the coil length to further support a constant force along the actuator stroke. Each cell has a stroke of 40mm and can deliver about 14N at a cylindrical stroke of 20mm, while having an initial length of about 100mm and a diameter of 48mm. In a further study [3], Obata shows how these solenoidal actuators can be designed in order to provide a maximum force when arrayed to a fiber, by incorporating high permeability casings and neodymium...
magnets to maximize the density of the flux and minimize the flux loss. Li et al. [2] characterizes the design of a “multi-class series artificial sarcomere array” that transfers the general microstructure of a skeletal muscle into a macroscopic device. The structure is described as a fiber consisting of consecutive planes, each housing several axially arranged identical electromagnetic actuator cells working in parallel. Each cell incorporates a locking mechanism, various coils and permanent magnets. While both concepts mentioned above reveal the advantages of a serial axial coupling of similar actuators, they constitute complex designs. This complexity limits the transfer of the fiber arrangement and its clear benefits into the micro domain. The required fabrication steps, the amount of parts, the wide diversity of materials and manufacturing processes impede a miniaturization.

In a simpler approach targeted on supporting human motion, Takai et al. [4] introduce a concept where all cores (actuators) are mechanically connected, though not attached to the housing that inherits multiple coaxially arranged solenoids (stators). Takai clearly points out the necessity “to investigate by how much the size can be reduced while retaining a reasonable amount of force”.

As such concepts have only used macroscopic unit cells, i.e., several cm/cell [4] and focused on the actuation force that can be generated, our design is also targeting a high actuation precision. We propose a design that is comparable to the fiber concept of Obata [1], but aims at miniaturization to make the array concept and its advantages available for microscopic application in actuation and in contrast to mentioned concepts for positioning technology (without the need of an antagonistic fiber).

The introduced concept limits the architecture to its vital elements. It can be described as a fully scalable electromagnetic artificial muscle (EMAM), which is supposed to consist of a multitude of fibers, each of them obtained by arraying (Fig. 1a) a large number of individual identical electromagnetic actuators (Fig 1b). As each cell is separated from its consecutive cell by a spring, the actuation motion becomes regardless of outer forces controllable and therefore definite and precise.

This is supported by further contributing an exact mathematical model for the behavior of a functional cell unit to increase both the accuracy of displacement in the micro domain and the speed and force of actuation within macroscopic spaces. Thereby a novel field of solutions for actuation and displacement challenges in micro world will be accessed.

The proposed design and its features are described in section 2. A mathematical model for a controlled actuation is given in section 3, while in section 4 a simplified calculation method is provided. Section five explains the experimental verification and section 5 draws the conclusion.

2. The electromagnetic artificial muscle (EMAM)

The EMAM concept presents a design that can meet the requirements of micro sized fabrication however retaining the benefits of this architecture in general.

The EMAM’s basic building block consists of a solenoidal coil wound around a ferromagnetic core, and a spring resetting the elements after attraction and leading to a controlled actuation as it delivers a counterforce for the magnetic actuation.

As this building block/smallest functional unit needs a second equivalent unit to function, it is considered a half-cell. Coaxially arranged and separated by mentioned springs, the cells form a fiber that inherits electrically parallel electromagnets. An application of a current induces the electromagnetic attractive forces that overtake the restoring forces of the springs and collapsing the

Figure 1. a) Concept of the EMAM muscle fiber composed of a series of individual electromagnetic actuators ;

b) The building block of the EMAM muscle fiber - individual half-cell.
fiber as a whole while delivering controllable, bidirectional actuation force. Experiments with a 1:20 scale prototype of a functional unit revealed the exact positioning capabilities as a specific stroke is repeatedly related to a certain current with a precision of up to 50 micrometer.

The EMAM draws its thrust force from the high ratio of diameter of solenoids to air gap between the consecutive electromagnets. Furthermore this design particularity raises the fiber density, as the cells have a height to diameter ratio of over 2. Therefore the EMAM fiber surpasses previous attempts [1, 3, 5] in terms of cell density of a fiber, leading to a more uniform actuation needed for precise positioning.

As the targeted cell has a diameter of about 3 mm and a height of 1,5 mm (+0.5mm actuation gap) a fiber with the length of 400mm is capable to inherit 200 cells. This will lead to a theoretically deliverable stroke of 100mm, while retaining a high precision section of about 50mm of the stroke due to the pull-in phenomena discussed in section 3.

Specific demands can be met by elongating the fiber as desired to alter the maximum stroke, while the actuation force is customizable through the amount of fibers bundled up and working in parallel. This is furthermore facilitated by the proposed hexagonal architecture that is designed to enable a high fiber density when joined to a bundle.

3. A mathematical model for describing the operation of the actuation unit of the EMAM

An understanding of the behavior of such an actuator is established by providing an exact mathematical model of the static pull-in point of a functional EMAM cell unit (mathematically described as two coaxially arranged solenoids with radius r, separated by a spring with the length l, while one solenoid is fixed to the ground and the other one sits congruently above.

The pull-in point is well-known within electrostatics, but poorly examined within the field of linear electromagnetic arrays. This point marks the verge of a stable and controllable vs. a powerful and fast displacement where the attraction grows exponentially and the two electromagnets collide with maximum force and velocity.

Utilizing the Maxwell formula for the mutual inductance between two coaxial wire loops, the inductance can be described dimensionless as

\[ L_m = \frac{1}{\mu_0} \left( 1 - \frac{k^2}{2} \right) K(k) - k^{-1} E(k) \]

where \( L_m = L_m \cdot (2\mu_0 r)^{-1} \), \( k^2 = (1 + \xi^2)^{-1} \) and \( \xi = \sqrt{2} r l \). K(k) and E(k) are complete elliptic integrals of the first and second kind, \( \mu_0 = 4\pi \cdot 10^{-7} \) H/m is the magnetic permeability of the vacuum, x the displacement of the movable coil and l the distance in-between.

Applying the Lagrange formalism, the energy of the system was exactly modeled. Hence the stability thresholds were derived from this nonlinear, analytical approach and the pull-in behavior has been predicted (Fig. 2). This direct dependence between the current and the displacement is given by

\[ I^2 = (1 - \varepsilon) \left( \frac{\delta L_m}{\delta k} \right) \]

which can be derived from the equilibrium, when

\[ F_{\text{total}} = F_{\text{el mag}} - F_{\text{spring}} = \frac{\delta L_m}{\delta x} I^2 - c(1 - x) \]

where c is the spring constant and thereupon exclusion of \( I \).

4. Simplified model for easy calculation of the magnetic pull-in point

Taking into account that the radii of the solenoids exceed their separating gap/distance of displacement by far (\( r >> l \)) the parameter k becomes practically one, leading to a highly simplified, calculation method, avoiding complex elliptical integrals (Fig.2) with an accuracy that grows with the ratio r to l:

\[ L_m = \mu_0 r \left[ M - \frac{4}{\xi(1+x/l)} - 2 \right] \]

5. Experiment

Thereupon the model was verified by experimental data obtained by a prototype that represents a scale model of a functional EMAM cell unit. It is constituted of 2 axial solenoidal coils with a diameter of
40mm and 220 windings each, separated by 3 band springs. Using a laser distance sensor the displacement was measured against the applied current, leading to the data points in diagram Fig. 2 including the pull-in point, that are in agreement with the modeling. In spite of being tailored for the observation of the pull-in phenomena, the coreless prototype is able to deliver a maximum thrust force of 0.4 N overcoming the collective stiffness of the springs of 1109 N/m while having a maximum stroke of 3.5 mm.

6. Conclusion
Utilizing a reliable fabrication of solenoidal micro-coils by wirebonding technology (Fig. 3) previously demonstrated in our group [5,6] and developing a micro fabrication compatible design of both reset/spring and carrier elements, we obtained the potential for further miniaturization of the EMAM, consequently increasing the displacement accuracy. The advantages of this miniaturization combined with the applied understanding of the pull-in behavior open up a novel field of solutions where time-saving, fast macro displacement and accurate, controllable micro positioning is required within the same actuator. Hence an application within the field of pick and place of MEMS-components utilizing this technology for micro grippers as well as various leverage systems becomes highly beneficial.

As the results of our modeling and prototyping are encouraging to go further we will be going to theoretically investigate the pull-in phenomena for n elements. From a constructive point of view we will examine the behavior of a complete fiber as well as the bundling up of multiple fibers with yet to build scale prototypes.

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