Magnetic Micro-Actuators and Systems (MAGMAS)

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***Abstract*—Magnetic interactions provide outstanding performances for powerful integrated micro-actuators. This paper explains how magnetic interactions involving permanent magnets, currents, and various magnetic materials remain very effective and even improve as dimensions are reduced. The technological problems that have slowed the development of magnetic micro-actuators and systems (MAGMAS) are progressively being solved. As long as materials scientists continue to develop better thick-film patterned permanent magnets compatible with microsystem technologies, MAGMAS will have a promising future.**

***Index Terms*—Electromagnetic forces, MAGMAS, MEMS, micro-actuators, microgenerators, scale reduction laws.**

I. A BRIEF HISTORY OF MEMS

MICROELECTROMECHANICAL SYSTEMS (MEMS) have originally evolved from the microelectronics industry, and thus electrostatic interactions have been privileged for actuation purposes from the very beginning. All that was needed (and still is needed) to move a thin, flexible beam micromachined from bulk silicon were some thin aluminum conductors and a couple of electrodes, all naturally available in the standard processes of microelectronics. Thermal actuation using the bimorph effect from the differential dilatation of an overheated thin conductor deposited on a thin silicon beam came to be used after a few years, for similar technological reasons. In the meantime, other actuation principles such as electromagnetism, piezoelectricity, magnetostriction, shape memory alloys, pneumatics, or hydraulics have been much slower in developing because their basic components and the specific materials involved are technologically more difficult to make.

We explain that magnetic interactions benefit greatly from scale reduction and, therefore, magnetic micro-actuators can exhibit great performance [1]. Early on, many articles stated boldly that electromagnetism had no future in the world of MEMS. Unfortunately these articles were not written by electrical engineers, and thus often based their point of view on the direct and homothetic scale reduction of the electrical machines that power our everyday macroscopic world. They use basic interactions between conductors or between a conductor and a piece of iron, which do not offer the most effective electromagnetic power conversion. Furthermore, the scale reduction laws usually used for comparison purposes do not take into account the fact that some important parameters are changed drastically in the process.

In the past decade, several articles have listed and compared the existing actuation principles for MEMS. It is interesting to note that the genial Richard Feynman mentioned magnetic interactions in his visionary speeches of 1959 and 1983, but without fully assessing their true potential [2], [3].

Trimmer published in 1989 an early study analyzing the implications of scaling down the various actuation principles for MEMS, with a clear approach but drawing neutral conclusions on magnetism [4]. Wagner *et al.* and Guckel *et al.* were among the first teams to design magnetic micro-actuators in the late 1980s and early 1990s, and to publish articles actively promoting magnetic actuation [5]–[7]. As early as 1991, MacKay *et al.* published an article comparing electrostatic and magnetic micromotors [8]. Guckel *et al.* wisely remarked in 1996 that permanent magnets are vital to magnetic actuation but that unfortunately their integration yet needs to be mastered [9], [10]. This is still mainly true today.

In 1992, Busch-Vishniac published a first, well-argumented article in which she exposes a thorough analysis of the benefits of electro-magnetic interactions in MEMS, and which is still well-worth reading or re-reading more than ten years later [11]. Jufer brought a strict electrical engineering approach to the problem in 1994, also with very positive conclusions [12]. Nami *et al.* wrote an analysis of reluctant magnetic micro-actuators, but without considering the use of permanent magnets [13].

We have recently published a collective book entirely dedicated to the principles, techniques, and applications of magnetic micro-actuators and systems (MAGMAS), in which the ideas presented in this article are developed at length [1].

II. SCALE REDUCTION LAWS

A. Magnetic Field Created by a Permanent Magnet

An elementary magnet of volume v_1 and magnetic polarization J_1 generates a scalar potential V in any point P located at a distance r, as shown in Fig. 1.

The scalar potential V at point P can be written

$$V(P) = \frac{v}{4\pi\mu_0}\,\frac{\vec{J_1}\cdot\vec{r}}{r^3}. \tag{1}$$

The magnetic field H at this point is directly defined as the local gradient of the scalar potential V

$$\vec{H} = \overrightarrow{\mathrm{grad}}V. \tag{2}$$

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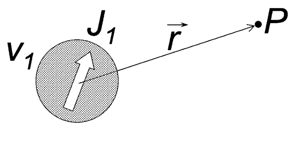


Fig. 1. Magnetic potential generated by a dipole.

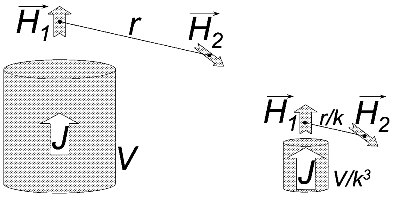


Fig. 2. Scale reduction of a magnet.

Let us imagine the homothetic miniaturization of such a magnetic system, with all dimensions reduced by the same factor k $(10, 100, 1000, \ldots ,)$ and with all the intrinsic physical properties (including the polarization J_1) preserved. When all scales are divided by k, both the distance r and the volume v are reduced, by k and k^3, respectively

$$r' = r/k \quad \text{and} \quad v' = v/k^3. \tag{3}$$

The resulting scalar potential $V(P)$, proportional to $v \cdot r/r^3$, is thus divided by k.

B. Evolution of the field Gradient Around a Magnet

However, as the magnetic field H in any point results from the local gradient of the scalar potential V, and as this is a derivation on distances, the relative geometry and the magnitude of the field map around a magnet remain unchanged after scale reduction (Fig. 2).

Therefore, around a reduced magnet, as the distances are divided by k but the fields are conserved, the field gradients are multiplied by k. This has many important implications on the evolution of interactions with magnets following a homothetic scale reduction: if the element interacting with the magnet is a current conductor, the Laplace–Lorenz force on each electron is proportional to the field and therefore remains unchanged and so does the overall volumic force on the conductor [Fig. 3(a)].

However, if the interacting element is a magnet or a soft ferromagnetic material [Fig. 3(b)], the volumic force acting on each particle is proportional to the local field gradient, and therefore it is multiplied by the reduction factor k.

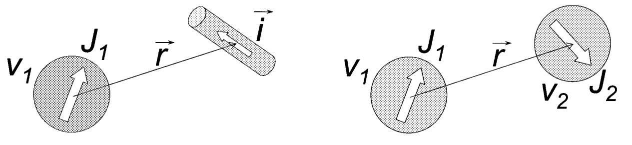
Magnet–magnet and magnet–iron interactions thus benefit immensely from a scale reduction, while the force-to-volume ratio of magnet–current interactions remain unchanged.

C. Interactions Between Magnets and Electrical Currents

Another way of understanding this is to look at it from the point of view of the conductor. Fig. 4 shows the interaction between an electrical current and a permanent magnet.

The Biot and Savart law states that the magnetic field H created in the point P by a conductor of length dl and section S, carrying a current density δ (current $i = \delta \cdot S$) is

$$\vec{H}(P) = \frac{1}{4\pi} \cdot \frac{\delta \cdot S \cdot \vec{dl} \wedge \vec{r}}{r^3}. \tag{4}$$



(a) (b)

Fig. 3. (a) Interactions between a magnet and a conductor. (b) Interactions between two magnetic particles.

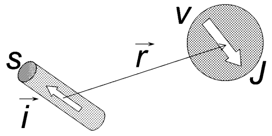


Fig. 4. Interaction between current and magnet.

After scale reduction, the magnetic field becomes

$$H'(P') = H(P)/k. \tag{5}$$

Let us now consider the magnet of volume v and polarization J, placed in P, in the field H created by the conductor. The magnetic force F exerted by the conductor on the magnet is obtained by the derivative of their magnetic interaction energy W_i

$$\begin{aligned} W_i &= -\vec{J} \cdot v \cdot \vec{H} \\ \vec{F} &= -\overrightarrow{\text{grad}} W_i. \end{aligned} \tag{6}$$

Scale reduction divides the energy W_i by k^4, and F by k^3

$$F' = F/k^3. \tag{7}$$

Since both the volume and weight are also divided by k^3, the force-to-weight (or force-to-volume) ratio does not change

$$F'/m' = F/m. \tag{8}$$

D. Torque on a Magnetic Moment

The torque experienced by a magnet of polarization J and volume v immersed in a homogeneous field H is proportional to M and H (where the magnetic moment $M = v \cdot J$). During the homothetic $1/k$ reduction, both H and J remain constant, thus the torque-to-volume ratio also remains constant.

E. Effects of Scale Reduction on Magnetic Interactions

All the above calculations can also be written for the magnetic interactions involving soft ferromagnetic material, currents, and time-variation induced currents [1, ch. 2]. Table I summarizes the general effects of a scale reduction of factor k on the massic and volumic forces interacting between the basic magnetic components (magnet, current, ferromagnetic material, and to a certain degree induction effects), for a constant current density.

The first learning from this table is that the main magnetic interactions can benefit from a scale reduction. The second learning is that in small-dimension devices, the most efficient magnetic interactions involve permanent magnets:

— *any electromagnetic structure with permanent magnets interacting with currents which is effective on a macroscopic scale remains as effective once miniaturized;*

TABLE I
OVERALL EFFECT OF SCALE REDUCTION $1/k$ ON BASIC MAGNETIC INTERACTIONS FOR A CONSTANT CURRENT DENSITY

Reduction factor 1/k	magnet	current	iron	induction E = dΦ /dt
magnet	× k 😃	😐	× k 😃	/ k 🙁
current	😐	/ k 🙁	/ k 🙁	/ k² ☹

- *interactions between permanent magnets are strongly improved by scale reduction;*
- *inductive effects are to be avoided.*

III. PERMANENT MAGNETS FOR MAGMAS

A. Equivalence Between a Permanent Magnet and a Coil

Let us consider a cylindrical magnet and a coil of same shape and size R. The magnetic moment of the magnet is proportional to its magnetization J and to its volume v

$$M_{\text{magnet}} \sim J \cdot R^3 \tag{9}$$

where the magnetization J of the magnet is an intrinsic property of the material and does not depend on the size.

The equivalent magnetic moment of a coil is proportional to the total current I flowing through it and to its surface

$$M_{\text{coil}} \sim I \cdot R^2. \tag{10}$$

The total current I is equivalent to a current density δ flowing through the section of the coil, and this section is proportional to R^2. The moment of the coil thus becomes

$$M_{\text{coil}} \sim \delta \cdot R^2 \cdot R^2 \sim \delta \cdot R^4. \tag{11}$$

During a homothetic scale reduction of $1/k$, the equivalent moment M_{coil} is therefore finally reduced by $1/k^4$, whereas M_{magnet} is only reduced by $1/k^3$. Thus, in order to maintain a magnetization equivalent to that of the magnet, the current density δ in the coil must increase as k (Fig. 5).

However, Joule losses in the conductor increase with the current density, and this implies thermal limitations as well as energy efficiency problems. As a result, even at micrometer scales, continuous current densities above 10 kA/mm^2 are hard to sustain, and micromagnets smaller than 100 μm are difficult to replace with microcoils [1, ch. 3].

B. Micromagnet Fabrication Techniques

The most common and most powerful micromagnets currently used in MAGMAS are individually micromachined from bulk Nd–Fe–B or Sm–Co magnets (generally using wire electro-discharge machining). However, this method is hardly compatible with full integration or batch fabrication [14].

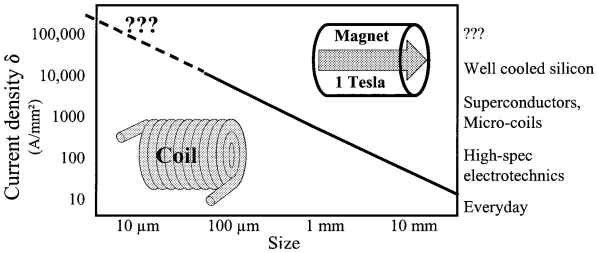


Fig. 5. Evolution of the current density needed in a microcoil in order to remain equivalent to a 1-T permanent magnet of the same size [1, ch. 5].

Many methods have been developed to make micromagnets for MAGMAS. These methods all provide good results but each suffers from a moderate or major drawback [1, ch. 5]. Some techniques are very well adapted to microfabrication (electroplating of Co–Pt, screen printing of bonded powders) but the resulting magnetic properties are relatively poor compared to bulk REPMs [15]–[22]. Other techniques give excellent magnetic properties (sputtering [23]–[29], pulsed laser deposition [30]–[33], low pressure plasma spraying [34], or direct sintering [35]) but either the thickness of the deposited layer is too thin or the process is too difficult to adapt to microtechnology and batch fabrication (high deposition temperature, chemical pollution, slow deposition rate, small deposition surface). An important aspect currently emerging is the patterning of thick films in order to shape the finished micromagnets [36]–[38]. Optimal magnetic orientation of micromagnets is also studied [39].

Ideally, low temperature electroplating of fully dense rare-earth-based intermetallic compounds or alloys would answer all our prayers, combining the full compatibility of electroplating to batch fabrication microtechnologies, with the best magnetic properties of fully dense rare-earth permanent magnets [40]!

Overall, although a fortunately increasing number of teams are working at it, there exists at present no perfect candidate for the integration of cheap and fast fabrication of thick patterned layers of good quality permanent micromagnets that are compatible with MEMS microtechnology batch fabrication processes. However, the various technologies have been evolving quickly in recent years and it is very likely that the near future shall witness great advances in this critical field.

IV. CURRENT DENSITY IN MICROCOILS

Microcoils are used in most magnetic sensors and actuators. Their fabrication processes are well mastered and they take many varied shapes and sizes [1, ch. 4]. Because of their small volume-to-surface ratio and planar geometry, microcoils withstand very high current densities without burning [1, ch. 3]. The admissible current density in microcoils is much higher than in large coils because Joule losses that heat up the conductor are proportional to its volume, whereas the heat flow that cools it down is proportional to its surface. Here again the scale reduction factor k is at work: losses will therefore be more easily evacuated by a factor of $k^3/k^2 = k$. Moreover, microconductors are usually flat and directly in contact with a good heat-conducting substrate (Si). However, it remains that energy waste through Joule losses reduces the autonomy.

Fig. 6 illustrates the factors allowing increased admissible current densities in microcoils.

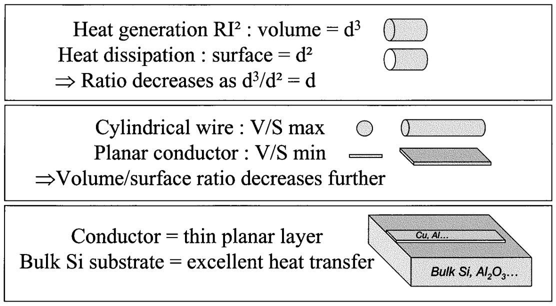


Fig. 6. Scale reduction of a conductor.

TABLE II

EFFECT OF SCALE REDUCTION $1/k$ ON MAGNETIC INTERACTIONS, TAKING INTO ACCOUNT INCREASED ADMISSIBLE CURRENT DENSITY

Reduction factor 1 / k	magnet	current	iron	induction $E = d\Phi / dt$
magnet	$\times k$ 🤩	$\times k_i$ ☺	$\times k$ 🤩	$/ k$ × frequency 😐
current	$\times k_i$ ☺	$\times k_{i1} \times k_{i2} / k$ 😐	$\times k_i / k$ 😐	$\times k_i / k^2$ × frequency ☹

According to the size and shape of the conductor, densities of 10^3 to 10^4 A/mm^2 are then sustainable, compared to the classical 5 to 10 A/mm ^{2} at normal scales. This has a great positive impact on energy density in micro-actuators. *(MacKay et al. produced pulsed magnetic fields up to 50 T in copper microcoils deposited on Si [41]. Pulsed currents of 1500 to 3500 A and 30 ns duration were run through the coils of dimensions $\varnothing_{\text{ext}}$ 150 μm, $\varnothing_{\text{int}}$ 50 μm, thickness 7 μm, amounting to several millions of amperes/square millimeter!)*

Let us introduce a factor k_i representing this current density increase. Those Laplace–Lorenz forces which are proportional to the current density are thus directly multiplied by k_i

$$F'/m' = k_i \cdot F/m. \tag{12}$$

Volumic Joule losses are also directly proportional to the current density. Taking into account the surface/volume heat ratio described above, calculations show that constant heating is respected for $k_i = k^{1/2}$[1, ch. 3]. But the current density can be increased further, up to $k_i = k$, provided sufficient cooling is available and energy wastage in Joule losses can be afforded. This direct increase in admissible current density means that the power-to-mass ratio in MAGMAS can be increased by the same factor k_i (Table II).

The main conclusions from this table are:

- *interactions with coils are improved by the increase in current density (within the admissible thermal limits);*
- *permanent magnets are the key to efficient MAGMAS.*

It should be noted that inductive effects do benefit from the redeeming fact that speeds and frequencies in microsystems are much faster due to several factors (see Section VI). Therefore, in Table II, the last column relating to induction effects has less negative implications.

V. ADDITIONAL BENEFITS OF MAGNETIC INTERACTIONS

In addition to the high energy density available in magnetic fields and electrical currents, electromagnetic interactions offer many advantages for the actuation of microsystems.

A. *Permanent Forces—Bistability Suspensions*

Permanent magnets provide constant magnetic fields. This means that simple or bistable permanent latching forces can maintain a system in a given configuration without the need for energy consumption. This feature not only ensures energy savings, but is also an excellent safety guarantee in the case of power failure in radio frequency or optical fiber communication network switchboards, for example [42]–[44].

Such permanent forces can also be implemented into passive magnetic suspensions/bearings, providing an elegant solution to the problem of friction in MEMS [45], [46].

B. *Long-Range Actuation*

Magnetic fields and gradients can be effective over long distances relatively to the size of MEMS. This allows for large-throw and/or wide-angular actuators, for which electrostatic actuation would need unrealistic voltages.

C. *Contactless Remote Actuation*

Contactless magnetic interaction allows remote actuation through sealed interfaces. This not only enables wireless actuation but also allows vacuum packaging of resonant systems, giving them a high quality factor Q by avoiding the dampening of the vibrations due to the viscosity of the air.

Remote interaction also means that a macroscopic permanent magnet providing a strong static magnetic field or gradient can be appended to the system without the need to be integrated within the system, thereby simplifying fabrication.

Furthermore, remote actuation through sealed interfaces makes magnetic actuators very well suited to harsh environments (e.g., ABS sensors).

D. *Superconductors*

We have seen that the major drawback of magnetic actuation lies in the Joule losses due to the resistivity of conductors, leading to overheating and to energy wastage. Superconducting films are already used in a few levitating prototypes using the Meissner diamagnetic effect [47], but the potential use of superconducting films for coil actuation of microsystems is not yet put to practice, for mainly cryogenic reasons. However, in particular instances, the supercooling of a micro-actuator might be possible and HTSC films may bring great advantages.

E. *Exotic Actuation Modes*

Some exotic modes of actuation offer very interesting new possibilities and should certainly be explored deeper.

- thermal demagnetization of a thermomagnetic material (this can be very fast in microsystems) [48];

— magnetic “reprogramming” of semi-hard materials by demagnetization and remagnetization [49];
— strain-induced modulation of the magnetization of a magnetostrictive material by hybridization with a voltage-actuated piezoelectric element [50].

VI. High Actuation Speeds in MEMS

Because of their reduced size, most micro-actuators are characterized by very high speeds.

— In actuation mode, for a given force, acceleration is proportional to the mass of the mobile element. Thus micro-actuators have very fast response times, often in the range of 1 to 100 μs.
— In physical terms, maximum admissible rotational speeds are limited by the radius of the rotating element and by the material's mechanical strength. This ω^2R dependency means that the speed ω can be increased by a factor $k^{1/2}$ when the radius R is divided by k. Operational speeds in the range 10^5–10^6 r/min are commonly achieved in MEMS (however, friction and viscous drag also increase with speed and new problems arise that must be tackled).
— Regarding electronics, the inductances and electrical energy levels involved are very low. This means that very high frequency control circuits can be built.

These high speed features enable higher working frequencies, and thus the column relating to induction effects in Tables I and II should not be neglected, despite being *a priori* less interesting that magnet–current and magnet–magnet interactions. However, during a reduction of $1/k$, the resistance R of a coil is multiplied by k while its inductance L is divided by k. Inductive effects thus keep some handicap compared to magnet–magnet and magnet–current interactions.

VII. Applications

Magnetic sensors are already well established in commercial products (HDD read heads, fluxgates, transmission coils, ABS sensors). However, at present only a handful of applications of MAGMAS have so far reached industrial products. Laboratory-developed prototypes include radio frequency microswitches for mobile phones, read/write heads and micropositioners, matrixes of optical microcommutators for fiber optic networks, micromotors for noninvasive surgery and microrobotics, micropumps and microvalves for lab-on-chip and micro-fluidic devices, electrical microgenerators for autonomous power supplies, micromirrors for adaptive optics, magnetic suspensions for hard disk drives, etc.

The reader will find many examples of prototypes in the conference proceedings and specialized journals and reviews listed in the Bibliography.

VIII. Power Supply and Control

Electrostatic actuators require high voltages and low currents. On the other hand, MAGMAS require moderate currents and low voltages. Also, the very rapid current pulses involved in micro-actuators need faster command and control. As a consequence, the power supplies currently developed for MEMS [51] are not adapted to MAGMAS. Our laboratory is currently working on new integrated structures that must be developed to match the particular needs of MAGMAS.

IX. Conclusion

We strongly affirm that electromagnetic interactions deserve a larger interest from the MEMS community. MAGMAS offer great opportunities for new devices in many domains of applications. Permanent-magnet thick films are developing rapidly and should soon greatly promote the development of MAGMAS. Specific dedicated low-voltage, integrated power supplies must be designed.

Bibliography

We recently published a first book dedicated to MAGMAS with Hermès-Sciences/Lavoisier (in French) [1]. The 340-page book, coordinated by the authors and co-written with several colleagues, follows the same pattern as this article. An English version is in progress. Also, a European Network of Excellence dedicated to MAGMAS is being structured.

The work of the MEMS community can be observed in the following conferences, journals, and reviews.

- MEMS: IEEE Int. Conf. on Micro-Electro-Mechanical Systems, Transducers/Eurosensors.
- Actuator: Int. Conf. on New Actuators.
- Mechatronics: Europe-Asia Conf. on Microtechnology.
- MME: Workshop on Micromachining, Micromechanics & Microsystems.
- EMSA: Eur. Conf. on Magnetic Sensors and Actuators.
- *Journal of Micromechanics and Microengineering*.
- *Journal of Micro Electro Mechanical Systems* (J. MEMS).
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