AN INTEGRATED MAGNET ARRAY FOR TRAPPING AND MANIPULATION OF MAGNETOTACTIC BACTERIA IN MICROFLUIDICS

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***Abstract* — We present a novel system for localized magnetic manipulation of magnetotactic bacteria in microfluidic systems. Where other methods require small conductive tracks directly below the sample, the new system consists of an array of permanent magnets switchable by a drive current to either trap or guide bacteria. This allows for much higher magnetic fields at reduced power consumption. Both a theoretical analysis and experimental analysis are presented. The system is scalable and is suited for integration in microfluidics.**

***Keywords:* Permanent magnets, magnetic array, microfluidics, magnetotactic bacteria**

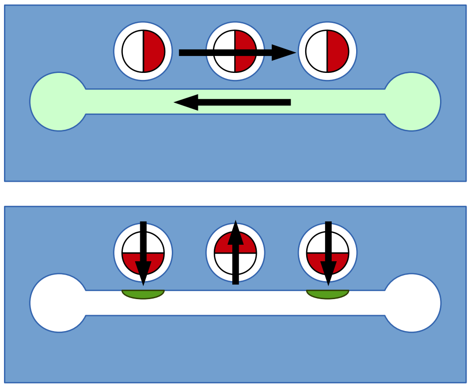

Figure 1: *An integrated permanent magnet array in the 'pass' state (top) and 'trap' state (bottom). The latter state will be used to form bacteria clusters.*

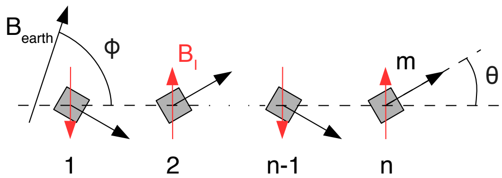

Figure 2: *Model of a chain of n permanent magnets with magnetic dipole moment* **m** *fanning out with angle θ with respect to the chain axis. The earth magnetic field B_{earth} and current-generated field B_I influence the stability of θ.*

I – Introduction

Since the discovery of magnetotactic bacteria (MTB) in 1975 [1] much research has been put into exploration of their properties. More recently people have started experimenting with utilizing these creatures as microbots by using external magnetic fields as steering signals [2, 3]. Most manipulation systems use global fields generated by single or multiple coils or permanent magnets. Only few works have described the generation of local magnetic fields on small scale, which allow local navigation and manipulation of MTB [4]. These methods are based on fields generated by current carrying wires in close proximity to the sample, requiring cooling to prevent thermal breakdown. [4]

An alternative would be to use arrays of permanent magnets which could be inserted directly next to a MTB-carrying channel in a microfluidic chip (see figure 1). This array is able to switch between a 'pass' state - allowing the bacteria to swim along the channel - and a 'trap' state - trapping the bacteria in clusters. Without external influence, the magnets will tend to align along each others magnetization axis. Switching to the other state can be achieved by generating a magnetic field by currents directly below the magnets. Jacobs and Bean [5] proved theoretically that rotating all magnets in parallel requires more magnetic energy than rotating each subsequent pair in anti-parallel direction, referred to as 'fanning'. In this contibution we describe theoretical and experimental data about the properties of such arrays.

II – Theoretical analysis

The behavior of permanent magnet arrays can be studied by calculating its magnetic energy, as the system will always fall back to a state with local minimum energy. Figure 2 shows a model of an array with n magnets with angle θ with respect to the array axis. They are modeled as magnetic dipoles with moment **m**. Background magnetic fields, such as the earth magnetic field, are not insignificant in this system. These background fields are modelled by B_{earth} at an angle ϕ with respect to the array axis. Red arrows indicate the direction of fields generated by currents via wire structures underneath the magnets.

The energy function as derived by Jacobs and Bean [5] has been rewritten to SI units and has been extended by including the magnetic energy of the switching current. In total we consider the energy of the non-parallel (L_n) and parallel (M_n) magnets, the energy of the earth magnetic field (B_{earth}), and the energy created by the drive current (B_I). The following function

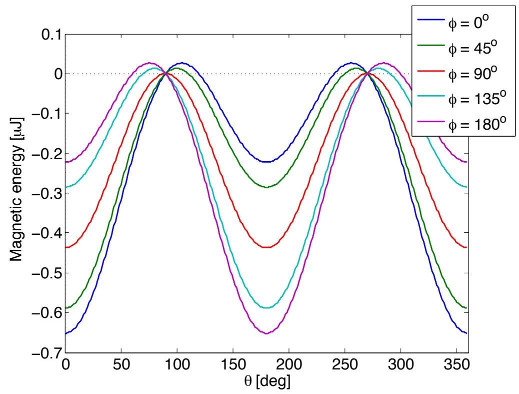

Figure 3: *Effect of the angle* ϕ *of the earth magnetic field* B_{earth} *on the magnetic energy contained by the array as a function of the magnet orientation* θ.

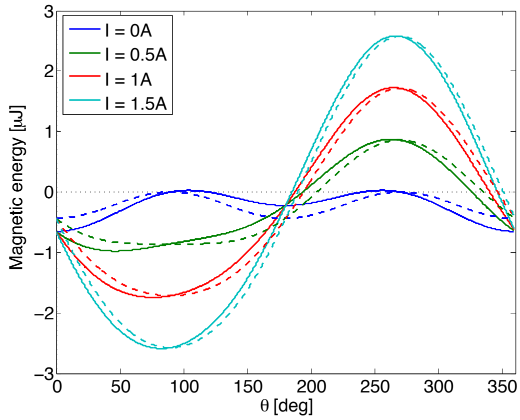

Figure 4: *Effect of drive current* I *on the magnetic energy contained by the array. Solid and dotted lines indicate respectively parallel and orthogonal alignment of the array axis with respect to* B_{earth}.

remains after omitting constant terms:

$$W_n = -\frac{\mu_0 m^2 n}{8\pi a^3}(L_n + 3M_n)\cos(2\theta) - mB_{\text{earth}}\left[n_1\cos(\phi-\theta) + n_2\cos(\phi+\theta)\right] - mnB_I\sin(\theta)$$

with

$$L_n = \sum_{j=1}^{\frac{1}{2}(n-1)<j\leq\frac{1}{2}(n+1)} \frac{n-(2j-1)}{n(2j-1)^3}$$

$$M_n = \sum_{j=1}^{\frac{1}{2}(n-2)<j\leq\frac{1}{2}n} \frac{n-2j}{n(2j)^3}$$

$$B_I = \frac{\mu_0}{4\pi}\frac{2I}{r}$$

Here, μ_0 is the permeability of vacuum, a is the spacing of the magnets and B_I is the magnetic field strength as a result of the switching current I at distance r from the wire.

Using realistic values for the parameters and setting $B_I = 0$, the influence of the earth magnetic field has been studied. Figure 3 shows the magnetic energy of the array as a function of the orientation of the magnets θ for several values of the angle of the earth magnetic field ϕ. A direct observation is the existence of only two local minima, which are along the array axis, of which the height but not the position is influenced by the earth magnetic field. The trap state of the array is a meta-stable state only.

Figure 4 shows the influence of drive current I on the system. The general trend, both for $\phi = 0^\circ$ and $\phi = 90^\circ$ is the shift of the global minimum towards $\theta = 90^\circ$ at increasing current, the latter case migrating faster.

III – Fabrication

Although intended for use in microfluidic chips, the behavior of a magnet array has been studied in larger dimensions. For this purpose, four grade N45 NdFeB magnets were spaced 10 mm apart by means of inserting them in holes with diameter 1.7 mm drilled in 1.5 mm thick PCB material (see figure 5). They automatically align along the array axis. Their magnetic force of attracting nature increases the friction of the magnets with their holder. The roughness of the hole will thus be an important factor in system behavior. The holder was placed on top of a second PCB containing copper leads directly underneath the magnets. A current induces a magnetic field on the magnets in such a way that the polarity of the current of subsequent magnets is reversed. For use in microfluidics, the distance between magnets should decrease. As a result, weaker magnets should be use in order to keep the required drive current from increasing.

Hole fabrication in microfluidic glass chips is less straightforward than in the current system. Several of the options include powder-blasting and milling using diamond tips. Figure 6 shows SEM images of cross-sections of all mentioned methods. PCB drilling delivers straight, vertical edges. Milling shows near-vertical edges, with V-shaped profiles at both ends, which is usable for the application. Powder-blasting shows a parabolic profile, which is problematic; if the bottom hole would be fit to the size of the magnets, it would become relative easy for them to rotate across horizontal axes.

IV – Experimental Details

Dynamics of the array were analyzed by applying a triangular-shaped current through the leads with an amplitude of 4 A_{pp} at 0.1 Hz. A digital camera was recording the array from the top at 25 fps, while it was manually synchronized to the waveform by a LED

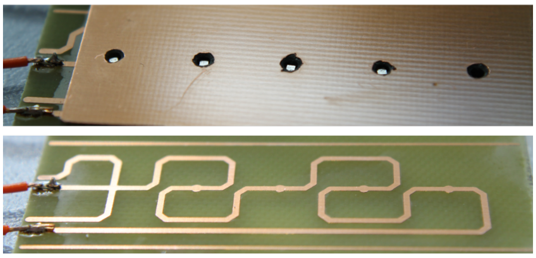

Figure 5: *Top: trapping layer for magnet array. Bottom: Actuation current tracks. Magnets are placed on the dot-shaped wire widenings.*

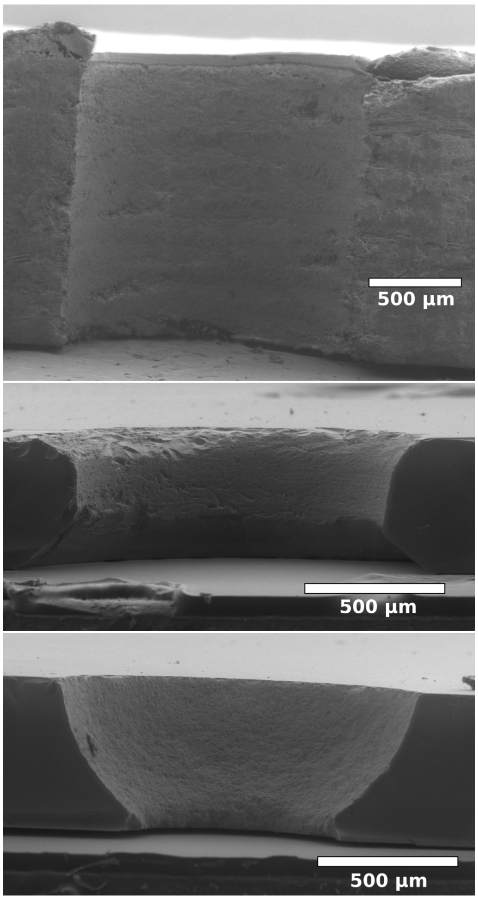

Figure 6: *SEM images of magnet insertion holes by various fabrication methods. Top: general drilling through PCB material. Middle: diamond-milling through glass. Bottom: Powderblasing through glass.*

signal in the video. The angle θ as a function of the current of a single magnet in the array was analyzed offline. Three waveforms were analyzed under both parallel and orthogonal orientation of the array with respect to the earth magnetic field in order to test reproducibility of the measured profile.

V – Results and Discussion

A. Parallel to earth magnetic field

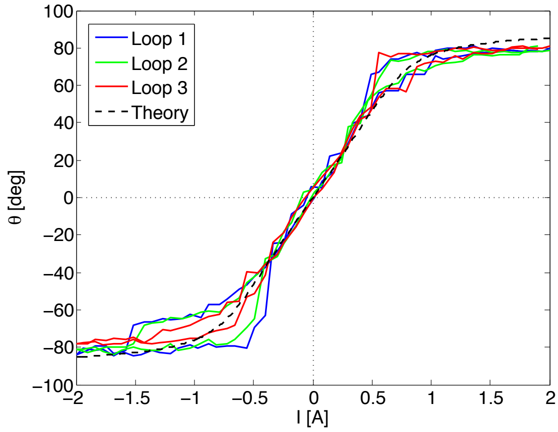

Figure 7: *Magnet orientation as a function of the drive current during parallel orientation of B_{earth} to the array axis. Different graphs represent multiple repetitions of the experiment.*

Figure 7 shows the array angle as a function of the applied current for the case where the array is in parallel alignment with the earth magnetic field. The S-shaped curve approaches the assymptotes at 90° and −90° but needs currents in excess of 2 A to get close. This can be explained by the fact that at high angles the magnetic field generated by the current will be (almost) orthogonal to the magnets' magnetic moment, losing most of the potential torque. The measured curves are near-saturated at 1.5 A and −1.5 A and match the theoretical curve. Hysteresis can be observed at higher currents (between −1.5 and −0.4 A and 0.5 and 1 A). At lower currents it is below measurement noise levels. This effect might be explained by non-linear Coulomb friction behavior. The results also prove that a continuous current is needed in order to maintain the desired magnet orientation. Finally, it can be observed that - although not completely overlapping - the curves of multiple hysteresis iterations show a high similarity and can be considered reproducible.

B. Orthogonal to earth magnetic field

Figure 8 shows the array angle as a function of the applied current for the case where the array is in orthogonal alignment with the earth magnetic field. The shape is completely different from the parallel situation, as assymptotic behavior is replaced by clipping of the magnet angle to −80° and 90°, occuring at drive currents of −1.2 A and 0.8 A respectively. There is a horizontal offset of −50 mA as well. This non-symmetric behavior is likely caused by the influence of the earth magnetic field, which has an orientation of 90°. This does not fit with the theory, which can be explained by the fact that the mathematical model only supports synchronous fanning, forcing the same angle on all magnets. In reality this constraint does not exist. The graph shows a much greater hysteresis effect than

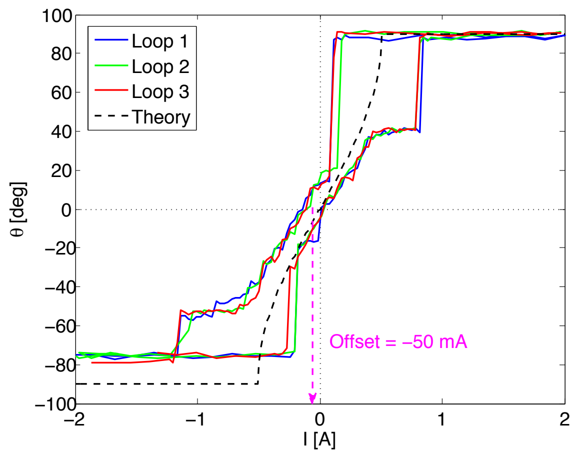

Figure 8: *Magnet orientation as a function of the drive current during orthogonal orientation of B_{earth} to the array axis. Different graphs represent multiple repetitions of the experiment.*

the parallel case. This effect at high angles might be explained by the fact that the magnetic energy slope for these currents is lower than in the parallel case, which amplifies the effect of non-linear Coulomb friction (see figure 4). At low currents the slope is higher and shows a less strong hysteresis effect. In comparison to the parallel situation, the currents to maintain the magnet orientation can be kept much lower as a result of the hysteresis. Finally, repeated experiments show reproducible results.

C. Evaluation of method

Although the theory and experiments show that the system can be utilized for the intended function, it has some significant drawbacks. First of all there is a need for a continuous current in order to keep the magnets aligned as desired. The use of elongated magnets could provide a more stable configuration for which less or no current is needed. By lowering the energy level of the orthogonal state, for instance by mounting rigid magnets in proximity to the array, this problem can be circumvented. The system shows a clear sensitivity to the direction of the earth magnetic field. Orthogonal orientation is most suitable for the application due to guaranteed 90° switching and lower continuous currents. Magnetically shielding the system could decrease the influence of external fields. Finally, the system is scalable to smaller dimensions.

VI – Conclusions

We investigated the possibility to apply magnetic fields to microfluidic chips using miniature cubic permanent magnets of 1 mm^3 on top a printed circuit board with current leads that can be used to rotate the magnets. A continuous current is needed to prevent the magnets from falling back to aligned state, as mutual magnetic forces drive the array to an aligned state. The current needed to switch the magnets from parallel alignment along the array axis towards orthogonal alignment is dependent on the direction of the background magnetic field.

If the background magnetic field is aligned with the array axis, asymptotic behavior can be observed, in which 1.5 A is needed for near-saturation of the angle at 80°. In case of orthogonal alignment of the background magnetic field with respect to the array axis, the switching behavior becomes asymmetric, requiring −800 mA in one direction versus 1200 mA in the other direction (the latter never reaching 90° rotation). Furthermore, a drive current offset of −50 mA has been observed. These asymmetries are caused by the background magnetic field.

In both alignments a reproducible hysteresis effect can be observed, which is more significant in the orthogonal situation. We believe that this is caused by non-linear Coulomb friction.

Our theoretical model describes the angular orientation of the magnet within measurements errors, but does not capture the hysteresis effect. The agreement in the orhogonal case is correct for low currents, but fails to predict the angle at higher current. For a more accurate prediction, non-linear friction and non-symmetric angles of the magnets with respect to the magnet array should be included.

These preliminary results show that miniature permanent magnets can succesfully be positioned by a simple printed circuit board using only single current leads. In this way one can easily generate strong local magnetic fields in microfluidics chips to manipulate magnetic objects such as magnetic particles or microrobots.

SEM images prove that powderblasting is an unsuitable method for creating holes in glass chips due to tapered edges. Glass milling provides a suitable alternative.

VII – Acknowledgements

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