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Mag-Guider: permanent magnet systems to steer and image super-paramagnetic particles

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Abstract

Permanent magnet systems are used for guiding superparamagnetic (nano)particles (SPP) on arbitrary trajectories over large volumes. The basic idea is to use two superimposed magnetic fields: one constant to magnetize and orient the particles, and the other with a constant gradient to exert a force. Changing the angle between them enables steering with constant force along a single direction. The same instrument can also be used for magnetic resonance imaging (MRI) using the inherent contrast of the SPP. The idea was realized by combining Halbach-cylinders of dipolar and quadrupolar configuration. Prototypes of various sizes and complexity were constructed for different applications (e.g. light-microscopy). An advanced system with two quadrupoles even allows canceling the force, hence stopping the SPP and moving them around sharp edges. This system also allows for MRI and some first experiments are presented. The velocity of SPPs under such conditions was also investigated and modelled.

I Introduction

Some applications of superparamagnetic nano-particles (SPP) require steering them remotely, for instance, inside biological systems (e.g. magnetic drug targeting [1] or maneuvering nano-robots [2]). To do so extremely strong magnetic field gradients are necessary which have to be quickly changed in amplitude and direction. At first glance, permanent magnets do not appear useful for this task, because their magnetic fields are –of course– permanent in strength and direction. However, if they could be used, they would offer many advantages (strength/volume, no cooling, no electrical power consumption, no time dependence (upscaling electromagnets typically leads to increased inductance and hence an increased time-dependence of the field, resulting in non-linear behavior of the magnetic force) [3], price, and convenience) in comparison to electromagnets in particular when the sample becomes larger than a few centimeters.

This presentation reveals some concepts in permanent magnet design, which overcome these problems. Particular the concentrically nested combination of Halbach cylinders with different polarity can be used to switch bijective magnetic forces on and off or change their direction. This is simply done by mutual rotation of the concentric rings which can be done fast and with negligible force [4,5].

II Concept and Method

The conceptual basic idea [6] is to use one magnet system to provide a strong, homogeneous, dipolar magnetic field (B_0) to magnetize the particles, and a second constantly graded ($dB/dr = G$), quadrupolar field, superimposed on the first, to generate a force on the magnetized particles. In this configuration, the motion of the particles is driven predominantly by the component of the gradient field which is parallel to the direction of the homogeneous field. As a result, particles are guided with constant force and in a single direction over the entire

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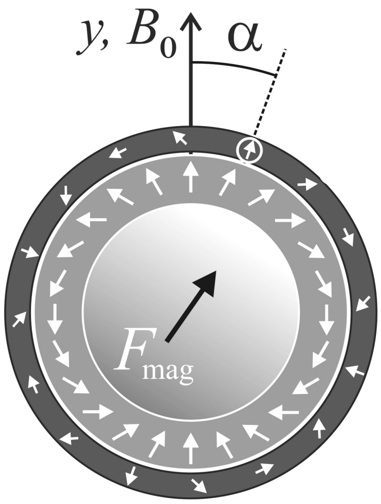

Figure 1: Schematic drawing of an ideal Halbach dipole (inner ring in lighter gray, white arrows indicate the magnetization of the permanent magnetic material) surrounded by an ideal Halbach quadrupole (darker gray). Since Halbach mutipols have no external (stray)field, the quadrupole can be rotated with negligible force around the dipole by an angle α. The resulting magnetic force points then along 2α.

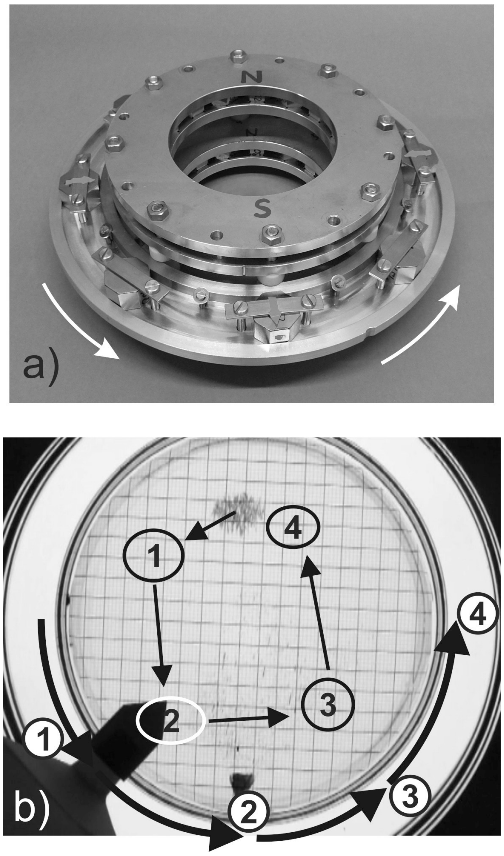

Figure 2: a) Photograph of a simple prototype. The inner dipole is made from 2 layers of 16 magnets each. The outer quadrupole is made from 8 of the same NdFeB-magnets and can be rotated without a noticeable force. This instrument generated $B_0 = 0.1$ T and $G \approx 0.2$ T/m. It has an accessible opening of 28 cm in diameter and weights 9.5 kg. b) Some SPP of 30 µm size (dark cloud at the top) are moved in a rough square through water by manual rotation of the quadrupole in four steps of $\alpha = 45°$. The particles move with a speed of about 5 mm/s to positions marked by the numbered circles (taken from a movie [6]).

volume. The direction is simply adjusted by varying the angle between quadrupole and dipole. Since a single gradient is impossible due to Gauß' law, the other gradient component of the quadrupole determines the angular deviation of the force at position r, which is negligible for $B_0 >> Gr$.

A possible realization of this idea is a coaxial arrangement of two Halbach cylinders [7,8]. Since only very hard rare earth permanent magnets can be used to construct it, no saturation effects and repolarizations (as long as the coercivity is not exceeded) have to be considered, and the magnetic field can be calculated via simple superposition [6]. Therefore, the magnetic force, F_{mag}, on SPPs in such a system is given by

$$\vec{F}_{\text{mag}} = \frac{mG}{\Xi}\begin{pmatrix} Gx + B_0 \sin 2\alpha \\ Gy + B_0 \cos 2\alpha \end{pmatrix} \tag{1}$$

with $\Xi \equiv \sqrt{B_0^2 + G^2(x^2+y^2) + 2B_0G(x\sin 2\alpha + y\cos 2\alpha)}$

where m is the magnetic moment of the SPP and α is the angle between dipole and quadrupole (see Fig. 1). If this system is surrounded by another quadrupole of identical gradient strength, the force can also be scaled and even be switched off via mutual rotation of the two quadrupoles [6].

III Results and Discussion

A simple prototype was constructed to demonstrate the principle in two dimensions on various SPP (diameters from 10 nm – 500 µm) [6], which were moved in water along a rough square by manual adjustment of the force angle (see Fig 2).

The observed velocities of the SPP were always several orders of magnitude higher (for instance 70 nm CoFe-particles had a velocity of 14 mm/s under these circumstances (compared to $2 \cdot 10^{-5}$ mm/s for a single particle)) than the theoretically expected value (for a single particle!). This discrepancy is attributed to the observed formation of long particle chains due to their polarization in the homogeneous field. The magnetic moment of such a chain is then the combination of that of its constituents, while its hydrodynamic radius stays low [6]. A simple hydrodynamic model allows predicting the velocities parallel and perpendicular to the chain axis [9]. However, the collective motion of entire fleets of such chains is still not completely understood.

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A more advanced system consists of another quadrupole (third cylinder) to scale the gradient/force strength by another rotation. It is demonstrated that with such a system the particles can be moved, stopped and thus steered on paths with sharp edges. Furthermore, this configuration [9] also allows to reduce the gradient strength such that it becomes suitable for MRI via backprojection. First 2D images are shown. Improved systems [10] of this type can then be used to move SPP (with high G) and image their position (low G) using their field distortion to generate contrast like in conventional MRI.

Finally, a "micro-robot" is presented consisting of liquid crystalline elastomers with incorporated SPP. The long range and coarse maneuvers of them are performed with the presented systems while their microscopic actuation is controlled by either light or temperature. Small objects were "grabbed", moved and released this way [11].

IV Conclusions

Magnetic systems like the presented clearly demonstrate that permanent magnet systems can be used in dynamical way that results in temporal and spatial variations of homogeneous magnetic fields and their higher derivatives. Such systems have the potential to replace electromagnets in larger installations due to their high strength and the sig-nificant lower power consumption for altering their properties. While the presented work focusses on applications for magnetic drug targeting, similar systems can be used for MPI and dedicated motion of microrobots.

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Author's Statement

Conflict of interest: Author states no conflict of interest.

References

[1] B. Shapiro, et al., WIREs Nanomed. Nanobiotechnol. (2014) doi: 10.1002/wnan.1311

[2] E. Diller, M. Sitti, Foundations and Trends in Robotics 2(3) (2013) pp. 143-259.

[3] A. Komaee, B. Shapiro, IEEE Trans. Control Sys. Tech. 20(4) (2012) pp. 1011-1024.

[4] H. A. Leupold, E. Potenziani II, M. G. Abele, J. Appl. Phys. 64(10) (1988) pp. 5994-5996.

[5] T. R. Ni Mhiocháin, et al., IEEE Trans. Magn. 35(5) (1999) pp. 3968-3970.

[6] O. Baun, P. Blümler, J. Magnetism Magn. Mat. 439 (2017) pp. 294-304.

[7] K. Halbach, Nucl. Instrum. Meth. 169(1) (1980) pp. 1-10.

[8] P. Blümler, F. Casanova, Hardware Developments: Halbach Mag-net Arrays in Mobile NMR and MRI: Developments and Applica-tions, M. L. Johns, E. O. Fridjonsson, S. J. Vogt, and A. Haber (Eds.) RSC, 2016, pp. 133-157.

[9] P. Blümler, Concepts Magn. Reson. B 46(1) (2016) pp. 41-48.

[10] C. Zimmerman Cooley, et al., Magn. Reson. Med. 73(2) (2015) pp. 872-883.

[11] D. Ditter, et al., Adv. Functional Mater. 1902454 (2019) pp. 1-12.

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