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Permanent Magnets based Actuator for 3D Navigation of Microrobots

Manel Abbes^{1,2}, Karim Belharet³, Hassen Mekki¹ and Gerard Poisson²

Abstract—This paper presents an optimal design for magnetic drug targeting of therapeutic microrobots. Drugs are transported through therapeutic magnetic boluses composed of magnetic particles controlled by magnetic gradients. In this study, to maximize the effect of the treatment and minimize adverse effects on the patient, a magnetic actuator have been developed to wirelessly control microrobots in the 3D space using four external magnets. Experimental validation is carried using the robotic arm Fanuc LD to demonstrate the steerability of the magnetic microrobots under different trajectory constraints in viscous fluidic environment.

Index Terms—Magnetic actuator, permanent magnet, micro-robot, 3D navigation.

I. INTRODUCTION

Targeted drug delivery is a field in full expansion, leading to the ability to treat only the infected zones. This helps minimizing drugs poor diffusion in targeted cells, avoiding risks of toxicity and maximizing the cures efficiency. Drug targeting using magnetic nanoparticules represents a promising and challenging new avenue for controlled drug delivery [1] [2]. They have a considerable capacity to easily cross tissue and blood barriers offering an intended delivery of drug to the infected ones in. This technique lasts for a short period of time and allows the diffusion of drugs in only targeted cells without causing any damage to the healthy ones. Several researches have been conducted on the control of targeted drug delivery into the human body, using magnetic source. Mainly two solutions have proven to be the most interesting, Electromagnetic Actuation (EMA) systems and permanent magnet actuation systems. EMA systems are generally obtained with Helmholtz and/or Maxwell coils. The combination of these coils allows the manipulation of magnetic microrobots. In [3], [4], [5], the authors used Helmotz and Maxwell coils for steering sub-millimeter magnetic microrobots inside body fluids. In [6], an EMA actuation system using the differential current coil approach was developed for steering magnetic nanoparticles in vessels. An EMA system with saddle coils was used in [7] for 3D locomotion of microrobot. OctoMag, a 5-DOF EMA system for wireless magnetic control of microrobots was developed in [8]. However, the control of the microrobots in the case of biomedical applications, these EMA systems require high power consumption. Which results in the liberation of intense

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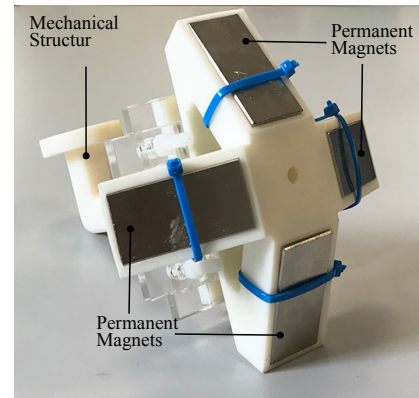


Fig. 1. Four permanent magnets based actuator prototype

heat in the workspace and the need of the cooling system. This will lead to a large systems volume and a very congested workspace.

If permanent magnets are instead used as the field source, the field is produced using no input power resulting in no heat generation near the workspace. Compared to electromagnetic devices, permanent magnet systems are able to generate strong magnetic fields and gradients by a factor of about 10-20, and 2-3, respectively, depending on the size of the workspace [9]. An increase in the field amplitude results in faster motions for magnetic crawling [10], [11] and swimming robots [12], whereas an increase in gradient magnitude induces stronger magnetic forces for microrobot pulling. Many systems using one or more permanent magnets have been developed for micro robotic manipulation. The ability of 5-DOF control of a magnetic capsule endoscope navigating in a fluid using one permanent magnet, coupled to a robotic manipulator, was described in [13]. A small permanent magnet was manipulated for three-dimensional levitation movement of a microrobot was described in [14]. Permanent magnet systems have been shown to be capable of providing 4-DOF control of a capsule endoscope by using a hand-held [15] or robotically actuated [16], [17] permanent magnet positioned outside the body. Due to the physics of magnetic fields and forces, any single magnet will always attract magnetically-responsive particles. However, there are a variety of clinical needs where it is advantageous to be able to push away therapeutic particles.

New configurations using several permanent magnets have been proposed to guide magnetic nanoparticles in biological fluids. Professor Shapiro has studied the possibility of injecting magnetic particles in the inner ear of mouse, using a combination of two permanent magnets [18]. The work pre-

sented in [19] used an equivalent system to accumulate stem cells coupled to Superparamagnetic Iron Oxide Nanoparticles (SPION) injected into cerebrospinal fluid. In our precedent work, we have proposed a motorized actuator based on two permanent magnet to control the navigation of microrobot in the cochlea [20]. Although this configuration based two permanent magnets has demonstrated its performances in the plan, it dose not ensure a symmetrical movement of the magnetic particle in the 3D space. This can have consequences on the accuracy of the magnetic particle control, especially in the open loop navigation case as presented in [20]. To ensure this symmetry, in this work we propose a four permanent magnets based actuator, for a wireless control of therapeutic microrobots in 3D workspace.

In this paper we propose a four permanent magnets based actuator, for a wireless control of therapeutic microrobots in 2D workspace. Mounted on a robotic manipulator, this actuator is able to guide nanoparticles.

II. MAGNETIC PRINCIPLE

Magnetic control technique uses the magnetic interaction principle between two or more objects. In our case, permanent magnets, placed at a defined position in the workspace, are the source of the generated magnetic field while magnetic nanoparticles are subjected to the same field. Introducing the parameters of the magnetic field B :

- The magnetization \vec{M} characterizes the magnetic object representing the magnetic moment density in a material;
- The magnetic excitation H .

Thus, the total magnetic field \vec{B} can be expressed as follows :

$$\vec{B} = \mu_0(\vec{M} + \vec{H}) \quad (1)$$

where μ_0 is the vacuum's magnetic permeability. Magnetically, \vec{M} depends on \vec{H} and the magnetic susceptibility χ , so that \vec{B} can be written as:

$$\vec{B} = \mu_0(1 + \chi)\vec{H} \quad (2)$$

The magnetic field leads to the presence of a magnetic force, Lorentz force, applied to the different magnetic objects. In the case of magnetic nanoparticles actuation, we use magnetic force or/and torque. The magnetic force and torque that act on magnetized particles can be expressed as follows [?]:

$$F_m = V_m(\vec{M} \cdot \nabla)\vec{B} = V_m \frac{\mu\chi}{1 + \frac{\chi}{3}} \vec{H} \nabla ||\vec{H}|| \quad (3)$$

$$\Gamma_m = V_m \vec{M} \wedge \vec{B} \quad (4)$$

Where V_m is the volume of the magnetized object, B represents the magnetic field's flux density and M the object's magnetization. However, when using spherical particles, which is the case in our study, a major simplification takes place. Due to the particle's shape, the magnetic field B and the vector of magnetization M are always aligned. Thus,

the particle does not undergone any magnetic torque. This allows to deduct that the magnetic force depends only on the magnetic field's magnitude [?] such as :

$$F_m = V_m ||M|| \cdot (\nabla) ||B|| \quad (5)$$

With a single permanent magnet, the magnetic field produces a magnetic gradient oriented toward it, which means that whatever the magnetic material placed in the workspace, it will always be attracted by the magnet (Fig. 2). In fact, forces go from low to high magnetic field strength. The best way to generate a pushing force is to create a local minimum magnetic field, called Lagrangian point, where the magnetic field strength \vec{H} will be zero, and increases outwards from this minimum, so, creating outward forces from this point. The authors in [9] proposed a magnetic configuration based on two permanent magnets. The first magnet is placed on the workspace and tilted clockwise compared to the z-axis, where the second magnet is tilted counter-clockwise compared to the same axis. Thus, each magnet generates magnetic field lines in the workspace. At a certain distance, a positive field line is generated from the first magnet, where the second one gives us a negative field line. We assume that when the magnets are positioned as (fig de 2 magnets actuator), the resultant of the magnetic field provides a zero magnetic field strength \vec{H} , which creates pushing forces oriented up along z-axis and the pulling forces are oriented down along z-axis.

III. FOUR PERMANENT MAGNETS BASED ACTUATOR

A. Two permanent magnets limits

The 1-DOF permanent magnets based actuator cited previously was developed in our laboratory for targeted drugs delivery with magnetic nanoparticles in the inner ear (see Fig 1). The system is composed of two permanent magnets arranged in a specific combination, inspired by the work of Shapiro [18]. This configuration allows to generate both push and pull forces along the actuators's axis. In fact, the transition from an attractive force to a repulsive one takes place when arriving at an area where all the magnetic forces are null, these areas are called Lagrange points. On the actuator's axis, we have two exploitable lagrange points L1 and L2 (see Fig 1-a). L1 is called unstable equilibrium point because of the divergence of magnetic forces from this position, whereas L2 is called stable equilibrium point. It represents a point of convergence of the magnetic forces, which also corresponds ta a trapping zone of the magnetic microrobots. Thus, trapping microrobots in a defined workspace point allows their control until reaching the target.

The actuator's degree of freedom makes it possible to control the angle between the two magnets in real time, leading to the ability to control the L2 point position in the workspace. This allows steering magnetic nanoparticles to the target by exploiting the transition between push and pull forces. However, experiments and simulations showed some limits of this actuator. We noticed that the magnetic forces converge to a fixed point only in one single plane,

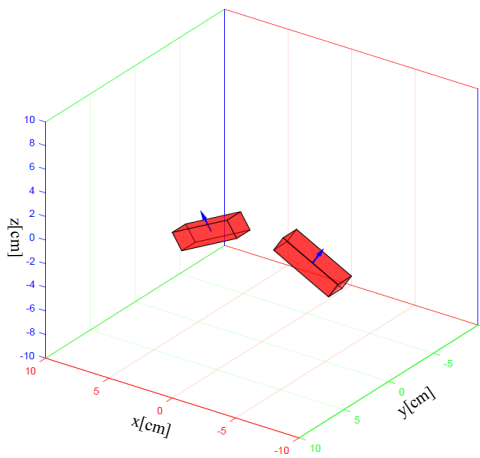


Fig. 2. Two-magnets actuator configuration.

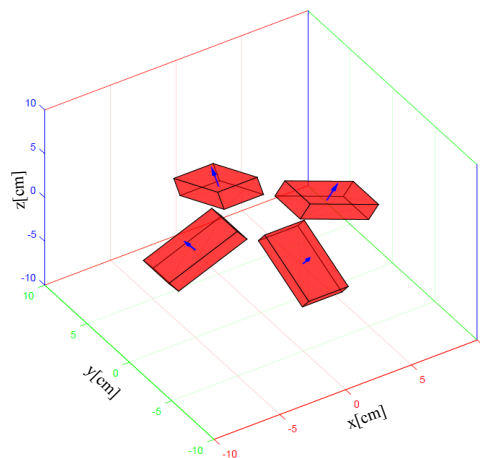


Fig. 4. Four-magnets actuator configuration.

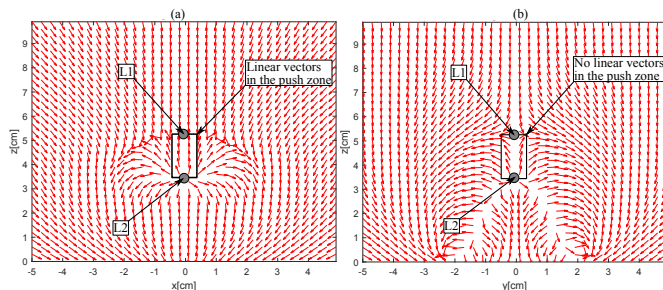


Fig. 3. Magnetic forces vectors generated by two-magnets actuator, which dimensions are 60*30*15cm : (a) xz plane, (b) yz plane.

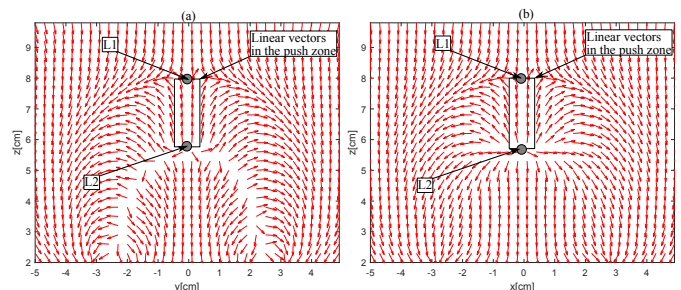


Fig. 5. Magnetic forces vectors generated by four-magnets actuator, which dimensions are 60*30*15cm : (a) xz plane, (b) yz plane.

which means we can only control the nanoparticles in this plane (see Fig 2). Thus, it is compulsory to position the actuator's axis on the desired direction with significant accuracy. Indeed, if the particle is off the axis, the actuator is not able to neither push or pull microrobots. So, the actuator requires to be coupled to a positioning system with a very high accuracy to be efficient. Therefore, a minimal error in the planning or in the positioning of the actuator may compromise the guidance procedure.

B. Four permanent magnets combination

The proposed system is a four magnets based actuator able to wireless steer nanoparticles in a 3D workspace (Fig.4). Compared to the two-magnets actuator, it has a symmetrical behavior in the two planes xz and yz (Fig.??). This allows to generate magnetic forces that converge to a fixed point in both planes, which facilitate the control of microrobots.

In addition, this configuration allows a margin of 2cm around the axis where magnetic forces still converge towards the equilibrium zone (see Fig.??). This margin makes possible to control the movement of a microrobot despite an error in the positioning of the actuator. Increasing the number of the permanent magnets also makes it possible to move the position of the stable lagrange point L2, from the center of the magnets frame as shown in (see Fig.??). Here the point L2 is situated at 7.55cm from the structure's center whereas in the two-magnet configuration, the stable point L2

is situated at a distance of 3cm from the magnets. However, while maximizing this distance we have to make sure that the magnetic field strength generated by the magnets maintains sufficient. So, it's clear that magnetic forces generated by the novel actuator are more important than the ones generated by the two magnets based actuator, while ensuring that the magnetic field strength is sufficient to steer microrobot to the stable equilibrium node.

Fig.6 shows the distribution of magnetic field vectors around the stable equilibrium point L2 that represents the magnetic force's local minimum. The stable equilibrium node is situated at a distance of 7.55cm from the center of the magnet's frame. Analyzing the strength of the magnetic field, we noticed that the actuator's influence zone is situated between $z=7\text{cm}$ and $z=9\text{cm}$ with a margin along x-axis of 2cm ($x=-1\text{cm}$ to $x=1\text{cm}$).

IV. EXPERIMENTAL VALIDATION

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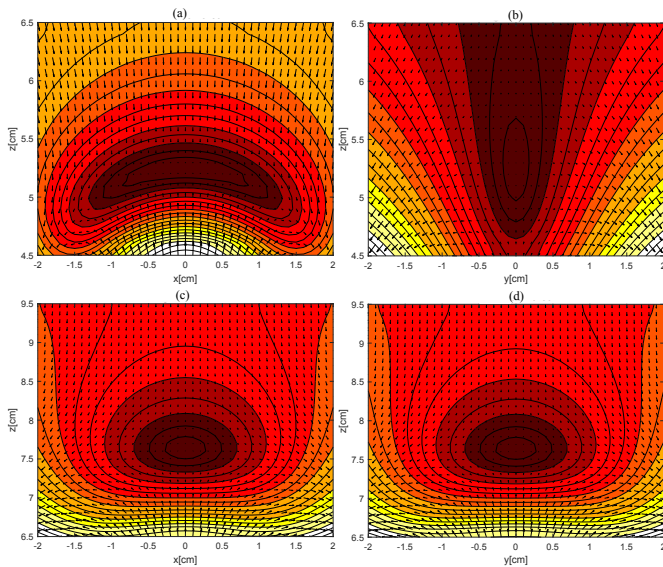


Fig. 6. Isolines of magnetic force strength around the convergence point with the direction of the magnetic force : (a) two-magnet system plan xz, (b) two-magnet system plan yz, (c) four-magnet system plan xz, (d) four-magnet system plan y

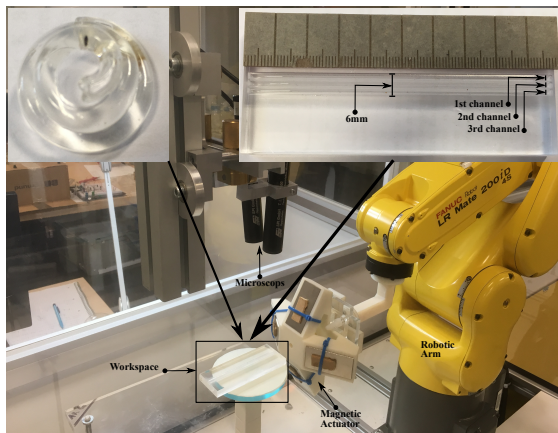


Fig. 7. Experimental setup used to validate the performances of the proposed magnetic actuator.

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