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► **To cite this version:**

Ruipeng Chen, David Folio, Antoine Ferreira. Analysis and Comparison of Electromagnetic Microrobotic Platforms for Biomedical Applications. Applied Sciences, 2022, 12 (1), pp.456. 10.3390/app12010456 . hal-03516817

**HAL Id: hal-03516817**




**<https://hal.science/hal-03516817>**

Submitted on 5 Apr 2024

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# Analysis and Comparison of Electromagnetic Microrobotic Platforms for Biomedical Applications

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**Featured Application:** Targeted drug delivery using magnetic micro/nanorobots.

**Abstract:** Magnetic microrobotics is a promising technology for improving minimally invasive surgery (MIS) with the ambition of enhancing patient care and comfort. The potential benefits include limited incisions, less hemorrhaging and postoperative pain, and faster recovery time. To achieve this, a key issue relies on the design of a proper electromagnetic actuation (EMA) setup which is based on the use of magnetic sources. The magnetic field and its gradient generated by the EMA platform is then used to induce magnetic torque and force for microrobot manipulations inside the human body. Like any control systems, the EMA system must be adapted to the given controlled microrobot and customized for the application. With great research efforts on magnetic manipulating of microrobots, the EMA systems are approaching commercial applications, and their configurations are becoming more suitable to be employed in real medical surgeries. However, most of the proposed designs have not followed any specific rule allowing to take into account the biomedical applications constraints. Through reviewing the different proposed EMA systems in the literature, their various specifications and configurations are comprehensively discussed and analyzed. This study focus on EMA platforms that use electromagnets. From this review and based on the biomedical application specifications, the appropriate EMA system can be determined efficiently.

**Keywords:** ElectroMagnetic Actuation, Medical Magnetic Microrobots, Minimally Invasive Surgery

## 1. Introduction

Magnetically actuated microrobots are of great interest for the development of innovative biomedical operations. The need to improve interventional operations has led to a wide range of minimally invasive procedures. Since most current operations are limited by the manual action of the surgeon, various robotic systems have been proposed to enhance minimally invasive surgery (MIS) [1–14]. Unlike the need of using rigid instruments with dexterous distal wrists, it is commonly more appropriate to use robotic tools that access internal tissues through small skin incisions [14–19]. Thanks to these medical robotic solutions the acceptance of their uses in clinical practice has been improved. For instance, researchers from the robotics field have developed solutions like robotized tele-echography to provide skilled medical care to isolated patients [20]. Meanwhile, various microrobotic systems have arisen to further reduce trauma, create new diagnosis tools and therapeutic procedures. For example, wireless microrobots with size of less than a millimeter are investigated to navigate within the body for targeted therapies [21–23].

Indeed, the design of miniaturized and versatile microrobotic systems potentially allows access to the entire human body, thus offering localized diagnoses and treatments with more precision and efficiency, but also to consider new procedures. For example, wireless microrobots, smaller than a millimeter, can navigate the body to perform targeted therapies [21–23]. A key issue lies in the actuation of such untethered microrobots within the human body. Among the various techniques developed so far, electromagnetic actuation (EMA) is considered to be the most promising one [13,21–50]. To this aim, many EMA



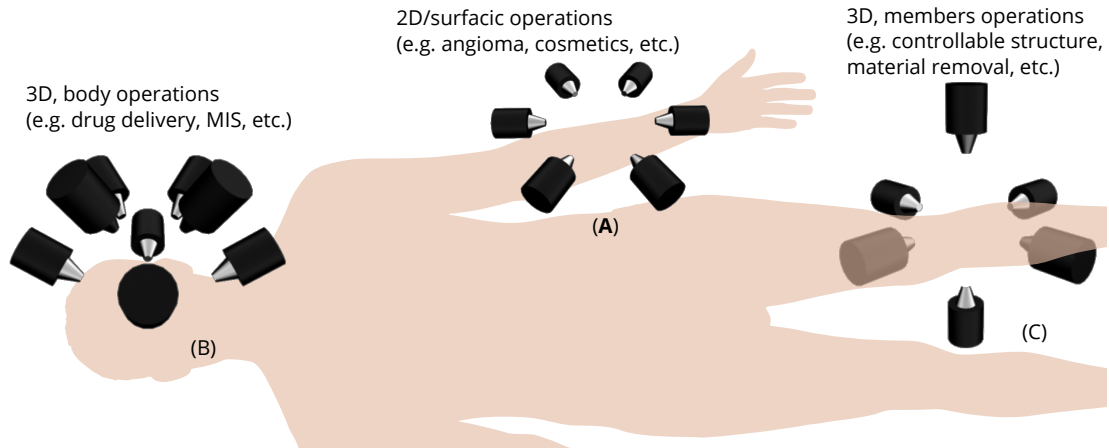
**Citation:** Chen, R.; Folio D.; Ferreira, A. Analysis and Comparison of Electromagnetic Microrobotic Platforms for Biomedical Applications. *Preprints* **2021**, *1*, 0. <https://doi.org/>

Received:

Accepted:

Published:

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**Figure 1.** The concept of EMA system applying for various biomedical applications.

platforms have been proposed to control untethered magnetic microrobots for biomedical applications [29,42,48–81]. Using EMA system circumvents the need of embedding power sources into the microrobot [13,21,22,25,46,82]. Magnetic microrobots can be operated remotely and precisely by controlling external electromagnetic fields. This allows the microrobots to assist the surgeon by increasing the dexterity of the MIS procedure [13,14,22,25,46,57,78,81].

To properly manipulate magnetic microrobots for the realization of reliable given biomedical applications, the EMA platform is one of the key elements. Consequently, the choice, the number and the placement of its magnetic sources are of prime importance [81]. Basically, magnetic sources can be produced by either permanent magnets [29, 51–56] or electromagnets [42,48,49,57–78]. Nevertheless, most of the numerous EMA designs proposed by researchers do not follow any specific rule. It is not easy to choose the appropriate solution for a given application. This review aims to summarize and compare the existing EMA systems regarding MIS procedures, focusing on those using electromagnets. At first, the electromagnetic sources of EMA systems could be organized either in a two-dimensional (2D) or in a three-dimensional (3D) arrangements, and apply properly to the different parts of the human body, as presented in fig. 1. As illustrated in fig. 1(A), the 2D placement of magnets could be useful for surface operations such as angioma or cosmetic treatments. In the meanwhile, most MIS interventions require a 3D workspace, hence, the EMA system should be arranged in 3D above fig. 1(B) or around fig. 1(C) the workspace as well.

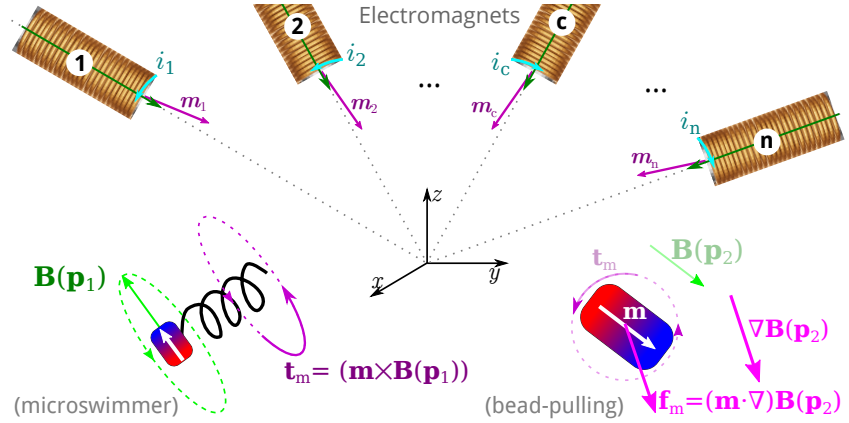
## 2. Theoretical Background

### 2.1. Magnetic Manipulation

EMA systems consisting of several electromagnets allow generating a magnetic field and/or a gradient field in a given workspace, as shown in fig. 2. These fields induce a magnetic torque and a force on the magnetized materials of the untethered microrobots. The expression of the magnetic field generated by an electromagnetic coil is derived from a single wire and the magnetic dipole. The magnetic field from any electromagnetic coil  $c$  can be approximated as a magnetic dipole characterized by its magnetic moment  $\mathbf{m}_c$ , and the point-dipole model is proposed. It can be shown that the magnetic field and its gradient are proportional to the electric current  $i_c$  flowing through the coil  $c$ . The overall magnetic field generated by the  $n$ -coils is the superposition of each field. The magnetic field and its gradient are then expressed as:

$$\mathbf{B}(\mathbf{p}) = \mathcal{B}(\mathbf{p})\mathbf{i} = (B_x \ B_y \ B_z)^T \mathbf{i} \quad (1)$$

$$\nabla \mathbf{B}(\mathbf{p}) = \mathcal{G}(\mathbf{p})\mathbf{i} = \left( \frac{\partial B_x}{\partial x} \ \frac{\partial B_x}{\partial y} \ \frac{\partial B_x}{\partial z} \ \frac{\partial B_y}{\partial y} \ \frac{\partial B_y}{\partial z} \right)^T \mathbf{i} \quad (2)$$



**Figure 2.** Illustration of the use of the magnetic manipulation of untethered microrobots.

where  $\mathbf{i} = (i_1, \dots, i_n)^t$  is the electric current vector.

When the magnetic dipole moment and the magnetic field are given, the induced magnetic torque and force can be easily obtained by the Maxwell's equations. The induced magnetic field aligns the microrobot to a desired direction, and the magnetic force provides the propulsion force to move the microrobot to complete the task. Through the mathematical transformation, and for more convenient investigations of the magnetic actuation properties, the equations of torque and force can be rearranged into the following expression:

$$\begin{pmatrix} \mathbf{t}_m \\ \mathbf{f}_m \end{pmatrix} = \begin{pmatrix} \mathbf{m} \times \mathcal{B}(\mathbf{p}) \\ \mathbf{m}^t \mathcal{G}(\mathbf{p}) \end{pmatrix} \mathbf{i} = \mathcal{A}(\mathbf{m}, \mathbf{p}) \mathbf{i} \quad (3)$$

where  $\mathcal{A}(\mathbf{m}, \mathbf{p}) \in \mathbb{R}^{6 \times n}$  is an *actuation matrix* mapping the current to the applied magnetic wrench. This magnetic actuation matrix is a function of both the position  $\mathbf{p} \in \Omega$ , and the magnetic moment  $\mathbf{m}$  of the microrobot.

Therefore, substituting the eq. (1) and eq. (2) into the eq. (3), the equations of torque and force can be presented by the actuation matrix  $\mathcal{A}(\mathbf{m}, \mathbf{p})$  in the further details as:

$$\mathcal{A}(\mathbf{m}, \mathbf{p})(\mathbf{i}) = \begin{pmatrix} m_x & m_y & m_z & 0 & 0 & 0 & 0 & 0 \\ 0 & m_x & 0 & m_y & m_z & 0 & 0 & 0 \\ -m_z & 0 & m_x & -m_z & m_y & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -m_z & m_y \\ 0 & 0 & 0 & 0 & 0 & m_z & 0 & -m_x \\ 0 & 0 & 0 & 0 & 0 & -m_y & m_x & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial \mathcal{B}_x}{\partial x} \\ \frac{\partial \mathcal{B}_x}{\partial y} \\ \frac{\partial \mathcal{B}_x}{\partial z} \\ \frac{\partial \mathcal{B}_y}{\partial x} \\ \frac{\partial \mathcal{B}_y}{\partial y} \\ \frac{\partial \mathcal{B}_y}{\partial z} \\ \mathcal{B}_x \\ \mathcal{B}_y \\ \mathcal{B}_z \end{pmatrix} (\mathbf{i}) \quad (4)$$

Each column of the matrix  $\mathcal{A}(\mathbf{m}, \mathbf{p})$  represents the wrench on the force and torque per unit current created by each electromagnet. If there are greater than  $n > 6$  electromagnets, the actuation matrix  $\mathcal{A}(\mathbf{m}, \mathbf{p})$  leads to a better conditioned matrix, a more isotropic workspace  $\Omega$ , a reduction of singularity configurations, and lower current requirements [72,73,81]. In such cases,  $n > 6$ , the EMA system is said "redundant" for the task. Especially, if

$\mathcal{A}(\mathbf{m}, \mathbf{p})$  has a full rank, for a desired force,  $\mathbf{f}_m^*$  and torque,  $\mathbf{t}_m^*$ , the actuation currents  $\mathbf{i}$  can be calculated from the pseudo-inverse:

$$\mathbf{i} = \mathcal{A}^+(\mathbf{m}, \mathbf{p}) \begin{pmatrix} \mathbf{t}_m^* \\ \mathbf{f}_m^* \end{pmatrix} \quad (5)$$

If  $n < 6$ , the pseudo-inverse would be a least-squares approximation. Hence, for a controlled force and torque, the input current can be obtained only if the pseudo-inverse of  $\mathcal{A}(\mathbf{m}, \mathbf{p})$  exists. This derivation on the controlled current  $\mathbf{i}$  can be similarly extended for controllers that require torque and/or force control [57].

## 2.2. Manipulation Analysis

From the mathematical analysis, the rank of force equation is 3 and the rank of torque equation is 2, the microrobot can maximally achieve 3 degrees-of-freedom (DOFs) in translation and 2 DOFs in rotation. Next, to achieve the 5 DOFs control of the microrobot, the minimum number of electromagnets is mathematically estimated. The 3 electromagnets can be used for 3 DOFs force control at a point, but normally 5 electromagnets are required when the orientation of the microrobot is dynamically changed. The number of electromagnets can be reduced to 4, but either a nonmagnetic restoring torque or a nonmagnetic restoring force is required to stabilize the system. For 2 DOFs torque control, only 3 electromagnets are required because the 3 coils can generate a 3D field in a workspace. Thus, combined torque and force control requires a minimum of  $n = 7$  stationary electromagnets. Similarly, the 7 electromagnets also need some additional external conditions. To stabilize the 5 DOFs control of the microrobot, the 8 electromagnets are suggested for the fixed configuration system [83]. Reconfigurable EMA system can achieve similar control authority to stationary system with fewer electromagnets. Only  $n = 5$  electromagnets are required for torque and force control. Therefore, the mobile electromagnets are more particularly considered for the biomedical applications. Indeed, the field shape in the workspace can be modified by changing the location or orientation of the electromagnets during the magnetic actuation of the microrobot [81].

## 2.3. Discussions

Various arrangements of electromagnetic coils can generate various magnetic field distributions. The EMA setup should be properly defined with respect to the envisioned biomedical application. To do so, the main characteristics should be specified, such as: the environment of the workspace, the type of microrobot and the various magnetic tasks. The required number of electromagnets for different motions control has been studied in past works [45,81,83]. On this basis, the relations between the specifications and the number of coils to design an EMA system can be proposed, and are depicted in fig. 3.

Specifically, for the choice of a proper EMA system, five main characteristics of an application are required:

1. The dimensions of workspace;
2. The media of the environment;
3. The type of microrobots;
4. The medical tasks;
5. The required motion control.

First of all, the dimension of workspace is determined by the desired biomedical application that can be either 2D or 3D. The media of workspace could be divided into easy-to-operate and non-easy-to-operate for the placed microrobot. Commonly, the media with high viscosity or non-Newtonian fluid and the flowing status are difficult conditions to manipulate microrobot. In contrast, low viscosity and static environment are easy for the operation of microrobot.

Moreover, the type of applied microrobot and its locomotion must be specified. Especially, the helical microrobot or microswimmer could be selected to move in a flowing

environment and/or high viscosity media since these microrobots can perform drilling motion by the rotating magnetic field (see also fig. 2). Combining with magnetic force produced by magnetic gradient, the helical microrobot or microswimmer can be also actuated by a strong propulsion force. Besides, the cylindrical, ellipsoidal, spheroidal and irregularly shaped microrobot are chosen to the suitable environments. In addition, the type of locomotion of the microrobot should be determined with respect to the given application. As presented in fig. 3, 6 main types of biomedical applications are here considered. But, a distinction is made according to a 2D or 3D workspace that is considered. For a 2D workspace, as illustrated in section 2.3, 4 main types of biomedical applications are considered for a 2D workspace: i) surface treatment, ii) marking/sensing, iii) *in vitro* micromanipulation, and iv) controllable structure. Whereas for a 3D biomedical operations, the main types of tasks are: i) material removal, ii) marking/sensing, iii) targeted therapy, and iv) controllable structure, as depicted in section 2.3. For instance, almost all types of microrobot could be used for targeted drug delivery. However, the spheroidal microrobot rather than the helical microrobot is suitable for marking/sensing application. If a helical microrobot is applied for targeted drug delivery, the possible motion of microrobot is required as translation and rotation. If a spheroidal microrobot is used for targeted drug delivery, the possible motion could be translation, rotation and punching.

Finally, the number of electromagnetic coils is determined by the specific motions of the selected microrobot. For instance, the translational locomotion can be achieved by the magnetic force on the spheroidal microrobot, and it can also be reached by the magnetic torque generated by rotating magnetic field on the helical microrobot. Considering a 3D workspace as an example, the reliable locomotion of spheroidal microrobot requires  $n = 5$  numbers of electromagnets, while the locomotion of a helical microrobot only demands  $n = 3$  numbers of electromagnets. Similarly, other necessary information for designing EMA system can also be obtained in the same way following the fig. 3. Therefore, from the above five requirements, the specifications of desired EMA system are obtained.

### 3. The Electromagnetic Microrobotic Systems

The magnetic microrobot can be efficiently actuated by the utilization of magnetic field and/or its gradient. This magnetic field could be generated from an EMA platform, that must obviously comprises some electromagnetic sources. The magnetic sources could be produced by either permanent magnets [29,51–56] or electromagnets [42,48,49,57–78], that should be selected according to the specified biomedical application. The main advantage of permanent magnet sources is that they do not require an external power supply, and they exhibit an advantageous volume to field-strength ratio [52]. But, in such case the magnetic fields can not be accurately adjusted or switched off [54]. In contrast, electromagnets can generate appropriate and flexible magnetic fields to effectively control the movement of microrobots. This study focuses on applications where magnetic fields and/or their gradients need to be continuously changed, and EMA setups using electromagnets are primarily considered in the following. The simplest electromagnet is wrapped around an air-filled core. In such case, the magnetic fields or their gradients can be uniformly defined in the workspace, and linear relationship can be expressed with their input currents. However, in such case, the strength of the magnetic field is weaker than using a permanent magnet on an equivalent volume. To increase the strength, a magnetic core with a high magnetic permeability can be added inside the coil to confine and guide the magnetic fields. The magnetic field is related to the electric current as well as to the properties of the magnetic core. Nevertheless, EMA system with several core-filled electromagnets may exhibit nonlinear and coupled behavior.

Furthermore, the EMA systems can also be distinguished into stationary and mobile. Stationary magnetic sources commonly use Helmholtz, Maxwell and saddle coils [61–65,67,69,71,74,84], as in MRI system [58,85–87], to induce magnetic fields and gradients that only are controlled by the current flowing into the electromagnetic coils. With such stationary configurations, the magnetic manipulation of the microrobot together with the

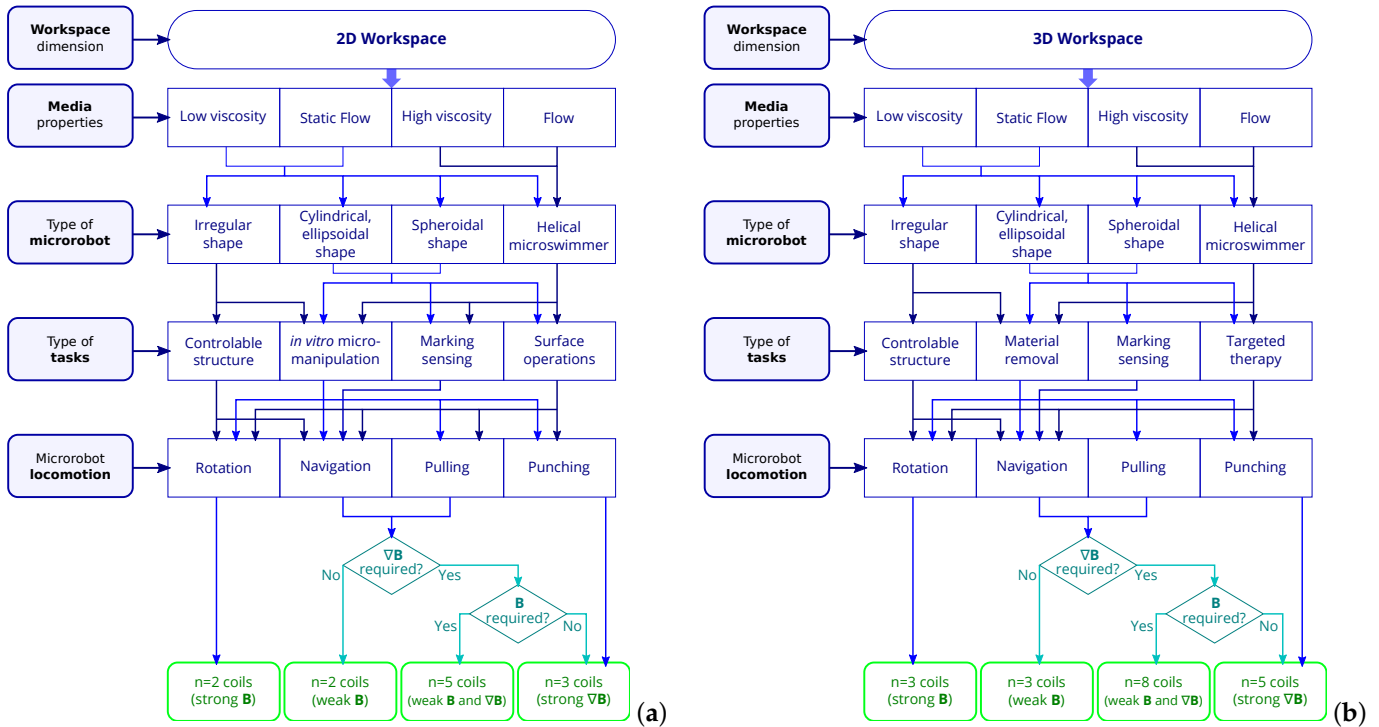


Figure 3. The diagram of the specifications of EMA system design for (a) 2D and (b) 3D workspace..

workspace geometry remains limited by the stationary arrangement of coils. Conversely, moving magnets (e.g. actuated by a robotic system) can move around the target to enhance the manipulability of microrobots [88,89]. As the magnetic sources usually remain close to the microrobot, the moving coils also reduce the energy demand. In addition, they can change the local field distribution by adjusting the positions and/or orientations of the magnets [60,73].

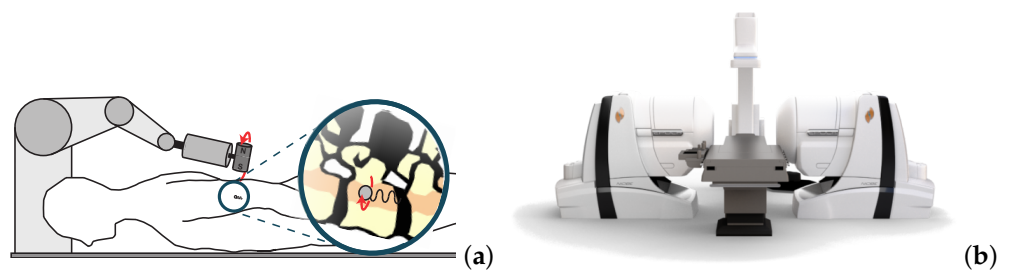
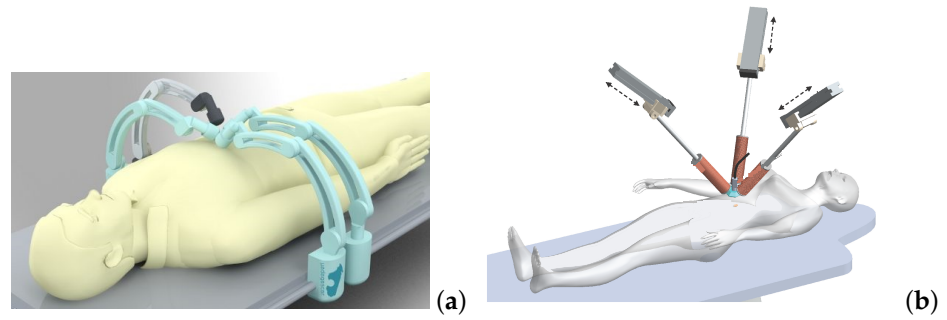


Figure 4. Examples of EMA systems with moving permanent magnets: (a) conceptual image of a rotating-permanent-magnet manipulator proposed by Fountain *et al.* [51], and (b) the Stereotaxis Niobe<sup>®</sup> consisting of two robotically-controlled magnets next to the table.

As shown in fig. 4(a), Fountain *et al.* [51] propose the use of nonuniform magnetic fields emanated from a single rotating-permanent magnet manipulator for the control of magnetic helical microrobots, where the robotic arm brings the magnet closer to the patient, and the axial and radial controls cause the local magnetic field to change. Stereotaxis<sup>1</sup> Inc. has developed and commercialized the Niobe<sup>®</sup> robotic magnetic navigation system presented in fig. 4(b). Niobe<sup>®</sup> uses two permanent magnets mounted on pivoting arms and positioned on opposing sides of the operating table to control proprietary catheters and guide-wires that have very small magnets at their distal tips. To circumvent the uncontrollability of the magnetic field generated by permanent magnets, Véron *et al.* [88] investigate a robot-assisted magnetic manipulation system with several mobile electromagnetic coils

<sup>1</sup> Stereotaxis Inc., St. Louis, MO, USA, <http://www.stereotaxis.com>



**Figure 5.** Examples of EMA systems with moving electromagnets: (a) the robot-assisted magnetic manipulation proposed by Véron *et al.* [88], and (b) the DeltaMag system consisting of three parallel mobile coils [89].

as represented in fig. 5(b), where a robotic system keeps full dexterity for the use of electromagnetic coils while reducing energy consumption by a nearer manipulation. Also, Yang *et al.* [89] demonstrate an electromagnetic manipulation system with three parallel mobile coils named DeltaMag and represented in fig. 5(b). The proposed EMA system can remotely control the magnetic untethered devices in an enlarged workspace, moreover, the electromagnetic coils are actuated through the parallel mechanism to achieve the flexibility of their placement. Thus, the DeltaMag system proves that the mobile sources generated by moving electromagnets can improve the manipulability of localization to close the vicinity of the desired area and bring the good space utilization.

Here, we present a brief overview of different EMA setups in the following paragraphs. These electromagnetic microrobotic platforms can be divided into two-dimensional and three-dimensional manipulations. The status of electromagnetic coils could be stationary or mobile. The functions of designed electromagnetic platform vary according to the configuration of electromagnets. The Helmholtz coils pair, Maxwell coils pair, uniform saddle coils pair and gradient saddle coils pair are basic electromagnets configurations as shown in fig. 6 and are commonly used to generate a uniform magnetic field or gradient in a given workspace. The magnetic field intensity  $H_h$ ,  $H_m$ ,  $H_u$  and  $H_g$  of them can be computed as follows, respectively:

$$H_h = (d_h x \quad 0 \quad 0)^T \quad (6)$$

$$d_h = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{i_h}{r_h} \quad (7)$$

$$H_m = (g_m x \quad -0.5g_m y \quad -0.5g_m z)^T \quad (8)$$

$$g_m = \frac{16}{3} \left(\frac{3}{7}\right)^{\frac{5}{2}} \frac{i_m}{r_m^2} \quad (9)$$

$$H_u = (0, d_u, 0)^T \quad (10)$$

$$d_u = 0.6004 \frac{i_u}{r_u} \quad (11)$$

$$H_g = (g_g x \quad -2.4398g_g y \quad 1.4398g_g z)^T \quad (12)$$

$$g_g = \cos^{-1} \left( 1 - \frac{3}{2a^2} \frac{16}{3\pi} \left(\frac{3}{7}\right)^{\frac{5}{2}} \frac{i_g}{r_g^2} \right) \quad (13)$$

where  $i_h$  and  $r_h = r$  are the current and the radius of the Helmholtz coils;  $i_m$  and  $r_m = r$  are the current and the radius of the Maxwell coils;  $i_u$  and  $r_u = r$  are the current and the radius of the uniform saddle coils; and  $i_g$  and  $r_u = g$  are the current and the radius of the gradient saddle coils.

As shown in fig. 6(a), the Helmholtz set includes two solenoids with same radius  $r_h$  separated by the distance:  $l = r_h$ , and the Maxwell coil consists of a pair of same coils

















allow up to a 3 DOFs (2 translations and 1 rotation).

When the workspace is expanded to the 3D, at least six stationary independent electromagnetic coils are required. If the coils pair is able to be rotated, the number of coils pair could be reduced. For instance, two pairs of the Helmholtz coils and two pairs of the Maxwell coils can actuate a 3D locomotion of the microrobot where one Helmholtz coils pair and one Maxwell coils pair can rotate along a same axis for rotating a 2D manipulation plane over a 3D workspace. When an electromagnetic coil is used to generate both magnetic field and gradient by adjusting the current, the number of stationary coils pairs can be further reduced to three pairs. In addition, the number and type of coils also depend on the manipulated microrobot. The motion of the microswimmer only requires three pairs of coils that generate the uniform magnetic field throughout the 3D workspace. With the exception of the 3DH and 9E platforms, the others allow up to the 5 DOF (3 translations and 2 rotations).



**Table 1.** Comparisons of the EMA systems

EMA	Coils & Workspace	Advantages	Limitations
HMr [49]	4 coils, 2D	Use few coils with simple structure; 2 DOFs of translation and 1 DOF of rotation; Manipulation of the orthotropic body.	Low magnetic gradient over larger areas; Rotating coils limit medical applications.
2C [70]	4 coils, 2D	Less number of coils, 18% smaller volume and 26.7% less power consumption to the same magnetic actuation.	Non-uniform magnetic field at the edge of the workspace.
2H2M [65]	8 coils, 2D	Simple current control strategy ; Uniform magnetic field and gradient; Manipulation of the orthotropic body.	Low flexibility of the confined workspace.
HMUG [62]	8 coils, 2D	Common current control strategy; Compact setup with easy access; More efficient compared to the Maxwell and Helmholtz coils; Manipulation of the orthotropic body.	Size of the proposed workspace is still limited ; Non-uniform magnetic field at the edge of the workspace; Effective workspace is limited to the 2D plane.
3H2M [90,91]	10 coils, 2D	Independent control of the multiple microrobots; Microparticles with different shapes.	Only 2 DOFs motions (1 DOF rotational and 1 DOF translational) on a 2D plane; Confined workspace with difficult access; Important number of coils and power consumption.
6E [92]	6 coils, 2D	Simultaneous independent positioning control of multiple microrobots; Simple structure and easy to implement; Heterogeneous sets of dissimilar magnetic microrobots have been tested.	Complex control algorithms, and limited trajectory.
3DMH [74]	6 coils, 3D	Compact and cheap setup; 3D manipulation of the orthotropic body.	Limited workspace.
2H2Mr [61]	8 coils, 3D	Precise 3D motion; Fewer number of coils; Manipulation of the orthotropic body.	Rotating coils limit medical applications; Large setup volume and power consumption.
HMUGr [67]	8 coils, 3D	Small setup volume and less consumption ; Workspace accessibility; Almost all kind of microrobots.	More powerful current suppliers are demanded that will cause overheating; The available workspace is still relatively small.
H2US-MUG [63]	10 coils, 3D	Compact structure ; Precise magnetic field and gradient for 3D manipulation; Potential large range of applications.	Large number of coils; Small and limited size.
3DH [94]	6 coils, 3D	6 DOFs motion; Simple structure and easy to build; Control of the helical microswimmer.	Complex algorithm and control strategy; Only the magnetic-field-based control.
8E [95]	8 coils, 3D	Compact structure ; Arbitrary forces can be exerted on each microrobot independently and simultaneously.	Small volume with few accessibility; Weak magnetic field and gradients.
[59,60]		Good magnetic field; Hemispherical coils arrangement.	Complex magnetic field description.
9E [96]	9 coils, 3D	Independent 3D control of pairs of microrobots; 6 DOFs motion; Workspace accessibility.	Advanced control strategies are required; Large amount of energy consumption and heating.

1           The independent manipulation of multiple microrobots has been also investigated [72,  
2           92,95,97]. It requires either complicated control strategy or special design of the microrobots.  
3           Such as, the eight independent electromagnetic coils are responsible for generating the  
4           common magnetic gradient to propel the multiple microrobots in the workspace. With the  
5           unique viscous drag due to the specific microrobots, their responses are independent to  
6           obtain their control. Basically, the electromagnetic actuation system is useful for various  
7           manipulation tasks with different configurations of electromagnetic coils under adjustable

8 current inputs and efficient control strategies.  
9 Table 1 summarizes the comparison of the different EMA setups. More comparative and  
10 mathematical analyses regarding different configurations of EMA systems have been  
11 presented in the previous study [81].

#### 12 4. Conclusions

13 We have provided a comprehensive review of the current advances of the biomedical  
14 microrobot in MIS and a comparison of various magnetic microrobotic systems developed  
15 by many researchers. One of the highest potential scientific and societal impact of the  
16 untethered microrobot would be the health-care and bio-engineering applications. As the  
17 robot size is decreased to the micro or nano-scale, previously inaccessible body locations  
18 would become available for high-resolution *in situ* and *in vivo* operations. Such remotely  
19 access will enable an extensive range of MIS operations. To this aim, the untethered  
20 microrobot would be wirelessly manipulated by the magnetic torque and force induced  
21 thanks to an EMA system. To precisely manipulate the biomedical microrobot, a key issue  
22 still relies on the suitable configuration of EMA platforms.

23 Therefore, this work is devoted to present a general review of magnetic microrobots  
24 and magnetic microrobotic actuation setups. Especially, the choice of suitable magnetic  
25 microrobotic platform is a significant issue for the desired biomedical applications. The  
26 magnetic microrobotic systems with different configurations can produce respectively the  
27 magnetic field and gradient. As illustrated in fig. 1(A), the magnetic field and gradient  
28 on the 2D surface generated by flat-arrangement magnetic microrobotic system are appro-  
29 priate for the surface or skin operations. For the deeper surgical treatment, the magnetic  
30 microrobotic system can be utilized to control the medical microrobot to operate on mem-  
31 bers (e.g. arms, legs) for targeted therapy. This allows increasing the concentration of drugs  
32 in the part to be treated and reduces the impact on other parts of the body, that makes the  
33 treatment more effective and minimize side effects. Thus, the magnetic microrobotic system  
34 could be designed to surround the desired workspace as represented in fig. 1(B) since the  
35 applied part could be placed through the setup. Once again, with the requirements of a  
36 specific intraocular application, since the magnetic field with a safe intensity is arduous to  
37 launch deep into the body tissue providing enough magnetic field and gradient, the coils  
38 generating the magnetic field placed behind the head would be futile for the eye operation.  
39 Hence, the applied coils are all arranged around the eye in the front of the head. It is clear  
40 that the various magnetic microrobotic systems are utilized specifically for the pertinent  
41 biomedical applications in order to perform efficiently their functions.

42 **Author Contributions:** Methodology, R.C.; Analysis, R.C. and D.F.; Writing-original draft, R.C  
43 and D.F.; Writing-review and editing, R.C., D.F. and A.F.; Project administration: A.F.; Funding  
44 Acquisition: A.F. All authors have read and agreed to the published version of the manuscript.

45 **Funding:** This work was supported by the French National Institute of Health and Medical Research  
46 (Inserm) "Plan Cancer" 2014-2019 program, Project: Microrobots Targeting Glioblastoma (MTG).

47 **Institutional Review Board Statement:** Not applicable.

48 **Informed Consent Statement:** Not applicable.

49 **Data Availability Statement:** The data presented in this study are available from the corresponding  
50 authors upon reasonable request.

51 **Conflicts of Interest:** The authors declare no conflict of interest.

#### 52 Abbreviations

53 The following abbreviations are used in this manuscript:

54	DOF	Degree of Freedom
55	EMA	Electromagnetic Actuation
	MIS	Minimally Invasive Surgery

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