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Electromagnetic Actuation Microrobotic Systems

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Abstract

Purpose of Review: this review presents different types of electromagnetic actuation (EMA) microrobotic systems that have been designed for various principles of magnetic microrobot locomotion for any given tasks.

Recent Findings: Many proposed EMA systems can be significantly improved in terms of performance including magnetic field and its gradient strength, size of the workspace, singularity of the magnetic control, energy consumption. . .

Summary: To manipulate untethered microrobots the EMA system has to be designed properly to provide sufficient propulsion with respect to application objectives. Great care must be taken in developing an efficient EMA setup, with sufficient degrees of freedom (DOF) and without singularity. Hence, the magnetic microrobotic system must be further investigated to be able to fully comprehend either their capabilities or limitations. Both specifications of the applications and the general design of EMA systems will be comprehensively discussed and analyzed in terms of requirements on the number of electromagnets used, the size of the workspace, the number of degrees of freedom for the locomotion, the manipulability of the control, the unexpected singularities, system stabilization, etc. Therefore, through the similar investigation in the characteristics of the application the suitable EMA microrobotic system can be designed with respect to the desired movement task with given type of the microrobot.

Keywords: Nanorobotics and Microrobotics; Magnetic Actuation System, Electromagnetic Manipulation, Medical Magnetic Microrobots

1 Introduction

Microrobotics has emerged as an attractive technology for developing innovative microsystems for many applications. In particular, in the biomedical field the ambition is to reduce significant trauma, provide more practical diagnostic tools and optimize the treatment experience. To achieve such goals, the actuation of the microrobots must

be fully investigated. Among the various actuation of techniques, untethered wireless control via magnetic sources is most considered [1–30]. Based on this, numerous electromagnetic actuation (EMA) systems have been developed for biomedical applications [6, 21, 29–57]. Commonly, either permanent magnets [6, 31–36] or electromagnets [21, 29, 30, 37–57] can be selected to produce the magnetic sources for the magnetic

manipulation. The main advantage of using permanent magnets is that it can generate a stronger magnetic field compared to equivalent electromagnets [32]. Also, the permanent magnets lead to a reduction of overheating and energy consumption. For instance, in [6] the authors have developed a robotic magnetic navigation system with permanent magnets to control a video capsule in the gastrointestinal tract. [33] have explored a 5 degrees-of-freedom (DOF) manipulator system to control a magnetic capsule endoscopy in fluid using a single permanent magnet. Amokrane *et al.*[36] have developed an EMA platform consisting of two permanent magnets. The proposed magnetic platform is allowed to control magnetic microrobot in the inner ear with good stability and robustness. Classically, permanent magnets are suitable for large-sized workspace thanks to their large magnetic field strength with respect to the volume ratio. However, there is one thing that should be noted. The magnetic field and gradient generated by the permanent magnet will always affect the workspace even it is not required [34]. It could bring uncontrollable factors in some medical surgery applications, which will cause potential surgical risks. Alternatively, the distribution of the electromagnetic field and its gradient produced by the electromagnet can be adjusted by changing the flowing current and placement [58, 59]. In order to strengthen the magnetic field of electromagnet and its magnetic gradient, electromagnet filled with a magnetic core (especially with a high magnetic permeability) is commonly proposed [38, 39, 60, 61]. It should be noted here that the induced magnetic field appears nonlinearly characteristics since the magnetic core guides and concentrates the electromagnetic field. The magnetic field is related to the current flowing through the electromagnetic coil and the filled magnetic core. Therefore, considering the controllability and flexibility of the magnetic field, we only discuss the EMA composed of electromagnetic coils in this review.

Commonly, the EMA microrobotic systems can be divided into systems that operate in a two-dimensional (2D) or a three-dimensional (3D) workspace. The dimensions of workspace depend on the geometry of the desired application, that is also decided by the objective of the application. When the dimensions of EMA system are chosen, the other four main elements should be

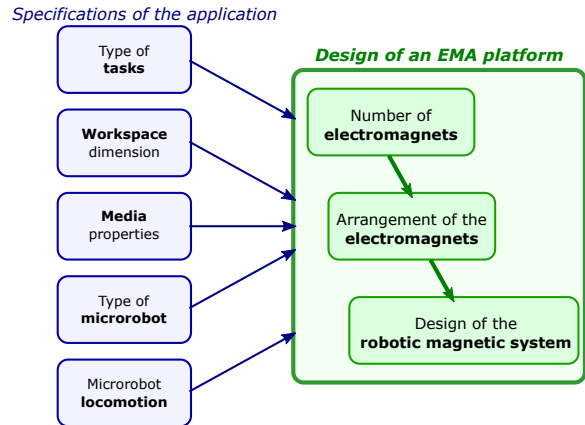


Fig. 1: Illustration of the design process of an EMA system.

also considered as reported in [58]. The fig. 1 illustrates the main design process of an EMA microrobotic system. From a given application, the specifications include the type of tasks, the dimension of workspace, the properties of media, the type of microrobot and the locomotion of microrobot. Then designers should consider the following questions:

- How many number of electromagnets should be used in the EMA setup?
- Which kind of electromagnet is suitable for generating the desired magnetic field and gradient?
- Which arrangement or configuration is most efficient for the motion control of the microrobot?
- How many degrees of mobility could be added, and how far the electromagnet can be moved in platform? etc.

The desired EMA microrobotic system can be designed properly when the number of electromagnetic coils, the size and shape of electromagnets, and arrangement of coils are determined. According to the investigation reported in [58], the relations between the specifications and the number of electromagnetic coils to design an EMA system can be proposed. In this paper, only the EMA systems with 3D workspace are discussed since the most of biomedical applications are required 3D manipulations. As depicted in fig. 2 different applied number of electromagnetic coils can be obtained to meet the different requirements.

First, the dimension of workspace is chosen to 3D. The classification of media depends on the characteristics of the activity space in which the microrobots move. Commonly, the media could have high viscosity, low viscosity or non-Newtonian fluid. Considering the flowing status, the media could be static or flowing. Obviously the high viscosity and flowing environment will carry a difficult condition for the microrobot manipulation. In contrast, low viscosity and static environment will lead to an easy operation for microrobot. Secondly, the type of applied microrobot must be selected that is affected by the property of media. The types of microrobots can be roughly divided into cylindrical, ellipsoidal, spherical, helical and irregular shape. A microrobot with a specific shape will have different types of movement and will perform different and more or less varied operative tasks. For instance, helical microrobots can be selected to move in flowing environment with high viscosity since it is able to perform drilling motion thanks to a rotating magnetic field. If the magnetic gradient is also applied to produce the magnetic force, the helical microrobot will be actuated by the stronger propulsion force. Besides, the cylindrical, ellipsoidal, spheroidal and irregularly shaped microrobot can be used in the suitable environments for diverse operating tasks. Four main types of potential tasks consisting of controllable structure, material removal, marking/sensing, and targeted therapy are considered [19]. For instance, marking/sensing needs precise navigation by translational movement, both cylindrical and spherical microrobots can reach this objective. However, when the potential movement requires a combination of translational and rotational motion, such as for material removal and targeted therapy, the helical microrobot should be the first choice. Thus, the type of motion should be considered with respect to the type of microrobot and the desired tasks. The types of motion are considered as rotation, navigation, pulling and punching, respectively. Lastly, the number of electromagnetic coils will be determined by the specific locomotion of the given microrobot. For example, in a 3D workspace, the reliable navigation of spheroidal microrobot requires at least $n = 5$ numbers of electromagnets since at least five magnetic gradients are needed; while the navigation of helical microrobot requires only

$n = 3$ numbers of electromagnets as manipulating the magnetic fields in the three axis direction are enough. Therefore, from the choice of the above five requirements, the specifications of EMA microrobotic systems can be analyzed thoroughly.

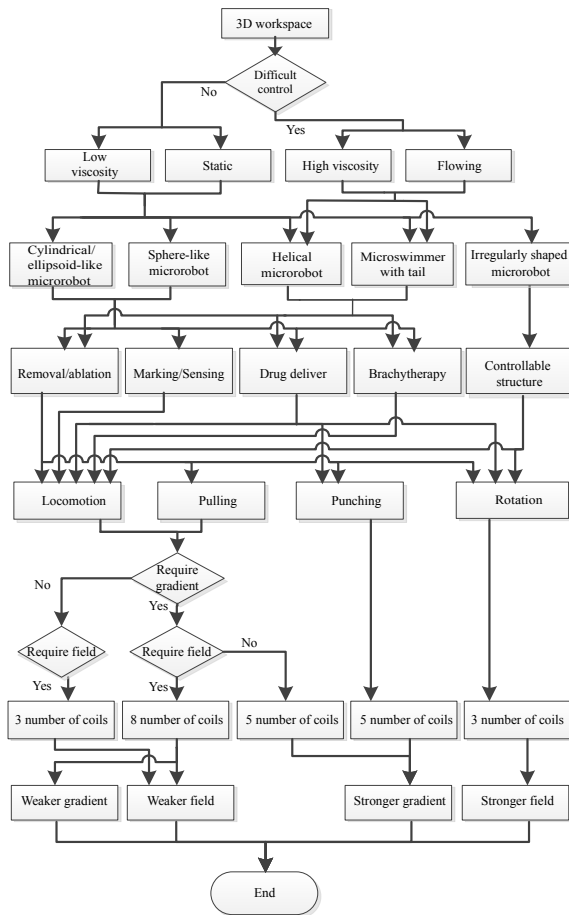


Fig. 2: The diagram of the specifications of EMA system design for 3D workspace.

2 Electromagnetic Actuation Setups

The EMA systems consisting of different number of electromagnets have been investigated by researchers for various applications, and especially for the biomedical field [6, 21, 29–57]. In this section, we will discuss the EMA platforms that enables precise and safer manipulations for the different microrobotic tasks. An excellent EMA

system should provide a higher degree of dexterity allowing a magnetic microrobot to navigate efficiently and reliably within a confined volume [61]. Therefore, the basic objective of the envisioned EMA setup must provide:

- the sufficient and adjustable magnetic actuation in any position and direction in the workspace, for any magnetic microrobot's location and orientation;
- a usable 3D workspace (e.g. about few cubic centimeters);
- a proper organization of electromagnets with enough versatility compared with the shape of applied human parts, such as head, limbs, shoulders, and so on.

With the above requirements, the arrangement of electromagnets will be designed. Indeed, on the one hand the magnetic actuation capabilities are related to the magnets source, and on the other hand the volume of the workspace is related to the placement of the electromagnets, hence both of them are affected intrinsically by the configuration of the electromagnets.

The electromagnetic coils should be placed as close to the workspace as possible to enable stronger field or gradient strength. In [62], the authors report some approximate reference values for the size of the workspace should provide on the different applications. The small EMA systems with a characteristic length of 50 mm are designed for *in vitro* applications and for small animals. The systems should consider a characteristic length of about 100 mm for small human body parts, such as the eyes. Whereas for the larger parts of the human body, such as the knee or abdomen, EMA systems will require a workspace with a characteristic length of about 400 mm. For instance, the OctoRob platform has been designed for intraocular MIS via the manipulation of the magnetic microrobot in a viscous fluid media enabling a 3D workspace of about $45\text{mm} \times 45\text{mm} \times 45\text{mm}$ [60]. The OctoRob platform is composed of eight coils: four mobile robotic arms to control the mobile electromagnets orientation and four stationary electromagnets. The OctoRob developed at the Laboratoire PRISME is represented in fig. 3b. From the fig. 2, the 8 electromagnetic coils are enough for generating magnetic fields and their gradients, and inducing magnetic torque and force. Thanks to the robotized arms, the OctoRob

can switch to a configuration like OctoMag[38] to a MiniMag configuration[39] by modifying the polar angles of the electromagnetic coils. Similar to OctoRob, both OctoMag and MiniMag are capable of providing up to 5 DOF (3 DOF in translation and 2 DOF in rotation) to control magnetically untethered microrobot. Since the number of electromagnetic coils is more than 5, the OctoMag and MiniMag is capable of pulling and punching control.

If a bigger workspace is required, the electromagnets could be set slightly away from workspace center. However, if the electromagnetic coil is placed too far away from the working area, the effective control of the corresponding EMA system will decrease significantly due to weak performance of the magnetic source. Thus, the choice of workspace size or the distance between the electromagnets should be balanced. Basically, it is difficult to induce a strong magnetic field or gradient in deep tissue. For the envisioned application, the boundary values of the generated magnetic field and gradient in the workspace should be investigated within various dispositions of electromagnets. One solution to this contradiction is to make the electromagnetic coils movable. Yang *et al.* [63] report a flexible EMA system composed of 3 mobile electromagnetic coils. The proposed DeltaMag system enables the parallel mechanism to actuate the three coils to realize large effective 3D workspace (diameter 280 mm and height 250 mm). The developed electromagnetic coil configuration has the ability to generate 3D arbitrary magnetic fields for its different poses in the workspace. Then DeltaMag can either control magnetic catheter or magnetic capsule or perform helical propulsion by rotating the magnetic field. As can be concluded from the fig. 2, three electromagnetic coils are required to produce the magnetic torque for the rotational motion.

In [64], authors design an EMA system called Advanced Robotics for Magnetic Manipulation (ARMM) with only single one mobile electromagnetic coil. This mobile electromagnetic coil approach allows for easy scaling of the actuation workspace, which depends on the range of designed robotic arm. As reported the ARMM system is capable of providing magnetic actuation within a spherical workspace with a radius of 1300 mm that is a quite larger space. Due to the limited payload of the applied robotic arm

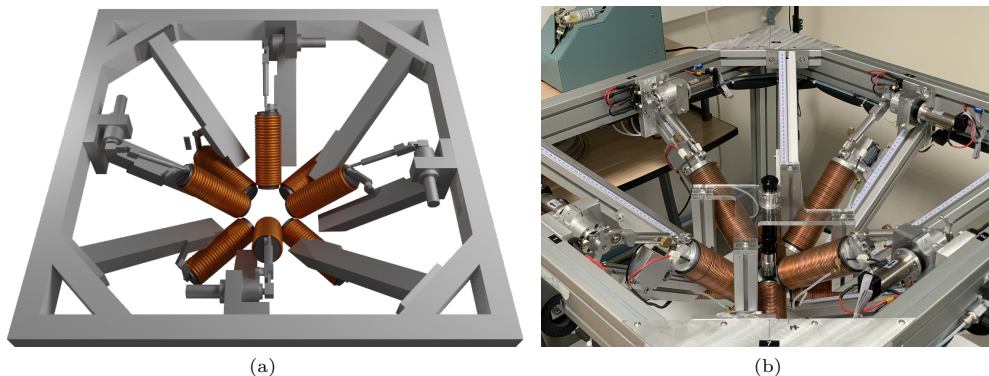


Fig. 3: OctoRob design. (a) CAD representation of the EMA platform and (b) experimental prototype named OctoRob.

employed in the ARMM system, they propose an optimization strategy to design the electromagnet generating the largest magnetic field possible under a heat dissipation constraint. Furthermore, a strategy to generate a prescribed magnetic field and its gradient has been proposed to the control system. Hence, the number of applied coil is not fixed or even can be further reduced when the coil is movable. The researchers have also proposed some EMA microrobotic system for the precise manipulation in small workspace, such as in [65], an EMA system consisting of six electromagnets are designed and the accuracy of the modeling of the desired force production at various positions within the $45\mu\text{m} \times 45\mu\text{m} \times 45\mu\text{m}$ cube has been evaluated. The proposed EMA system is actually utilized as a model system to study the mathematical relationship between the desired 3D magnetic force exerting on the magnetic particle and the six applied input currents.

3 Discussion

The electromagnetic actuation of magnetic microrobotic systems is designed to control microrobots with the ambition to be able to perform different types of tasks and operations. Commonly, different kinds of magnetic microrobots are manipulated in a workspace via the two following methods: i) rotating magnetic field to provide swimming motion, and ii) propelling by magnetic gradient directly. For the rotational motion, the generation of forward thrust is produced by a magnetic torque spinning an asymmetric structure such as

a helix. For translational movement, the magnetic gradient directly induces the net propulsive force on microrobots that can achieve the motion with desired translational DOF control. Besides EMA systems with core-filled electromagnets, EMA systems consisting of air-filled electromagnets have also been widely studied[30, 40–42, 44, 45, 51]. Uniform magnetic field is produced by Helmholtz coils pair and uniform saddle coils pair; while uniform gradient is induced by Maxwell coils pair and the gradient saddle coils pair with the different settings. Such electromagnetic coils pairs form the EMA system with different desired functions. The four stationary coils pairs, such as two pairs of Helmholtz coils and two pairs of Maxwell coils, are able to manipulate a magnetic microrobot in 2D workspace. The same function of control is also achieved by the saddle coils or combination of four different coils pairs with a proper configuration. If the electromagnetic coils are mobile, one rotating Helmholtz and one rotating Maxwell coils pairs are capable of contributing a 2D position and orientation control. Similarly, the two rotating saddle coils pairs are also able to provide the same control with an appropriate setting. When the workspace is expanded to the 3D as we discussed in this paper, more electromagnetic coils are required. If electromagnetic coils have a capability of rotation, the number of coils pair could be reduced. For instance, two pairs of Helmholtz coils and two pairs of Maxwell coils can actuate 3D locomotion of microrobot where one Helmholtz coils pair and one Maxwell coils pair are rotated along a same axis for rotating 2D manipulation

plane into 3D workspace. When an electromagnetic coil is used to generate both magnetic field and gradient by means of adjusting the current, the number of stationary coils pairs can be further reduced to three pairs. Furthermore, if the electromagnetic coil is movable, the number of coil even can down to only one. In addition, the number of electromagnetic coils also depends on the type of microrobots, the performed tasks and the desired locomotion. Therefore, the applied electromagnets can be placed in different orientations and positions concerning the given application to assemble different shapes of the active workspace.

4 Conclusion

The electromagnetic manipulation of microrobots and the various magnetic actuation systems have been investigated in this review. The magnetic locomotion of microrobots requires either the magnetic field or the spatial magnetic gradient. The different kinds of microrobots are suitable to realize the corresponding motion control. The magnetic manipulation is also affected by the placed environment. Thus, the given microrobot with its obtained motion can perform the desired tasks in the applied media. When the above specification of the application are clear, the design parameters of EMA system including the number of electromagnetic coils, arrangement of the electromagnets and the needed external device can be investigated and determined easily and explicitly. Such as, the spheroidal shape microrobot can be actuated by magnetic force to reach navigation in 3D workspace for sensing or targeted therapy tasks via an EMA system consisting of at least 5 number of electromagnets. The helical shape microrobot is able to implement material removal task in 3D workspace by its rotational motion through an EMA system with at least 3 number of electromagnets. When more factors such as mobility of electromagnets are involved, the design parameters of the EMA system can be further changed. Therefore, the EMA microrobotic system can manipulate magnetic microrobot efficiently for the desired tasks when suitable magnetic actuation system has been chosen. The suitable EMA microrobotic system can select properly only when the specifications of the applied application have been thoroughly investigated.

Declarations

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- Authors’ contributions: Writing—original draft, R.C. and D.F.; Writing—review and editing, R.C., D.F.; All authors have read and agreed to the published version of the manuscript.

References

- [1] Honda, T., Arai, K., Ishiyama, K.: Micro swimming mechanisms propelled by external magnetic fields. *IEEE Trans. Magn.* **32**(5), 5085–5087 (1996)
- [2] Abbott, J.J., Peyer, K.E., Lagomarsino, M.C., Zhang, L., Dong, L., Kaliakatsos, I.K., Nelson, B.J.: How should microrobots swim? *The international journal of Robotics Research* **28**(11-12), 1434–1447 (2009)
- [3] Alapan, Y., Yasa, O., Schauer, O., Giltinan, J., Tabak, A.F., Sourjik, V., Sitti, M.: Soft erythrocyte-based bacterial microswimmers for cargo delivery. *Science Robotics* **3**(17), 4423 (2018)
- [4] Barbot, A., Decanini, D., Hwang, G.: The rotation of microrobot simplifies 3d control inside microchannels. *Scientific reports* **8**(1), 438 (2018)
- [5] Carlsen, R.W., Edwards, M.R., Zhuang, J., Pacoret, C., Sitti, M.: Magnetic steering control of multi-cellular bio-hybrid microswimmers. *Lab on a Chip* **14**(19),

- 3850–3859 (2014). <https://doi.org/10.1039/C4LC00707G>
- [6] Carpi, F., Kastelein, N., Talcott, M., Pappono, C.: Magnetically controllable gastrointestinal steering of video capsules. *IEEE Trans. Biomed. Eng.* **58**(2), 231–234 (2011)
- [7] Diller, E., Sitti, M., *et al.*: Micro-scale mobile robotics. *Foundations and Trends® in Robotics* **2**(3), 143–259 (2013)
- [8] Ghosh, A., Fischer, P.: Controlled propulsion of artificial magnetic nanostructured propellers. *Nano letters* **9**(6), 2243–2245 (2009)
- [9] Hosney, A., Abdalla, J., Amin, I.S., Hamdi, N., Khalil, I.S.: In vitro validation of clearing clogged vessels using microrobots. In: *IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, pp. 272–277 (2016). *IEEE*
- [10] Ceylan, H., Giltinan, J., Kozielski, K., Sitti, M.: Mobile microrobots for bioengineering applications. *Lab on a Chip* **17**(10), 1705–1724 (2017). <https://doi.org/10.1039/C7LC00064B>
- [11] Jeon, S., Kim, S., Ha, S., Lee, S., Kim, E., Kim, S.Y., Park, S.H., Jeon, J.H., Kim, S.W., Moon, C., Nelson, B.J., Kim, J.-y., Yu, S.-W., Choi, H.: Magnetically actuated microrobots as a platform for stem cell transplantation. *Science Robotics* **4**(30), 4317 (2019). <https://doi.org/10.1126/scirobotics.aav4317>
- [12] Kim, S., Qiu, F., Kim, S., Ghanbari, A., Moon, C., Zhang, L., Nelson, B.J., Choi, H.: Fabrication and characterization of magnetic microrobots for three-dimensional cell culture and targeted transportation. *Advanced Materials* **25**(41), 5863–5868 (2013)
- [13] Du Nguyen, V., Le, V.H., Zheng, S., Han, J., Park, J.-O.: Preparation of tumor targeting cell-based microrobots carrying nir light sensitive therapeutics manipulated by electromagnetic actuating system and chemotaxis. *Journal of Micro-Bio Robotics* **14**(3-4), 69–77 (2018)
- [14] Lee, S., Lee, S., Kim, S., Yoon, C.-H., Park, H.-J., Kim, J.-y., Choi, H.: Fabrication and characterization of a magnetic drilling actuator for navigation in a three-dimensional phantom vascular network. *Scientific reports* **8**(1), 3691 (2018)
- [15] Li, J., de Ávila, B.E.-F., Gao, W., Zhang, L., Wang, J.: Micro/nanorobots for biomedicine: Delivery, surgery, sensing, and detoxification. *Sci. Robot* **2**(4) (2017)
- [16] Li, J., Li, X., Luo, T., Wang, R., Liu, C., Chen, S., Li, D., Yue, J., Cheng, S.-h., Sun, D.: Development of a magnetic microrobot for carrying and delivering targeted cells. *Sci. Robot* **3**(19) (2018)
- [17] Martel, S.: Microrobotics in the vascular network: present status and next challenges. *Journal of Micro-Bio Robotics* **8**(1), 41–52 (2013)
- [18] Mitchell, B., Koo, J., Iordachita, I., Kazanzides, P., Kapoor, A., Handa, J., Hager, G., Taylor, R.: Development and application of a new steady-hand manipulator for retinal surgery. In: *IEEE Int. Conf. on Robotics and Automation (ICRA)*, pp. 623–629 (2007). *IEEE*
- [19] Nelson, B.J., Kaliakatsos, I.K., Abbott, J.J.: Microrobots for minimally invasive medicine. *Annual review of biomedical engineering* **12**, 55–85 (2010)
- [20] Palagi, S., Fischer, P.: Bioinspired microrobots. *Nature Reviews Materials*, 1 (2018)
- [21] Park, S., Cha, K., Park, J.: Development of biomedical microrobot for intravascular therapy. *International Journal of Advanced Robotic Systems* **7**(1), 1 (2010)
- [22] Peyer, K.E., Zhang, L., Nelson, B.J.: Bioinspired magnetic swimming microrobots for biomedical applications. *Nanoscale* **5**(4), 1259–1272 (2013)
- [23] Qiu, F., Nelson, B.J.: Magnetic helical micro-and nanorobots: Toward their biomedical applications. *Engineering* **1**(1), 021–026

(2015)

- [24] Schürle, S., Kratochvil, B.E., Pané, S., Zeehan, M.A., Nelson, B.J.: Generating magnetic fields for controlling nanorobots in medical applications. In: *Nanorobotics*, pp. 275–299. Springer, ??? (2013)
- [25] Sitti, M.: Miniature devices: Voyage of the microrobots. *Nature* **458**(7242), 1121 (2009)
- [26] Sitti, M., Ceylan, H., Hu, W., Giltinan, J., Turan, M., Yim, S., Diller, E.D.: Biomedical applications of untethered mobile milli/microrobots. *Proceedings of the IEEE* **103**(2), 205–224 (2015)
- [27] Xie, H., Sun, M., Fan, X., Lin, Z., Chen, W., Wang, L., Dong, L., He, Q.: Reconfigurable magnetic microrobot swarm: Multimode transformation, locomotion, and manipulation. *Science Robotics* **4**(28), 8006 (2019). <https://doi.org/10.1126/scirobotics.aav8006>
- [28] Yang, G.-Z., Bellingham, J., Dupont, P.E., Fischer, P., Floridi, L., Full, R., Jacobstein, N., Kumar, V., McNutt, M., Merrifield, R., *et al.*: The grand challenges of science robotics. *Science Robotics* **3**(14), 7650 (2018)
- [29] Yesin, K.B., Exner, P., Vollmers, K., Nelson, B.J.: Design and control of in-vivo magnetic microrobots. In: *International Conference on Medical Image Computing and Computer-Assisted Intervention*, pp. 819–826 (2005). Springer International Publishing
- [30] Yesin, K.B., Vollmers, K., Nelson, B.J.: Modeling and control of untethered biomicrobots in a fluidic environment using electromagnetic fields. *The International Journal of Robotics Research* **25**(5-6), 527–536 (2006)
- [31] Fountain, T.W., Kailat, P.V., Abbott, J.J.: Wireless control of magnetic helical microrobots using a rotating-permanent-magnet manipulator. In: *IEEE Int. Conf. on Robotics and Automation (ICRA)*, pp. 576–581 (2010). IEEE
- [32] Torres, N.A., Ruggeri, S., Popa, D.O.: Untethered microrobots actuated with focused permanent magnet field. In: *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, pp. 004–0902400409024 (2014). American Society of Mechanical Engineers
- [33] Mahoney, A.W., Abbott, J.J.: Five-degree-of-freedom manipulation of an untethered magnetic device in fluid using a single permanent magnet with application in stomach capsule endoscopy. *The International Journal of Robotics Research* **35**(1-3), 129–147 (2016)
- [34] Lucarini, G., Ciuti, G., Mura, M., Rizzo, R., Menciassi, A.: A new concept for magnetic capsule colonoscopy based on an electromagnetic system. *International Journal of Advanced Robotic Systems* **12**(3), 25 (2015)
- [35] Ryan, P., Diller, E.: Magnetic actuation for full dexterity microrobotic control using rotating permanent magnets. *IEEE Trans. Robot.* **33**(6), 1398–1409 (2017)
- [36] Amokrane, W., Belharet, K., Souissi, M., Grayeli, A.B., Ferreira, A.: Macro-micromanipulation platform for inner ear drug delivery. *Robotics and Autonomous Systems* **107**, 10–19 (2018)
- [37] Martel, S., Mathieu, J.-B., Felfoul, O., Chanu, A., Aboussouan, E., Tamaz, S., Pouponneau, P., Yahia, L., Beaudoin, G., Soulez, G., *et al.*: Automatic navigation of an untethered device in the artery of a living animal using a conventional clinical magnetic resonance imaging system. *Applied physics letters* **90**(11), 114105 (2007)
- [38] Kummer, M.P., Abbott, J.J., Kratochvil, B.E., Borer, R., Sengul, A., Nelson, B.J.: Octomag: An electromagnetic system for 5-dof wireless micromanipulation. *IEEE Trans. Robot.* **26**(6), 1006–1017 (2010)
- [39] Kratochvil, B.E., Kummer, M.P., Erni, S., Borer, R., Frutiger, D.R., Schürle, S., Nelson, B.J.: Minimag: a hemispherical electromagnetic system for 5-dof wireless micromanipulation. In: *Experimental Robotics*, pp.

- 317–329 (2014). Springer International Publishing
- [40] Jeong, S., Choi, H., Choi, J., Yu, C., Park, J.-o., Park, S.: Novel electromagnetic actuation (EMA) method for 3-dimensional locomotion of intravascular microrobot. *Sensors and Actuators A: Physical* **157**(1), 118–125 (2010)
- [41] Jeon, S., Jang, G., Choi, H., Park, S.: Magnetic navigation system with gradient and uniform saddle coils for the wireless manipulation of micro-robots in human blood vessels. *IEEE Trans. Magn.* **46**(6), 1943–1946 (2010)
- [42] Jeon, S., Jang, G., Choi, H., Park, S., Park, J.: Magnetic navigation system for the precise helical and translational motions of a microrobot in human blood vessels. *Journal of Applied Physics* **111**(7), 07–702 (2012)
- [43] Choi, H., Choi, J., Jeong, S., Yu, C., Park, J.-o., Park, S.: Two-dimensional locomotion of a microrobot with a novel stationary electromagnetic actuation system. *Smart Materials and Structures* **18**(11), 115017 (2009)
- [44] Choi, H., Choi, J., Jang, G., Park, J.-o., Park, S.: Two-dimensional actuation of a microrobot with a stationary two-pair coil system. *Smart Materials and Structures* **18**(5), 055007 (2009)
- [45] Choi, H., Cha, K., Choi, J., Jeong, S., Jeon, S., Jang, G., Park, J.-o., Park, S.: EMA system with gradient and uniform saddle coils for 3D locomotion of microrobot. *Sensors and Actuators A: Physical* **163**(1), 410–417 (2010)
- [46] Choi, H., Park, J.-O., Park, S.: 6. Electromagnetic Actuated Micro- and Nanorobots, pp. 113–135 (2018). https://doi.org/10.1142/9789813232280_0006
- [47] Go, G., Choi, H., Jeong, S., Lee, C., Ko, S.Y., Park, J.-O., Park, S.: Electromagnetic navigation system using simple coil structure (4 coils) for 3-d locomotive microrobot. *IEEE Trans. Magn.* **51**(4), 1–7 (2015)
- [48] Schuerle, S., Erni, S., Flink, M., Kratochvil, B.E., Nelson, B.J.: Three-dimensional magnetic manipulation of micro-and nanostructures for applications in life sciences. *IEEE Trans. Magn.* **49**(1), 321–330 (2013). <https://doi.org/10.1109/TMAG.2012.2224693>
- [49] Diller, E., Giltinan, J., Jena, P., Sitti, M.: Three dimensional independent control of multiple magnetic microrobots. In: *IEEE Int. Conf. on Robotics and Automation (ICRA)*, pp. 2576–2581 (2013). IEEE
- [50] Diller, E., Giltinan, J., Lum, G.Z., Ye, Z., Sitti, M.: Six-degree-of-freedom magnetic actuation for wireless microrobotics. *The International Journal of Robotics Research* **35**(1-3), 114–128 (2016)
- [51] Dadkhah, M., Kumar, N., Yoon, J.: Design and simulation of a 3d actuation system for magnetic nano-particles delivery system. In: *International Conference on Intelligent Robotics and Applications*, pp. 177–187 (2013). Springer International Publishing
- [52] Fu, Q., Guo, S., Huang, Q., Hirata, H., Ishihara, H.: Development and evaluation of novel magnetic actuated microrobot with spiral motion using electromagnetic actuation system. *Journal of Medical and Biological Engineering* **36**(4), 506–514 (2016)
- [53] Tehrani, M.D., Kim, M.O., Yoon, J.: A novel electromagnetic actuation system for magnetic nanoparticle guidance in blood vessels. *IEEE Trans. Magn.* **50**(7), 1–12 (2014)
- [54] Yu, C., Kim, J., Choi, H., Choi, J., Jeong, S., Cha, K., Park, J.-o., Park, S.: Novel electromagnetic actuation system for three-dimensional locomotion and drilling of intravascular microrobot. *Sensors and Actuators A: Physical* **161**(1-2), 297–304 (2010)
- [55] Abbott, J.J., Diller, E., Petruska, A.J.: Magnetic methods in robotics. *Annual Review of Control, Robotics, and Autonomous Systems* **3** (2015)
- [56] Choi, H., Cha, K., Jeong, S., Park, J.-o.,

- Park, S.: 3-d locomotive and drilling micro-robot using novel stationary EMA system. *IEEE/ASME Trans. Mechatronics* **18**(3), 1221–1225 (2012)
- [57] Go, G., Choi, H., Jeong, S., Lee, C., Park, B.J., Ko, S.Y., Park, J.-O., Park, S.: Position-based magnetic field control for an electromagnetic actuated microrobot system. *Sensors and Actuators A: Physical* **205**, 215–223 (2014)
- [58] * Chen, R., Folio, D., Ferreira, A.: Analysis and comparison of electromagnetic micro-robotic platforms for biomedical applications. *Applied Sciences* **12**(1), 456 (2022). This report a detailed comparison of EMA platforms for biomedical applications.
- [59] * Chen, R., Folio, D., Ferreira, A.: Mathematical approach for the design configuration of magnetic system with multiple electromagnets. *Robotics and Autonomous Systems* **135**, 103674 (2021). This study provides an in-depth analysis of the performance of an EMA system in different configurations.
- [60] Chen, R., Folio, D., Ferreira, A.: Study of robotized electromagnetic actuation system for magnetic microrobots devoted to minimally invasive ophthalmic surgery. In: *International Symposium on Medical Robotics (ISMR)*, pp. 1–7 (2019). IEEE
- [61] Chen, R., Folio, D., Ferreira, A.: Performance metrics for a robotic actuation system using static and mobile electromagnets. In: *2019 International Conference on Robotics and Automation (ICRA)*, pp. 2474–2480 (2019). IEEE
- [62] Erni, S., Schürle, S., Fakhraee, A., Kratochvil, B.E., Nelson, B.J.: Comparison, optimization, and limitations of magnetic manipulation systems. *Journal of Micro-Bio Robotics* **8**(3-4), 107–120 (2013)
- [63] * Yang, L., Du, X., Yu, E., Jin, D., Zhang, L.: Deltamag: An electromagnetic manipulation system with parallel mobile coils. In: *Int. Conf. on Robotics and Automation (ICRA)*, pp. 9814–9820 (2019). IEEE
- This report a parallel EMA platform for large workspace.
- [64] Sikorski, J., Heunis, C.M., Franco, F., Misra, S.: The armm system: An optimized mobile electromagnetic coil for non-linear actuation of flexible surgical instruments. *IEEE transactions on magnetics* **55**(9), 1–9 (2019)
- [65] Long, F., Cheng, P., Meng, T.-M., Menq, C.-H.: Optimal current allocation rendering 3-d magnetic force production in hexapole electromagnetic actuation. *IEEE/ASME Transactions on Mechatronics* **26**(5), 2408–2417 (2020)