Advances in Precision Control of Magnetic Microrobots

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Abstract. Magnetic actuated systems promise great commercial applications. For instance, it can be used to precisely control the targeted drug delivery and minimally invasive medical applications. In this paper, we have summarized recent advances in the field of control and path planning of magnetic microrobots. We have investigated the main differences between approaches, materials, trajectories, control methods and the main features of each research paper.

1. Introduction
The study of magnetic microrobots dates back to 3 decades [1]. The research gained special attention due to the potential usage in drug delivery industry [2-9] as well as medical applications such as MRI-scanners [10-16]. Multiple publications documented the progress of magnetic microrobots [17-22]. Nevertheless, there is no recent review focused on development of control strategies applied in microrobots for path following. Figure 1 describes the progress of magnetic microrobots experimental research in the last ten years based on our data. It shows the number of publications including the phrase “magnetic microrobot” in its title. The statistics we got is closely matching an analysis by ISI web of knowledge®, reported in March 2019, when searched by the same phrase.

![Distribution of scientific papers (reported in this review) in the last ten years.](image)

In this survey, we will concentrate on research developed on experimental setups for magnetic microrobots controlling and tracking. The paper is organized as follows: section II provides a background of magnetic actuation and past contributions in the topic. Section III presents information...
on magnetic robot’s specifications, size, geometry, material, magnetic device configuration and the working medium. Section IV offers samples of trajectories designed in literature for magnetized microrobots to follow. Section V discusses the control methods applied to stabilize the magnetic robots, reject disturbances and follow the desired trajectory. Section VI covers the conclusion and provides recommendations for future studies.

2. Background
Magnetic field is a popular actuation method for microrobots due to its high actuation force, compact system size, and low hardware cost. Microrobots are made of permanent magnetic, ferromagnetic, or paramagnetic material. Any magnetized robot will experience a torque and a force due to the electromagnetic field that can be described as follows:

\[ F_m = V_r (\nabla \cdot \mathbf{M}) \mathbf{B}(x, y, z) \]  

\[ T_m = V_r \mathbf{M} \times \mathbf{B}(x, y, z) \]

\( F_m \) and \( T_m \) are the force and torque experienced by the robot, \( V_r \) is the volume of the robot, \( \mathbf{M} \) is the magnetization of the robot, and \( \mathbf{B} \) is the magnetic potential produced by the electromagnetic field. By controlling the magnetic field, the dynamics of the microrobot can be controlled to realize autonomous navigation. Significant body of simulation and experimental research work have been invested in the field [23]. Navigation in high viscous fluids under pulsatile flow was studied [24]. Additionally, controlling multi-agent independent microrobots [15,25-28] who share a global driving magnetic signal is another complex field that has been investigated.

3. Microrobot Specifications
By far the most reported geometry for the microrobots is the sphere. It has a diameter range between \( 20 \) – \( 600 \) \( \mu m \). Additionally, cuboid and cylindrical microrobot were reported. Table 1 shows geometry, dimensions, and materials of the microrobots. It is worthwhile noting that all dimensions listed in Table 1 are in micrometer. The sole article we found that reported millimeter size robots is article [29] (almost 50 times bigger than a typical microrobot).

| Ref. | material          | Shape    | dimension | Ref. | material        | shape    | dimension       |
|------|-------------------|----------|-----------|------|-----------------|----------|-----------------|
| [24] | neodymium-iron-boron | spherical | \( r = 250 \mu m \) | [34] | Polymer (SU-8)+CoNi | cuboid | 50 x 60 x 300 \( \mu m \) |
| [30] | NdFeB N35         | spherical | \( r = 257 \mu m \) | [35] | neodymium-iron-boron | spherical | \( r = 250 – 300 \mu m \) |
| [31] | Fe3O4             | spherical | \( r = 100 \mu m \) | [36] | Polymer (BJB M-3184) | spherical | \( r = 10 \mu m \) |
| [32] | Fe3O4             | spherical | \( r = 15 \mu m \) | [37] |                  |          |                 |
| [30] | NdFeB             | cylindrical | \( r = 15.87 mm \) \( h = 31.75 mm \) | [28] |                |          | \( r = 250 \mu m \) |
| [33] | NdFeB+PDMS        | cylindrical | \( r = 300 \mu m \) \( h = 200 \mu m \) | |                |          |                 |
The position of the electromagnets of a system in space has a large influence on the reachable magnetic fields and gradients in certain orientations [38]. Additionally, the medium surrounding the microrobot has an effect on systems performance. Researchers tried to use interfaces and solutions with properties closed to the blood viscosity and density, since most suggested applications of magnetic microrobots are in the medical field. Table 2 shows some water solutions used as a working medium.

### Table 2. Working medium of the microrobots

| Ref. | Coils configuration | Medium                  | Magnetic field strength | Ref. | Coils configuration | Medium                          | Magnetic field strength |
|------|---------------------|-------------------------|-------------------------|------|---------------------|---------------------------------|-------------------------|
| [24] | 3 Maxwell + 1 Helmholtz | water + glycerol        | 300 – 350 mT            | [35] | MiniMag             | ultra-sonicated ethanol+water   | 20 mT                   |
| [30] | 3 Maxwell + 1 Helmholtz | glycerine-water solution | 300 mT                 | [36] | 3 Maxwell + 1 Helmholtz | water + glycerol                | 30 mT                   |
| [31] | OctoMag             | poly d,L-lactic acid+water | 100 mT                 | [28] | Helmhotz            | water-oil                       | 15 mT                   |
| [39] | OmniMagnet          | water                   | 1.5 mT                 | [40] | 3 Maxwell + 1 Helmholtz | water + glycerol                | 40 mT                   |

### 4. Trajectories

The studied literature has a wide range of selected trajectories designed for the magnetic microrobot’s motion. Some authors considered the two-dimensional motion of the magnetic microrobots [41-44], while others generalized to the three-dimensional motion [45-51]. In reality, paths of the robot can be blocked, thus many researches studied online path planning and designed obstacle avoidance algorithms.

Figure 2 shows five open-loop linear trajectories [24, 29, 30-31, 33-35 and 52]. Figure 3 shows four closed-loop trajectories (30, 32 and 33)).

![Figure 2. Open-loop linear trajectories](image1.png)

![Figure 3. Closed-loop trajectories](image2.png)
Figure 4 shows three trajectories with combination of both linear and curved segments [53], [33], and a circular trajectory with obstacle avoiding [35]. Figure 5 shows two trajectories in three dimensions, a 3D helical trajectory [37] and a 3D cubic trajectory [39].

Figure 4. Linear and curved segments trajectories

Figure 5. Three dimensions trajectories

5. Control Strategy

Open-loop controllers are sometimes used to control motion of magnetic microrobots [36]. More commonly, feedback controllers were widely used to precisely control magnetic microrobots under complex environment and subject to variability. Complexity of controlling magnetic microrobots increases exponentially with the degrees of freedom of the system [18, 54-59].

[60] applied a proportional plus integral controller to drive the magnetic field to follow a specified trajectory. [52] applied a proportional derivative controller for tracking position and velocity of the microjet. [34] applied a proportional derivative controller and a force observer for disturbance compensation of the microrobot motion. [61] used a proportional derivative (PD) controller with a Disturbance Observer (DOB) to accurately track the position command and compensate for non-predicted disturbances. They also applied Kalman filter for noise rejection. [28] applied a proportional controller to control the 2D motion of small scale (mm sized) identical magnetic microrobots in close proximity to each other. The research studied different control inputs based on the tracking method, whether to track a desired radial or transverse distances, or angels between the two reports.

[24] used generalized predictive controller (GPC). It is sufficiently robust against nonlinear model uncertainties (e.g. drag force and viscosity), external perturbations (systolic pulsatile flow) and noisy trajectory tracking measurements. In GPC scheme design the system is usually modeled using the model Controlled Auto-Regressive Integrated Moving-Average (CARIMA). [35] Designed a model predictive controller (MPC) on a linearized model, to perform the task of trajectory tracking and obstacle avoidance. [40] proposed a linear quadratic integral (LQI) controller to demonstrate the optimal stabilization of a desired positions of two magnetic microrobots navigating in a microfluidic channel.

[30] developed a control law for the nonlinear model using an adaptive back-stepping control approach, coupled with a high gain observer. [32] designed a controller based on the theory of input-to-state stability and recursive application of back-stepping to drive the micro particle to follow successfully the desired trajectory. [53] designed a model-free extended state observer (ESO) based trajectory tracking control scheme for two magnetic microrobots. [29] designed a kinematic controller.
as well as a trajectory generation technique that takes the non-holonomic constraint of the robot into account. It was a model-free approach based on visual feedback of the micro object.

[31] developed a two-loops control system. The inner loop estimates the disturbance force and provides a compensating control input based on the disturbance force observer, while the outer loop achieves stability of the overall magnetic system through a proportional derivative controller. [37] compared three control techniques for trajectory tracking. First, input-to-state stability (ISS) based controller, second, high-gain observer-based controller, and compared both of them with a traditional PID controller.

[33] proposed a control algorithm to control a microrobot with an electromagnetic manipulation system. The microrobot performs a point-by-point path-tracking motion. With the control algorithm and the visual feedback, the driving force is reducing when the microrobot is nearing a target point. The tracking path was separated to several segments with target points. The moving speed was controlled to reduce to zero when the microrobot arrives at every target point.

6. Conclusion
In this article, we have provided a categorical summary of published articles in the field of magnetic microrobots. Size of the application, trajectory type as well as control scheme were the categories we used. The different types of controllers applied in literature performed a fairly acceptable tracking, in spite of complexity of the reference trajectory. The position error was always less than half of the microrobot size.

The geometry of microrobots under study was mostly spherical, with a maximum radius of $300 \mu m$. Manipulation of this very small size needed a magnetic field strength around $300 \text{ mT}$, which indicates the proportional relation between size of the microrobot and the strength of the applied magnetic field. Scaling the robots poses a challenge related to magnetic coil limitations. When coil dimension increases, it will be subjected to an excessive heating, which requires a proper cooling system.

In order to simulate the magnetic microrobots applications, the workspace of most mentioned articles was manipulated in liquid environments. These have viscosity and density similar to blood. In liquid mediums, drag force reduces the velocity of the magnetic microrobots, therefore, attention should be taken to overcome this loss of speed.

Based on success and development of magnetic microrobots, it has a great potential for many medical, biological and industrial applications. They have a very small sizes, low weight, and they are able to perform tasks accurately in complex environments. Scaling them to bigger applications is still a challenge.

7. References
[1] T. Honda, K. I. Arai, and K. Ishiyama, “Micro Swimming Mechanisms Propelled by External Magnetic Fields,” IEEE Trans. Magn., vol. 12, no. 5, pp. 5085–5087, 1996.

[2] S. T. T. A, F. Mishima, S. Fujimoto, Y. Izumi, and S. Nishijima, “Development of magnetically targeted drug delivery system using superconducting magnet,” J. Magn. Magn. Mater., vol. 311, pp. 367–371, 2007.

[3] M. S. Sakar, E. B. Steager, A. Cowley, V. Kumar, and G. J. Pappas, “Wireless Manipulation of Single Cells using Magnetic Microtransporters,” 2011 IEEE Int. Conf. Robot. Autom., pp. 2668–2673, 2011.

[4] I. S. M. Khalil, M. P. Pichel, L. Abelmann, and S. Misra, “Closed-loop control of magnetotactic bacteria,” Int. J. Rob. Res., vol. 32, no. 6, pp. 637–649, 2013.

[5] I. S. M. Khalil, V. Magdanz, S. Sanchez, O. G. Schmidt, L. Abelmann, and S. Misra, “Magnetic Control of Potential Microrobotic Drug Delivery Systems: Nanoparticles, Magnetotactic Bacteria and Self-Propelled Microjets,” 35th Annu. Int. Conf. IEEE Eng. Med.
[6] M. Sitti, H. Ceylan, W. Hu, J. Giltinan, M. Turan, Y. Sehyuk, and E. Diller, “Biomedical Applications of Untethered Mobile Milli/Microrobots,” Proc. IEEE, vol. 103, pp. 205–224, 2015.

[7] S. M. Jeon, G. H. Jang, H. C. Choi, S. H. Park, and J. O. Park, “Utilization of Magnetic Gradients in a Magnetic Navigation System for the Translational Motion of a Micro-Robot in Human Blood Vessels,” IEEE Trans. Magn., vol. 47, no. 10, pp. 2403–2406, 2011.

[8] P. Vartholomeos and C. Mavroidis, “In Silico Studies of Magnetic Microparticle Aggregations in Fluid Environments for MRI-Guided Drug Delivery,” IEEE Trans. Biomed. Eng., vol. 59, no. 1, pp. 3028–3038, 2012.

[9] C. Chen, L. Chen, P. Wang, L. Wu, and T. Song, “Steering of magnetotactic bacterial microbots by focusing magnetic field for targeted pathogen killing,” J. Magn. Magn. Mater., vol. 479, no. 6, pp. 74–83, 2019.

[10] J. Mathieu, G. Beaudoin, and S. Martel, “Method of Propulsion of a Ferromagnetic Core in the Cardiovascular System Through Magnetic Gradients Generated by an MRI System,” IEEE Trans. Biomed. Eng., vol. 53, no. 2, pp. 292–299, 2006.

[11] L. Arcese, M. Fruchard, F. Beyeler, A. Ferreira, and B. J. Nelson, “Adaptive backstepping and MEMS force sensor for an MRI-guided microrobot in the vasculature,” 2011 IEEE Int. Conf. Robot. Autom., pp. 4121–4126, 2011.

[12] J. Mathieu and S. Martel, “Steering of Aggregating Magnetic Microparticles Using Propulsion Gradients Coils in an MRI Scanner,” Magn. Reson. Med., vol. 1345, pp. 1336–1345, 2010.

[13] J. Mathieu and S. Martel, “Magnetic Steering of Iron Oxide Microparticles Using Propulsion Gradient Coils in MRI,” 2006 Int. Conf. IEEE Eng. Med. Biol. Soc., pp. 472–475, 2006.

[14] K. Belharet, D. Folio, and A. Ferreira, “Endovascular Navigation of a Ferromagnetic Microrobot Using MRI-based Predictive Control,” 2010 IEEE/RSJ Int. Conf. Intell. Robot. Syst., pp. 2804–2809, 2010.

[15] A. Eqtami, O. Felfoul, and P. E. Dupont, “MRI-powered Closed-loop Control for Multiple Magnetic Capsules,” 2014 IEEE/RSJ Int. Conf. Intell. Robot. Syst. (IROS 2014), no. Iros, pp. 3536–3542, 2014.

[16] S. Tamaz, R. Gourdeau, A. Chanu, and J. Mathieu, “Real-Time MRI-Based Control of a Ferromagnetic Core for Endovascular Navigation,” IEEE Trans. Biomed. Eng., vol. 55, no. 7, pp. 1854–1863, 2008.

[17] S. Chowdhury, W. Jing, and D. J. Cappelleri, “Controlling multiple microrobots: recent progress and future challenges,” J. Micro-Bio Robot., pp. 1–11, 2015.

[18] S. Boucheboub, A. Bolopion, and J. A. S. Régnier, “An overview of multiple DoF magnetic actuated micro-robots,” J. Micro-Nano Mechatronics, pp. 97–113, 2012.

[19] M. Arruebo, R. Fernández-pacheco, M. R. Ibarra, and J. Santamaria, “Magnetic nanoparticles for drug delivery,” Drug Dev. Res., vol. 2, no. 3, pp. 22–32, 2007.

[20] B. J. Nelson, I. K. Kaliakatsos, and J. J. Abbott, “Microrobots for Minimally Invasive Medicine,” Annu. Rev. Biomed. Eng., pp. 55–85, 2010.

[21] T. Xu, J. Yu, X. Yan, H. Choi, and L. Zhang, “Magnetic Actuation Based Motion Control for Microrobots: An Overview,” Micromachines, pp. 1346–1364, 2015.

[22] Y. Jia, Z. Chuang, W. Xiao-dong, W. Wexue, X. Ning, and L. Lian-Qing, “Development of micro- and nanorobotics: A review,” Sci. CHINA Technol. Sci., vol. 62, no. 1, pp. 1–20, 2019.

[23] L. Sadelli, M. Fruchard, and A. Ferreira, “2D Observer-Based Control of a Vascular Microrobot,” IEEE Trans. Automat. Contr., vol. 62, no. 5, pp. 2194–2206, 2017.

[24] K. Belharet, D. Folio, and A. Ferreira, “Control of a Magnetic Microrobot Navigating in Microfluidic Arterial Bifurcations through Pulsatile and Viscous Flow,” 2012 IEEE/RSJ Int. Conf. Intell. Robot. Syst., vol. 1, pp. 2559–2564, 2012.

[25] D. R. Frutiger, K. Vollmers, B. E. Kratochvil, and B. J. Nelson, “Small , Fast , and Under Control : Wireless Resonant Magnetic Micro-agents,” Int. J. Robot. Res. Vol., 2010.

[26] P. Vartholomeos, M. R. Akhavan-sharif, and P. E. Dupont, “Motion planning for multiple millimeter-scale magnetic capsules in a fluid environment,” 2012 IEEE Int. Conf. Robot.
[27] S. Floyd, E. Diller, C. Pawashe, and M. Sitti, “Control methodologies for a heterogeneous group of untethered magnetic micro-robots,” *Int. J. Rob. Res.*, 2011.

[28] M. Salehizadeh and E. Diller, “Two-agent formation control of magnetic microrobots in two dimensions,” *J. Micro-Bio Robot.*, pp. 9–19, 2017.

[29] R. Pieters, H. Tung, S. Charreyron, D. F. Sargent, and B. J. Nelson, “RodBot: a Rolling Microrobot for Micromanipulation,” *2015 IEEE Int. Conf. Robot. Autom.*, pp. 4042–4047, 2015.

[30] L. Arcese, M. Fruchard, A. Ferreira, L. Arcese, M. Fruchard, A. Ferreira, A. Controller, M. Microrobot, L. Arcese, M. Fruchard, and A. Ferreira, “Adaptive Controller and Observer for a Magnetic Microrobot,” *EEE Trans. Robot.*, 2013.

[31] I. S. M. Khalil, L. Abelmann, and S. Misra, “Magnetic-Based Motion Control of Paramagnetic Microparticles With Disturbance Compensation,” *IEEE Trans. Magn.*, vol. 50, no. 10, pp. 1–10, 2014.

[32] W. Ma, F. Niu, X. Li, H. Ji, J. Yang, and D. Sun, “Modeling and Closed-Loop Control of Electromagnetic Manipulation of A Microparticle,” *2015 IEEE Int. Conf. Robot. Autom.*, pp. 143–148, 2015.

[33] J. Wang, N. Jiao, S. Tung, and L. Liu, “Automatic Path Tracking and Target Manipulation of a Magnetic Microrobot,” *Micromachines*, pp. 1–14, 2016.

[34] H. Abass, M. Shoukry, and A. Klingner, “Disturbance Observer-Based Motion Control of Paramagnetic Microparticles Against Time-Varying Flow Rates,” *2016 6th IEEE Int. Conf. Biomed. Robot. Biomechatronics*, pp. 67–72, 2016.

[35] R. Pieters, S. Lombriser, A. Alvarez-aguirre, and B. J. Nelson, “Model Predictive Control of a Magnetically Guided Rolling Microrobot,” *IEEE Robot. Autom. Lett.*, vol. 1, no. 1, pp. 455–460, 2016.

[36] D. Folio, K. Belharet, and A. Ferreira, “Motion control analysis of two magnetic microrobots using the combination of magnetic gradient and oscillatory magnetic field,” *2017 Int. Conf. Manip. Autom. Robot. Small Scales*, 2017.

[37] W. Ma, J. Li, S. Member, F. Niu, H. Ji, and D. Sun, “Robust Control to Manipulate a Microparticle with Electromagnetic Coil System,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 11, pp. 8566–8577, 2017.

[38] S. Afshar, M. B. Khamesee, and A. Khajepour, “Optimal Configuration for Electromagnets and Coils in Magnetic Actuators,” *IEEE Trans. Magn.*, vol. 49, no. 4, pp. 1372–1381, 2013.

[39] A. J. Petruska, J. B. Brink, and J. J. Abbott, “First Demonstration of a Modular and Reconfigurable Magnetic-Manipulation System,” *2015 IEEE Int. Conf. Robot. Autom.*, pp. 149–155, 2015.

[40] D. Folio, K. Belharet, and A. Ferreira, “Optimal Control of Multiple Magnetic Microbeads Navigating in Microfluidic Channels,” *2016 IEEE Int. Conf. Robot. Autom.*, no. 1, 2016.

[41] S. Floyd, C. Pawashe, and M. Sitti, “Two-Dimensional Contact and Noncontact Micromanipulation in Liquid Using an Untethered Mobile Magnetic Microrobot,” *IEEE Trans. Robot.*, vol. 25, no. 6, pp. 1332–1342, 2009.

[42] C. Pawashe, F. Steven, E. Diller, and M. Sitti, “Two-Dimensional Autonomous Microparticle Manipulation Strategies for Magnetic Microrobots in Fluidic Environments,” *IEEE Trans. Robot.*, vol. 28, no. 2, pp. 467–477, 2012.

[43] U. Lehmann, S. Hadjidj, V. K. Parashar, A. Rida, and M. A. M. Gijs, “TWO DIMENSIONAL MAGNETIC MANIPULATION OF MICRODROPLETS ON A CHIP,” *13th International Conf. Solid-State Sensors, Actuators Microsyst.*, pp. 77–80, 2005.

[44] E. Diller, S. Floyd, C. Pawashe, and M. Sitti, “Control of Multiple Heterogeneous Magnetic Microrobots in Two Dimensions on Nonspecialized Surfaces,” *IEEE Trans. Robot.*, vol. 28, no. 1, pp. 172–182, 2012.

[45] K. Belharet, D. Folio, and A. Ferreira, “Three-Dimensional Controlled Motion of a Microrobot using Magnetic Gradients,” *Adv. Robot.*, vol. 1864, 2011.

[46] I. S. M. Khalil, R. M. P. Metz, B. A. Reefman, and S. Misra, “Magnetic-Based Minimum Input Motion Control of Paramagnetic Microparticles in Three-Dimensional Space,” *2013 IEEE/RSJ Autom.*, pp. 1927–1932, 2012.
Int. Conf. Intell. Robot. Syst., pp. 2053–2058, 2013.

[47] S. Schuerle, S. Erni, M. Flink, B. E. Kratochvil, and B. J. Nelson, “Three-Dimensional Magnetic Manipulation of Micro- and Nanostructures for Applications in Life Sciences,” *IEEE Trans. Magn.*, vol. 49, no. 2, pp. 321–330, 2013.

[48] E. Diller and M. Sitti, “Three-Dimensional Programmable Assembly by Untethered Magnetic Robotic Micro-Grippers,” *Adv. Funct. Mater.*, pp. 4397–4404, 2014.

[49] Z. Zhang, F. Long, and C. Menq, “Three-Dimensional Visual Servo Control of a Magnetically Propelled Microscopic Bead,” *IEEE Trans. Robot.*, vol. 29, no. 2, pp. 373–382, 2013.

[50] S. J. Kim, S. M. Jeon, J. K. Nam, and G. H. Jang, “Closed-Loop Control of a Self-Positioning and Rolling Magnetic Microrobot on 3D Thin Surfaces Using Biplane Imaging,” *IEEE Trans. Magn.*, vol. 50, no. 11, pp. 1–4, 2014.

[51] E. Diller, J. Giltinan, and M. Sitti, “Independent control of multiple magnetic microrobots in three dimensions,” *Int. J. Rob. Res.*, 2013.

[52] I. S. M. Khalil, V. Magdanz, S. Sanchez, and O. G. Schmidt, “The Control of Self-Propelled Microjets Inside a Microchannel With Time-Varying Flow Rates,” *IEEE Trans. Robot.*, vol. 30, no. 1, pp. 49–58, 2014.

[53] L. Yang, Q. Wang, and L. Zhang, “Model-Free Trajectory Tracking Control of Two-Particle Magnetic Microrobot,” *IEEE Trans. Nanotechnol.*, vol. 17, no. 4, pp. 697–700, 2018.

[54] S. Verma, W. Kim, S. Member, and J. Gu, “Six-Axis Nanopositioning Device With Precision Magnetic Levitation Technology,” *IEEE/ASME Trans. Mechatronics*, vol. 9, no. 2, pp. 384–391, 2004.

[55] M. P. Kummer, S. Member, J. J. Abbott, B. E. Kratochvil, R. Borer, A. Sengul, S. Member, B. J. Nelson, and S. Member, “OctoMag: An Electromagnetic System for 5-DOF Wireless Micromanipulation,” *IEEE Trans. Robot.*, vol. 26, no. 6, pp. 1006–1017, 2010.

[56] B. Kratochvil, M. Kumar, S. Erni, R. Borer, D. Frutiger, S. Schurle, and B. Nelson, *MiniMag: A Hemispherical Electromagnetic System for 5-DOF Wireless Micromanipulation*. 2014.

[57] E. Diller, J. Giltinan, G. Z. Lum, Z. Ye, and M. Sitti, “Six-Degrees-of-Freedom Remote Actuation of Magnetic Microrobots,” *Robot. Sci. Syst. 2014*, 2014.

[58] A. W. Mahoney and J. J. Abbott, “5-DOF Manipulation of an Untethered Magnetic Device in Fluid using a Single Permanent Magnet,” *Robot. Sci. Syst. 2014*, 2014.

[59] J. Giltinan, “Simultaneous Six-Degree-of-Freedom Control of a Single-Body Magnetic Microrobot,” *IEEE Robot. Autom. Lett.*, vol. 4, no. 2, pp. 508–514, 2019.

[60] E. B. Steager, M. S. Sakar, C. Magee, M. Kennedy, A. Cowley, and V. Kumar, “Automated biomanipulation of single cells using magnetic microrobots,” *Int. J. Rob. Res.*, pp. 346–359, 2013.

[61] A. De Langlade, “Position Control of a Magnetic Levitation Device Using a Non-Linear Disturbance Observer and Influence of the Position Sensing,” *IECON 2017 - 43rd Annu. Conf. IEEE Ind. Electron. Soc.*, 2017.

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