

# Nonuniform Fields for Magnetic Control

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**Abstract**—Wireless control using magnetic fields will enable the next generation of untethered micromanipulators and medical microrobots. In this presentation, we will discuss limitations inherent to orthogonal electromagnet arrangements and uniform-field methods that are typical in the control of magnetic microrobots: limitations due to both scaling, as well as due to fundamental limitations in degrees of freedom of wireless control. We will discuss two ongoing research efforts that have capitalized on complex nonuniform fields for wireless microrobot control: the OctoMag system developed at ETH Zurich, which enables 5-DOF control of a fully untethered microrobot, and the rotating-permanent-magnet manipulator developed at the University of Utah, which enables the wireless control of helical swimming microrobots. Both systems accomplish their respective tasks without the need to fully surround the workspace. We will discuss how the concepts utilized in these two projects generalize to other types of microrobot control.

## I. INTRODUCTION

Magnetic microrobots can be used as wirelessly controlled micromanipulators under the guidance of an optical microscope [1], [2], and magnetic microrobots that navigate the natural pathways of the body have the potential to revolutionize minimally invasive medicine and biomedical research [3]. Engineers have been intrigued by the possibilities of wireless power transfer using magnetic fields since the time of Nikola Tesla. However, practical limitations in the generation of strong controlled magnetic fields make the creation of even basic wireless magnetic manipulation systems challenging. Fully untethered magnetic microrobots successfully demonstrated in laboratory settings have typically utilized orthogonal arrangements of air-core electromagnets as field-generation sources to create decoupled uniform fields (i.e. fields relatively free of spatial gradients) and so-called uniform-gradient fields (i.e. fields with gradients that are relatively constant spatially). However, it would be difficult and costly to scale up many of these field-generation systems to the size required for clinical use. The use of air-core electromagnets as decoupled field-generation sources simplifies the control problem, but this simplified control comes at a huge cost. Moving away from the use of air-core electromagnets, as well as from the need for field uniformity, will enable us to build field-generation sources that are smaller and less expensive than a competing uniform-field system. Understanding the use of complex nonuniform magnetic fields for wireless control may be the key to translating nearly every previously developed magnetic microrobot into clinical use. We use “microrobot” herein for lack of a better concise term; for many envisioned medical

applications, devices may be as large as a few millimeters [3], but many concepts in the control of true microrobots accurately approximate what is seen experimentally with such mesoscale devices.

## II. ON UNIFORM ELECTROMAGNETIC SYSTEMS

Experimental systems for real-time control with magnetic fields have typically relied on coaxial electromagnetic coil pairs. Electrical current flowing in the same direction results in a uniform field in the center of the workspace, and current flowing in opposite directions results in a uniform-gradient field. When the coils are separated by a distance that maximizes the size of the uniform region of the field, the coil pairs are referred to as Helmholtz pairs and Maxwell pairs, respectively. A Helmholtz pair and a Maxwell pair can also be combined coaxially such that the field and field gradient (pointing along the common axis) can be controlled independently in the center of the workspace [4], since the fields simply superimpose under quasistatic operation. Since the magnitude and direction of the magnetic field are responsible for torque generation, and spatial gradients in the field are responsible for force generation, the wireless application of torque and force can be decoupled.

Experimental systems have typically been constructed as orthogonal arrangements of the aforementioned coil pairs. With air-core electromagnets, each of the orthogonal directions are decoupled, making control simple. Using this type of arrangement, it is possible to generate a uniform magnetic field pointing in any direction, although the magnitude of the field that is achievable may decrease substantially as the system’s size is increased [5]. It is not possible, however, to create arbitrary gradients in the magnetic field, which results in the workspace of the system being poorly conditioned, with a loss of control authority (i.e. ability to generate forces) in certain configurations [6]. Examples of control that are difficult using the aforementioned arrangements are laterals movement of the microrobot (i.e. perpendicular to its long axis), and levitation of a microrobot against its own weight if it is oriented horizontally. If the object to be controlled is a sphere, then an orthogonal arrangement will enable 3-DOF control [7]. However, if the geometry of the object is nonspherical and more degrees of freedom are desired, or if it is not possible to fully surround the desired workspace, then we must explore alternatives for control.

## III. QUASISTATIC MANIPULATION AND OCTOMAG

The recently developed OctoMag system provides 5-DOF manipulation of a fully untethered microrobot [8]. The system does not require the workspace to be fully surrounded

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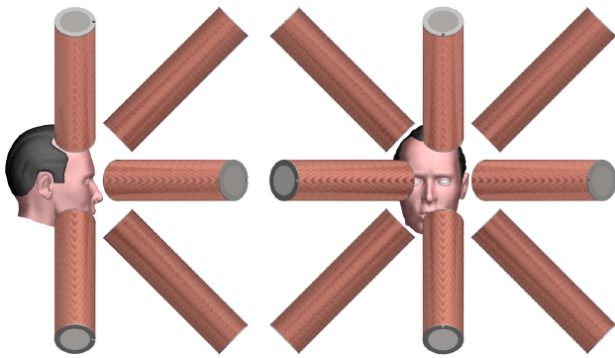


Fig. 1. Concept image of the OctoMag electromagnetic system for the control of intraocular microrobots [8]. An eyeball is at the center of the systems workspace. The electromagnet arrangement accommodates the geometry of the head, neck, and shoulders. The OctoMag is designed for a camera to fit down the central axis to image the microrobot in the eye.

(Fig. 1), yet still enables complex 5-DOF movements. Control is achieved using eight soft-magnetic-core electromagnets. The soft-magnetic cores amplify the field by  $\sim 20\times$ , which is very desirable, but the electromagnets are no longer decoupled. However, we find that if the cores are operated in their linear-magnetization region, then the contribution of an individual electromagnet current, which magnetizes every core to some extent, modifies the total field linearly. With only a simple calibration of the electromagnets *in situ*, we can use linear methods to achieve real-time wireless magnetic control, allowing the benefits of the cores to be realized. Because the system need not surround the workspace, we can design systems that respect the geometric limitations of our workspace. We will discuss how the methods used in the design of OctoMag, and the techniques for real-time control, generalize.

#### IV. HELICAL MICROROBOTS AND THE ROTATING-PERMANENT-MAGNET MANIPULATOR

Helical microrobots [9]–[11] use a swimming technique inspired by the propulsion of bacterial flagella, which is well suited to a low-Reynolds-number regime. A rotating magnetic field generates torque on the microrobot, resulting in propulsion and steering. In all prior work, the magnetic-field-generation system is an orthogonal arrangement of electromagnetic coil pairs that generates a rotating uniform field at the center of the system’s workspace. Uniform-field systems that have proven to be effective under a microscope and in other laboratory settings are difficult to scale up to the size required for *in vivo* medical devices, since a reliance on uniform fields requires that the microrobot be located in the small central region of the system’s workspace and be fully surrounded by the system.

Consider a microrobot swimming up the spinal canal, as shown in Fig. 2: the spine is located much closer to the back of the patient than to the front, and it is very difficult to truly surround the microrobot in the direction along the length of the spine (the torso is a significant obstacle). For many other systems in the body, it is also

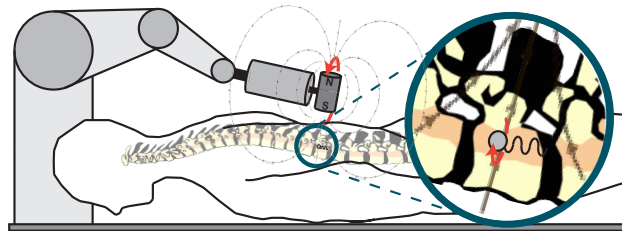


Fig. 2. Concept image of a helical microrobot (inset) propelled through the spinal canal using a rotating-permanent-magnet manipulator [12].

possible to get very close if one approaches from certain, but not all, directions. It is possible to use the nonuniform magnetic fields emanating from a single rotating permanent magnet for control of helical microrobots [12]. Allowing nonuniform magnetic fields makes it possible to place the magnet closer to the patient, which permits the use of a smaller and less-expensive systems. The use of nonuniform fields results in potentially undesirable field-gradient forces, making control more challenging, but may ultimately result in superior systems—in terms of size and cost—compared to using uniform fields. We will discuss the proposed concept, as well as preliminary experimental and theoretical results that indicate that this is a wireless control method warranting further investigation. One particularly promising result is that, in the configuration that provides maximum magnetic torque, the undesirable magnetic forces vanish.

#### REFERENCES

- [1] M. Sitti. Microscale and nanoscale robotic systems. *IEEE Robotics and Automation Mag.*, 14(1):53–60, 2007.
- [2] J. J. Abbott, Z. Nagy, F. Beyeler, and B. J. Nelson. Robotics in the small, part I: Microrobotics. *IEEE Robotics and Automation Mag.*, 14(2):92–103, 2007.
- [3] B. J. Nelson, I. K. Kaliakatsos, and J. J. Abbott. Wireless microrobots for minimally invasive medicine. *Annual Review of Biomedical Engineering*, To appear in 2010.
- [4] K. B. Yesin, K. Vollmers, and B. J. Nelson. Modeling and control of untethered biomicrorobots in a fluidic environment using electromagnetic fields. *Int. J. Robotics Research*, 25(5–6):527–536, 2006.
- [5] J. J. Abbott, K. E. Peyer, M. Cosentino Lagomarsino, L. Zhang, L. X. Dong, I. K. Kaliakatsos, and B. J. Nelson. How should microrobots swim? *Int. J. Robotics Research*, 28(11–12):1434–1447, 2009.
- [6] D. C. Meecker, E. H. Maslen, R. C. Ritter, and F. M. Creighton. Optimal realization of arbitrary forces in a magnetic stereotaxis system. *IEEE Trans. Magnetics*, 32(2):320–328, 1996.
- [7] S. Martel, J.-B. Mathieu, O. Felfoul, A. Chanu, E. Aboussouan, S. Tamaz, and P. Pouponneau. Automatic navigation of an untethered device in the artery of a living animal using a conventional clinical magnetic resonance imaging system. *Applied Physics Lett.*, 90(11):114105(1–3), 2007.
- [8] M. P. Kummer, J. J. Abbott, B. E. Kratochvil, R. Borer, A. Sengul, and B. J. Nelson. OctoMag: An electromagnetic system for 5-DOF wireless micromanipulation. In *Proc. IEEE Int. Conf. Robotics and Automation*, 2010.
- [9] M. Sendoh, K. Ishiyama, and K.-I. Arai. Fabrication of magnetic actuator for use in a capsule endoscope. *IEEE Trans. Magnetics*, 39(5):3232–3234, 2003.
- [10] L. Zhang, J. J. Abbott, L. X. Dong, K. E. Peyer, B. E. Kratochvil, H. Zhang, and B. J. Nelson. Characterizing the swimming properties of artificial bacterial flagella. *Nano Lett.*, 9(10):3663–3667, 2009.
- [11] A. Ghosh and P. Fischer. Controlled propulsion of artificial magnetic nanostructured propellers. *Nano Lett.*, 9(6):2243–2245, 2009.
- [12] T. W. R. Fountain, P. V. Kailat, and J. J. Abbott. Wireless control of magnetic helical microrobots using a rotating-permanent-magnet manipulator. In *Proc. IEEE Int. Conf. Robotics and Automation*, 2010.