ICRA2026 Late Breaking Results Poster presented at
2026 IEEE International Conference on Robotics and Automation (ICRA 2026)
June 1-5, 2026. Vienna, Austria

Continuous Real-Time Inductive Tracking of Magnetic Microagents for Closed-Loop Control

Tim Grossrieder, Cameron Forbrigger, Myungjin Park, Michael Christiansen, and Simone Schuerle

***Abstract*—Magnetic microrobots are on the rise, with many designs controlled via rotating magnetic fields (RMFs). Realizing their potential in medical treatments requires overcoming the difficulty of tracking them during navigation. We propose an inductive detection method leveraging RMFs simultaneously for sensing and control. By extracting inductive signals from the actuated agents, we achieve magnetic based tracking of position and phase lag without the need for secondary imaging modalities.**

***Index Terms*—Micro/Nano Robots, Medical Robots and Systems, Sensor-based Control**

I. Introduction

Magnetic actuation and microrobotics have the potential to significantly advance medical technologies by enabling less invasive interventions and improving patient outcomes [1]. Currently, localization and sensing of magnetic agents primarily rely on external imaging modalities such as ultrasound [2] or radiography [3]. However, these external systems increase procedural complexity and often fail to capture the dynamic response of the microrobot. To enable the successful clinical translation of magnetic agents, alternative sensing methods are needed. To address this, various magnetic field-based sensing techniques have been proposed [4], [5]. However, these techniques require secondary high-frequency excitation and additional hardware, necessitating interleaved operation. In contrast, we leverage an inductive sensing approach based on voltages induced directly by the RMF used for actuation. This enables parallel actuation and localization, as the excitation signal is inherently embedded within the actuation itself. In this work, we expand this concept to demonstrate its applicability across various RMF sources, showcasing 3D sensing capabilities and implementing 1D closed-loop control. This integrated approach enables high-fidelity, continuous navigation of magnetic microagents without the need for secondary hardware or the bottlenecks of sequential operation.

II. Inductive Detection – The Concept

The sensing method is based on measuring the electromotive force (EMF) induced in pickup coils by a rotating magnetic agent. However, the external driving fields are typically orders of magnitude larger than the field produced by the microagent itself. Consequently, the voltage induced in a single pickup coil is heavily dominated by the driving field (the background signal), with only a small fraction originating from the microagent. This discrepancy in signal levels poses a significant challenge due to the resolution limits of analog-to-digital converters. To address this, we implement an analog cancellation step to isolate the magnetic agent's signal before digitization (see Fig. 1). The system employs a primary pickup coil located close to the magnetic agent (the sense coil) alongside multiple pickup coils placed further away (the compensation coils). The magnetic agent will induce a voltage that is comparatively higher in the sense coil than in the compensation coils. In contrast, the voltage induced by the driving field is independent of the microagent present in all pickup coils. Using a summing amplifier circuit with tunable weights, the voltages of the sense coil and the compensation coils are balanced to effectively nullify the background signal. The isolated microagent signal is then amplified and digitized, enabling localization, phase sensing, and closed-loop control.

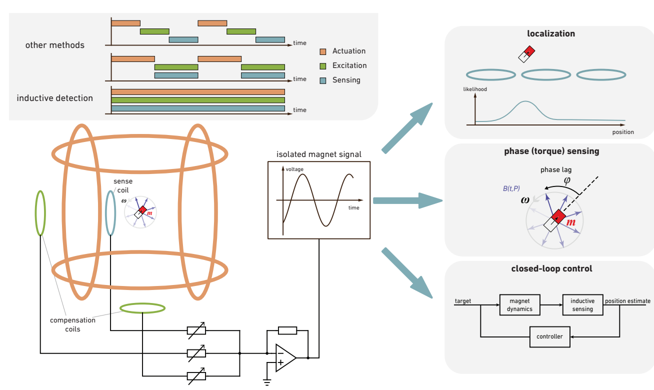

Fig. 1. Overview of inductive detection. Unlike traditional interleaved methods, the proposed approach achieves continuous parallel actuation and sensing. Position and phase lag can be extracted from the isolated signal and used for control.

III. 3D Localization

Using multiple pickup coils as sense coils, this work demonstrates 3D localization of a spherical permanent magnet (3 mm diameter), as shown in Fig. 2. The magnet was submerged in a glycerol-filled chamber and positioned using a micropositioner. Magnetic actuation was provided by a commercial 8-coil electromagnet system (MFG-100, Magnebotix AG). To perform inductive detection, a sense coil was mounted at the front of each electromagnet. Correspondingly, a compensation coil was mounted on the back of each electromagnet for every sense coil (totaling 64 compensation coils). For localization, the workspace was first coarsely mapped to

T. Grossrieder, C. Forbrigger, M. Park, M. Christiansen, and S. Schuerle are with the Institute of Robotics and Intelligent Systems, D-HEST, ETH Zurich, Zurich, Switzerland, email: simone.schuerle@hest.ethz.ch.

create a look-up table (LUT) for the signal amplitudes across the different channels. As the magnet was moved along a predefined path, its trajectory was successfully reconstructed by applying an interpolator to the LUT.

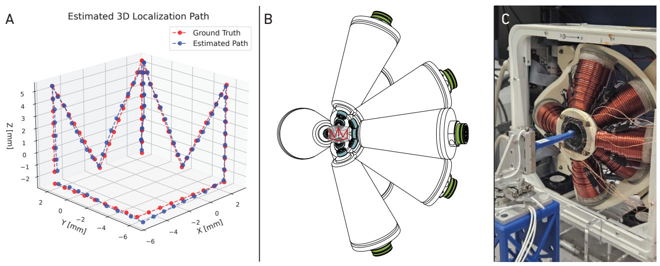

Fig. 2. (A) 3D tracking of a magnetic sphere (3 mm). (B) Sketch and (C) photograph of a commercial 8 coil electromagnet equipped with custom sense coils (blue) and compensation coils (green).

IV. Phase and Torque Sensing

A unique feature of the proposed inductive sensing method is the ability to estimate the phase lag between the applied RMF and the magnetization of the agent. A compensation coil is utilized to provide a reference signal, as its output depends solely on the driving field. By performing a sine fit on both the reference signal and the isolated magnet signal, the phase shift between the driving signal and the microagent's magnetization can be estimated. In the frequency sweep experiments shown in Fig. 3, a spherical magnet (3 mm diameter) in a glycerol-filled chamber was actuated with an RMF generated by different systems. A linear increase in amplitude and a nonlinear increase in phase lag were observed until the step-out frequency was reached. Consequently, this phase lag estimation provides a direct measure of the effective torque applied to the agent.

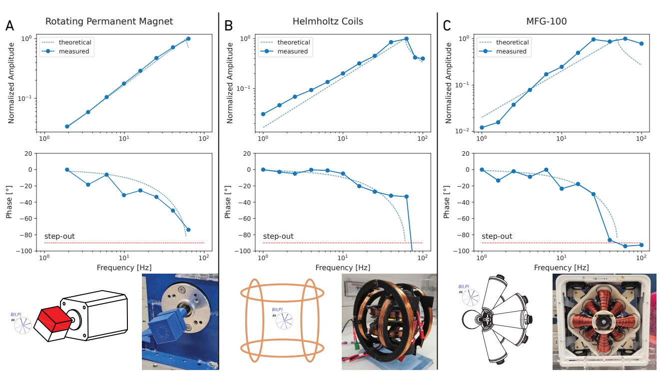

Fig. 3. Step responses of a 3 mm spherical magnet, actuated by a (A) rotating permanent magnet, (B) Helmholtz coil, and (C) a commercial electromagnet

V. 1D Closed-Loop Control

Since the proposed inductive detection method uses the low-frequency actuation signals for localization, it can be used to achieve closed-loop control of magnetic agents. This capability is demonstrated using a magnetic helical swimmer that moves in a water-filled tube against fluid flow. The swimmer consists of a cylindrical magnet (300 µm in diameter and 500 µm in length) with a helical tail. In the first experiment, shown in Fig. 3A, inductive feedback was used to steer the swimmer to a target position. A Helmholtz coil was used as the actuation system, together with an array of sense and compensation coils around the tube. In Fig. 3B, the experiment was extended such that the helical swimmer maintained its position while the magnetic flux was continuously reduced. This reduction lowers the step-out frequency, causing a measurable increase in phase lag. This transition was successfully tracked until the swimmer reached the step-out threshold and control was lost.

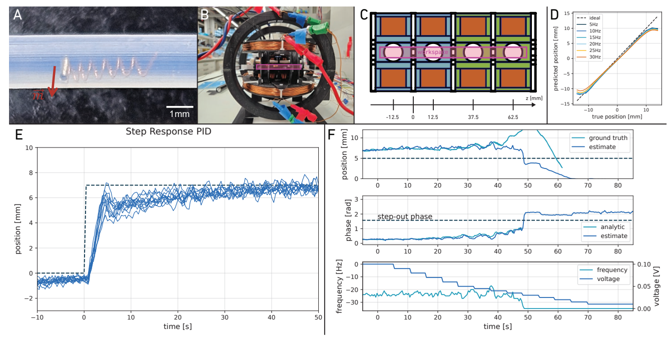

Fig. 4. (A) Magnetic swimmer, (B) actuation setup, and (C) sensing system. (D) Tracking for various frequencies. (E) Step responses (N=11) against flow. (F) Reducing the magnetic field increases the phase lag until step-out occurs.

VI. Conclusion

This work demonstrated that inductive sensing enables the 3D localization and phase sensing of magnetic agents. By leveraging the driving field as an excitation source, this approach facilitates uninterrupted closed-loop control alongside a simultaneous evaluation of the agent's dynamic response, regardless of the actuation system utilized. This integrated sensing-actuation concept paves the way for more efficient and controlled microrobotic interventions. Future research will focus on expanding the control space and investigating signals generated by magnetic swarms.

References

[1] B. J. Nelson, S. Gervasoni, P. W. Y. Chiu, L. Zhang, and A. Zemmar, "Magnetically actuated medical robots: An in vivo perspective," *Proceedings of the IEEE*, vol. 110, no. 7, pp. 1028–1037, 2022.

[2] Q. Wang, X. Du, D. Jin, and L. Zhang, "Real-time ultrasound doppler tracking and autonomous navigation of a miniature helical robot for accelerating thrombolysis in dynamic blood flow," *ACS nano*, vol. 16, no. 1, pp. 604–616, 2022.

[3] G. Go, A. Yoo, K. T. Nguyen, M. Nan, B. A. Darmawan, S. Zheng, B. Kang, C. S. Kim, D. Bang, S. Lee, K. P. Kim, S. S. Kang, K. M. Shim, S. E. Kim, S. Bang, D. H. Kim, J. O. Park, and E. Choi, "Multifunctional microrobot with real-time visualization and magnetic resonance imaging for chemoembolization therapy of liver cancer," *Science Advances*, vol. 8, no. 46, p. 8545, 11 2022. [Online]. Available: https://www.science.org/doi/10.1126/sciadv.abq8545

[4] B. Gleich, I. Schmale, T. Nielsen, and J. Rahmer, "Miniature magneto-mechanical resonators for wireless tracking and sensing," *Science*, vol. 380, no. 6648, pp. 966–971, 6 2023. [Online]. Available: https://www.science.org/doi/10.1126/science.adf5451

[5] D. von Arx, B. J. Nelson, and Q. Boehler, "Orthogonal Pulse-Width-Modulation for Combined Electromagnetic Actuation and Localization," *IEEE Robotics and Automation Letters*, pp. 1–8, 2025. [Online]. Available: https://ieeexplore.ieee.org/document/10993301/