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Rotating Micromachines with Stratified Disk Architecture for Dynamic Bioanalysis

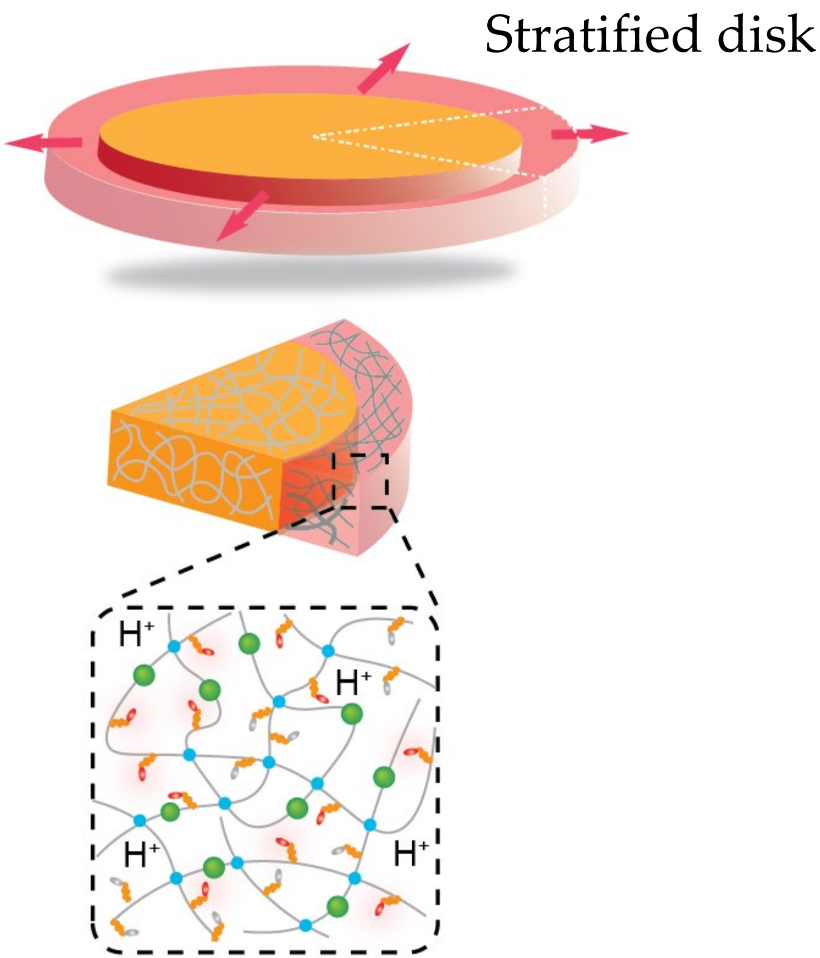
Gungun Lin[1,*], Yuan Liu[1], Guan Huang[1], Yvonne Chen[1], Denys Makarov[2], and Dayong Jin[1]

[1] University of Technology Sydney, 15 Broadway, Ultimo, 2007, Sydney, NSW, Australia;
[2] Helmholtz-Zentrum Dresden-Rossendorf e.V. Institute of Ion Beam Physics and Materials Research, Bautzner Landstrasse 400, 01328 Dresden, Germany

* Corresponding author: gungun.lin@uts.edu.au

UTS UNIVERSITY OF TECHNOLOGY SYDNEY

Graphic abstract



Abstract

Magnetic microrobots with versatile mechanical motion will enable many ex- and in-vivo applications. Unfortunately, monolithic integration of multiple functions in a streamlined microrobotic body is still challenging due to the compromise between fabrication throughput, device footprints, and material choices. In this talk, I will present a unified framework architecture for microrobotic functionalization to enable magnetically steered locomotion, chemical sensing and in-vivo tracking. This has been achieved through stratifying stimuli-responsive nanoparticles in a hydrogel micro-disk. We uncovered the key mechanism of leveraging spatially alternating magnetic energy potential to control a Euler's disk-like microrobot to locomote swiftly on its sidewall. The results suggest great potential for microrobots to locomote while cooperating a wide range of functions, tailorable for universal application scenarios.

Keywords: Magnetic micromachine; stratified disk; dynamic bioanalysis; rotating magnetic field; microrobot functionalization

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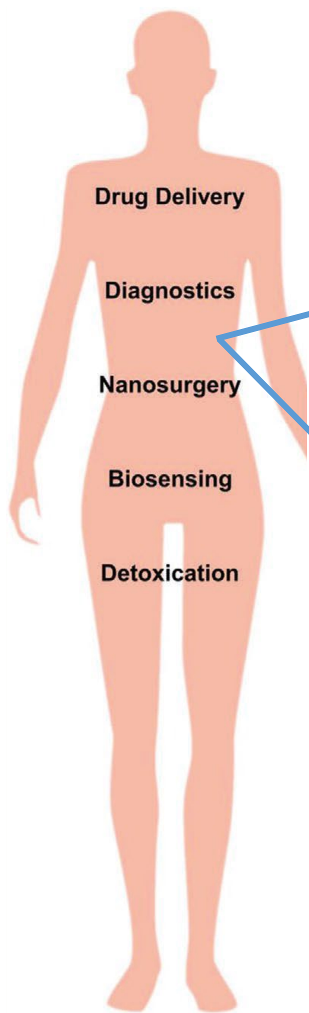
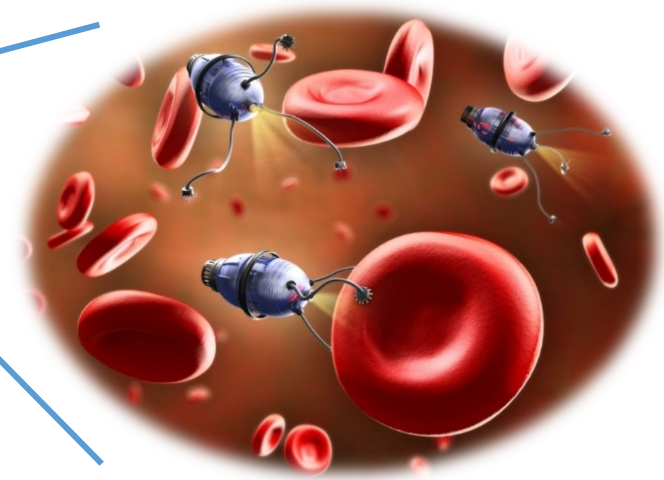
Introduction: Micromachines for *In-vivo* Applications

Microrobots are envisioned to perform site-selective tasks in-vivo

- **Biocompatibility & degradability**
- **Actuation**
- **Navigation**
- **Bio-barriers**
- **Imaging**

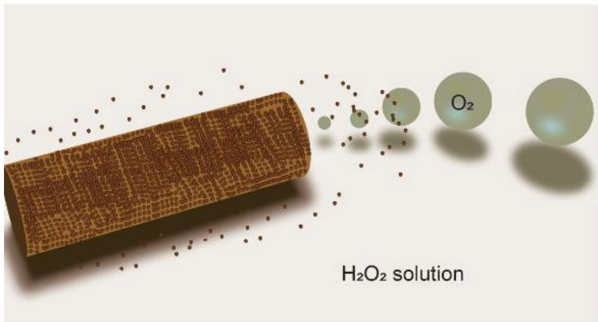




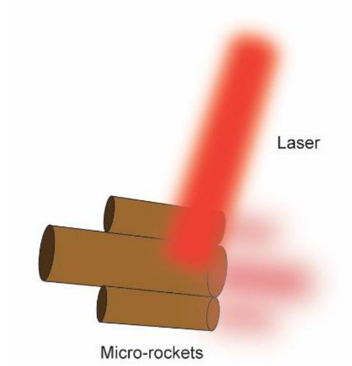
https://www.news-medical.net/

Adv. Mater. **2021**, *33*, 2000512, doi:10.1002/adma.202000512.

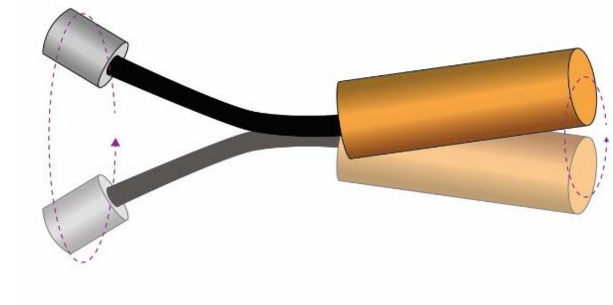
Introduction: Various Microrobot Body Designs



Tubular



Rocket-like



Cilia

Power source

- Light
- Chemical
- Humidity
- Magnetic field

- **Monolithic integration of multiple microrobotic functions is still challenging**
- **Lack of compatible surface chemistry to functionalise microrobots fabricated by advanced 3D micro- and nanofabrication technique**

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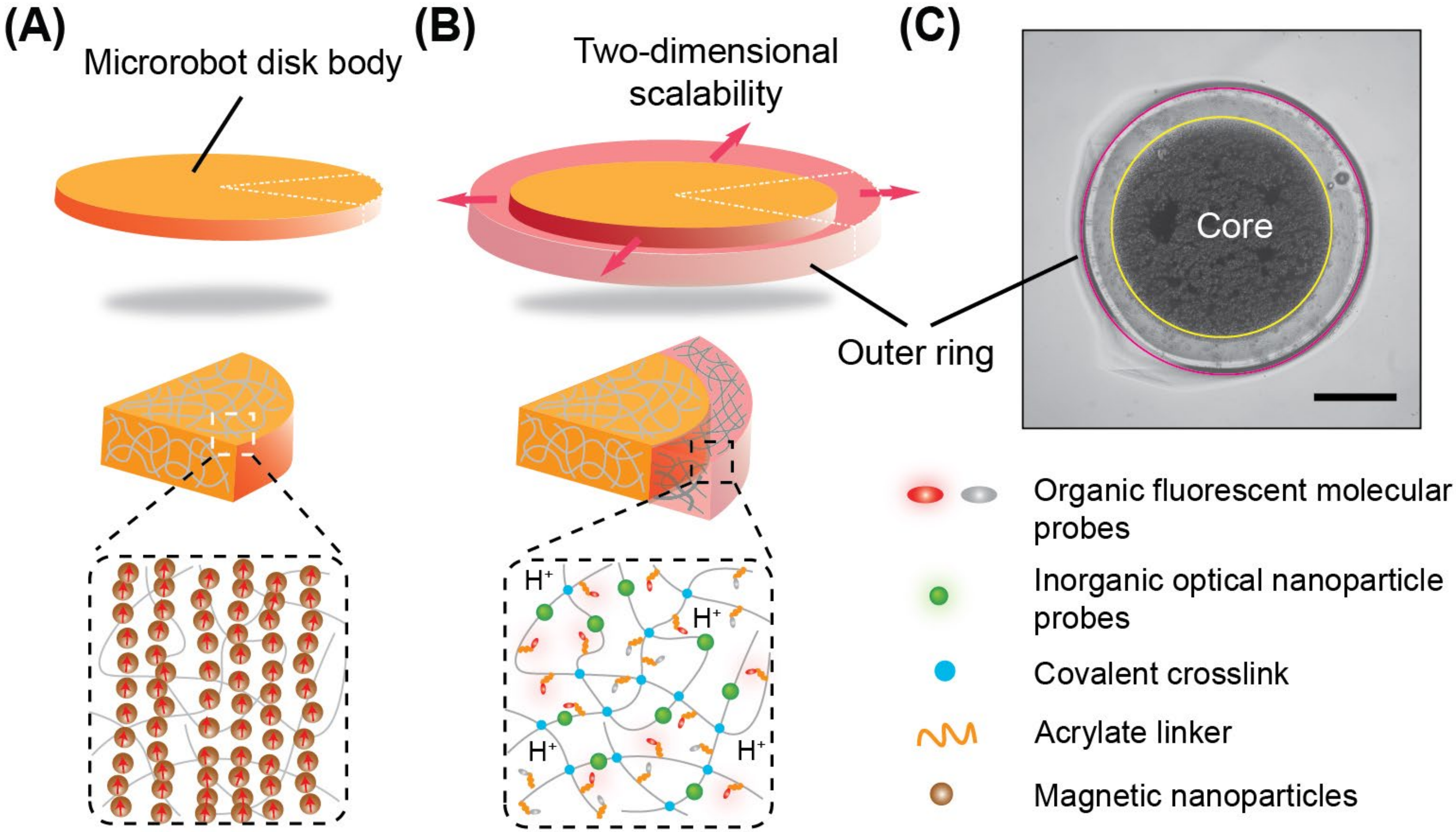
Concept of this Work: Streamlined Stratified Disk Body



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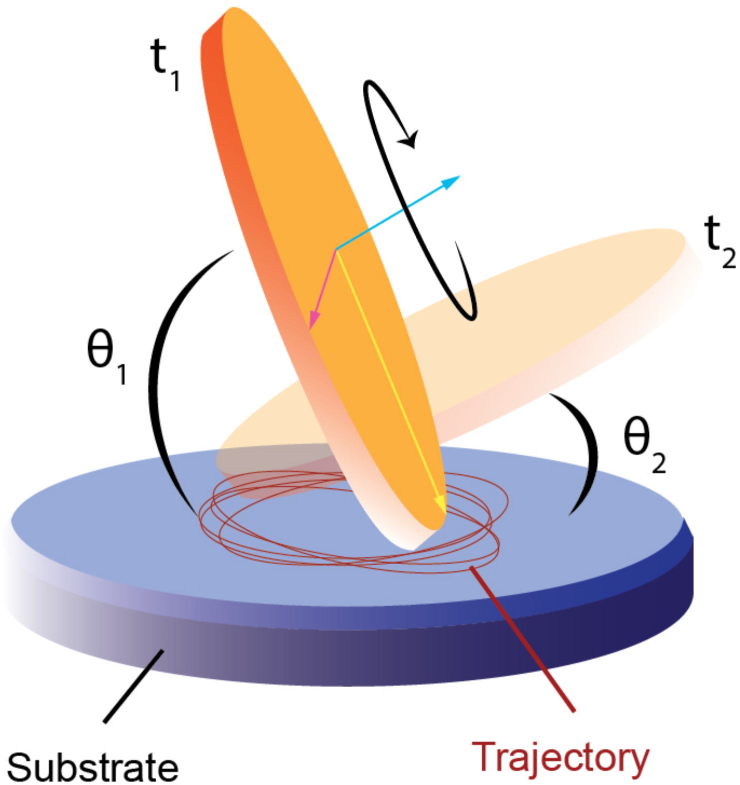
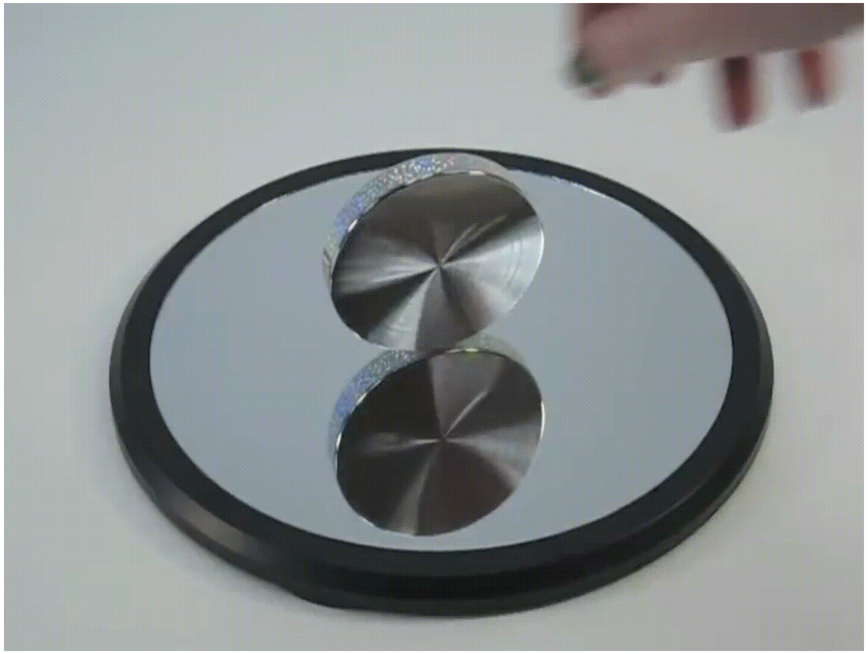
Approach: Inspired by Euler'disk-like Gyration

Euler's disk-like gyration



Euler'disk gyrating on a surface



Video source: http://www.teachersource.com

- **Inspiration: rapid gyration along its low-friction sidewall**

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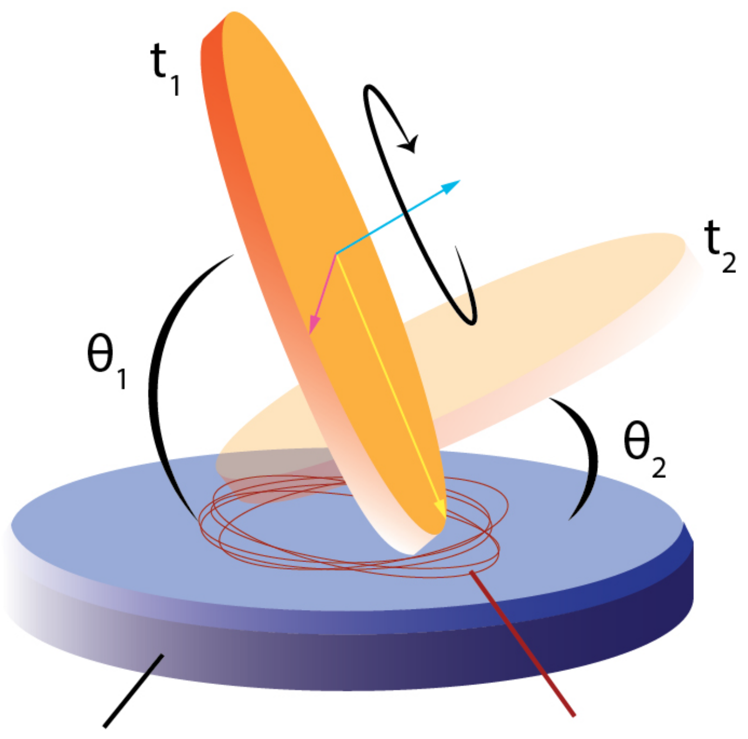
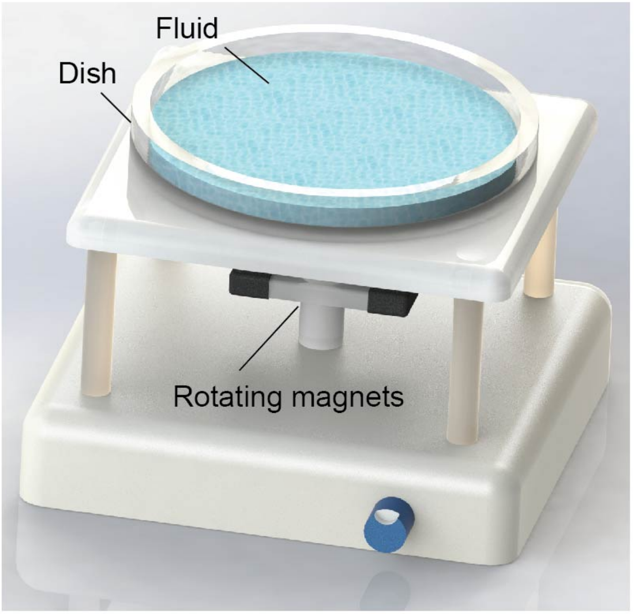
Our Approach: Magnetic Actuation of the Micro-disk





Magnetic stirrer as power source

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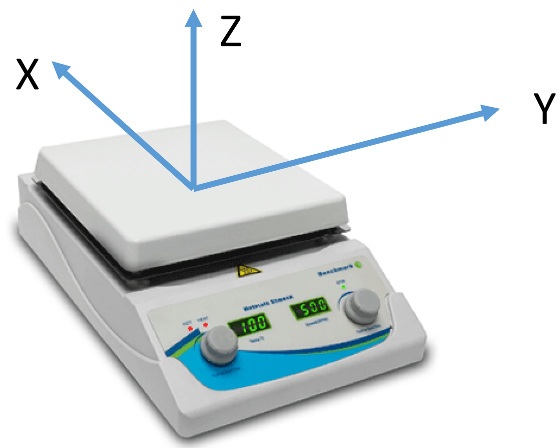
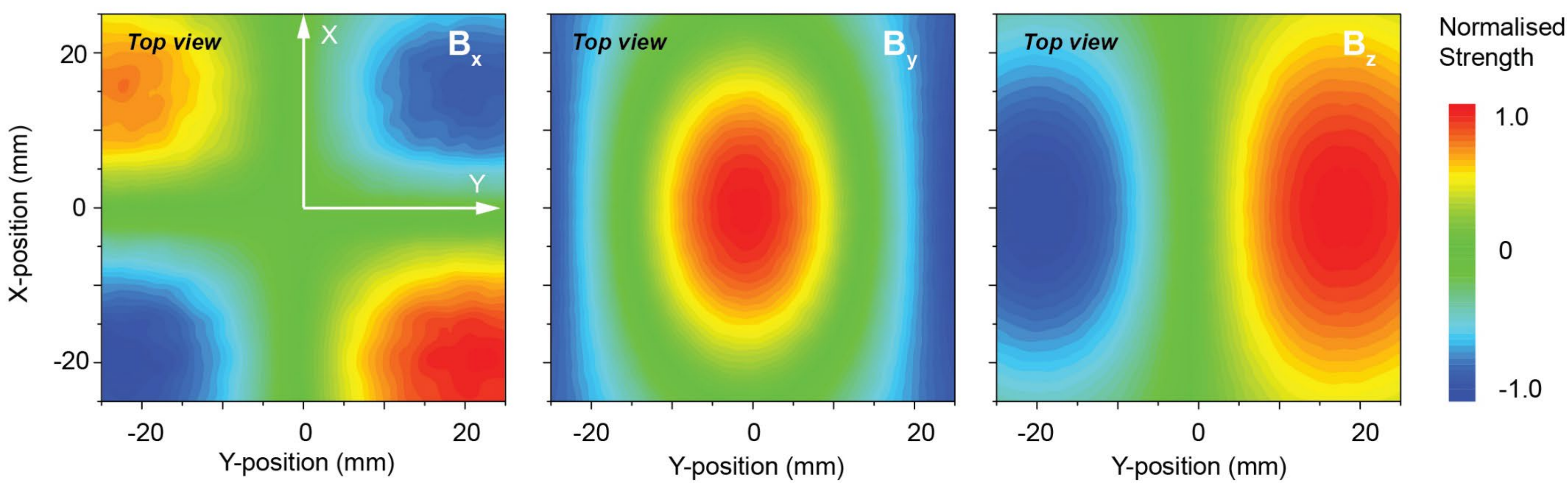
Results: Mapping of the Magnetic Field Distribution above the Stirrer



Spatially non-uniform magnetic field



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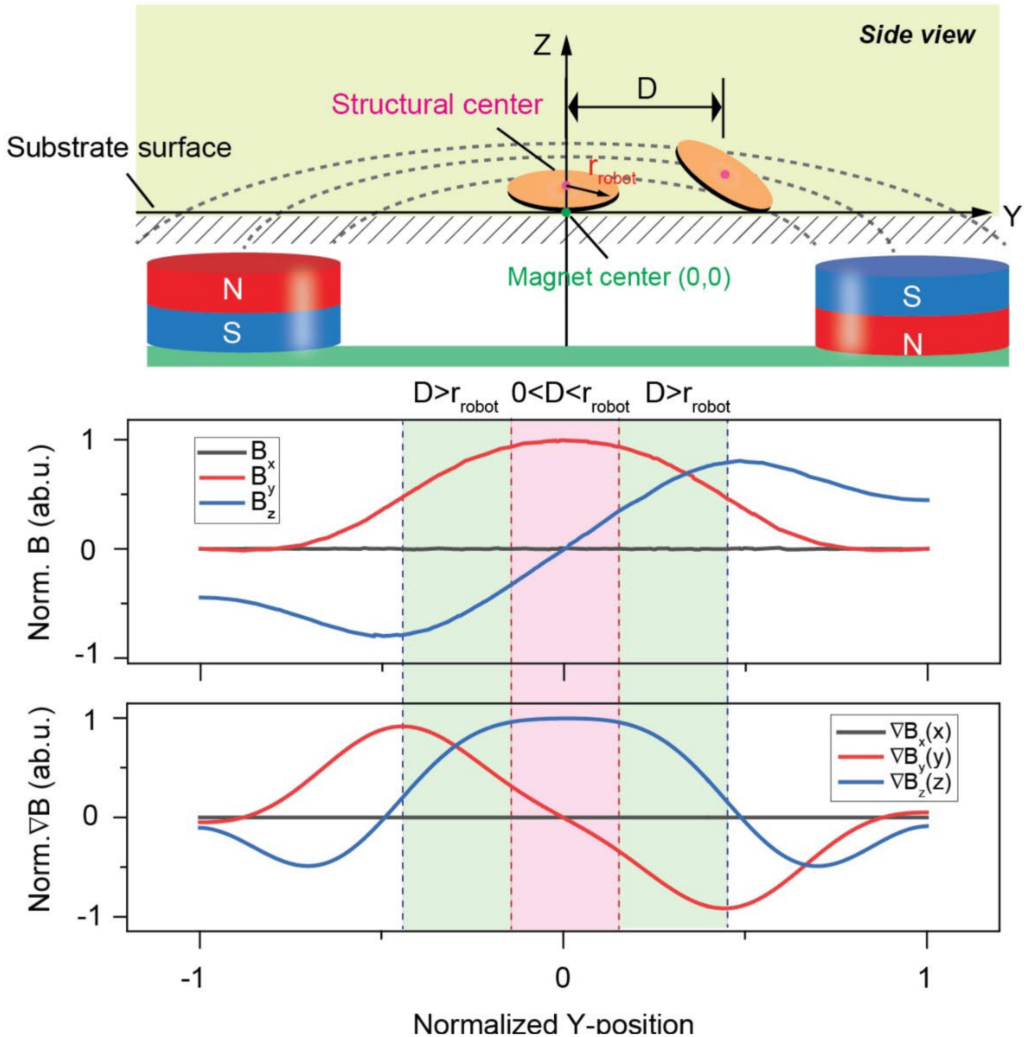
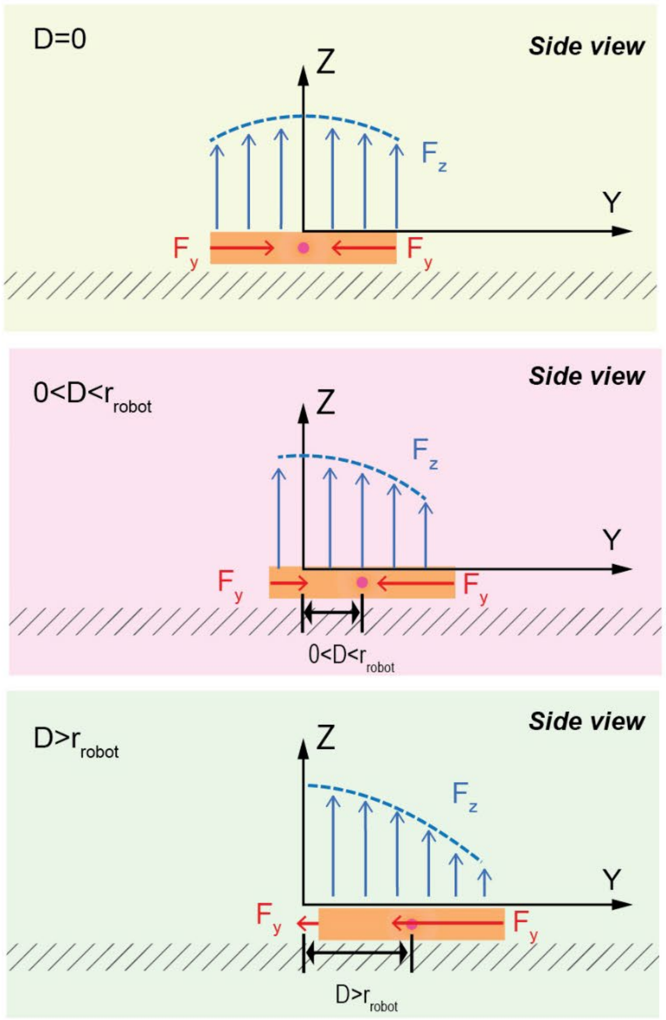
Results: Analysis of the Forces Exerted on the Disk





Asymmetric magnetic force components

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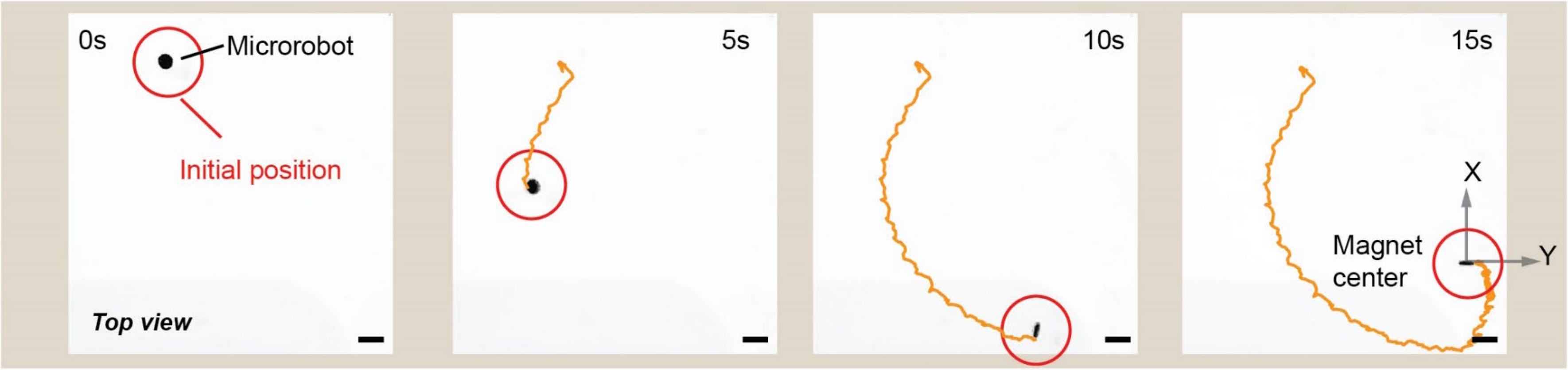
Results: Magnetic Actuation at Low Rotating Speeds



- **The disk stays still before rotating the magnet**
- **The onset of locomotion at low speed of rotation (< 200 rpm)**

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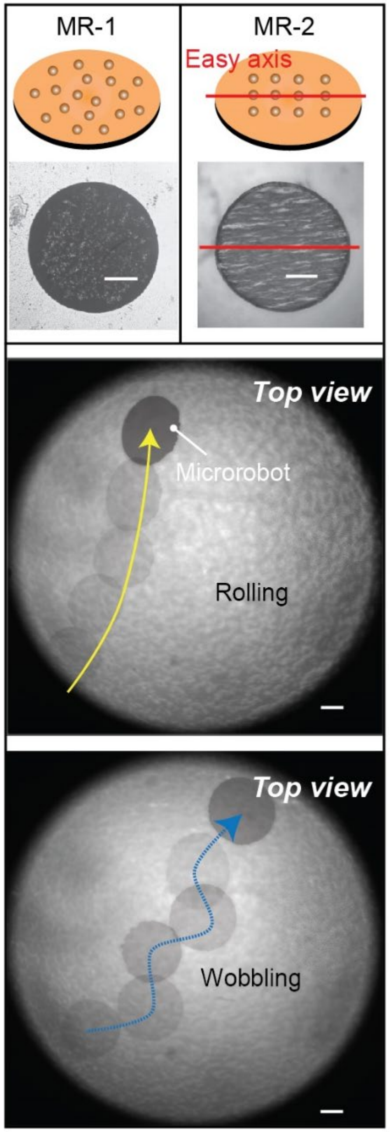
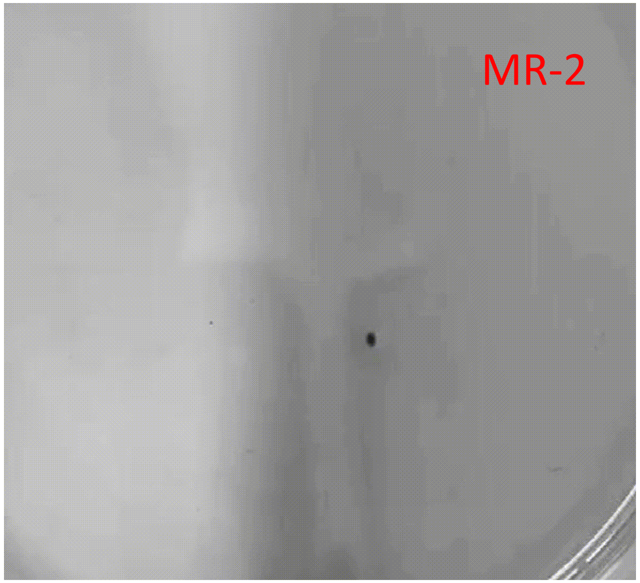
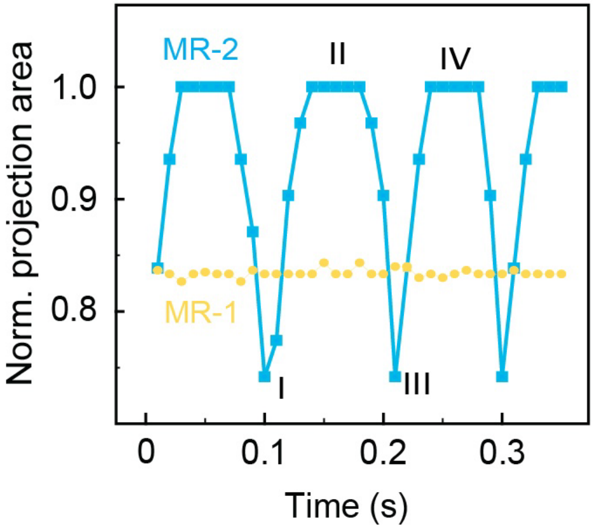
Results: Orbital Revolution of Disks with Varied Modes





MR-1: Disk with random distribution of magnetic nanoparticles

MR-2: Disk with aligned magnetic nanoparticle chains



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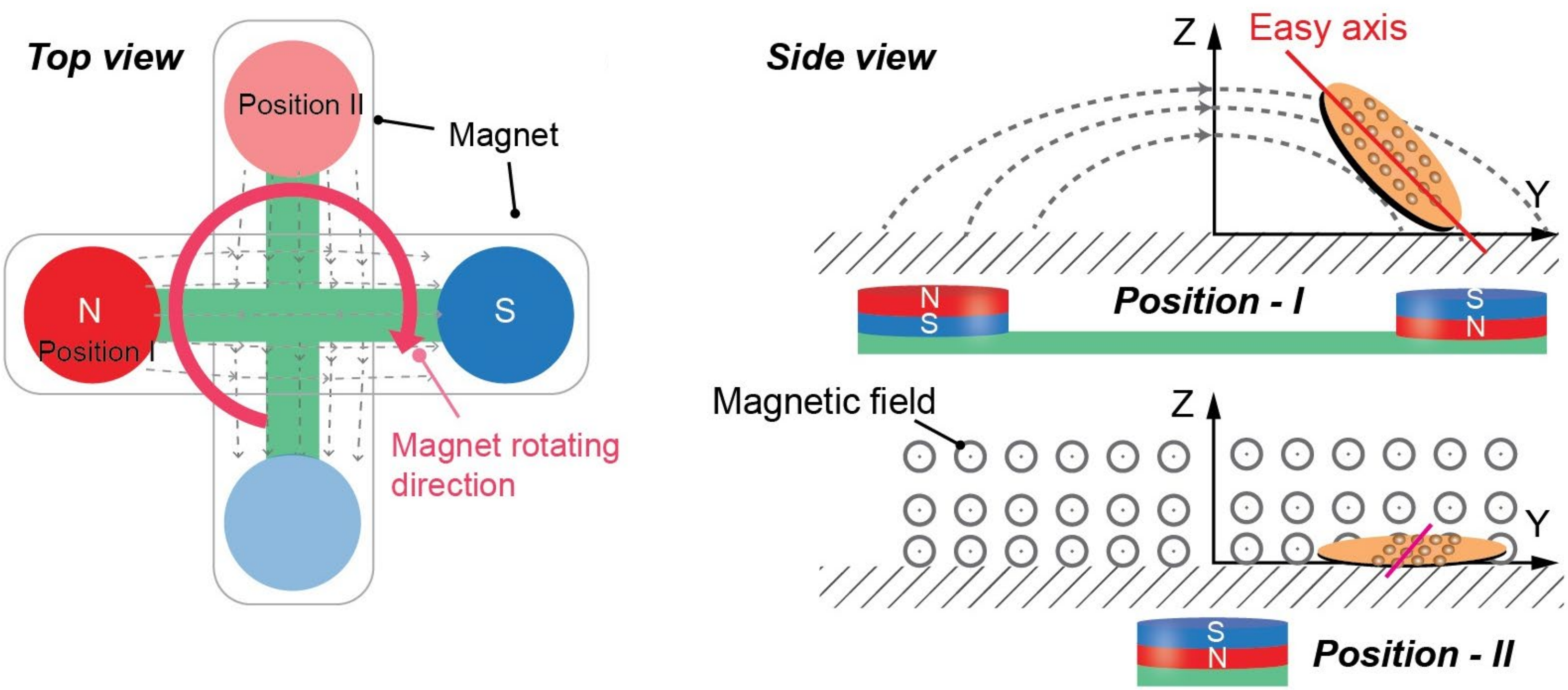
Results: Mechanism of the Wobbling Revolution Stance



- **Ordered magnetic nanoparticles (easy axis) in the disk can enhance the magnetic field-structure interactions**
- **Addition torque is induced to couple the structure orientation with the magnetic field**

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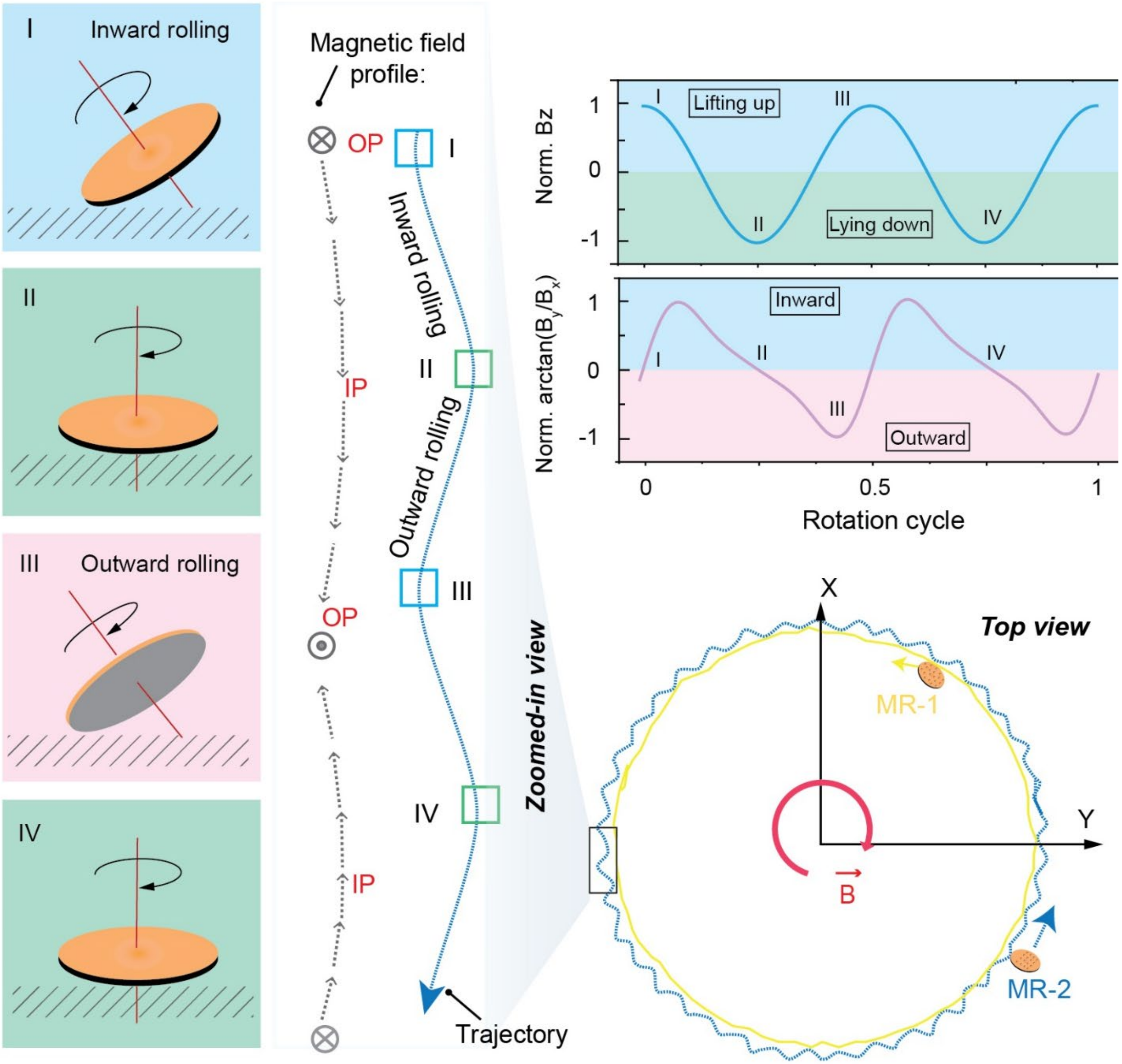
Results: Mechanism of the Wobbling Revolution Stance



- **Bz and By are playing different roles in the steering of the disk movement**

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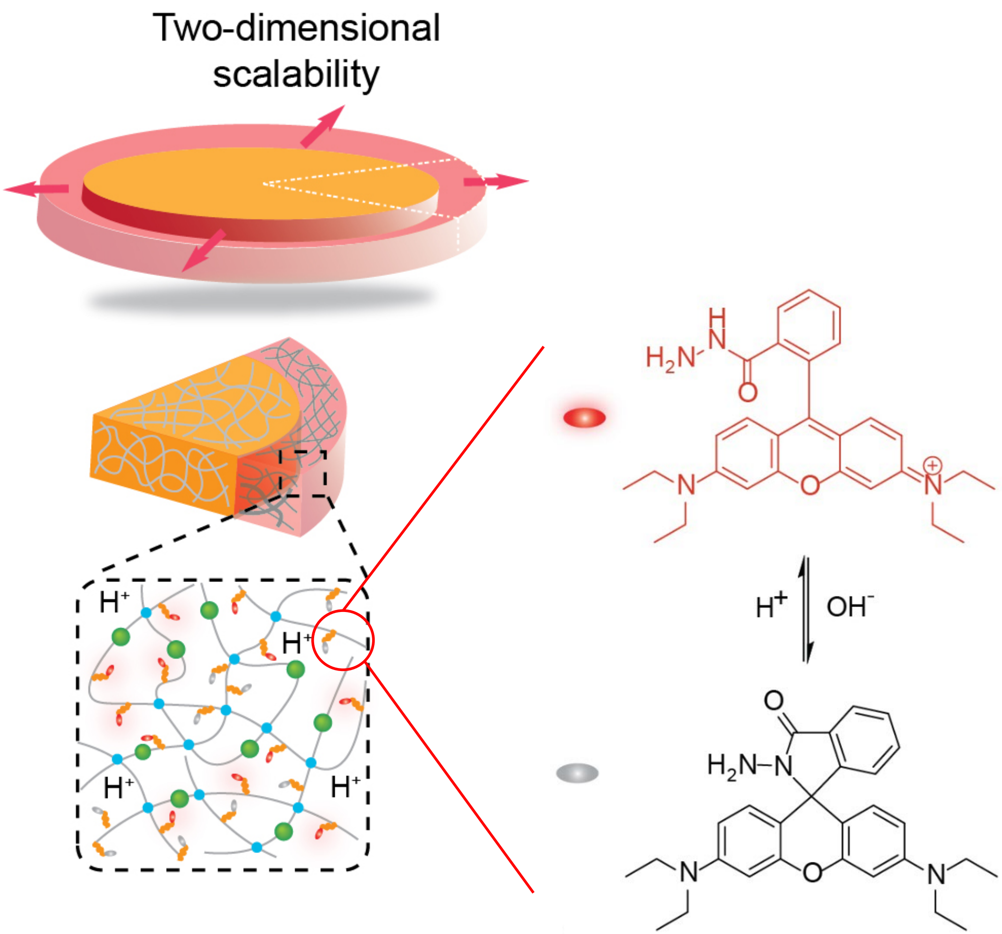
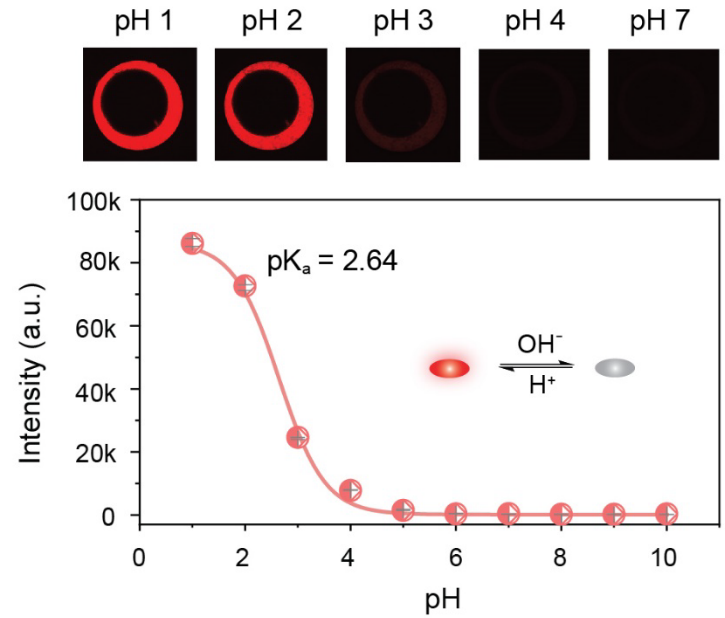
Scalable Function – (I): Disk microrobot scalable for magneto- and sensing- motilities





- **Grafting Rodamine B derivatives to the polymer chains of the hydrogel matrixes**

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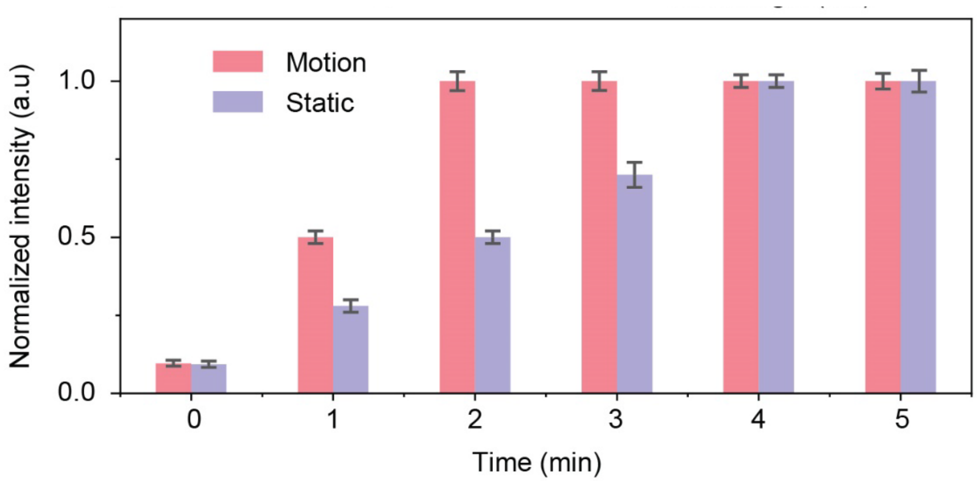
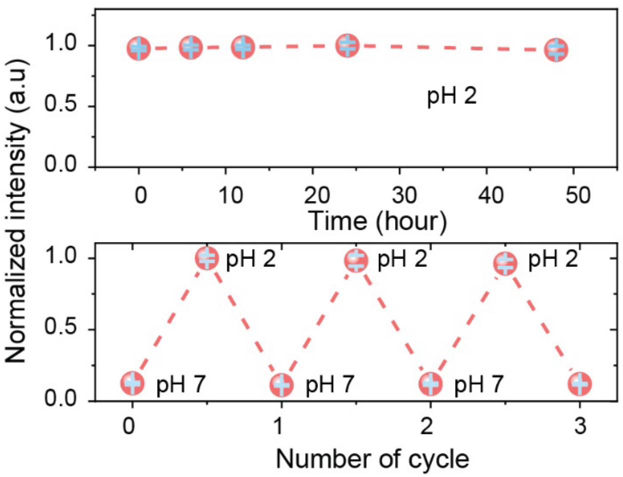
Scalable Function – (I): Disk microrobot scalable for magneto- and sensing- motilities





- **Cooperation of magneto-motility and proton sensing ability**
- **Enhanced reaction rates lead to reduced response time**
- **Reusable and reversible proton-activated fluorescence response**

Unpublished data

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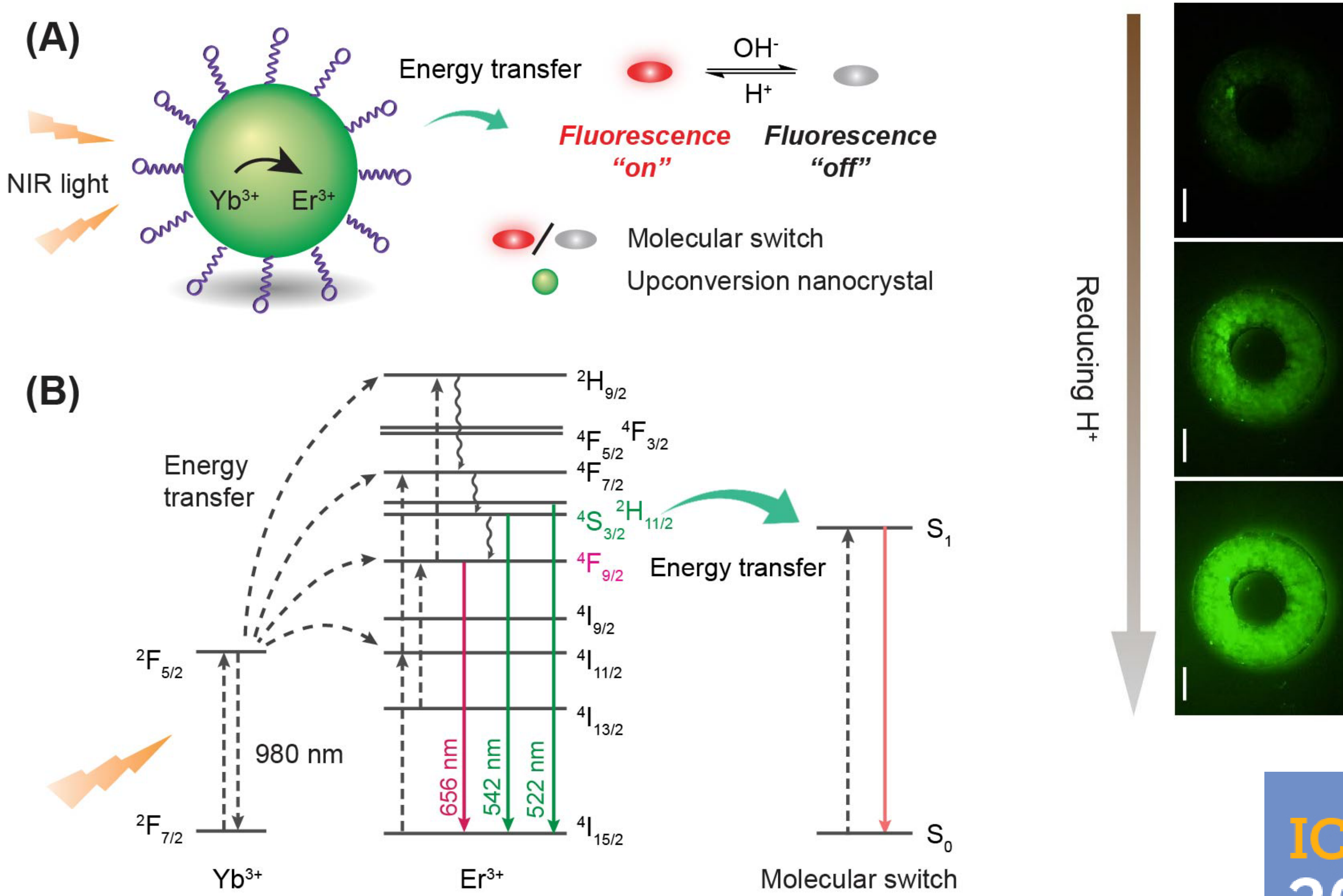
Scalable Function – (II): Ratiometric protochromic microrobots by Embedding Upconversion Nanoparticles



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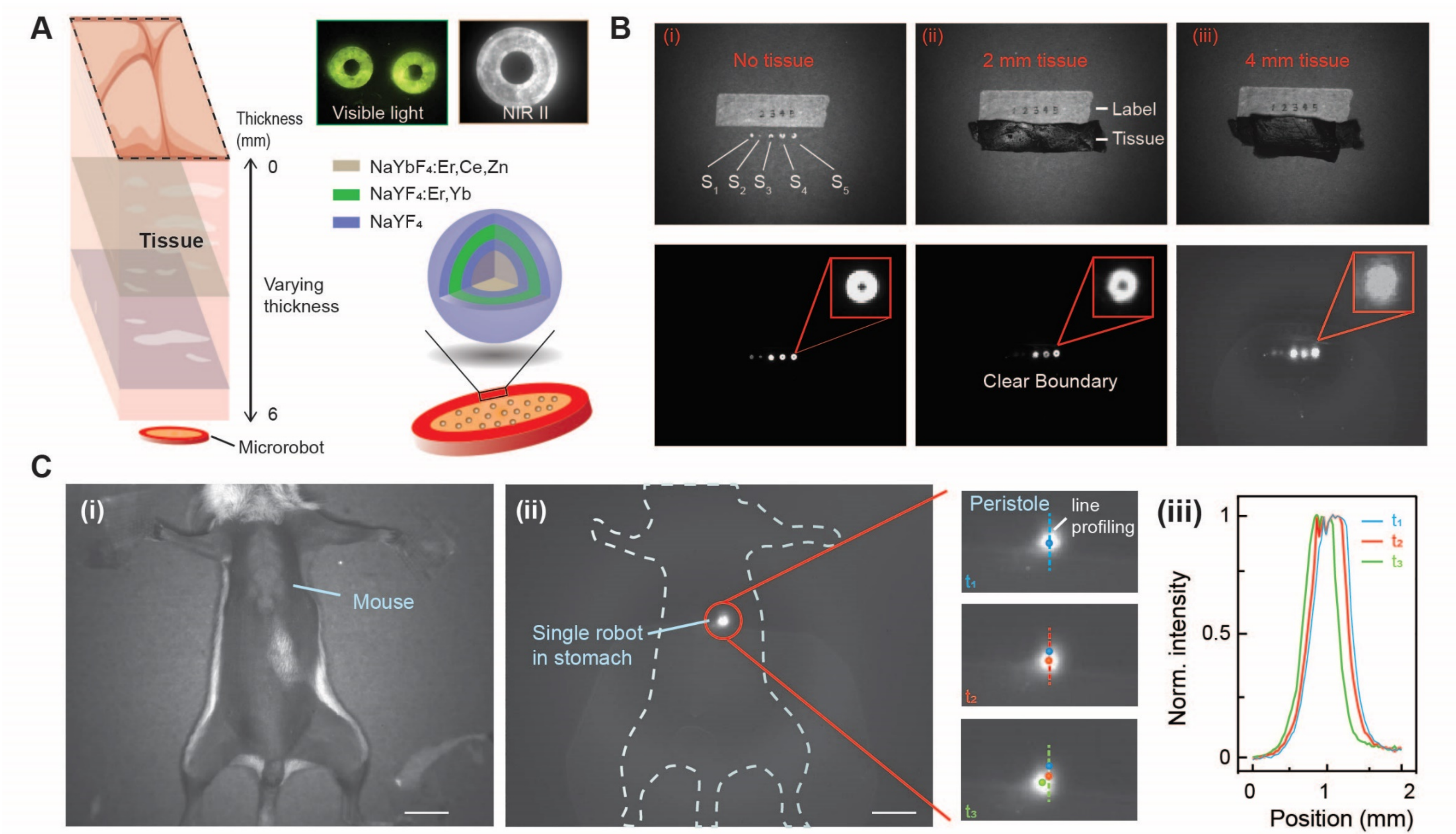
Scalable Function – (III): Deep-tissue imaging of single microrobot by NIR-II nanoparticles



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Conclusions

- We have proposed a stratified disk design of microrobots using a class of microfabricated PEGDA hydrogel polymers.
- This scalable architecture can monolithically integrate a broad spectrum of microrobotic functions with enhanced robotic maneuverability.
- The key to steering the disk structure lies in breaking the symmetry in the magnetic field control and magnetic composition.
- The disk microrobot can be rendered with high motility, manifesting itself as fast locomotion aslant in relative to the surface along the structural sidewall at a speed up to around 36 mm/s, about 60 body length (BL)/s.
- The cooperation of magneto-motility and chemical sensing functions of the microrobots were found to significantly reduce the response time. The use of UCNPs unlocked a ratio-metric protochromic microrobot by NIR excitation, and the use of NIR-II nanocrystals allows deep-tissue imaging of single microrobots.

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Transforming Diagnostics Technologies

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