Microscale Helical Swimmers: Two-Photon Fabrication and Magnetic Actuation

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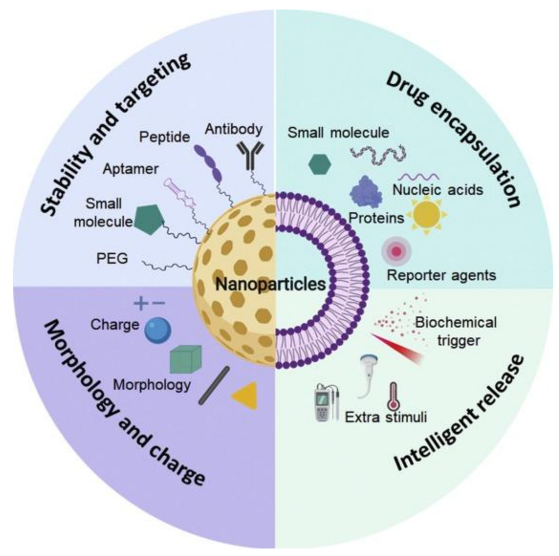
Introduction

- Micro and nanoswimmers have been increasingly utilized to navigate the complex viscous fluids of the human body for biomedical applications.
- Despite progress, current synthetic microswimmers still suffer scaling and control limitations.
- The morphology and highly sensitive construction of helical microswimmers fabricated via two-photon polymerization (2PP) address these issues by enabling finely attunable swimming behavior and manufacture control.



Nanoparticles with optimized properties for drug delivery. Adapted from PubMed, by Song *et al*., 2020.

Research Objectives:

- Produce magnetic helical microswimmers under varied printing parameters.
- Characterize swimming performance under different magnetic field conditions to assess controllability.
- Examine how microswimmer conditions influence printability, mechanical properties, and swimming behavior.

Experimental Methods

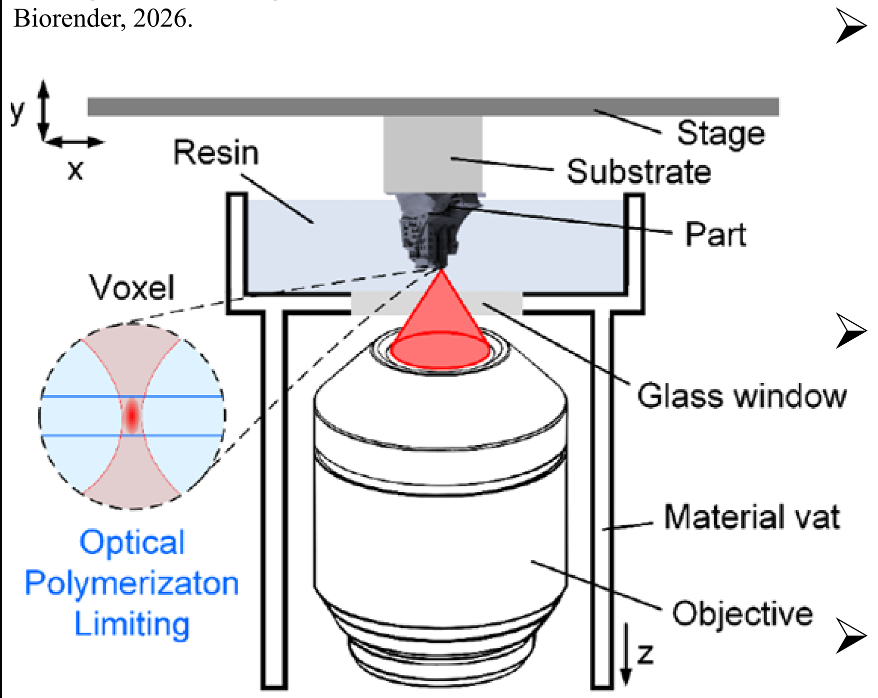
Printing Process for Magnetic Helical Microswimmers

A 2-photon resin, selected based on refractive index and drug-loading potential, is prepared with superparamagnetic iron oxide nanoparticles.

The resin is transferred to PDMS chamber atop a glass substrate.

The printing matrix is loaded into the 2-photon printer and parameters such as laser power, scanning speed, and layer resolution are varied to evaluate effects on swimming performance.

Printing Process for Magnetic Helical Microswimmers. Biorender, 2026.

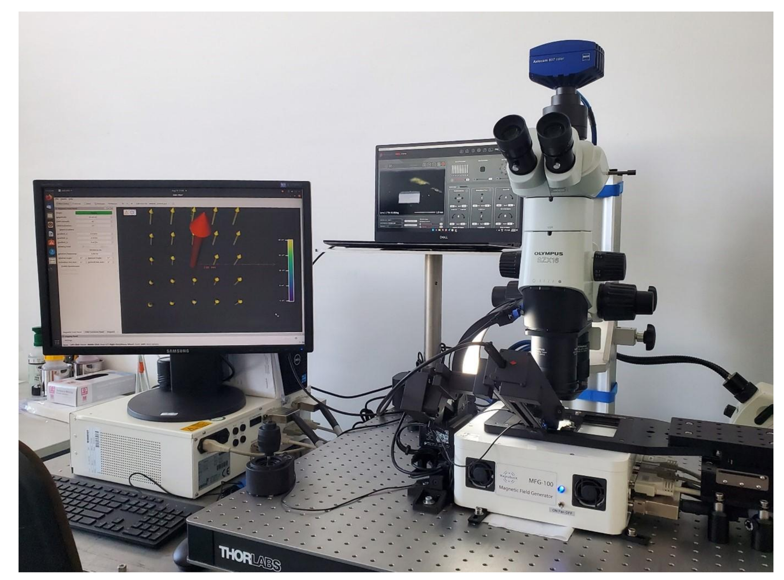


Two-Photon Polymerization. Adapted from Texas A&M Univ., by Woo, S., 2024.

- To print, a focused, pulsed infrared laser follows a user-programmed array path to focus on the resin, which is transparent to its wavelength.
- Photoinitiator molecules at the laser focal point absorb two infrared photons simultaneously, generating free radicals that initiate crosslinking and locally harden the resin.
- The substrate is removed from the printer and chemically processed to isolate the printed helices.

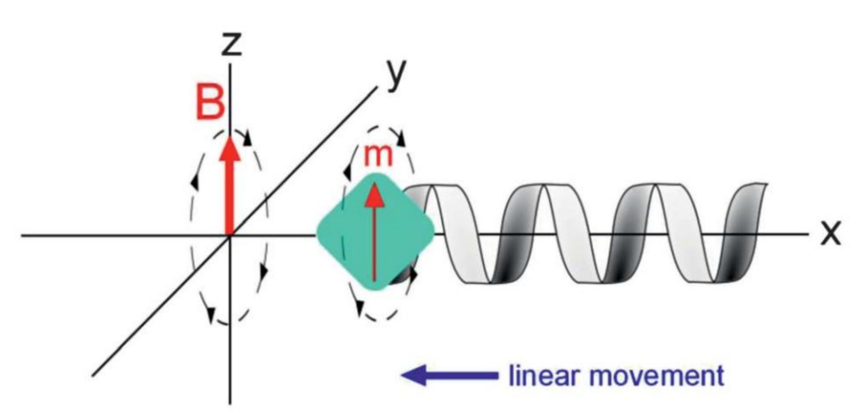
Characterization

Magnetic Field Generation



Magnetic Field Generator. Adapted from ETHzürich, by Heyderman, L., *et al*.2024.

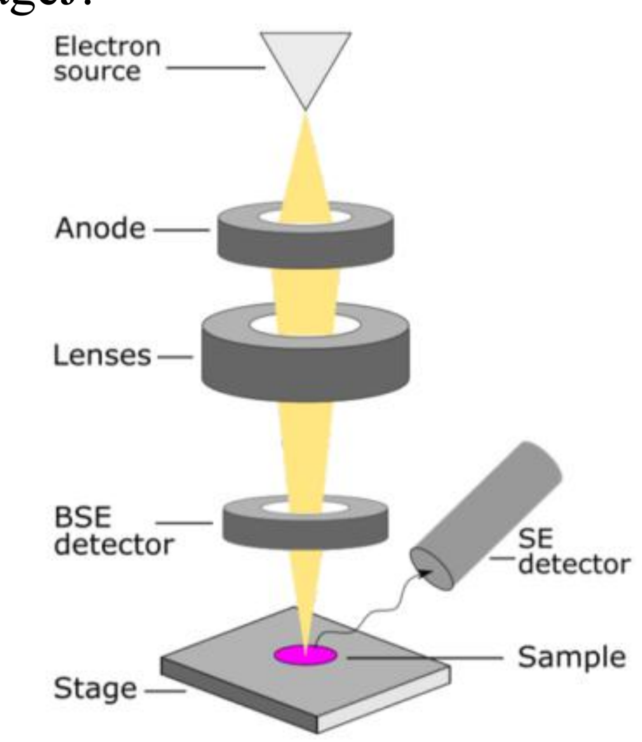
- Helices are actuated using a magnetic field generator.
- Uniform rotating external magnetic field is applied.
- Step-out frequency (point where applied magnetic torque is no longer strong enough to keep micromotors synchronized with the field and velocity is decreased) is determined using ImageJ.



Helix in Rotating Magnetic Field. Adapted from ResearchGate, by Rikken *et al*., 2014.

Scanning Electron Microscopy

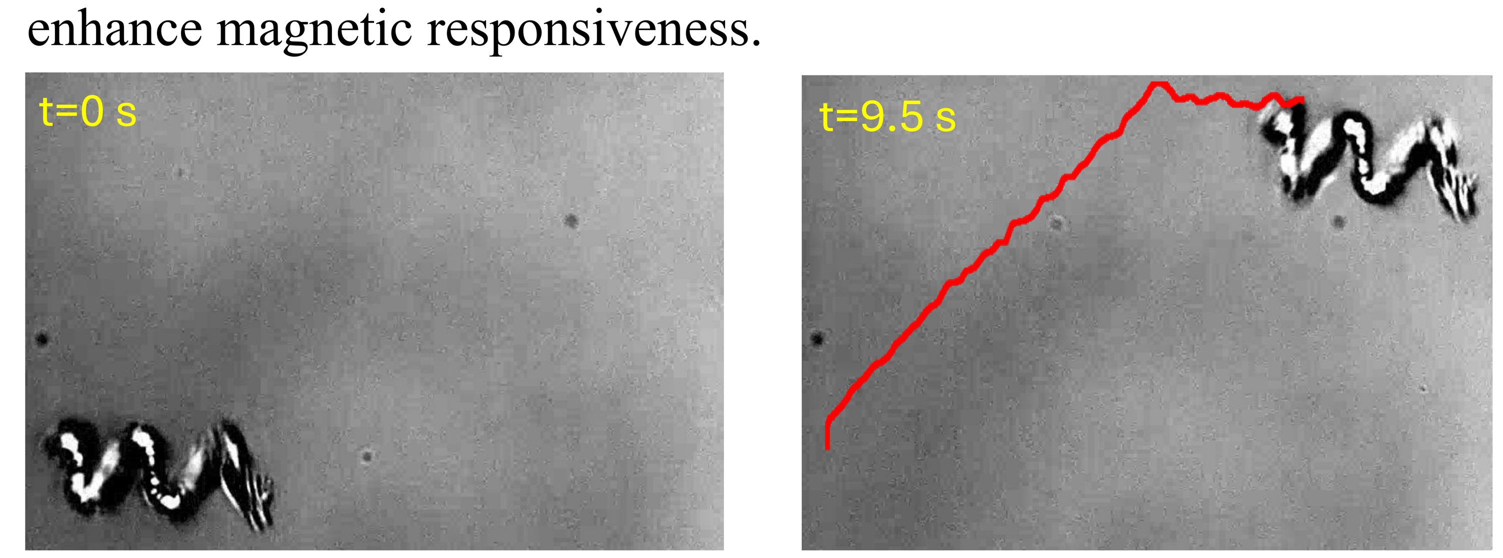
- Allows for high-resolution microswimmer imaging to characterize and measure the helices.



Scanning Electron Microscope. Adapted from IPLTS, 2025.

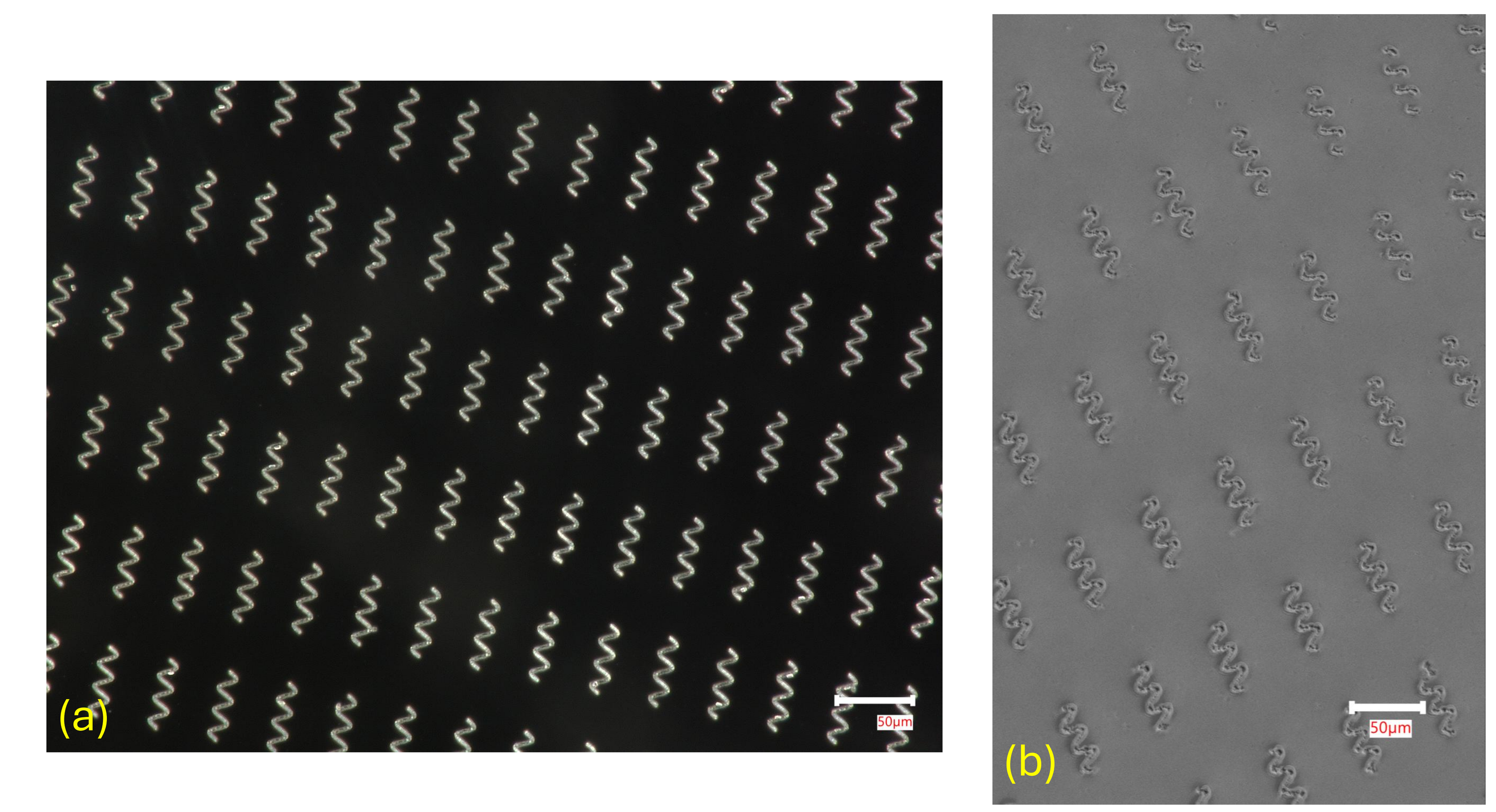
Results & Discussion

- Helical magnetic microswimmers were successfully fabricated with a commercial 2PP resin using a 2PP 3D Printer.
- Experiments were performed with varying magnetic nanoparticle (MNP) concentrations to identify the maximum printable loading without structural failure.
- The maximum swimming speed was estimated to be 10 µm/s at 15 mT.
- In addition to commercial resin, helices were also fabricated using a custom biomatrix polymer-protein system. This study focuses on optimizing key fabrication parameters such as laser power and stage speed.
- Increasing magnetic nanoparticle concentration was observed to enhance magnetic responsiveness.



Swimming behavior of a printed helix under rotating magnetic field

Results & Discussion Cont'd



Printed helix array using (a) commercial resin and (b) custom biomatrix

- Magnetic Nanoparticles were gradually added to the matrix and dispersed using ThinkyMixer.
- Helical structures were printed on glass coverslips and visualized via optical microscope.

Conclusion & Future Work

- Future work includes improving MNP dispersion to enable higher loading in the commercial resin and custom biomatrix. Alternative approaches, including surface attachment of MNPs, are also being explored to enhance magnetic responsiveness.
- The parameters identified for successful printing will support the development of customizable microswimmer platforms for both in vitro and in vivo applications.

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