Dong Lab

Emily Buckner

VANDERBILT INSTITUTE FOR SURGERY AND ENGINEERING

Wirelessly Actuated Soft Miniature Robots with Integrated Microfluidic Modules for Targeted Drug Delivery

Emily Buckner[1, 3, 5], Boyang Xiao[1,3,4], Yilan Xu[1,3,4], Xiaoguang Dong[1,2,3,4]

[1] Department of Mechanical Engineering, Vanderbilt University, Nashville, TN 37212, USA
[2] Department of Biomedical Engineering, Vanderbilt University, Nashville, TN 37212, USA
[3] Vanderbilt Institute of Nanoscale Science and Engineering, Vanderbilt University, Nashville, TN 37212, USA
[4] Vanderbilt Institute for Surgery and Engineering, Vanderbilt University, Nashville, TN 37212, USA
[5] Department of Mechanical, Aerospace and Biomedical Engineering, University of Tennessee, Knoxville, TN 37916, USA

VANDERBILT UNIVERSITY

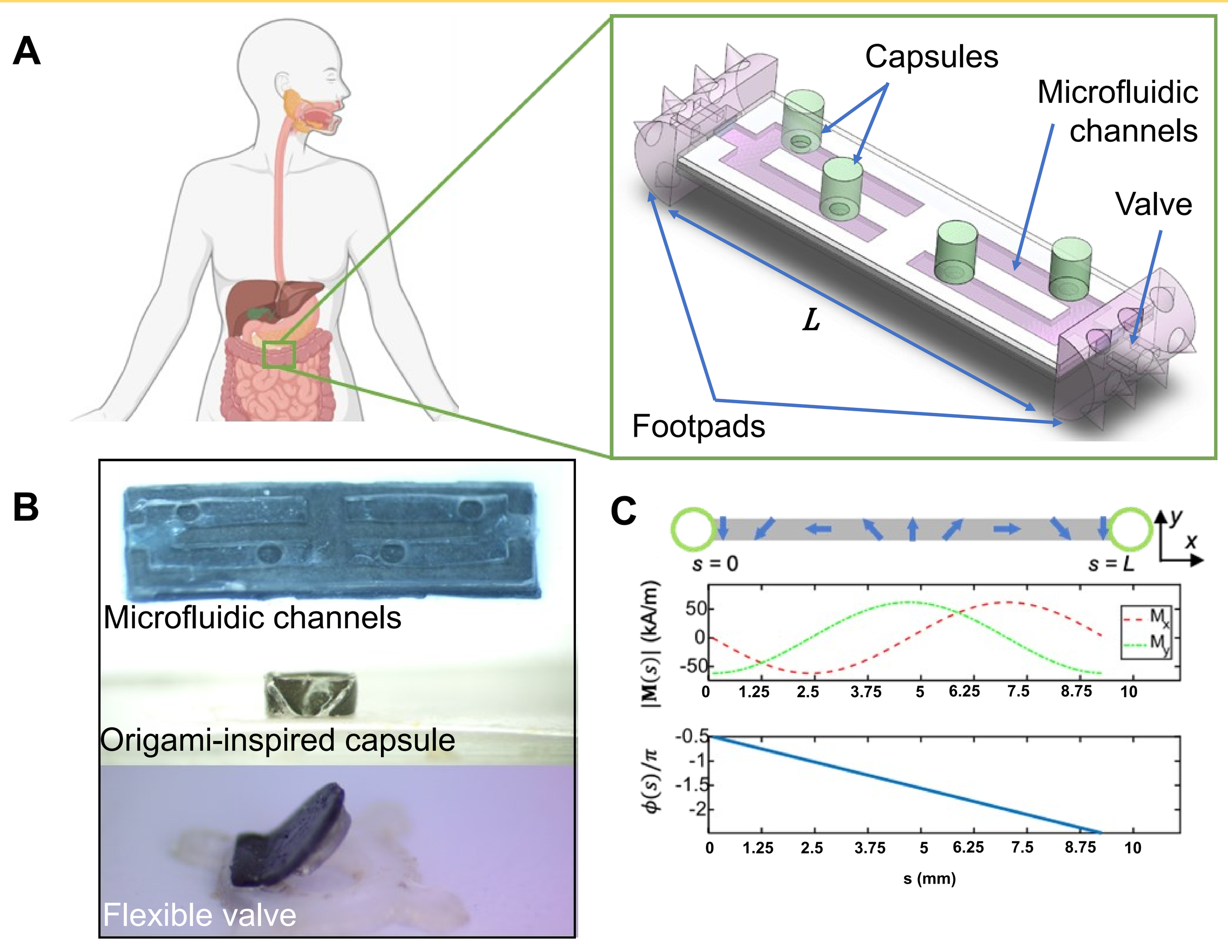
VINSE

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Background and Motivation

- **Background**: Magnetically actuated soft robots are capable of traversing complex and confined environments within the human body with minimal invasion.
- **Existing works**: Previous works have demonstrated soft millirobots with precise spatial control achieved by multimodal locomotion. Upon reaching a target, the soft robot can be controlled to adhere to and penetrate in the mucus layer for drug delivery [1].
- **Challenge:** While existing soft robots are capable of locomotion and long-term retention at desired locations within the body, integrating an additional drug delivery mechanism requires further development of the design, fabrication, and control of the robot.
- **Proposed method**: Here we present a wireless soft robot integrated with microfluidic modules to achieve liquid cargo transport and on-demand drug release via multimodal locomotion and penetration of the mucus layer.

Research Significance



Major contribution:
- The integration of microfluidic modules into a wireless soft robot enables on-demand and targeted drug delivery.
- This robot demonstrates optimized material properties and dimensions to facilitate multi-modal locomotion and targeted drug delivery functions.

Practical application
- This wireless soft robot holds great potential to navigate complex terrains and serve therapeutic functions in biomedicine.
- On-demand and targeted drug delivery can minimize the side effects of overdosing during medical treatments.

Fig. 1 Concept of the wireless soft robot. A. Delivery in the gastrointestinal tract and robot design. **B.** Microfluidic modules of the robot. **C.** Magnetization profile design of the robot body.

Design of Microfluidic Channels Inside Soft Robot

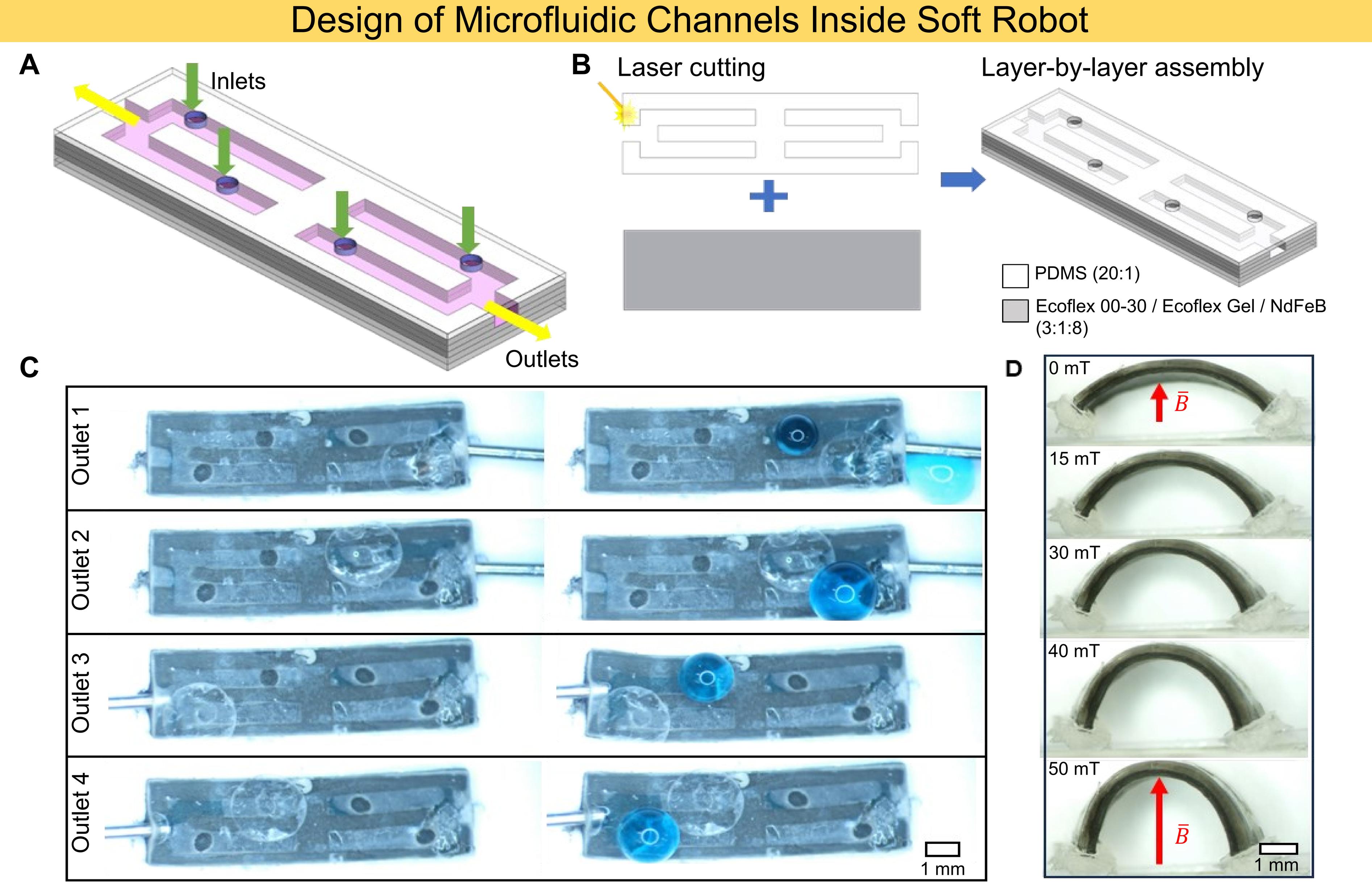


Fig. 2 Microfluidic channels integrated into the soft robot body enable fluid flow from capsules into the robot's surrounding environment. A. 3D rendering of the microfluidic channels. **B.** Schematic outlining the assembly of the robot body with channels. **C.** Connectivity between microfluidic channel inlets and outlets. **D.** The robot body's deformation increases in tandem with the applied magnetic field.

Design of Foldable Structures for Controllable Release of Liquids

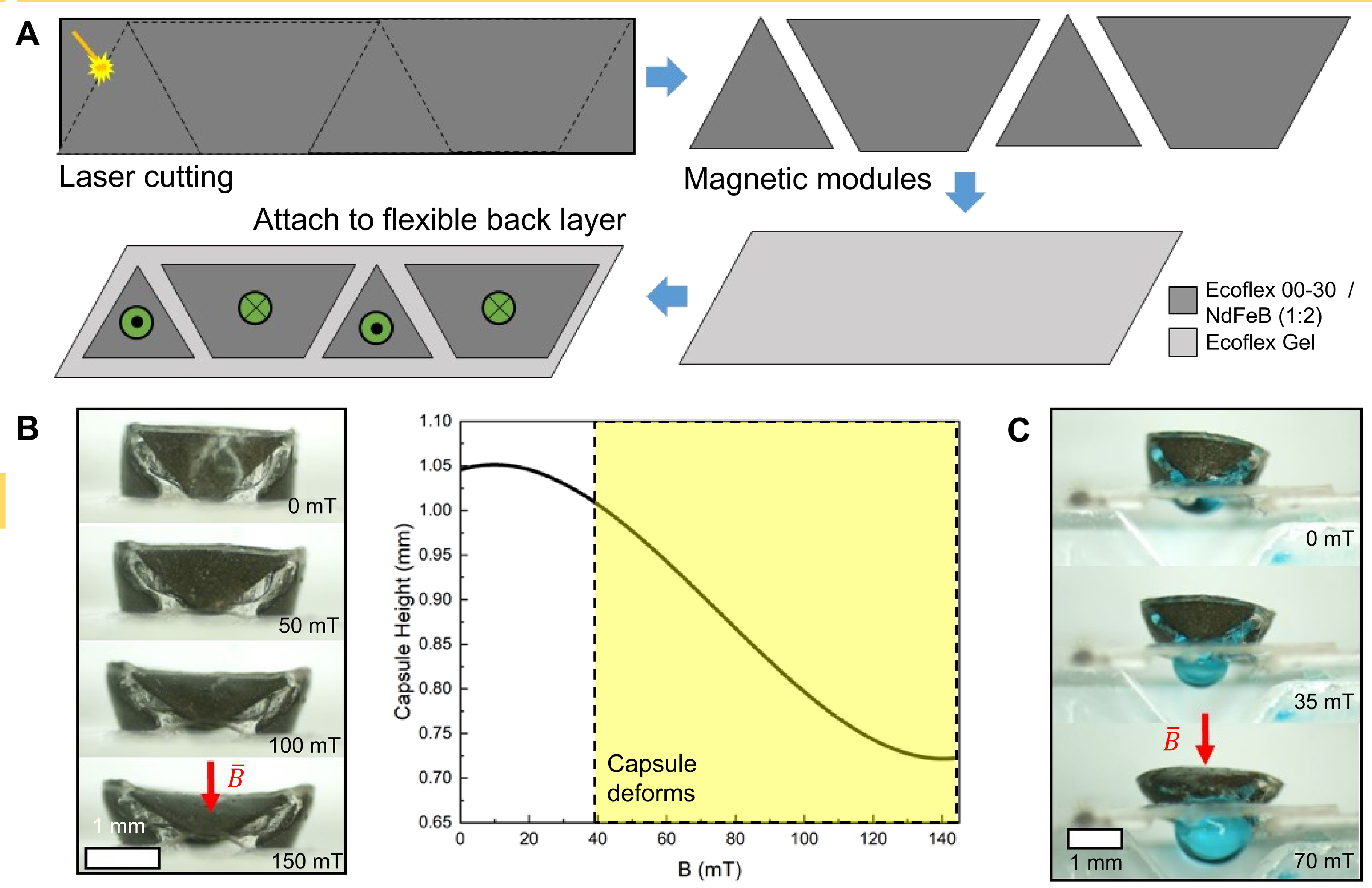


Fig. 3 Design of origami-inspired self-folding capsule for drug container and on-demand release. A. Schematic of self-folding capsule materials, assembly, and magnetization. **B.** The capsule's height decreases as it deforms with increasing magnetic field. **C.** Demonstration of capsule's drug release ability using dyed water as model.

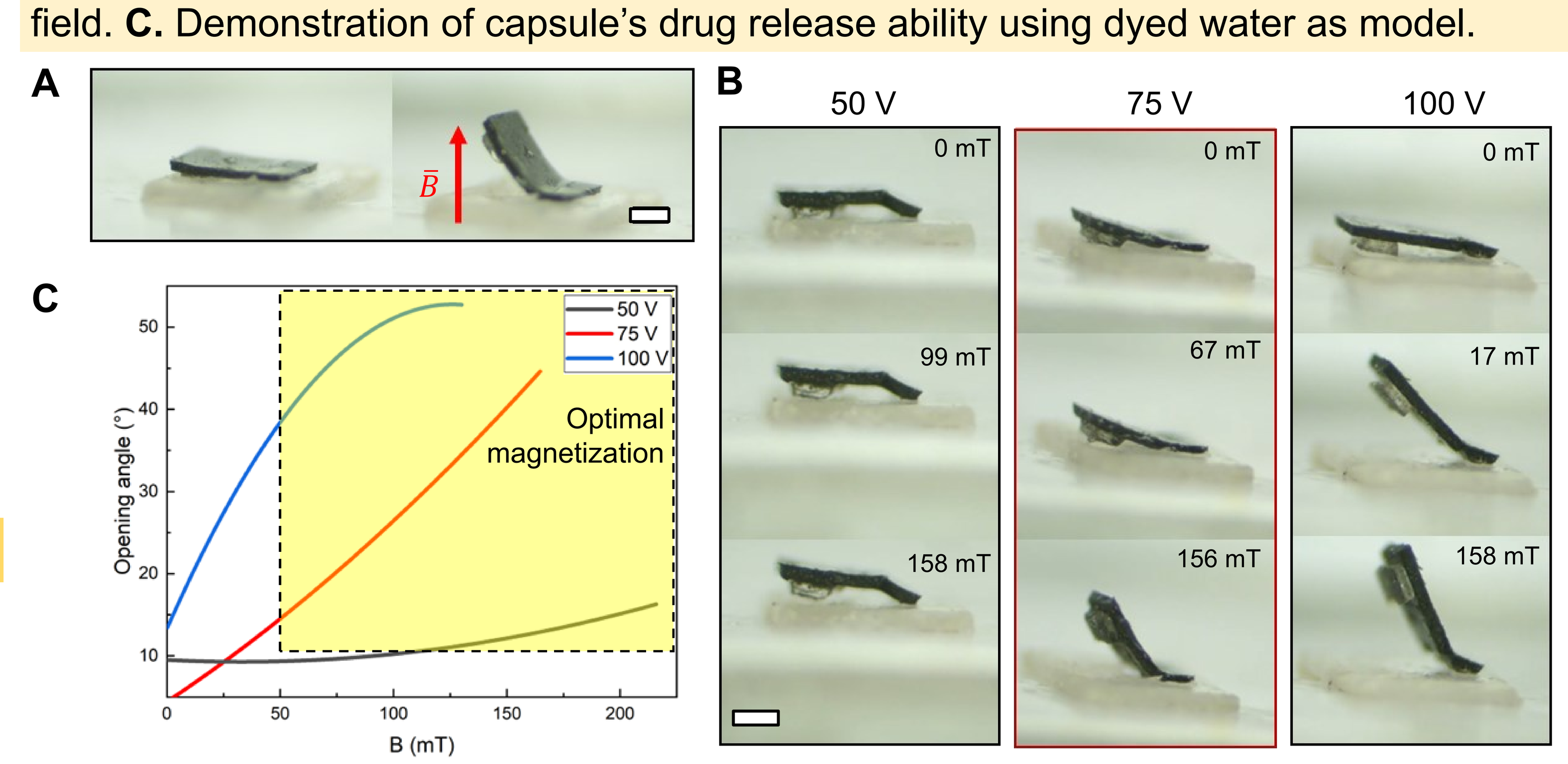


Fig. 4 Design of flexible valve for controllable drug delivery. A. Images of valve in closed orientation compared to open when magnetic field is applied. Scale bar is 0.5 mm. **B.** Optimal magnetization for decoupled actuation is 75 volts. Scale bar is 0.5 mm. **C.** Valve opening angle with respect to magnetic field after magnetization at varying voltages with functioning parameters highlighted.

Drug Delivery Demonstration

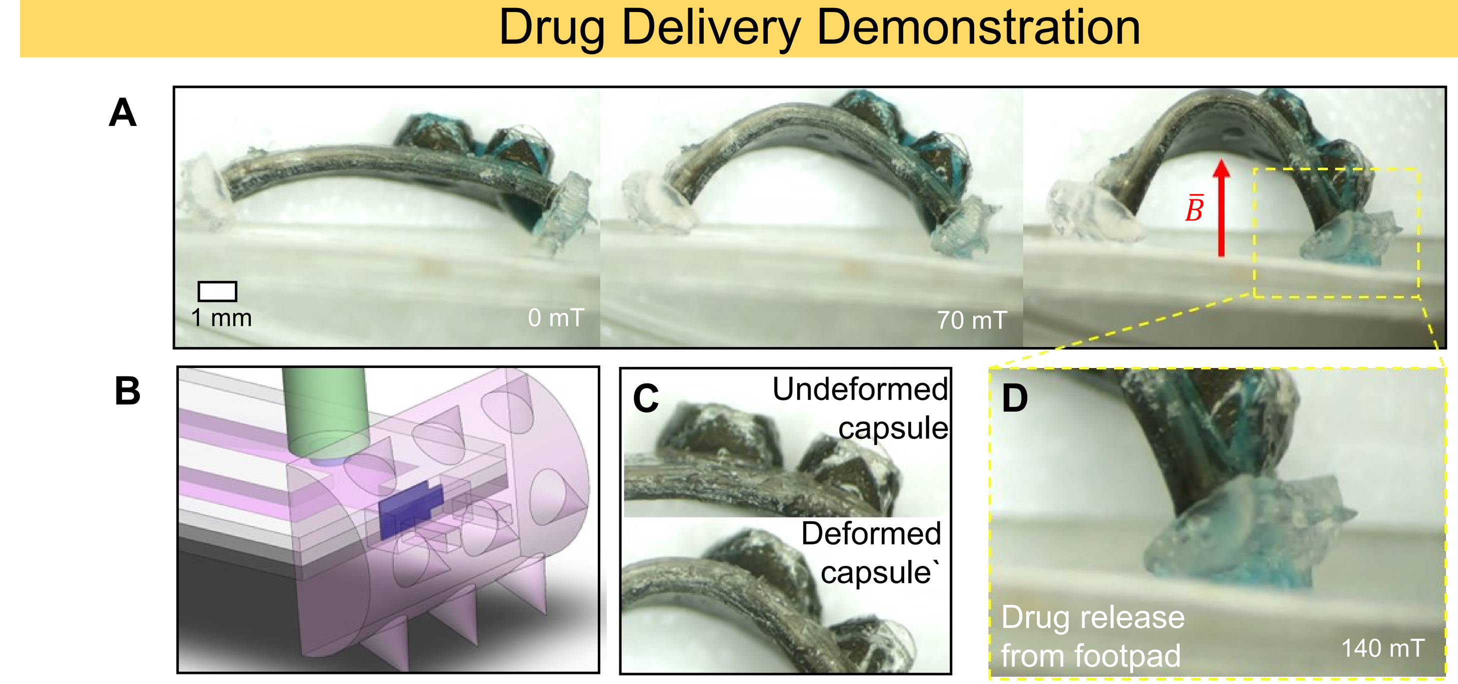


Fig. 5 Decoupled deformation of soft robot body and capsule self-folding. A. Demonstration of robot body deformation follow by drug release at stronger magnetic field. **B.** Rendering of valve integration into robot body. **C.** Images of capsule self-folding after robot body deformation. **D.** Close up image of dyed water released from footpad after capsule self-folding.

Multimodal Locomotion in Phantom and on Ex Vivo Porcine Tissue

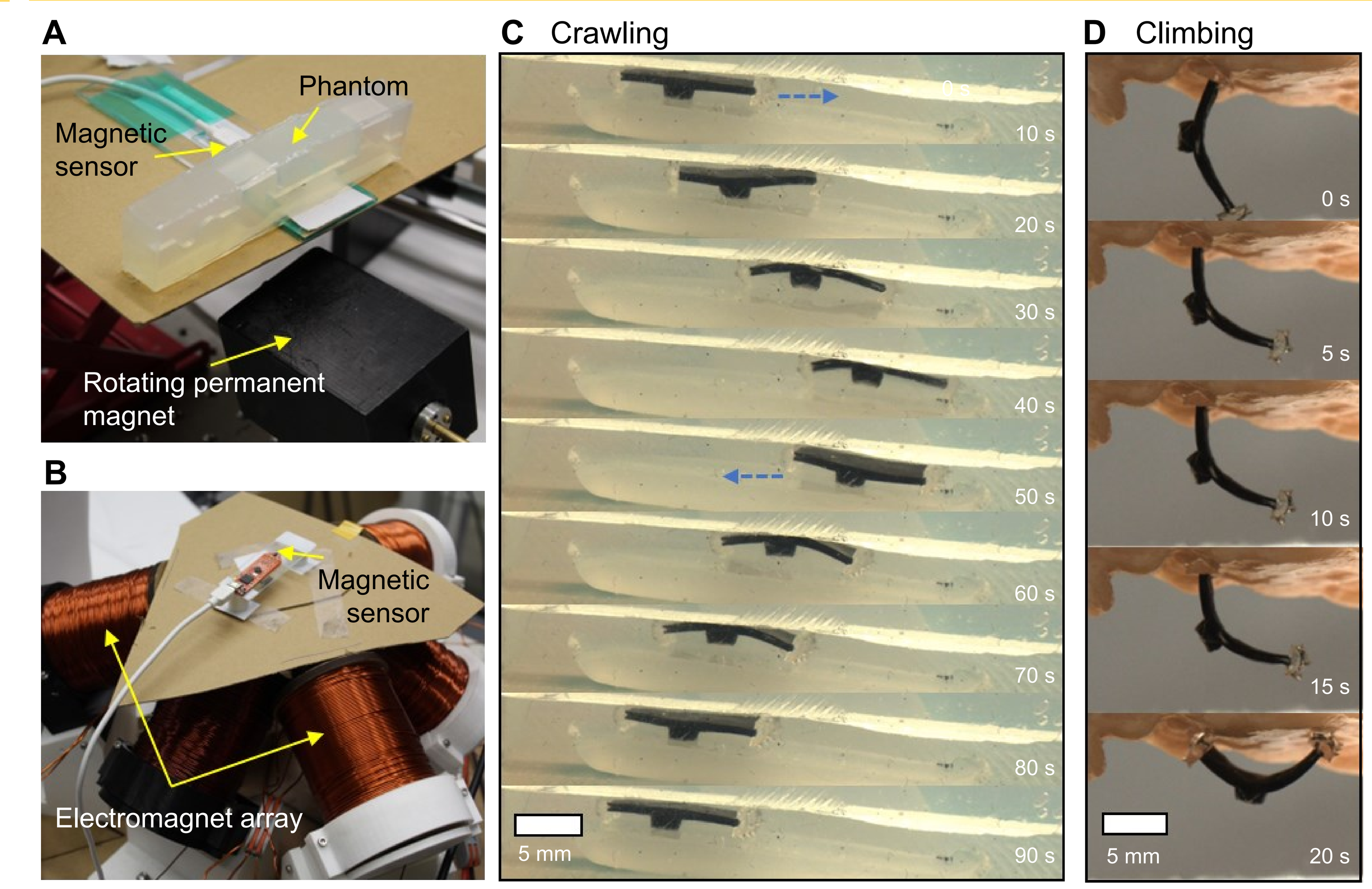


Fig. 6 Multimodal locomotion of soft robot. A. Experimental set up for crawling locomotion performed in phantom structure with use of rotating permanent magnet. **B.** Experimental set up for climbing locomotion performed on porcine tissue with use of electromagnet array. **C.** Crawling locomotion demonstrated in confined space. **D.** Demonstration of climbing locomotion and tissue adhesion for close, sustained contact on porcine colon tissues.

Conclusions

- This multifunctional soft robot design is capable of **multimodal locomotion and targeted drug delivery in complex, confined environments**.
- The integration of microfluidic modules including **channels, an origami-inspired self-folding pump, and a flexible valve** potentially enables controlled drug release within the body for therapeutic functions.
- The robot design and use of footpads allows for climbing along complex surfaces such as soft biological tissues in the GI tract.
- By tailoring the magnetization profile of each individual component, decoupled actuation can be achieved such that the robot can locomote without releasing the drug. Once the desired location is reached, a stronger magnetic field can be applied to open the valve and deform the capsule, enabling on-demand drug delivery.
- The use of biocompatible materials such as PDMS allows for transition to in vivo testing.

Future Work

- Further characterization is required to optimize the coordinated magnetization of the microfluidic modules.
- The proposed multifunctionality of our soft robot can be expanded for other medical operations.
- After validation of the robot's functions in phantom structures, in vivo clinical tests can be performed.

Acknowledgements

- Special thanks to the Vanderbilt Institute of Nanoscale Science and Engineering and the members of the Dong Lab.
- This research was funded by the National Science Foundation Grant (Grant: NSF-DMR 1852157) and the Vanderbilt Institute for Surgery and Engineering.

References.

[1] Y. Wu#, X. Dong#, J. Kim#, C. Wang, Z. M. Sitti*. "Wireless Soft Millirobots for Climbing Three-dimensional Surfaces in Confined Spaces". *Science Advances*, in press, 2022.

xiaoguang.dong@vanderbilt.edu