Mizzou
University of Missouri - Columbia

Autonomous Systems for Intelligent Inspection and Multimaterial Assembly

Presented by

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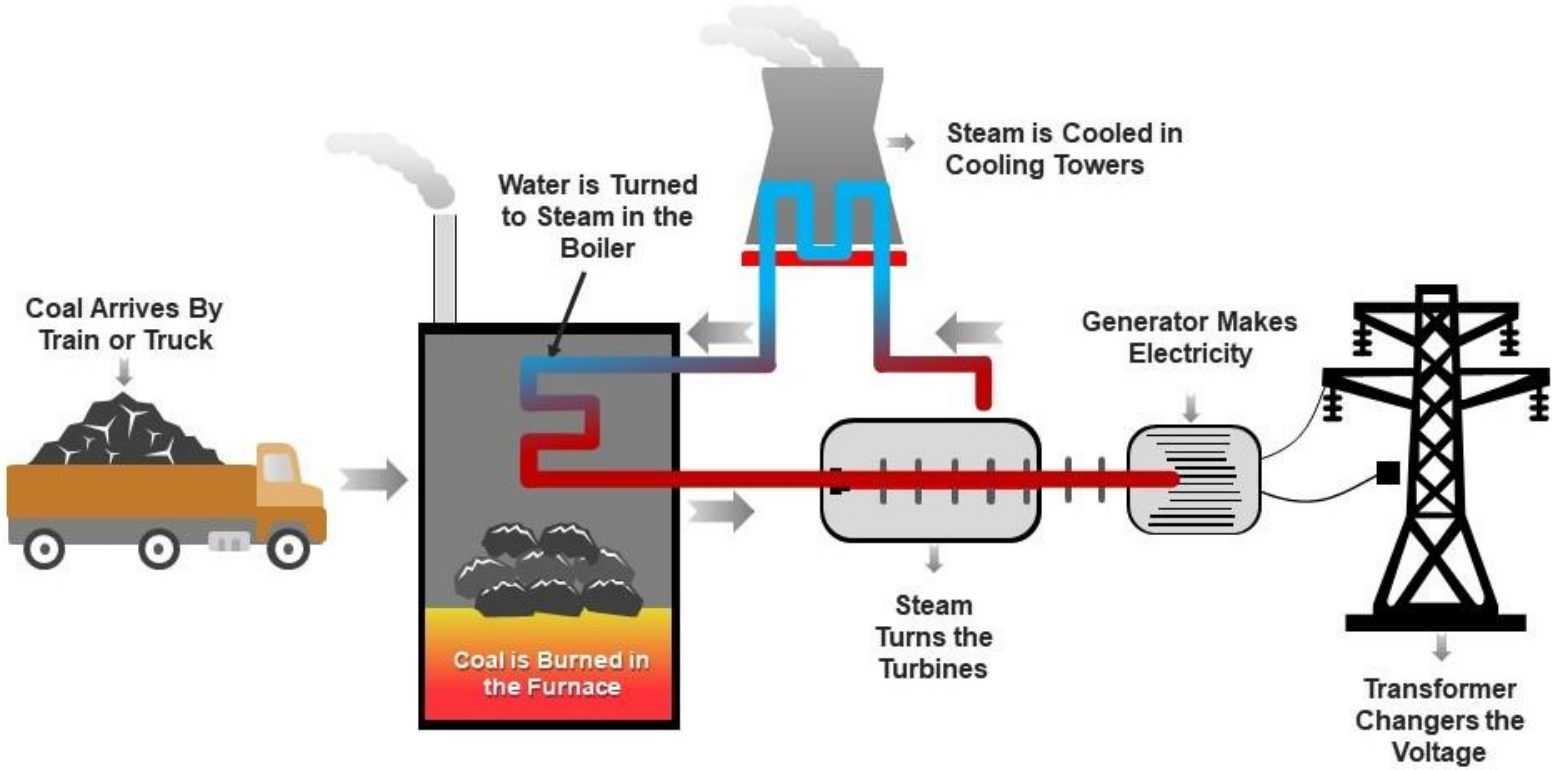
Advisor: Jian Lin, PhD

Project 1: Introduction

How does a coal-fired power plant work?



Project 1: AI-enabled Autonomous STHE defects detection

Motivation

1.Shell and tube heat exchanger (STHE) failures affect power plant efficiency.

2.STHE inspection heavily rely on experienced technicians.

3.Eddy current testing (ECT) inspections demand steady operational parameters.

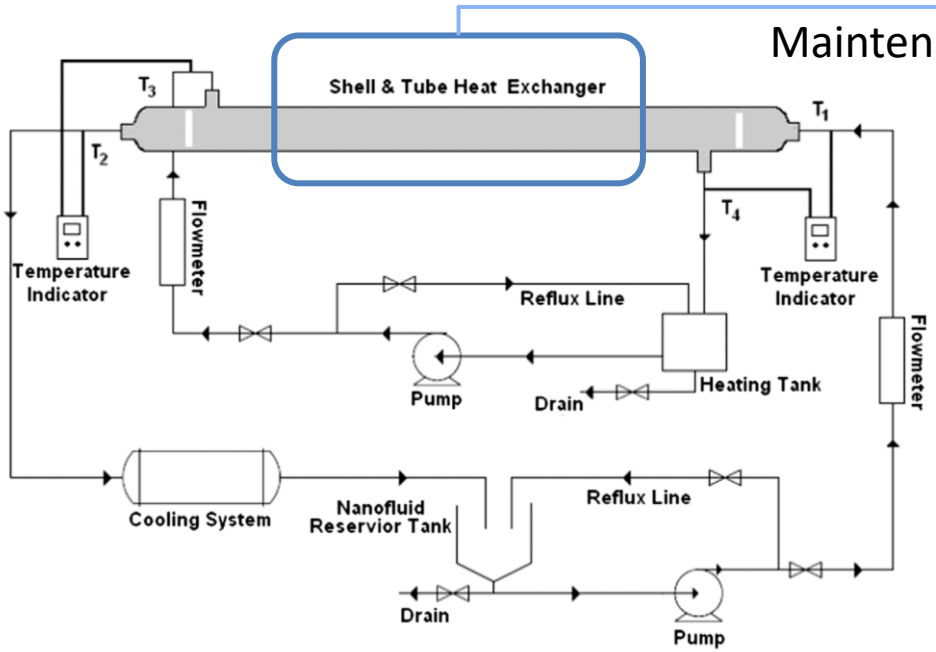


Fig.1 diagram of a typical power plant

Farajollahi, B, , et al. *International Journal of Heat and Mass Transfer* 53.1-3 (2010): 12-17.

Fig.2 Inspecting STHE with ECT

Demo image from Russell NDE System Inc

Previous advances in tackling the challenges

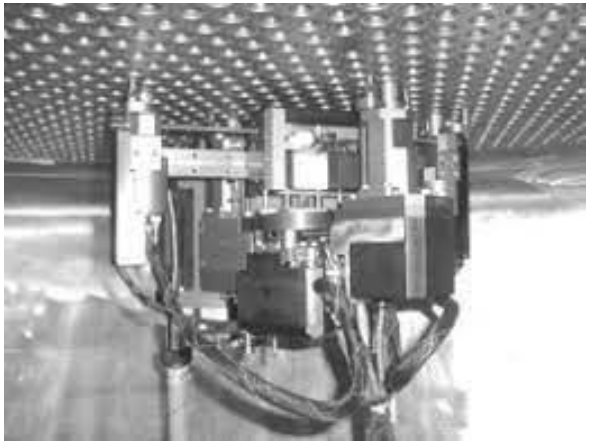


Fig.1 STHE flaw detection crawler robot developed by *Westinghouse corporation*

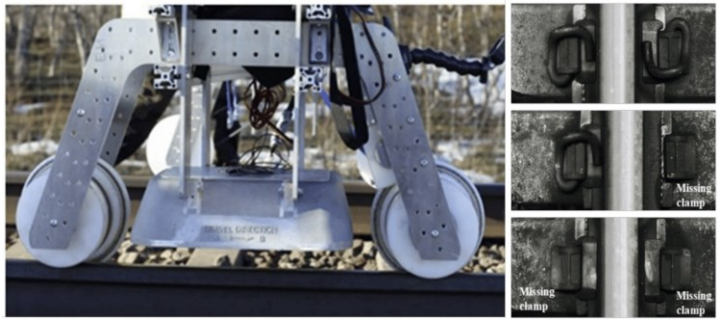


Fig.3 Railway missing fastener detection with AI and ECT

Chandran, P, et al. *Applied Sciences* 11.9 (2021): 4018.

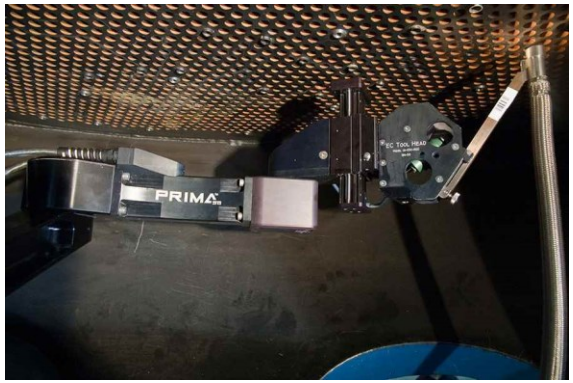


Fig.2 PRIMA system for STHE inspection developed by BWX technologies

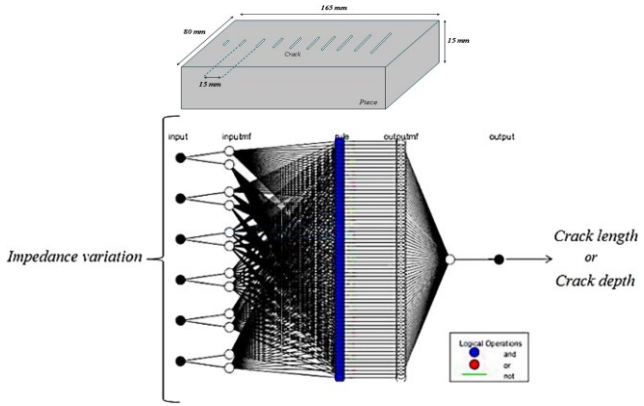
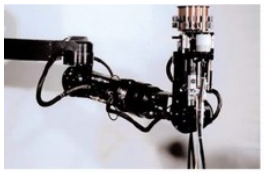
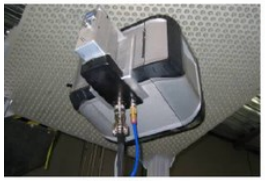


Fig.4 Surface crack characterization with AI and ECT

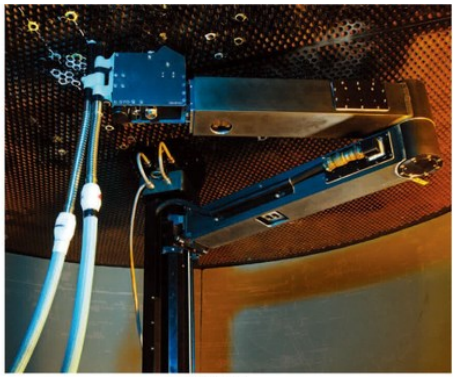
Barrarat, Fatima, et al. *Devices and Fields* 35.6 (2022): e2876.

Knowledge gap and proposed solutions



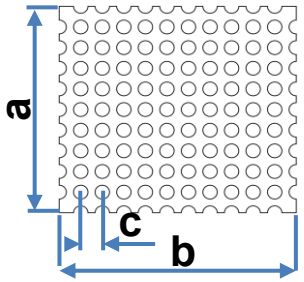


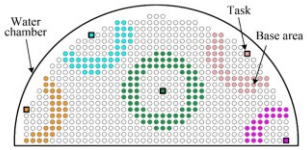
ZR-100



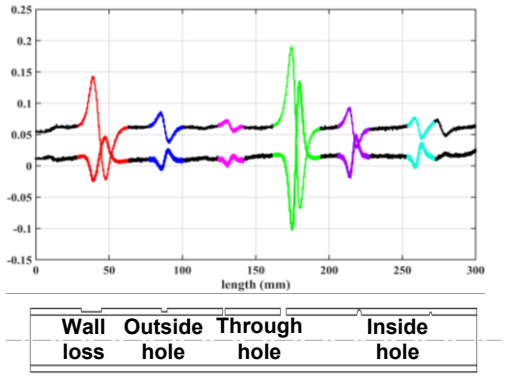
ROGER

1. Previous robots required manual setup before starting work.





2. Previous robots required knowledge of tube configuration



3. Significant amount of data required for model training

Goal and proposed solutions:

Develop an autonomous robotic system:

- Robot with high degree of freedom (DOF).
- ECT manipulator with consistent delivery rate.
- STHE localization using machine vision.
- Deep learning for data analysis.

Mechanical system design

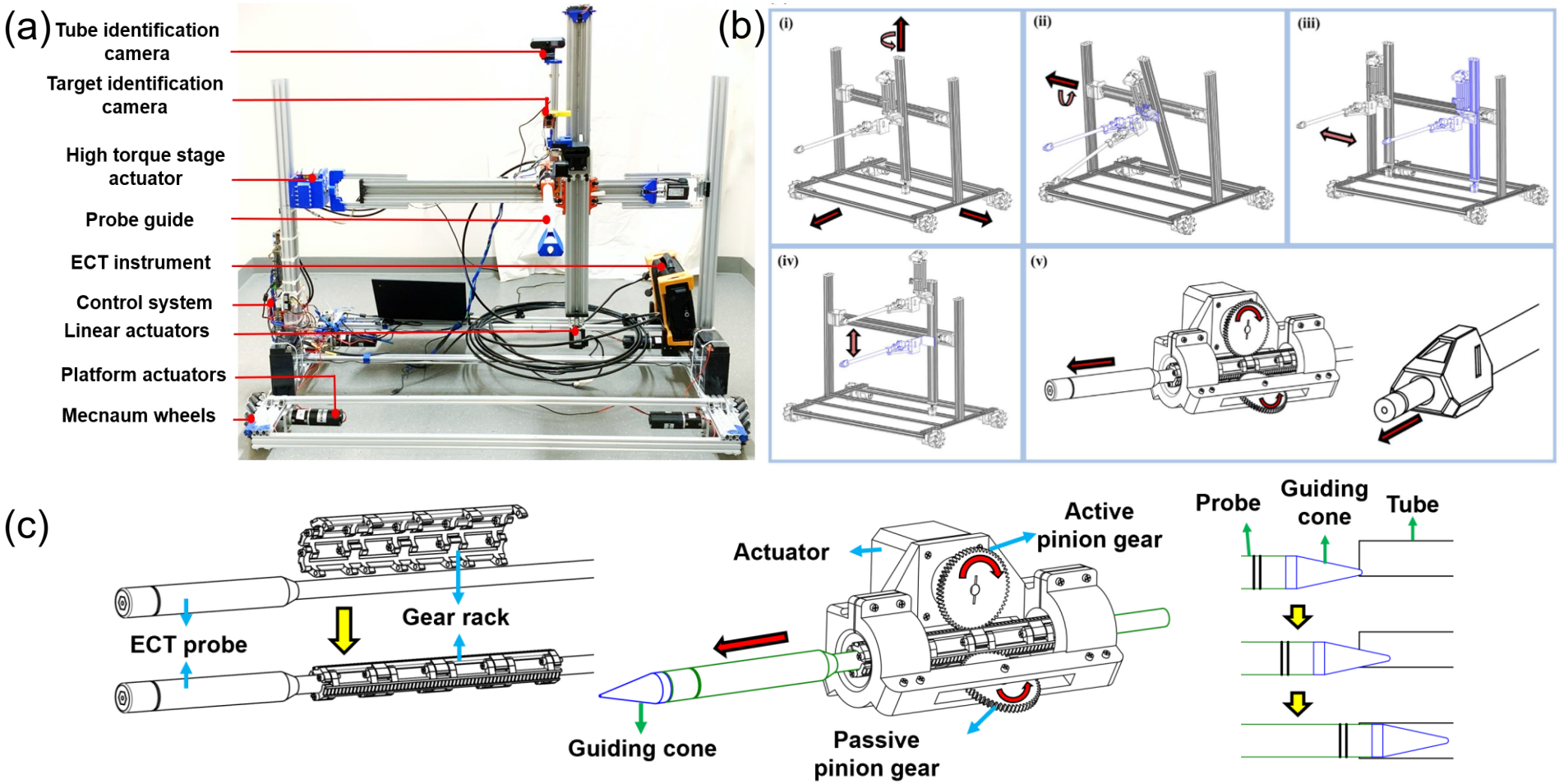


Fig. (a) Prototype of the developed robotic system, (b) distribution of the 7 DOF, (c) constant speed ECT delivery mechanism

Control system design and integration

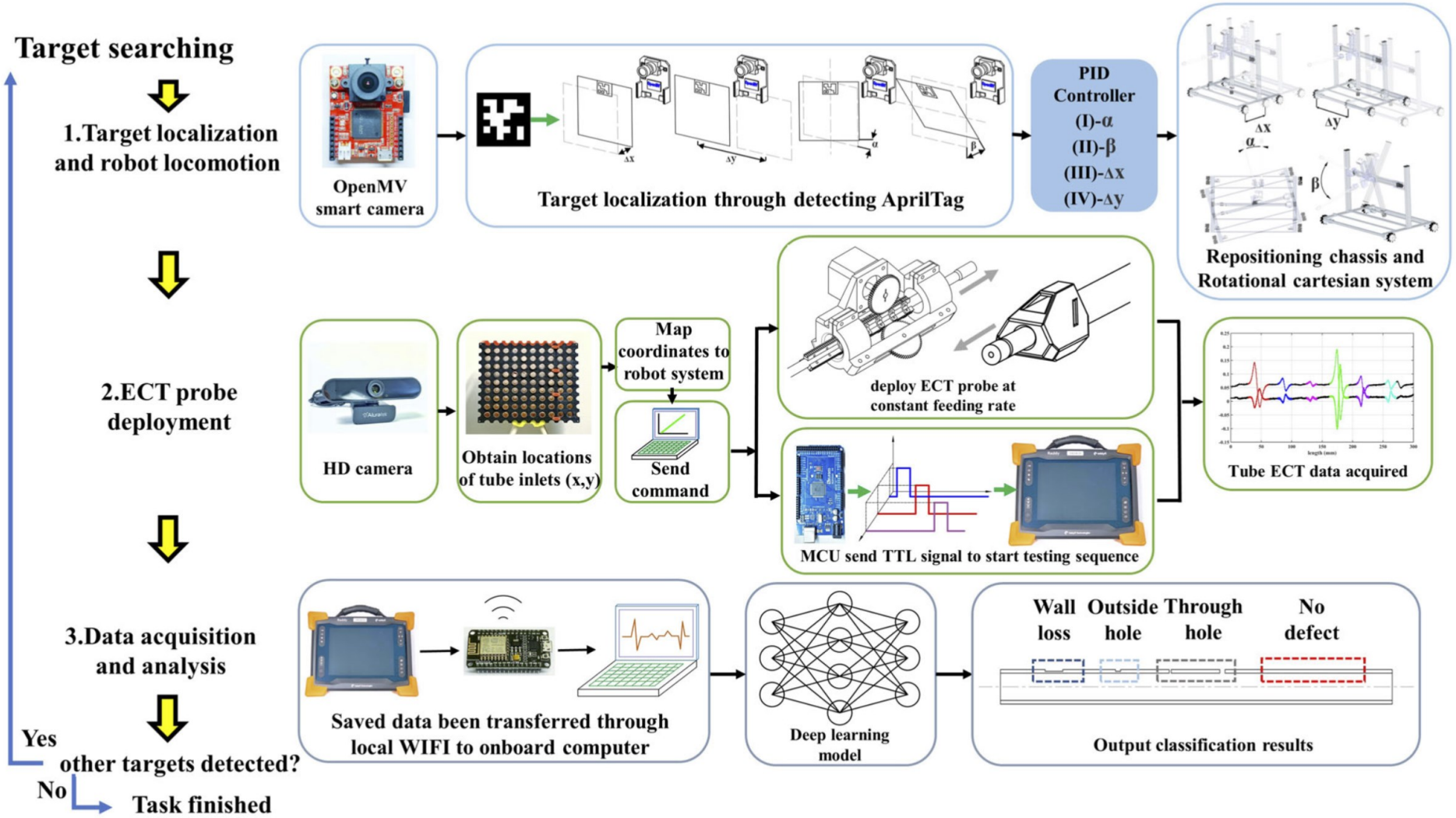


Fig. task sequence of the robot for autonomous STHE inspection

Data augmentation and deep learning model training

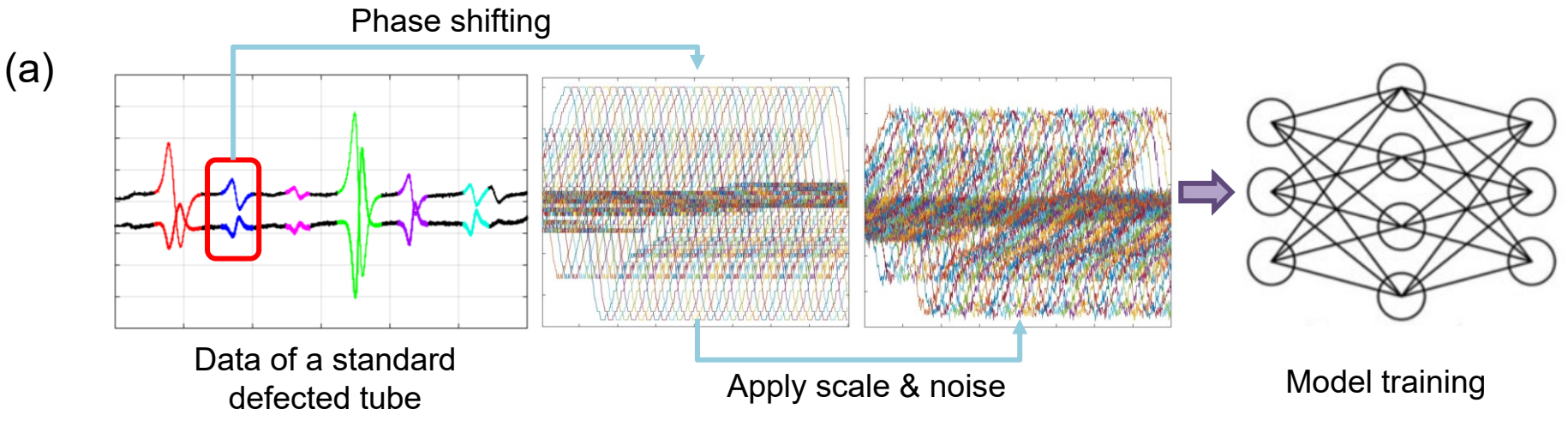
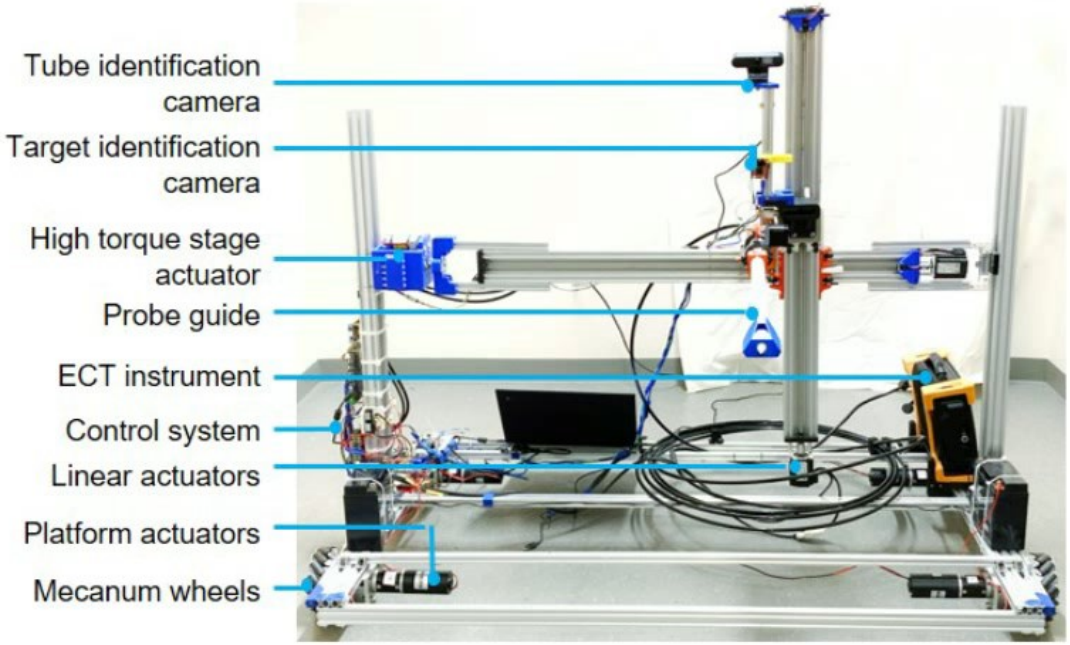
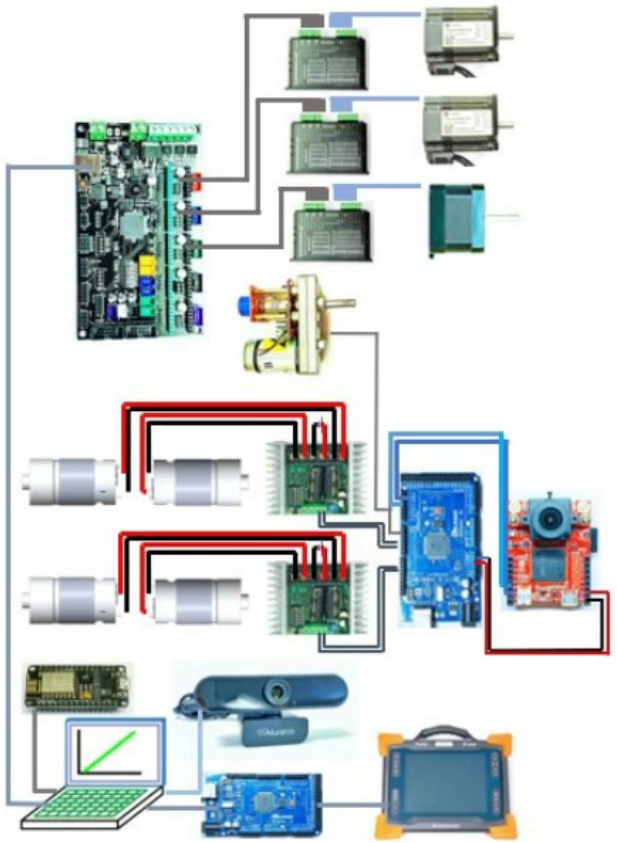


Fig. (a) data augmentation process, (b) ECT data of 4 types of tubes, (c) CNN architecture

Video demonstration: Autonomous STHE inspection

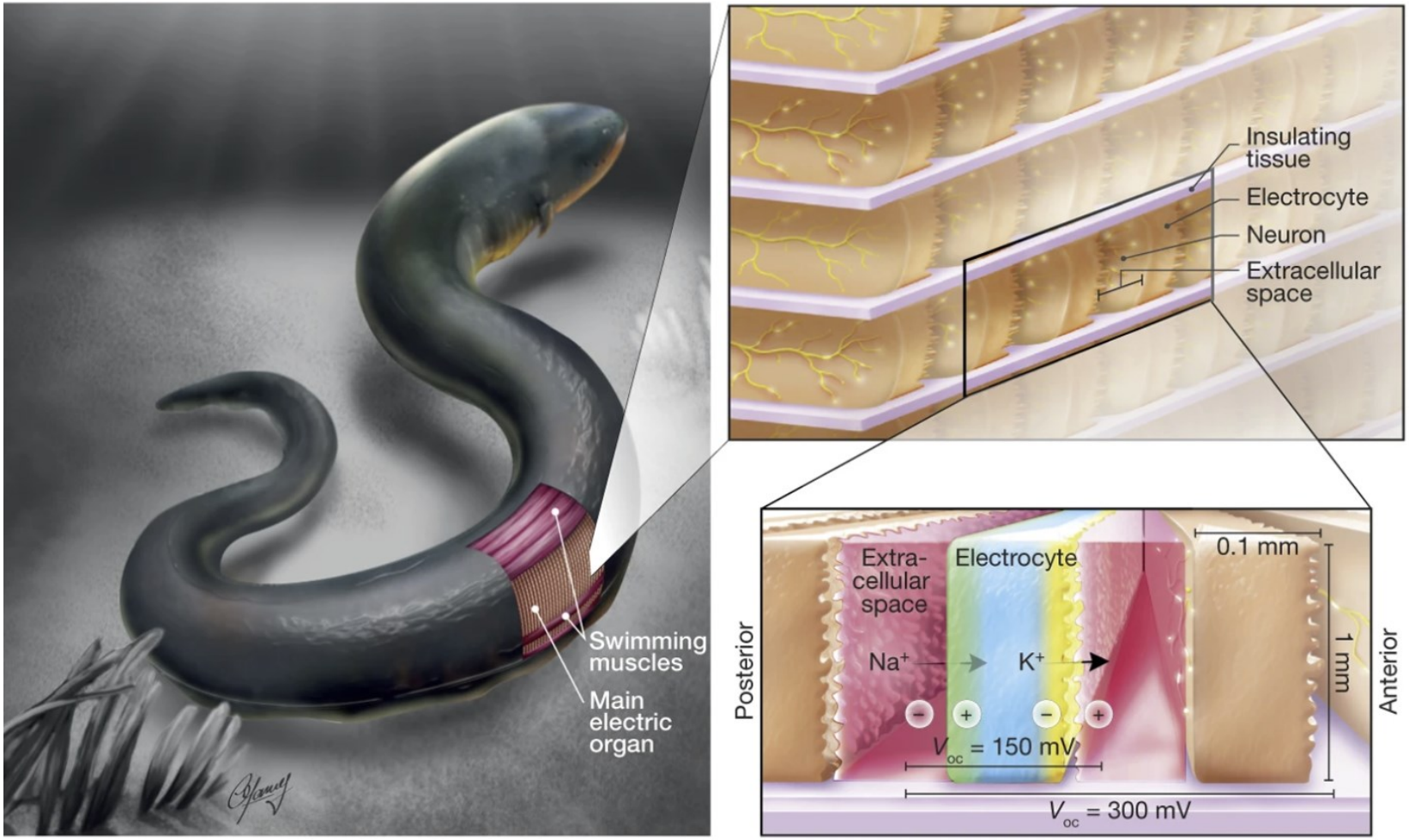




Autonomous System Layout

Zheng, B., et al. *Journal of Field Robotics* 39.8 (2022): 1165-1177.

Structural and functional components of an electric eel

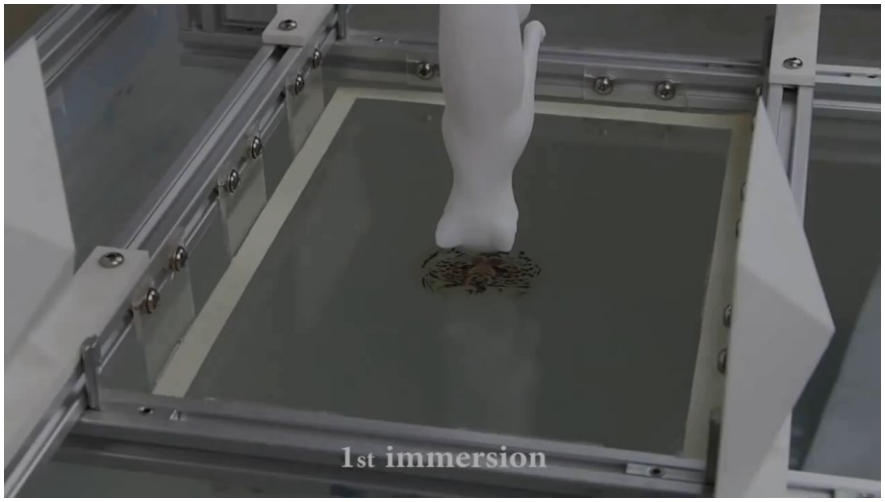


Schroeder, T, BH, et al. *Nature* 552.7684 (2017): 214-218.

Project 2: Fabrication of structural and functional materials

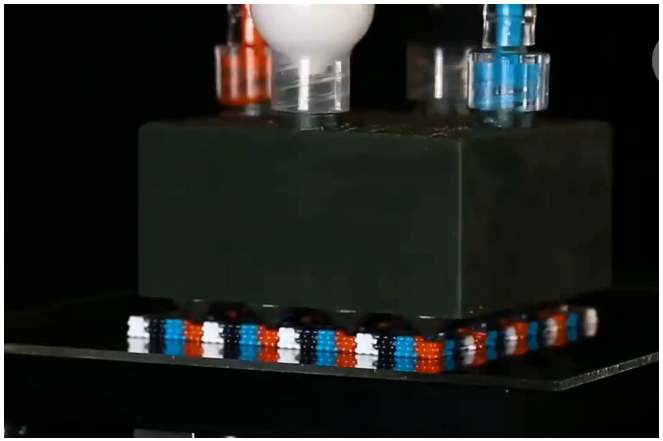
Vid.1 Aerosol jet printing

Paulsen, J. A., et al. *2012 Future of Instrumentation International Workshop (FIIW) Proceedings*. IEEE, 2012.



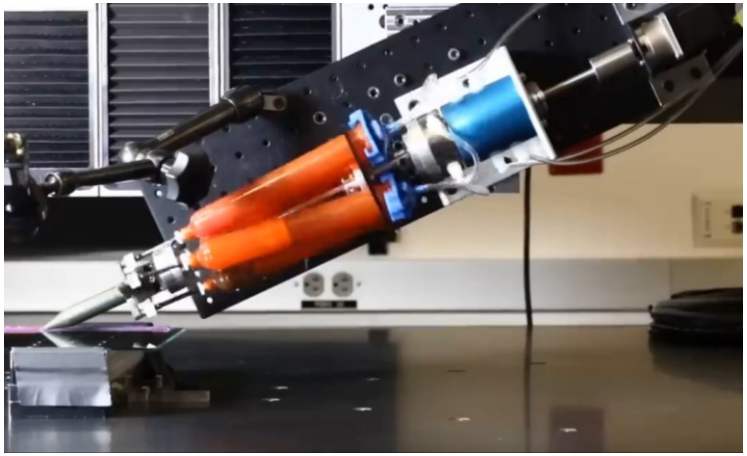
Vid.2 Computational hydro printing

Zhang, Y, et al.*ACM Transactions on Graphics (TOG)* 34.4 (2015): 1-11.



Vid.3 multi-nozzle 3D printing

Skylar-Scott, M. A., et al. *Nature* 575.7782 (2019): 330-335.



Vid.4 core-shell 3D printing

Larson, Natalie M., et al. *Nature,* 613 (2023), 682–688.

Motivations

1.Developing a technique for the spatially manufacturing of structural and functional materials.

2.The technique developed should overcome problems:

- **Low material accessibility**
- **Low positioning accuracy**
- **Post-process**

Preliminary work 1: Freeform fabrication of 3D electronics by laser induction

Preliminary work 2: 3D Programmable Assembly of Multi-materials by Freeform Spatial Laser Induction and Printing

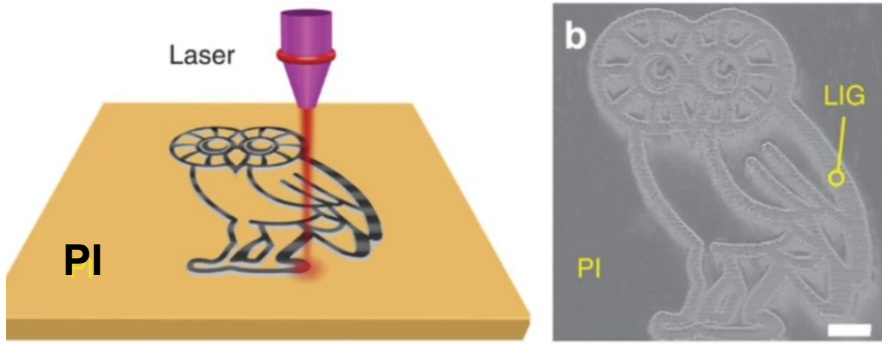
Current work: Fully 3D-printed actuators , mechanical components and robots fabricated by freeform manufacturing of multi-material.

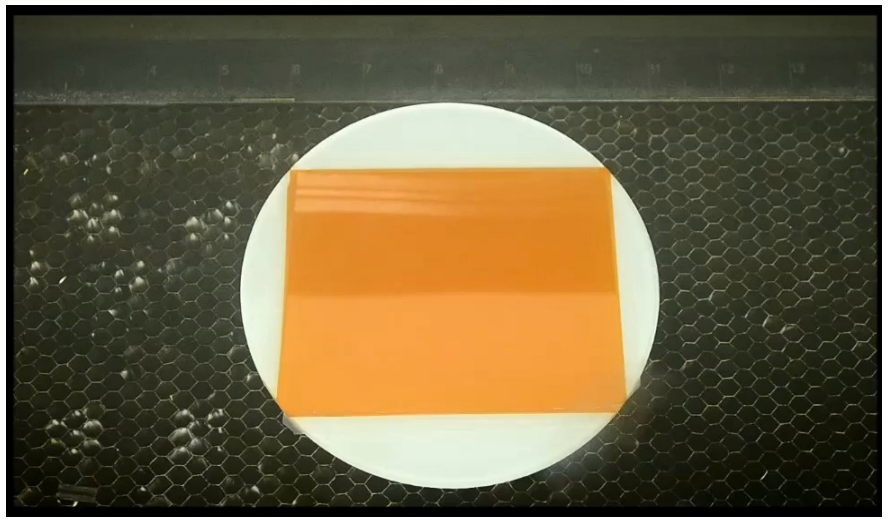
Preliminary work 1

Freeform fabrication of 3D electronics by laser induction

Direct Laser Writing method

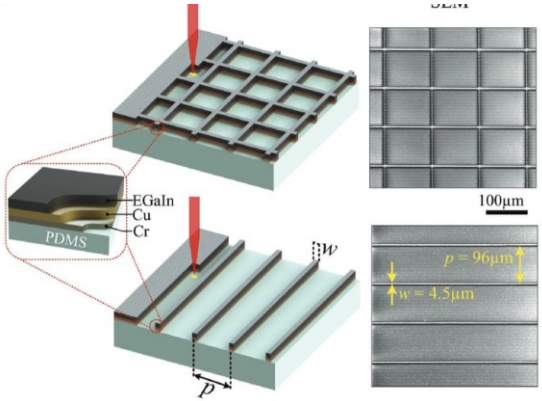
DLW: a **rapid**, **mask-free**, **postprocess-free** fabrication method.





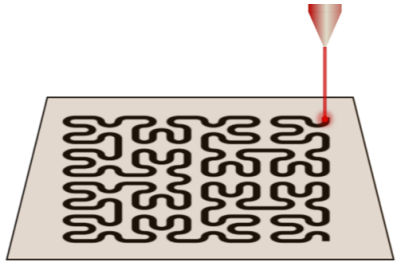
Laser induced graphene

Lin, J, et al. *Nature communications* 5.1 (2014): 5714.



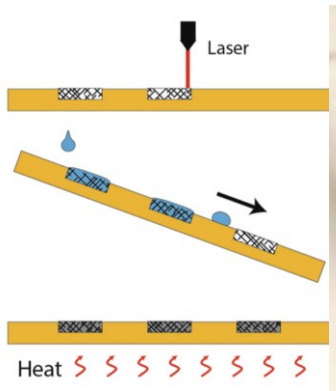
Metal alloy (EGlan)

Pan, C, et al. *Advanced Materials* 30.12 (2018): 1706937.



Metal oxide (MoO_2)

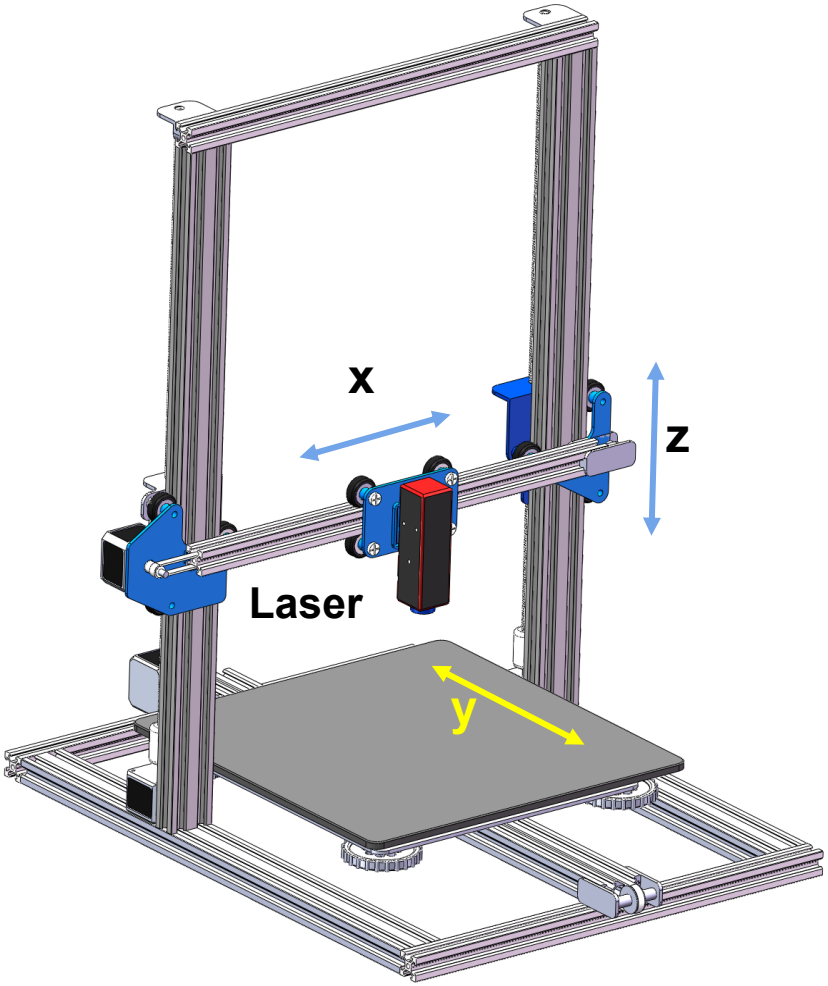
Zhao, G, et al. *Science advances* 8.25 (2022): eabp9734.



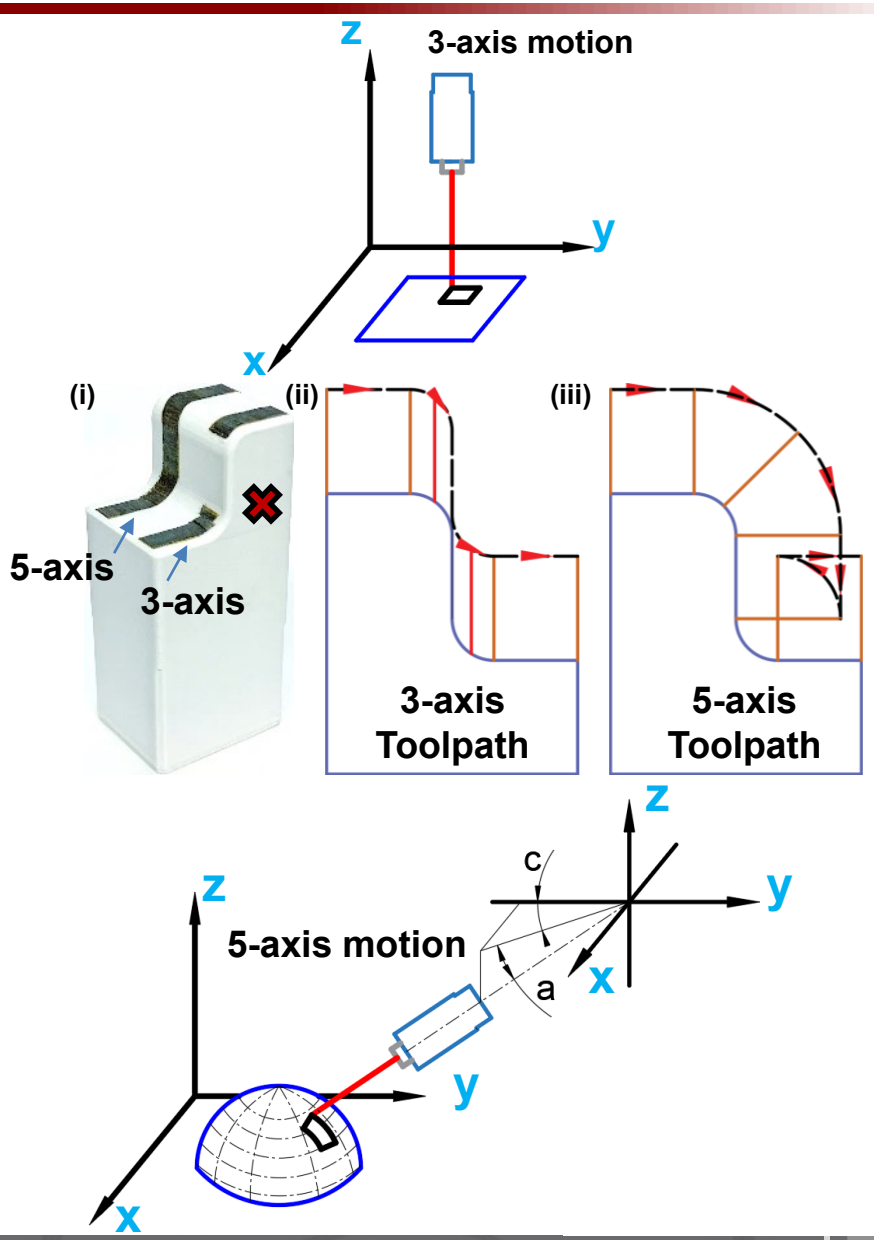
Metal (Ag)

Dallinger, Alexander, et al. *ACS applied materials & interfaces* 12.17 (2020): 19855-19865.

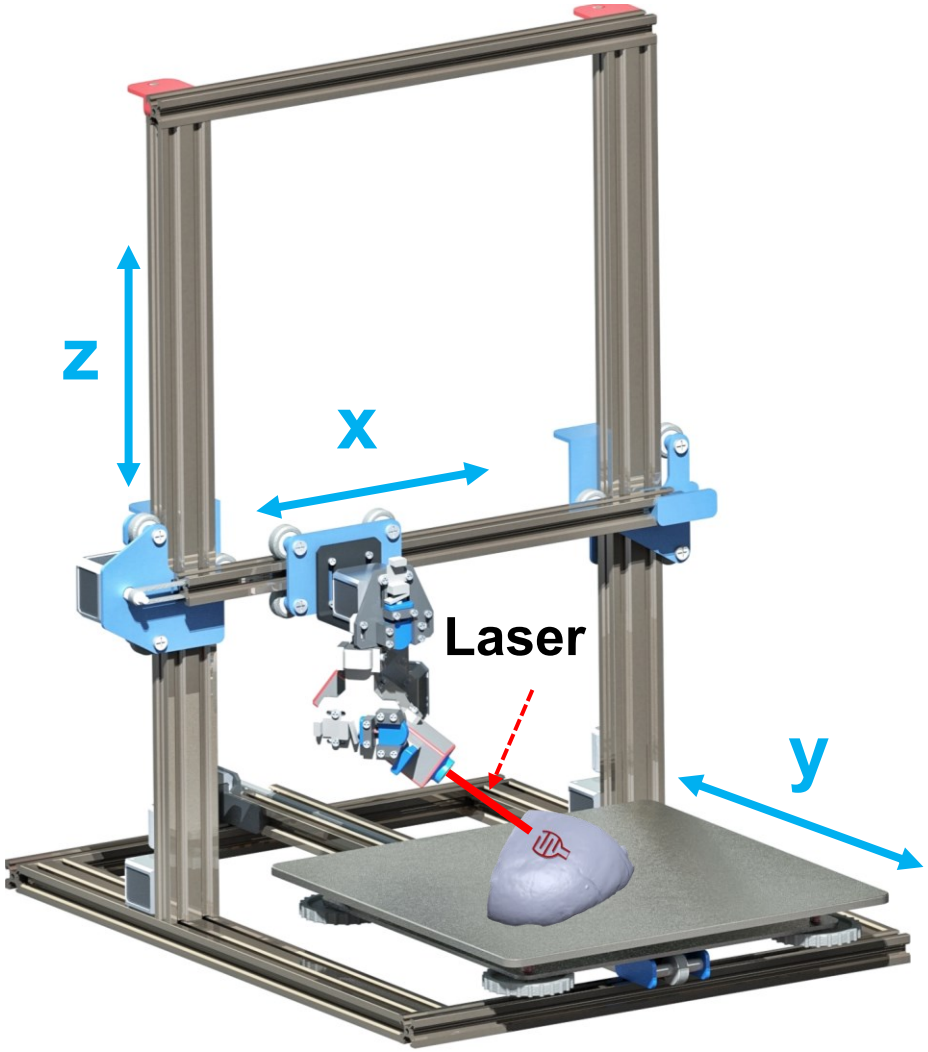
Limitation of Direct laser writing

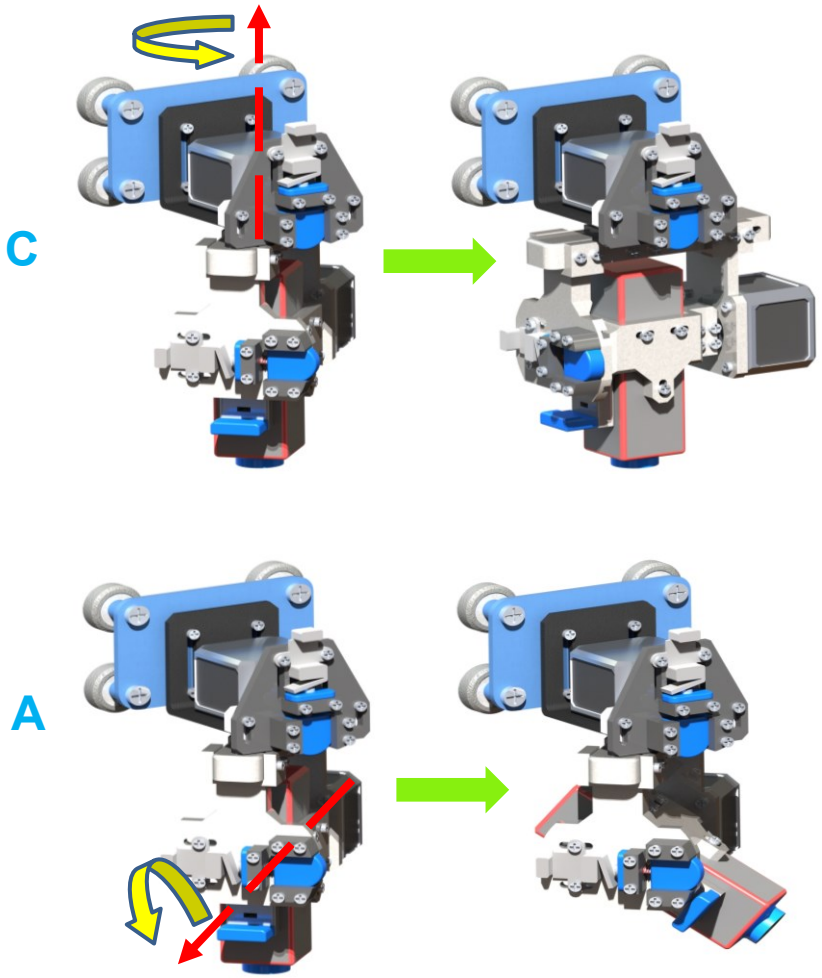


Traditional 3-axis laser platform



Freeform DLW platform

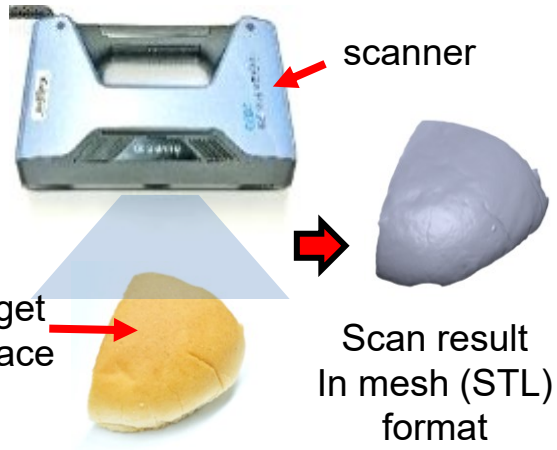




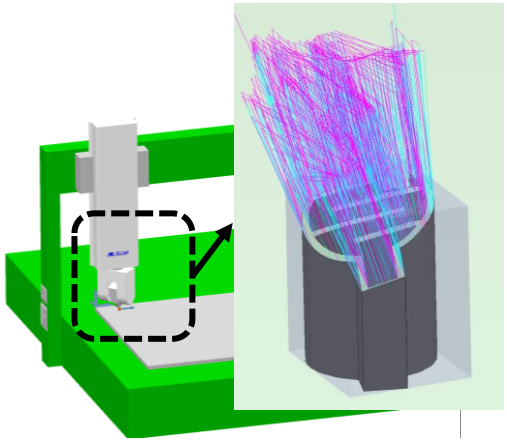
Linear motion

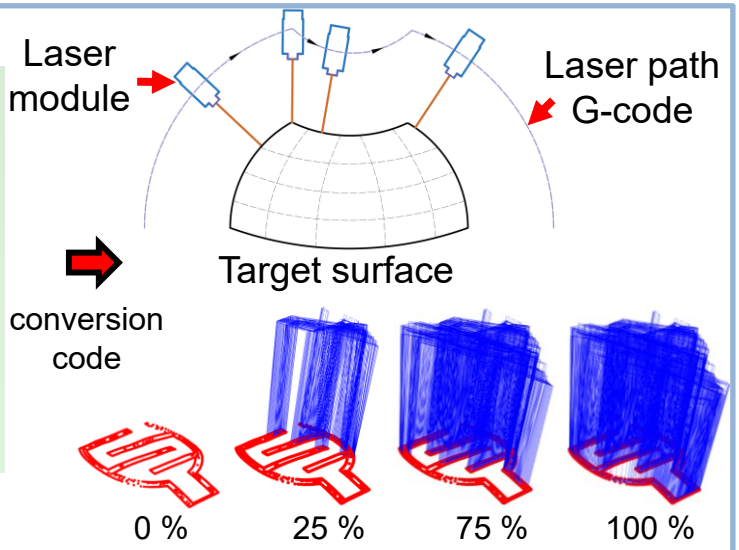
Rotational motion

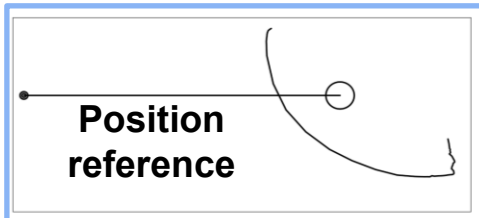
Target surface reconstruction and toolpath generation

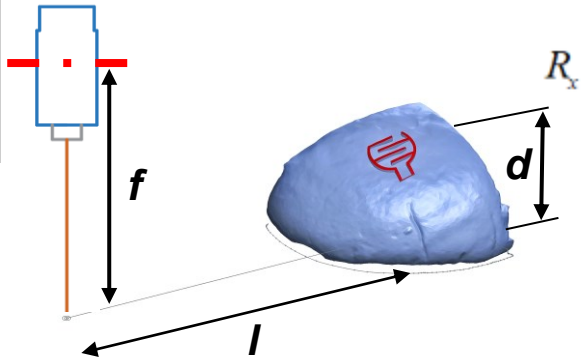


3D scanning









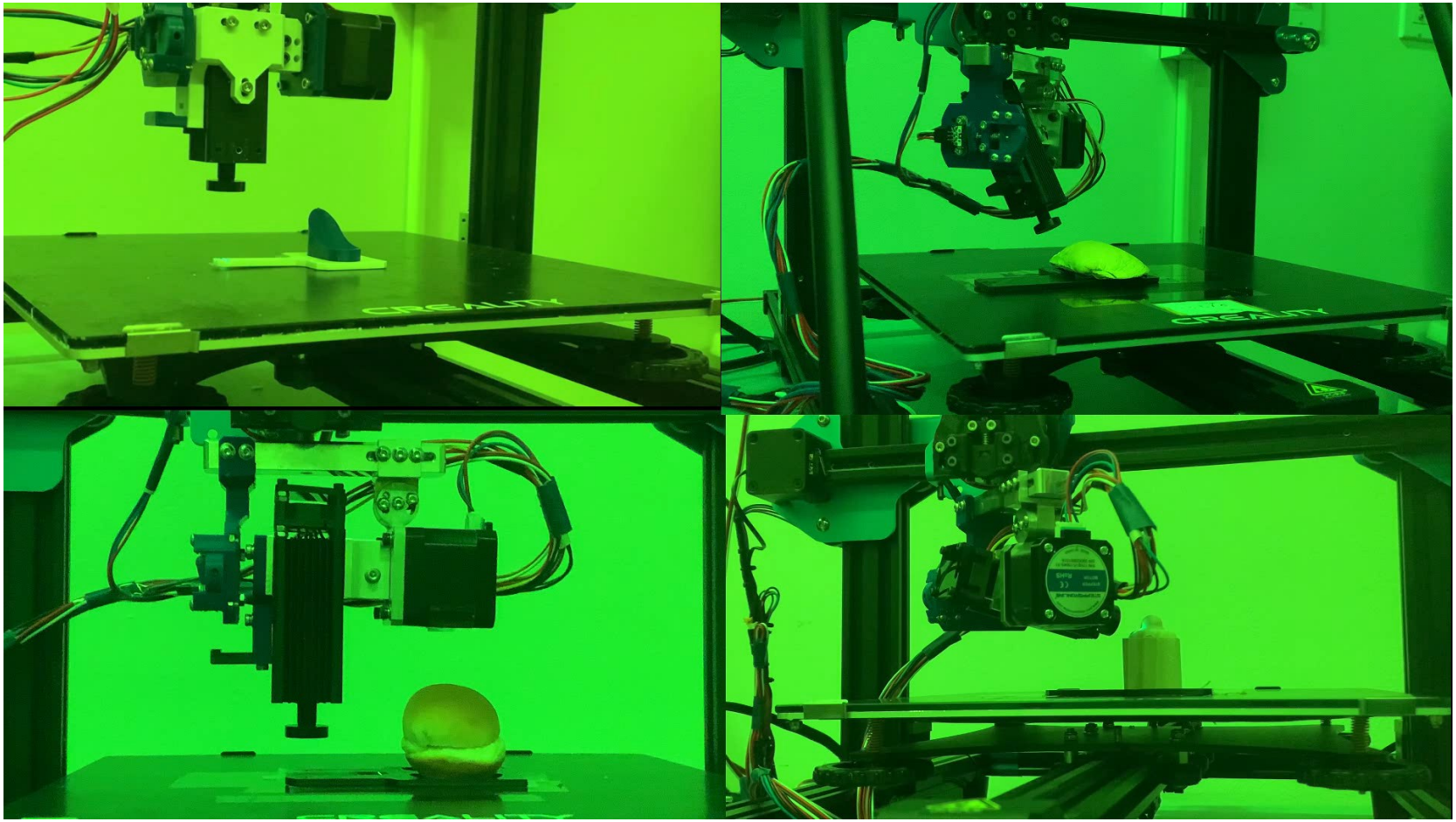
Laser initial position presetting

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos a & -\sin a \\ 0 & \sin a & \cos a \end{bmatrix} \quad R_z = \begin{bmatrix} \cos c & -\sin c & 0 \\ \sin c & \cos c & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} x_{MCS} \\ y_{MCS} \\ z_{MCS} \end{bmatrix} = R_z \cdot R_x \cdot \begin{bmatrix} 0 \\ 0 \\ f \end{bmatrix} + \begin{bmatrix} x_{PCS} \\ y_{PCS} \\ z_{PCS} \end{bmatrix} + \begin{bmatrix} l \\ 0 \\ d \end{bmatrix}$$

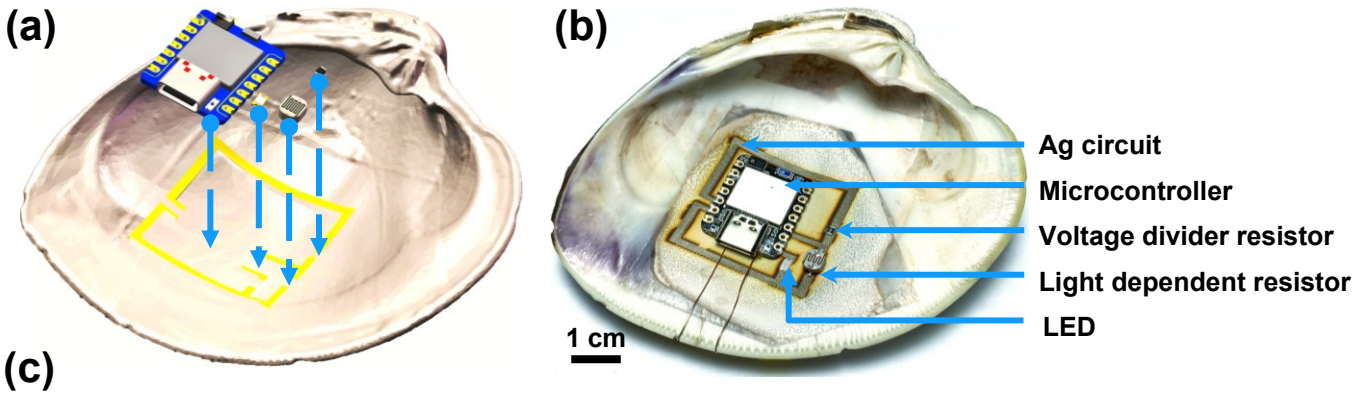
MCS: machine coordinate system
PCS: part coordinate system

Video demonstration: Freeform laser writing on different substrates



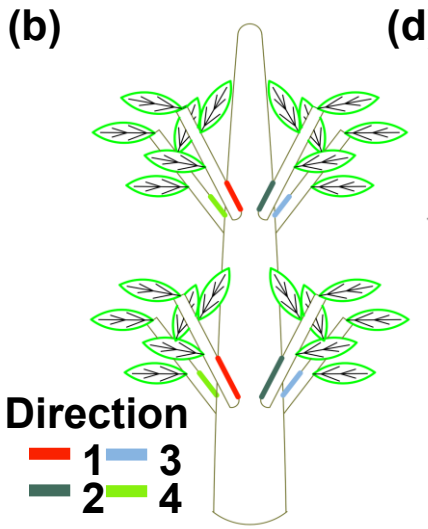
Video. a clip showing 5-axis laser processing on different substrate

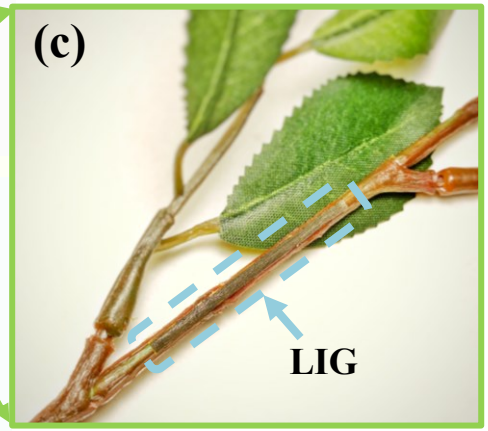
Application: Conformal PCB

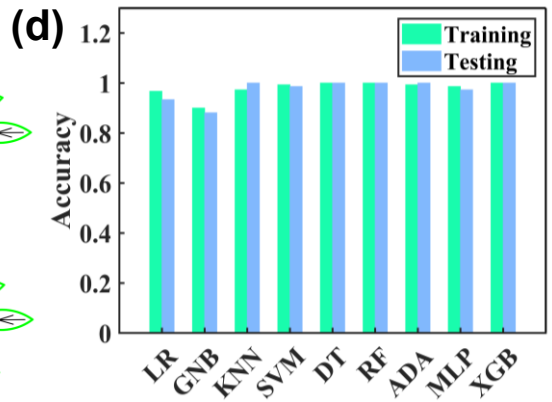


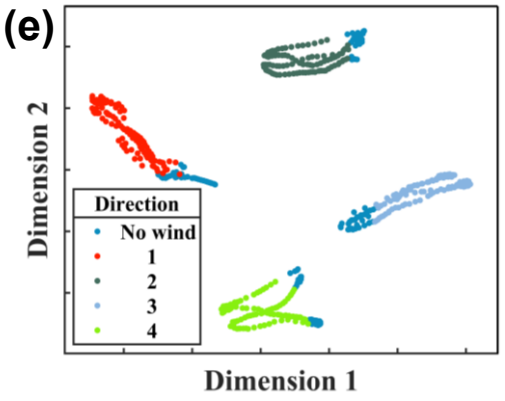
Video. a clip showing light intensity monitoring

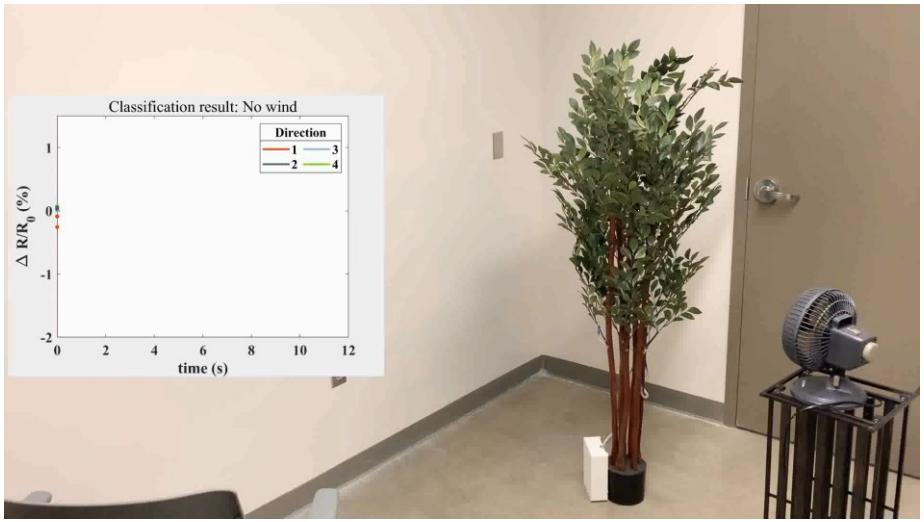
Application: IoT smart furniture











Video. a clip showing wind monitoring

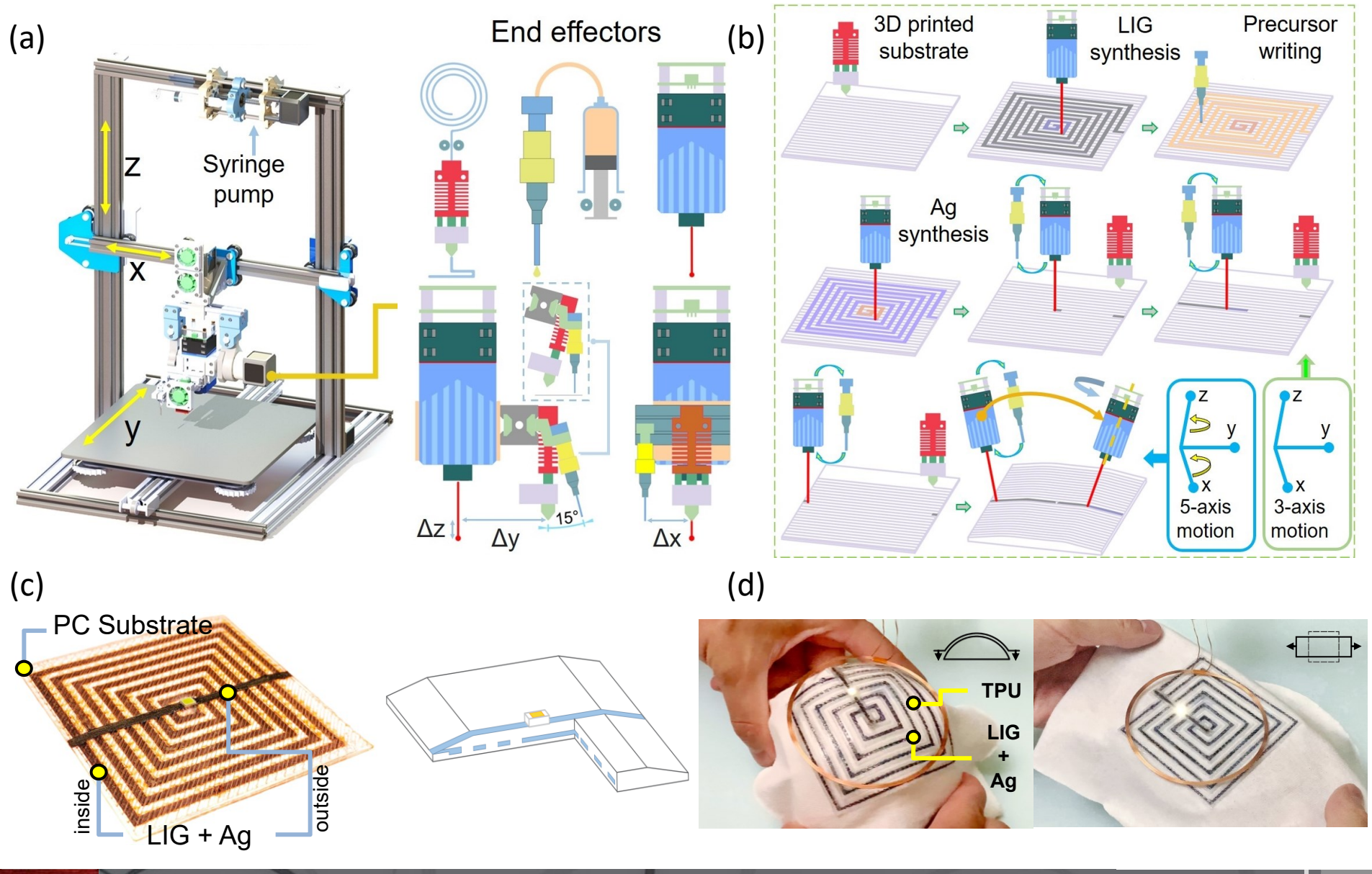
Discussion

DFL-fabricated devices are currently **single-layered** and limited to **existing 3D surfaces**. The realization of truly programmable manufacturing of structural and functional materials with 3D spatial control has not yet been demonstrated.

Preliminary work 2

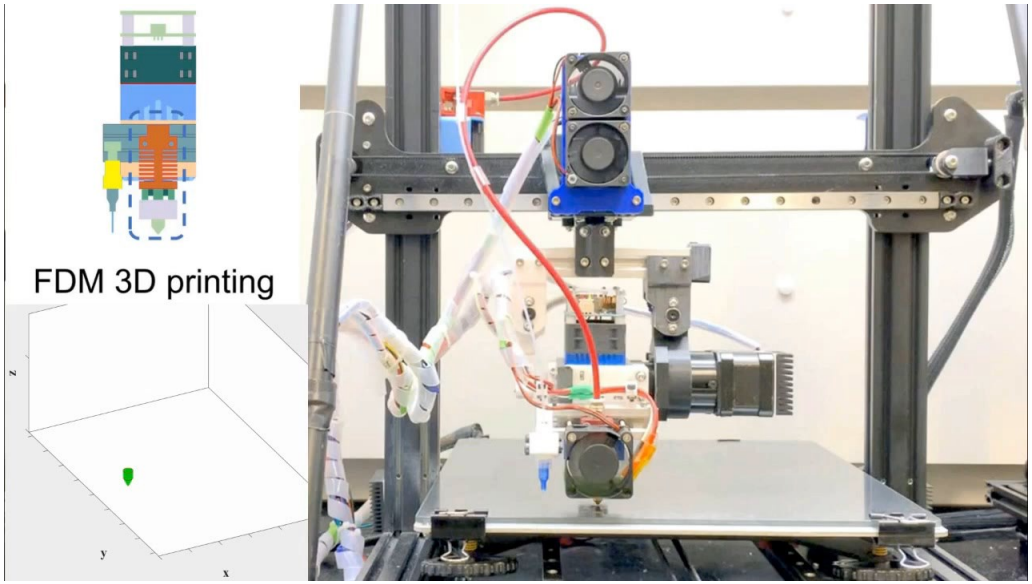
3D Programmable Assembly of Multi-materials by Freeform Spatial Laser Induction and Printing

Freeform Multimaterial Assembly Process (FMAP)

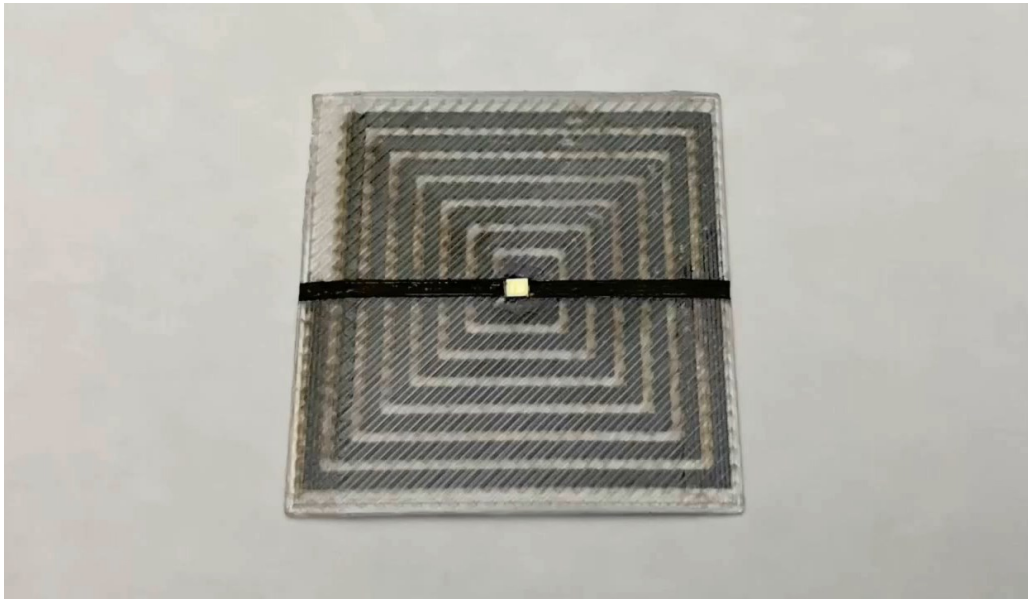


Video demonstration: Wireless LED coil fabrication process

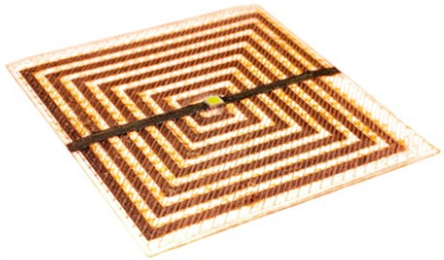
Video 1. Fabrication process

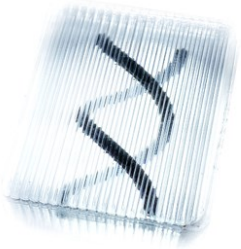
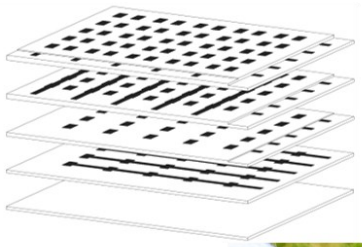
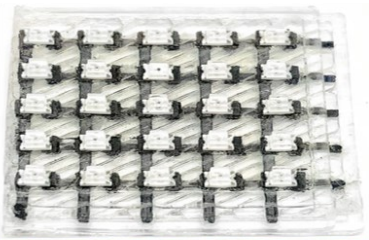
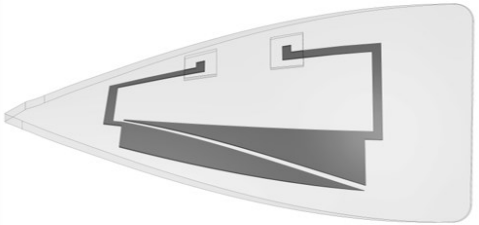


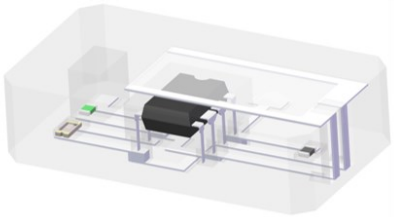
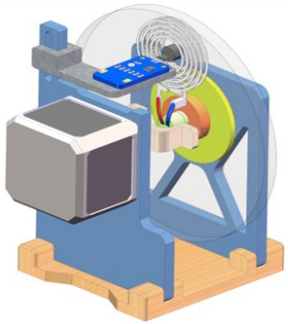
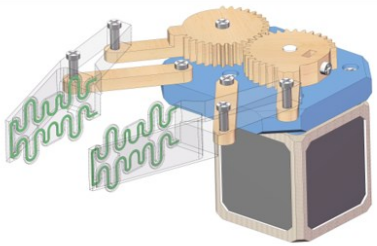
Video.2 Device testing

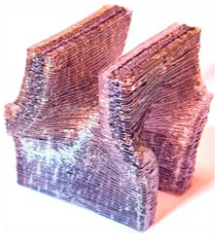
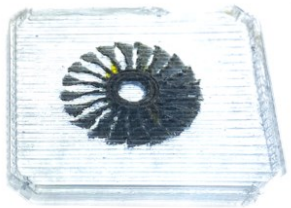


applications



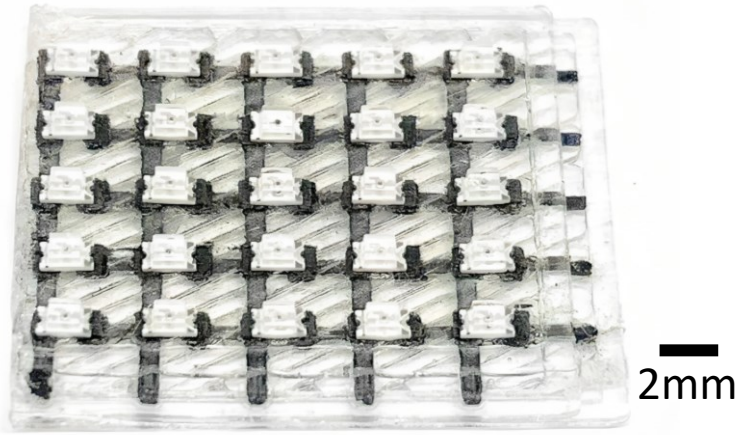





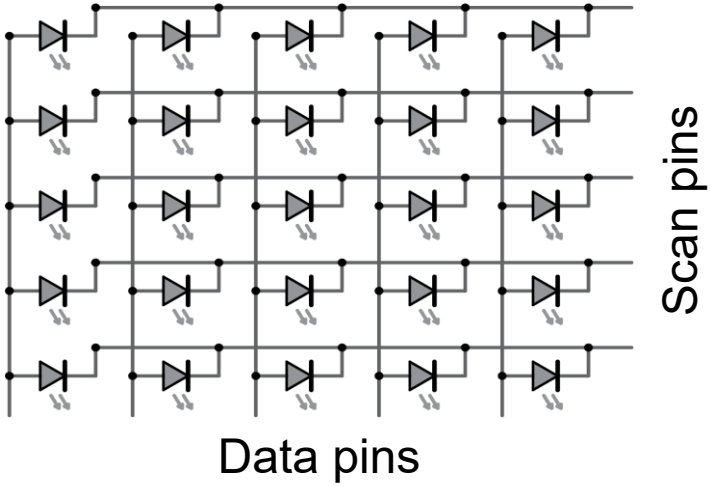





Application: Cross-bar LED circuit

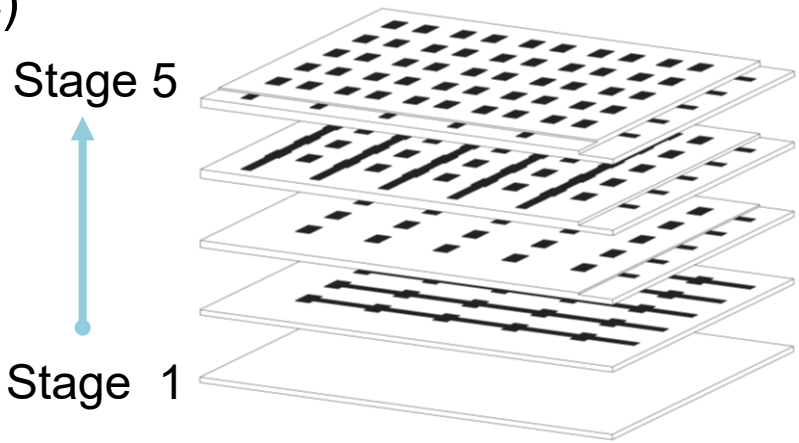
(a)

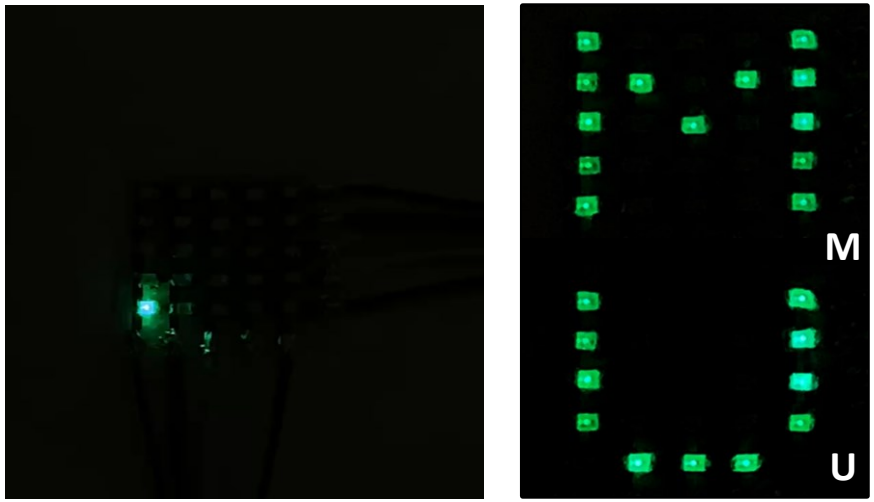


(b)



(c)

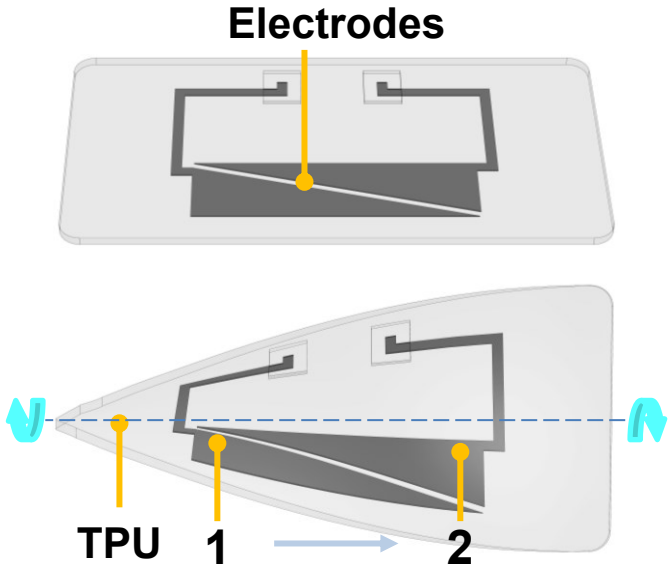




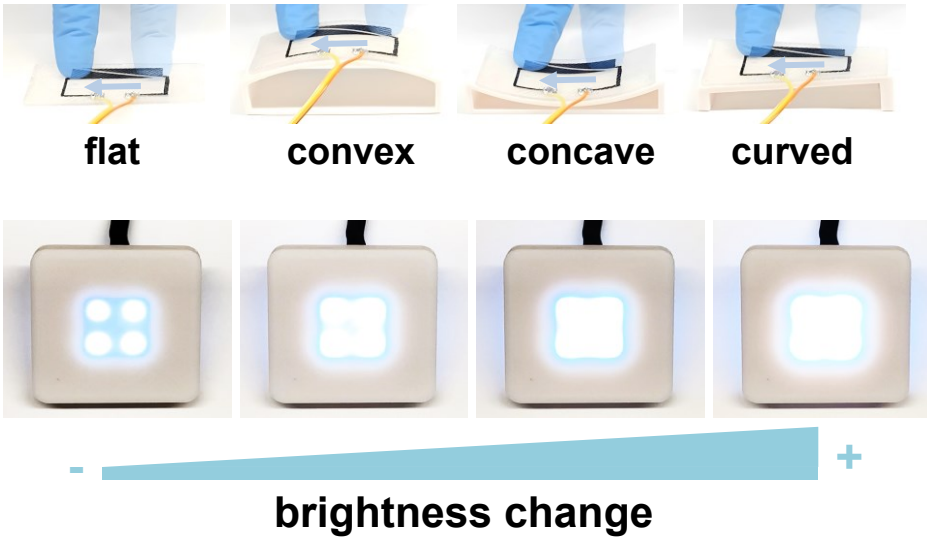
Video. Testing of LED matrix

Application: Capacitive sensing

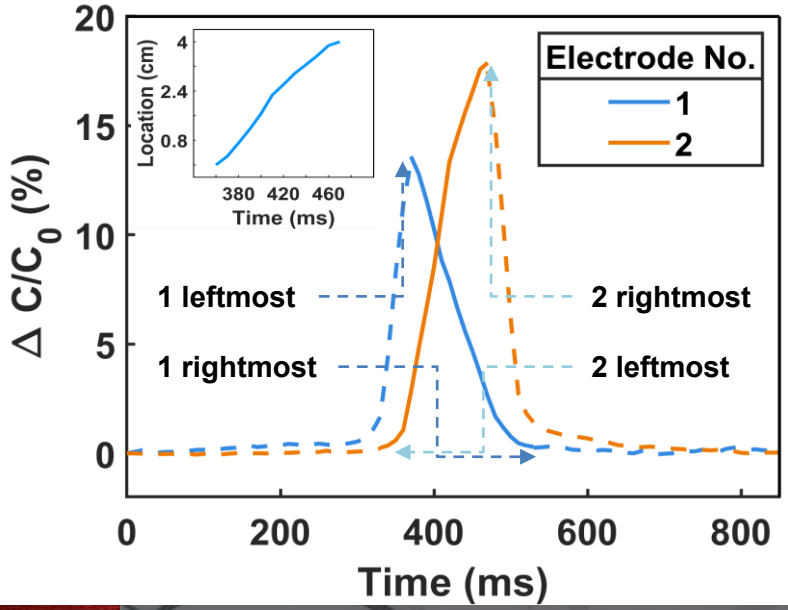
(a)



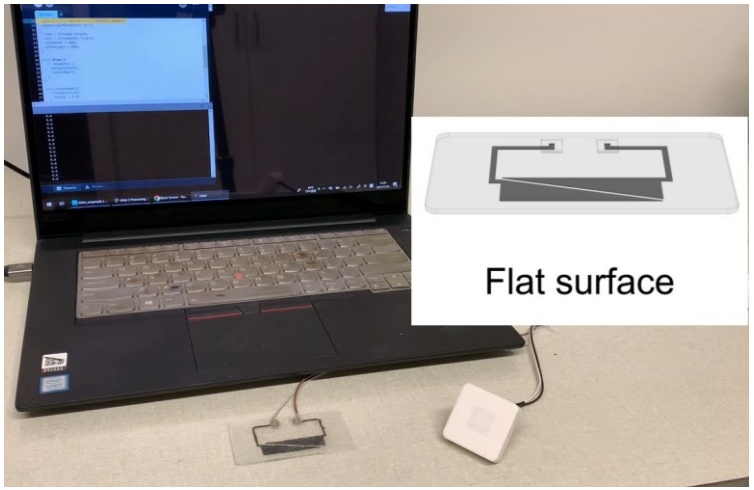
(b)



(c)



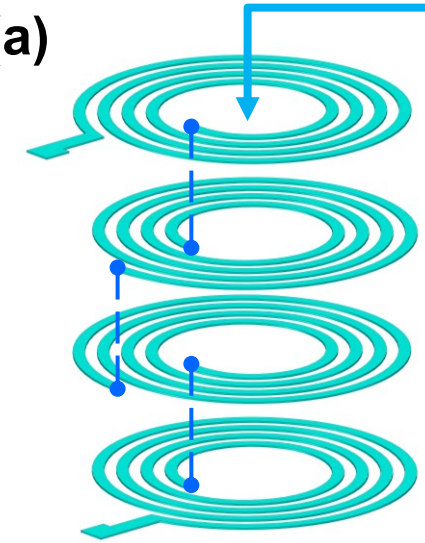
(d)



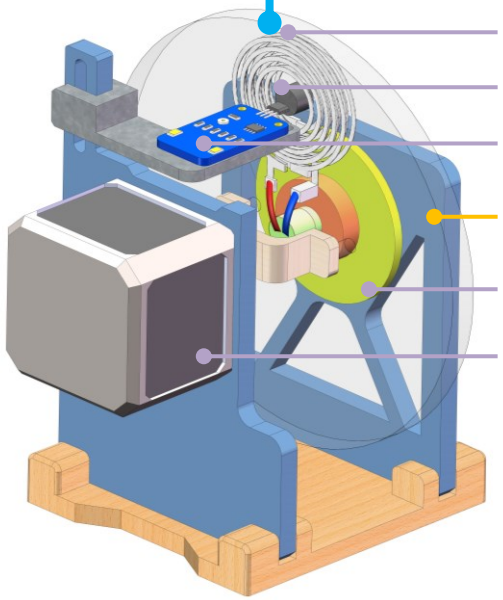
Video. Testing of a FMAP fabricated slider

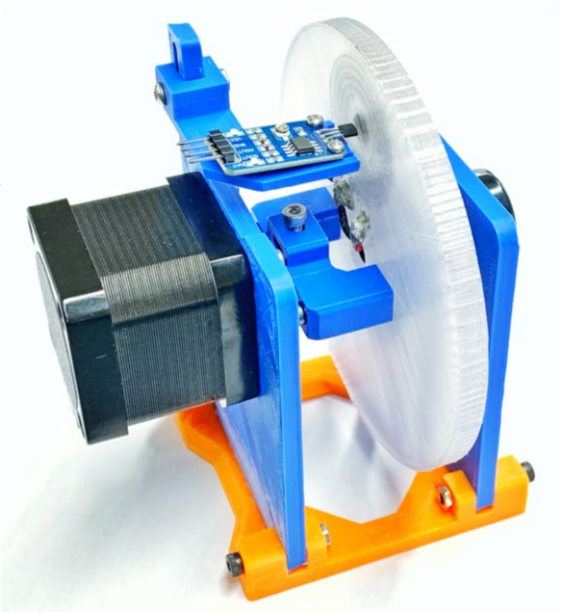
Application: Electromagnet

(a)

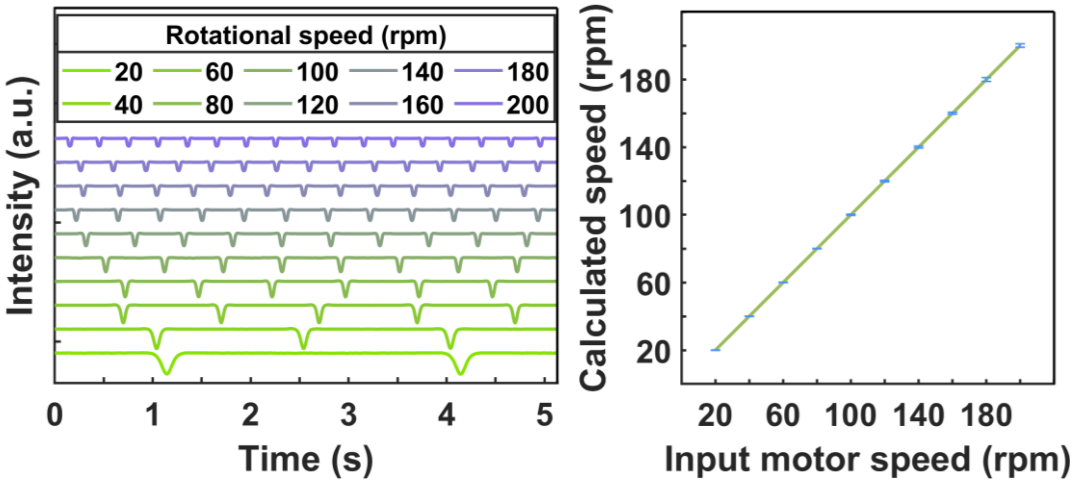


Multilayer stacked coil

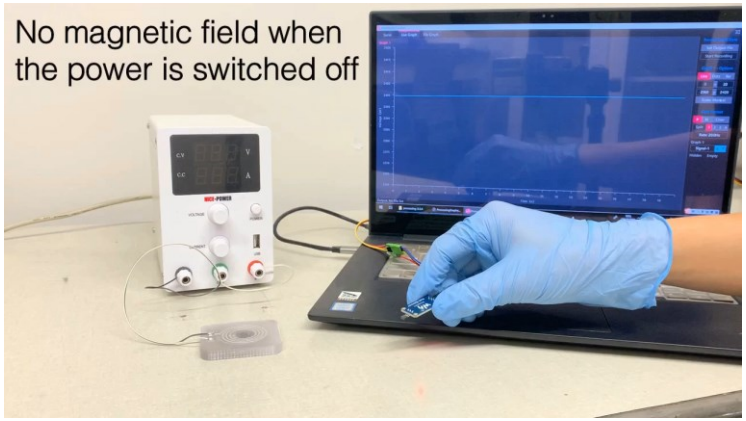




(b)



(c)



Video. Electromagnet for rotational encoder

Publications

Published:

1. **Zheng, B**., Zhao, G., Yan, Z., Xie, Y., & Lin, J. (2023). Direct freeform laser fabrication of 3D conformable electronics. *Advanced Functional Materials*, 33(1), 2210084.
2. **Zheng, B**., Su, J. W., Xie, Y., Miles, J., Wang, H., Gao, W., ... & Lin, J. (2022). An autonomous robot for shell and tube heat exchanger inspection. *Journal of Field Robotics*, 39(8), 1165-1177.
3. Xie, Y., Zhang, C., Deng, H., **Zheng, B**., Su, J. W., Shutt, K., & Lin, J. (2021). Accelerate synthesis of metal–organic frameworks by a robotic platform and bayesian optimization. *ACS Applied Materials & Interfaces*, 13(45), 53485-53491.
4. Wu, Y†, Su, C†, Wang, S, **Zheng B**, ... & Lin, J.(2023). A Photocured Bio-based Shape Memory Thermoplastics for Reversible Wet Adhesion. *Chemical Engineering Journal*, 144226.
5. Qiu, F., Bu, K., **Zheng, B**., & Tian, G. (2020). Control of edge plate stray grain of single-crystal turbine blade by using process bar method. *International Journal of Metalcasting*.

Under review:

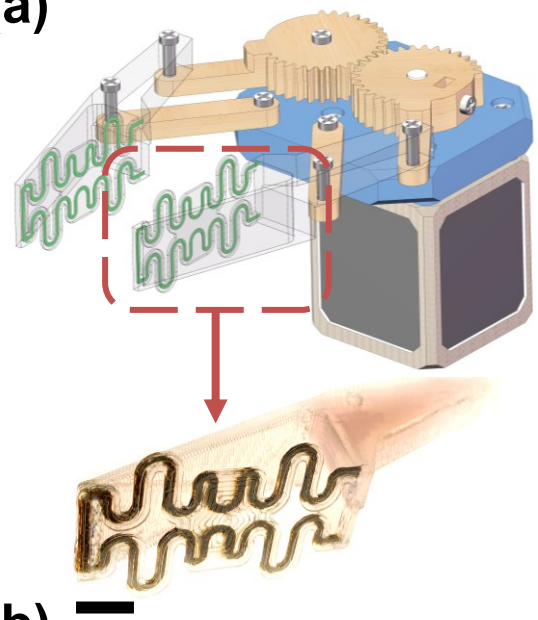
- **Zheng, B**., et.al (2024). Programmable multi-material assembly by freeform spatial laser induction. *Nature Communications.*
- Yang, S., **Zheng, B**., Qian H., Zhang H., Yan Q., Huang G., Lin, J., Wan, C. (2024) Low-defect Laser-induced Graphene from Lignin for Smart Triboelectric Touch Sensors. *Small*

Current work：

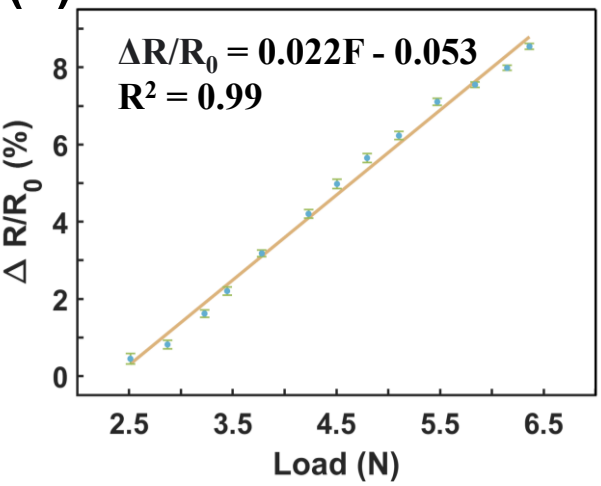
Fully 3D-printed actuators , mechanical components and robots fabricated by freeform manufacturing of multi-material.

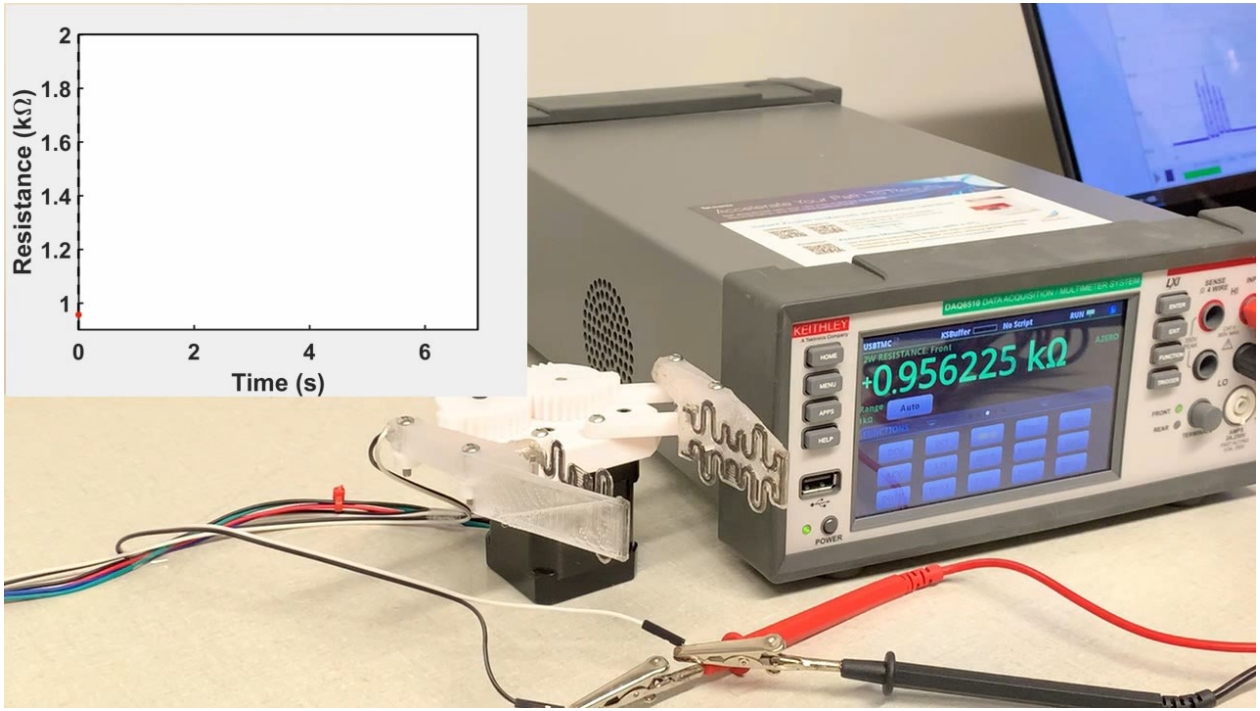
Fully 3D printed stress-responsive robotic finger

(a)



(b)





Video. Testing of FMAP fabricated force responsive gripper

Future research plans

Research plan

- AI-enabled autonomous lab/factory

I would like to leverage my experience in System integration, manufacturing and AI to develop human-free manufacturing system for personalized device. Since its invention in 1989, the consumer-level 3D printer market has continued to grow, with a trend towards integrating AI to enhance quality, speed, and usability. If highly automated and intelligent FDM printing extends to other sectors like materials synthesis and equipment manufacturing, it will impact the whole industry.

- Swarm self-growing robots for building construction

I aim to develop swarm robots utilizing 3D printing for building construction, exploring advanced coordination, and material deposition techniques. By integrating sensing and machine learning, these robots will enhance adaptability and efficiency in complex environments. I will also address scalability and sustainability challenges to revolutionize construction and space exploration.

Thanks for your attention!
Any questions?