

# 基于软磁弹性体的触觉传感器及其抓取应用

夏子炜

2025.10.15



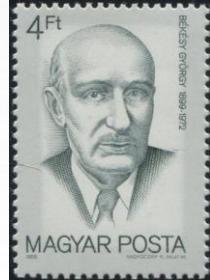
## 目录



1. 研究背景
2. 当前研究进展
3. 总结展望



听觉  
1961



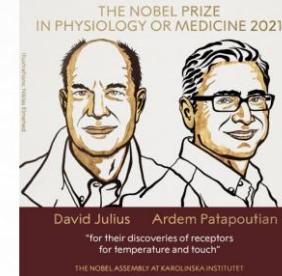
视觉  
1967



嗅觉  
2004



触觉  
2021



感受器



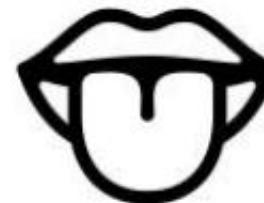
视觉



听觉



嗅觉



味觉



触觉

环境交互

接触 (按压、震动)

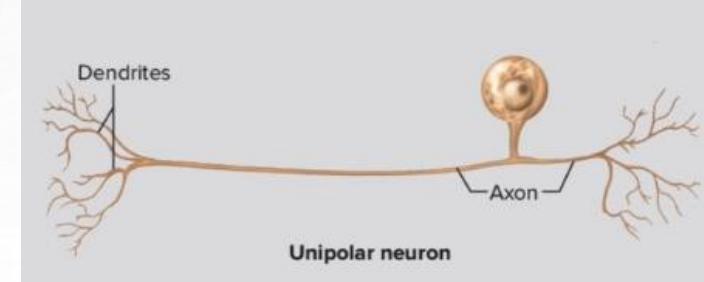
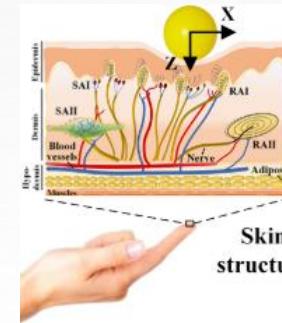
温度、湿度

纹理、粗糙度、材质

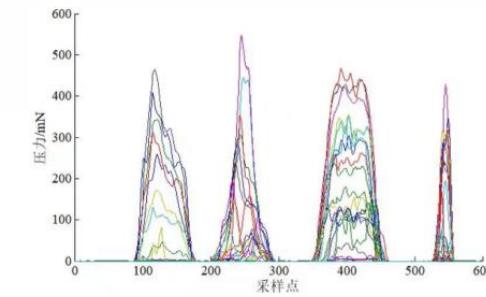
本体感觉 (位置、姿态)

## 感知通路

### Tactile for Human



### Tactile for Robotic

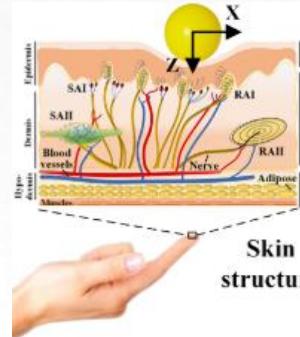


与人类的触觉感知总体流程相似，机器人触觉感知通常采取将外部的接触信号转化为电信号的方式，后续通过对电信号的特征提取，得到接触信号中的触觉信息。



人类的感知能力

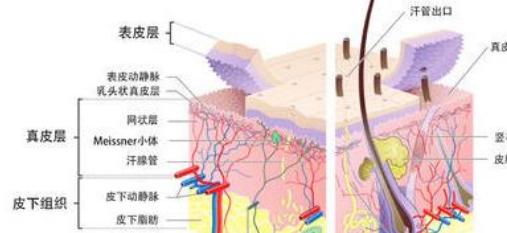
感知外部环境



感知自身姿态

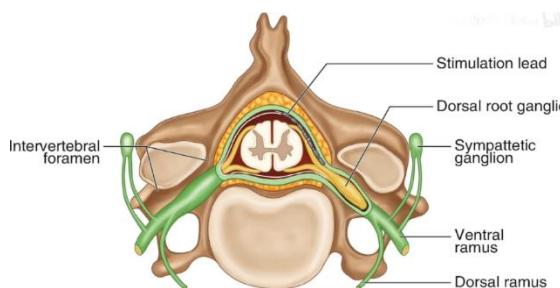


皮肤感知



皮肤内的多类感受器

运动感知



脊髓背根神经节感觉细胞

皮肤感知

机械刺激

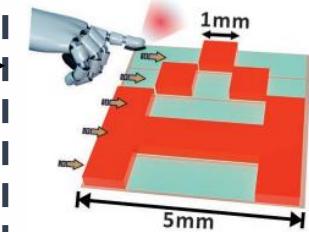
温度、湿度

痛觉

触觉传感器

关节传感器

对应



对应



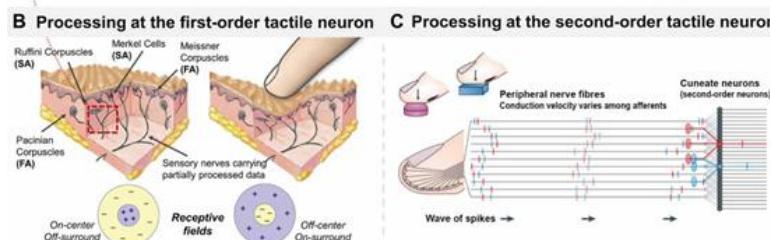
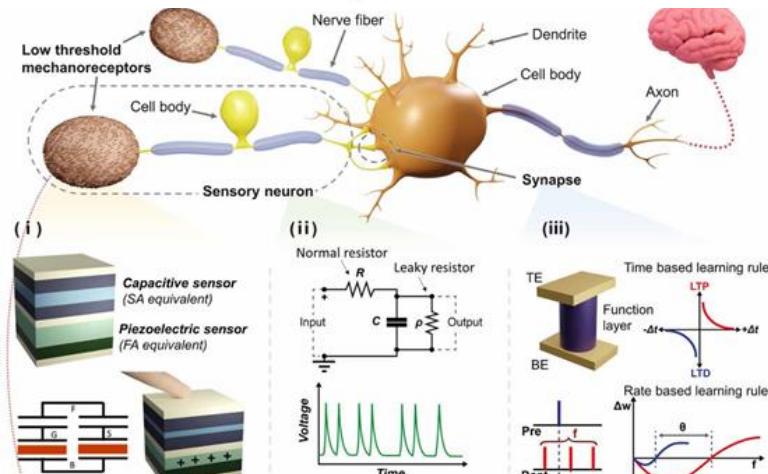
静态肢体位姿

动态肢体位姿

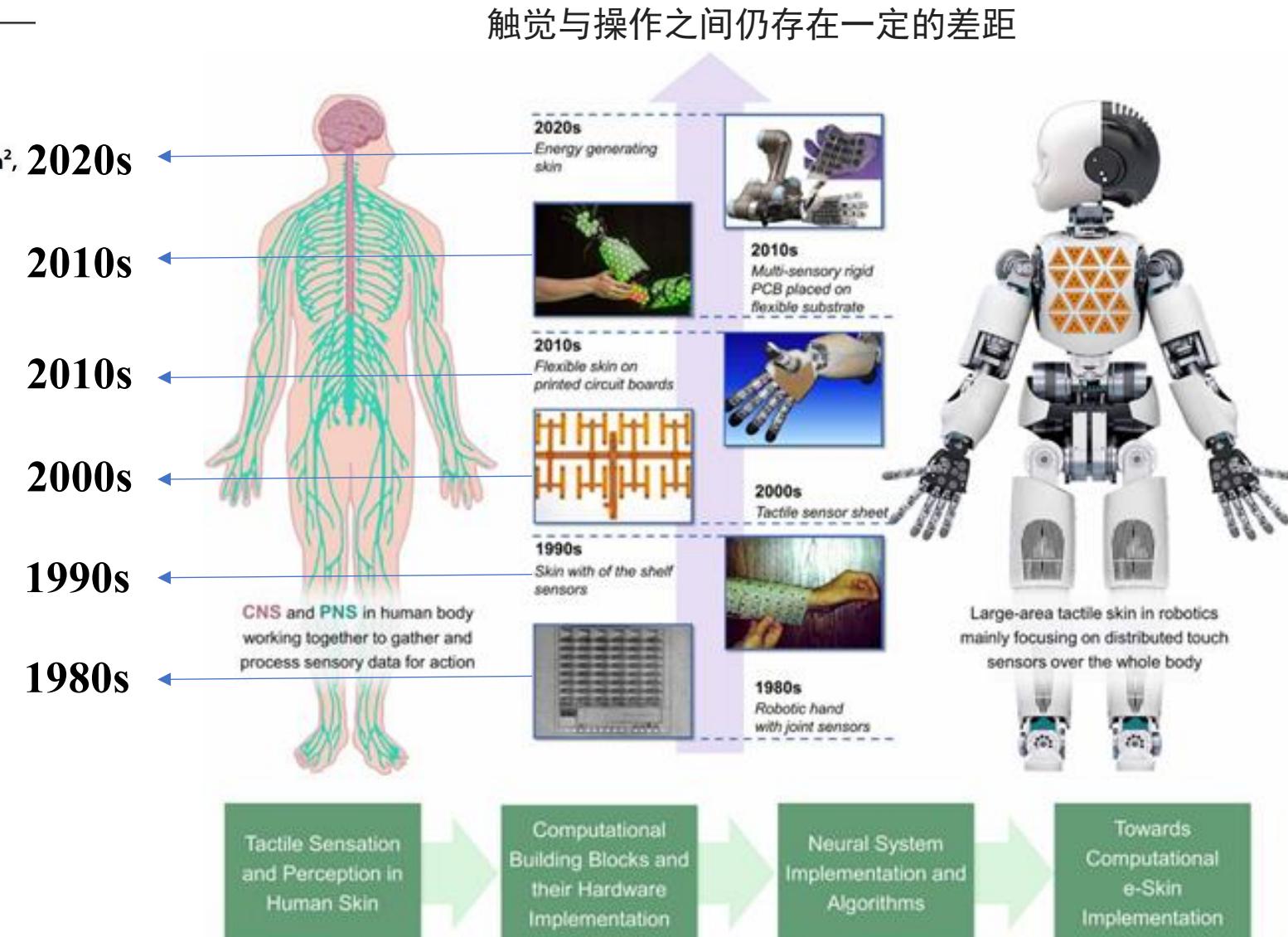
## SENSORS

### Neuro-inspired electronic skin for robots

Fengyuan Liu<sup>1†</sup>, Sweety Deswal<sup>1†</sup>, Adamos Christou<sup>1</sup>, Yulia Sandamirskaya<sup>2</sup>, Mohsen Kaboli<sup>3,4</sup>, Ravinder Dahiya<sup>1\*</sup>

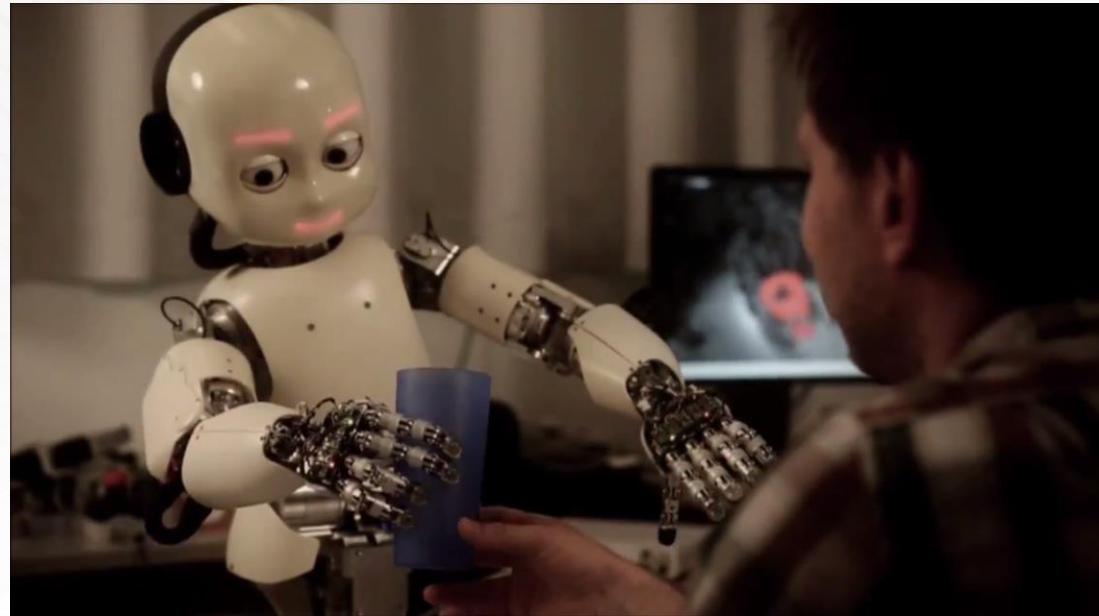


人体皮肤触觉数据处理的神经通路及其使用基本器件和电路的简单实现方案。

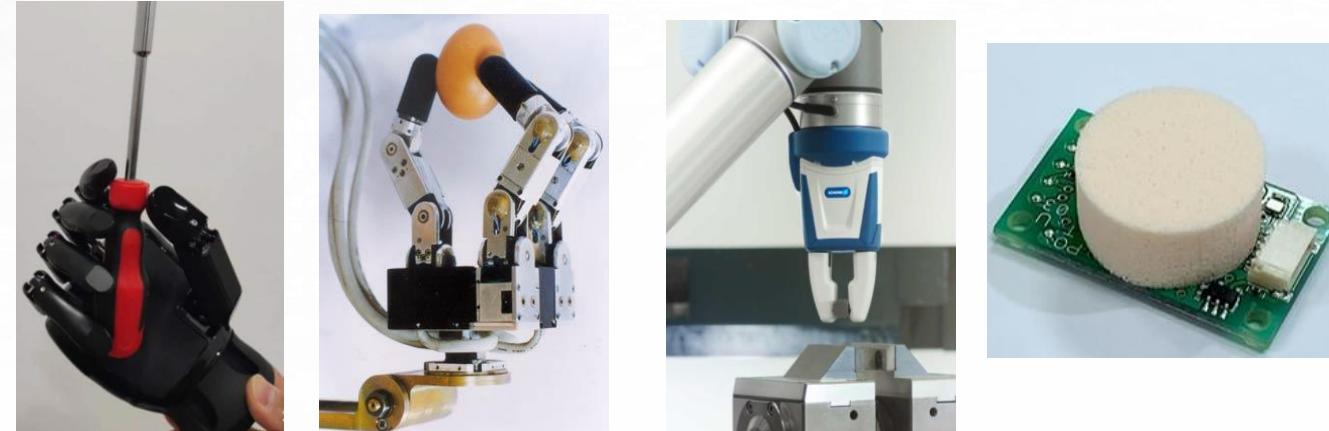


触觉传感器：机器人与环境交互的必要条件，机器人落地应用的必要条件。

# 当前触觉传感器的不足

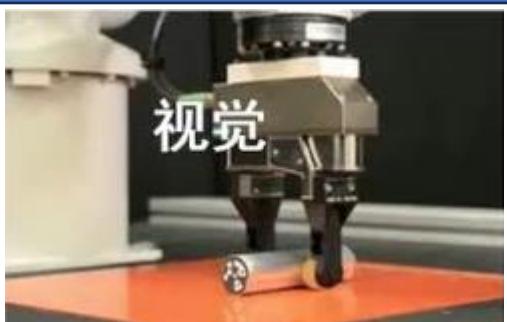


触觉传感器是提供交互的信息的核心器件



触觉感知的应用

抓住 (视觉)



抓稳 (触觉)

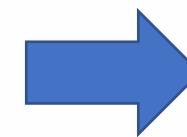
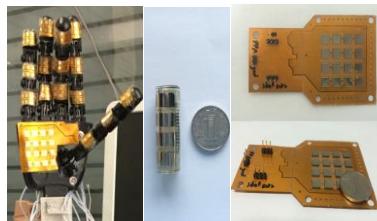


操作 (大模型)



## 触觉感知：重要性

## 机器人触觉



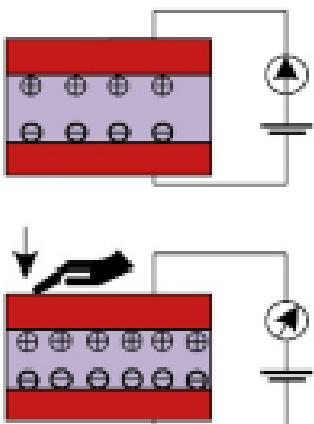
## 机器人触觉感知操作



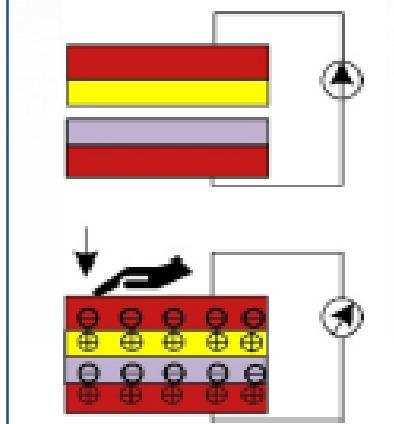


### 机器人的触觉感知

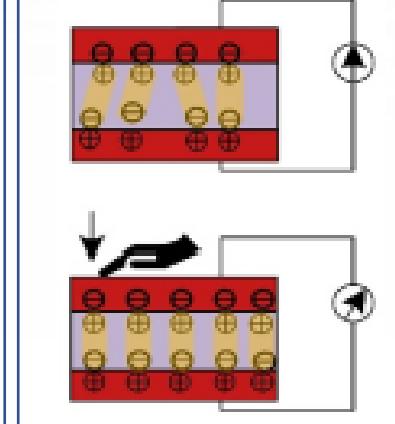
#### 压电式



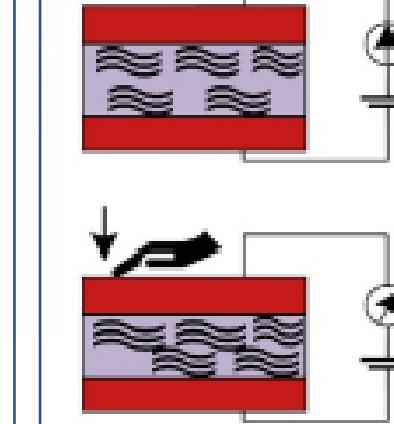
#### 电阻应变式



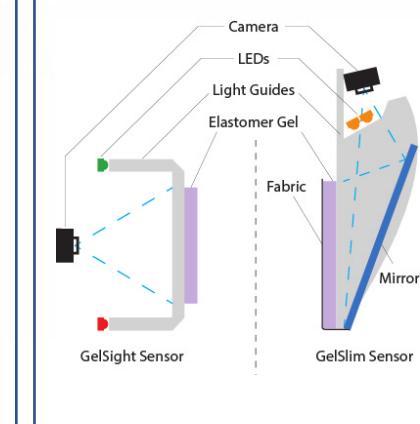
#### 电容式



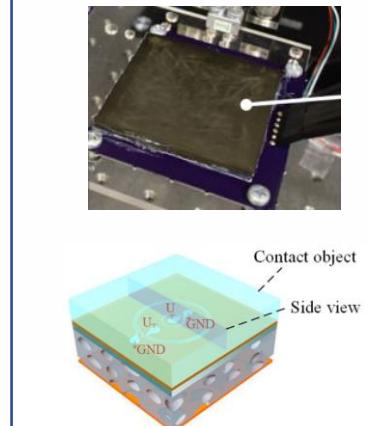
#### 压阻式



#### 视觉式



#### 磁触觉感知



性能指标

稳定与可靠

灵敏与量程

动态与迟滞



## 触觉传感器发展趋势

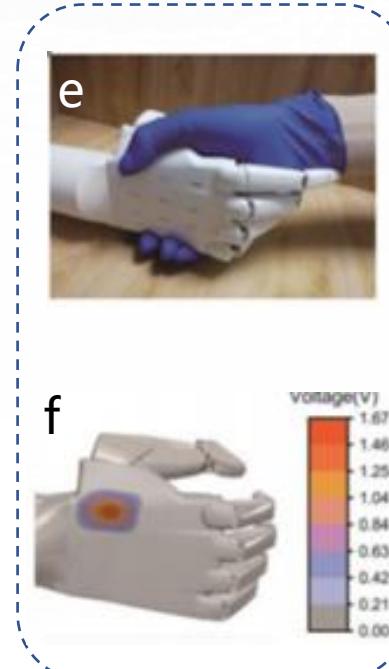
### ■ 柔性化



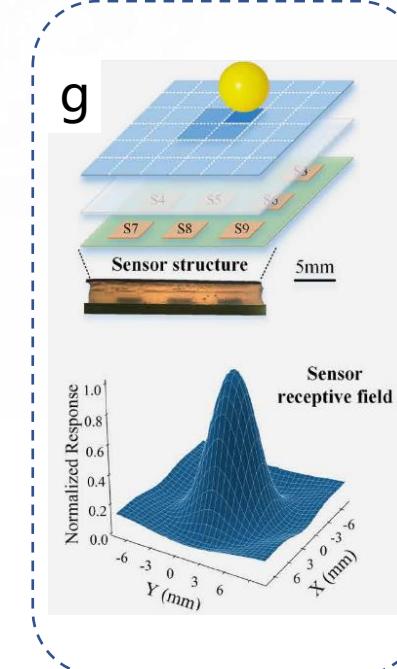
### ■ 多功能



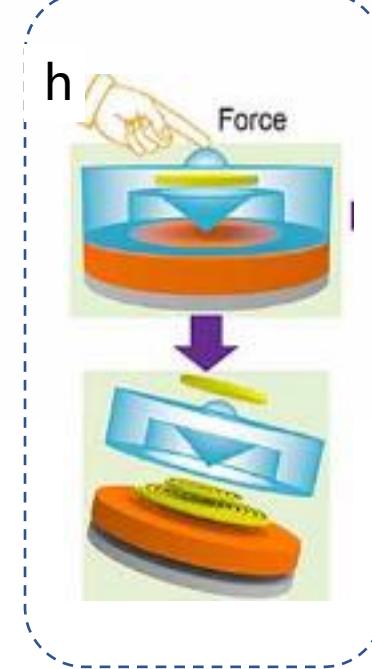
### ■ 大面积



### ■ 高灵敏度



### ■ 高安全性



- 保障传感器在复杂表面正常工作

- 获取多模态信息

- 获取大范围的触觉信息

- 精细操作、灵巧操作

- 保障操作的安全性

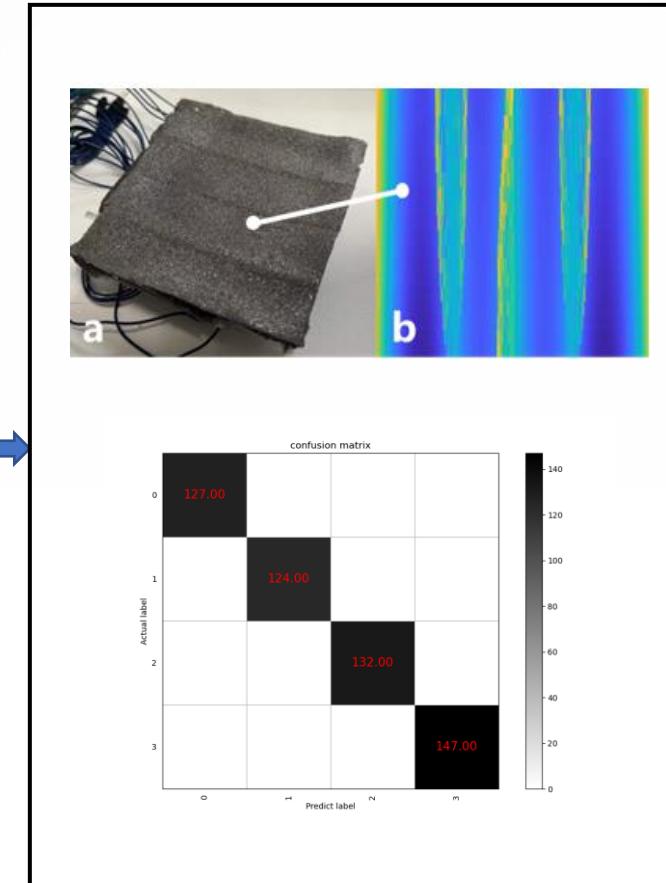
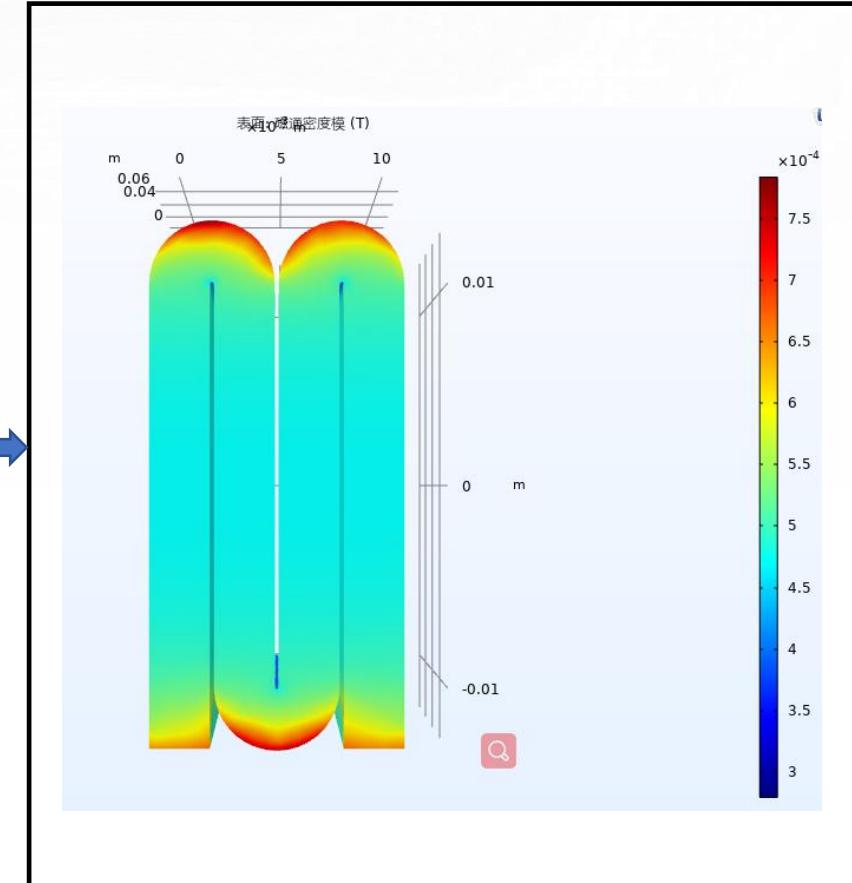


### 关键问题：大范围触觉感知及触觉识别

#### 研究目标

结合磁触觉传感器的优势，实现一款可扩展性强、安全性高、检测模态多、感知精度高  
的可用于大范围检测柔性磁触觉传感器

#### 研究思路



磁触觉手掌结构设计

磁场分布优化及感知算法

一体化集成测试

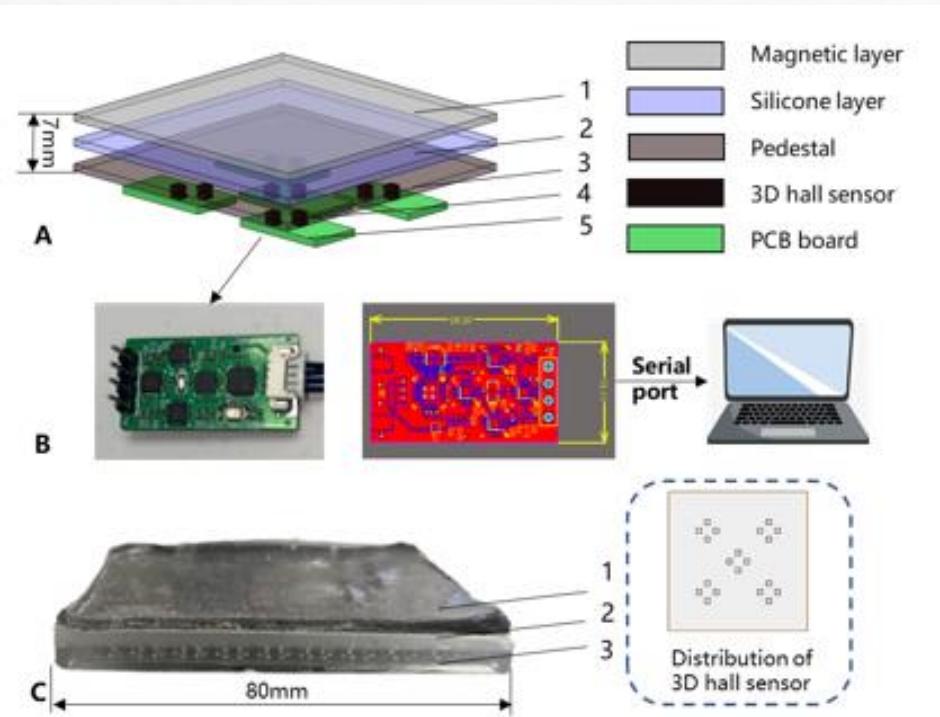
# 大面积磁触觉感知传感器



北京邮电大学  
Beijing University of Posts and Telecommunications

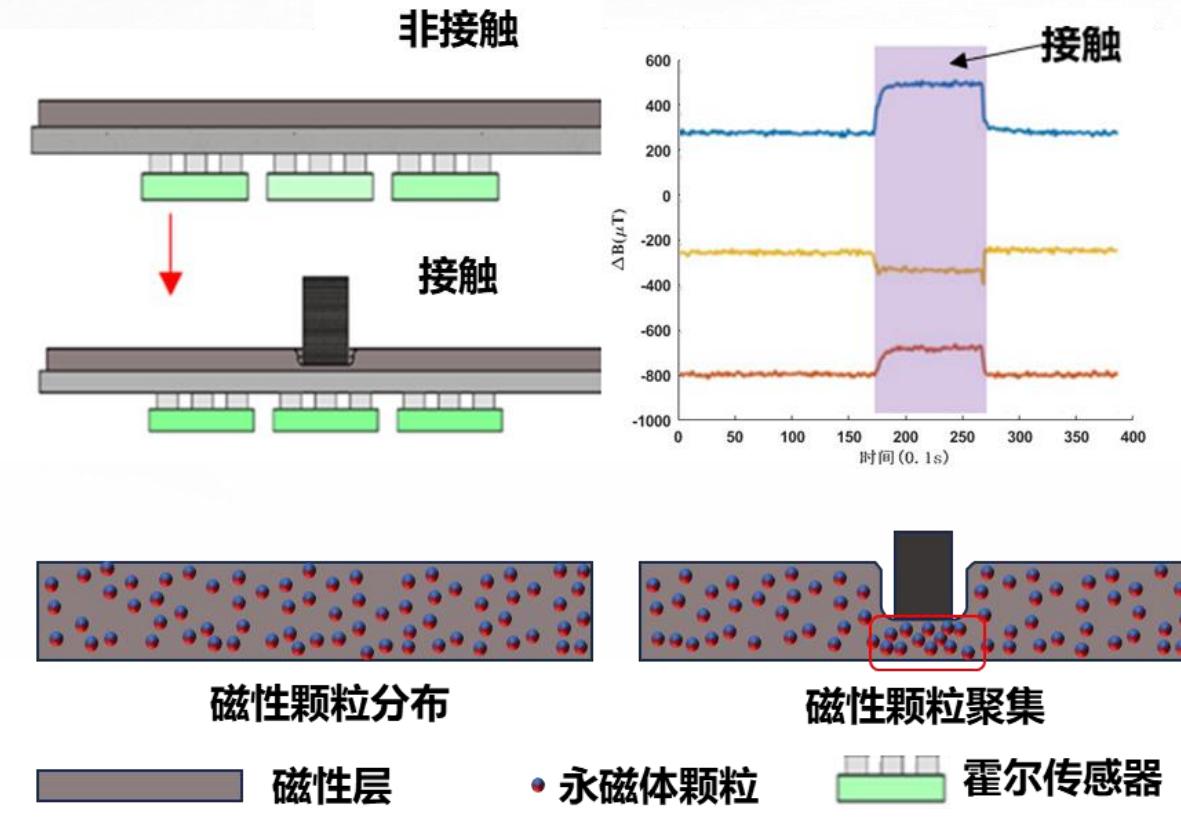
人工智能学院

## 磁触觉传感器设计方案

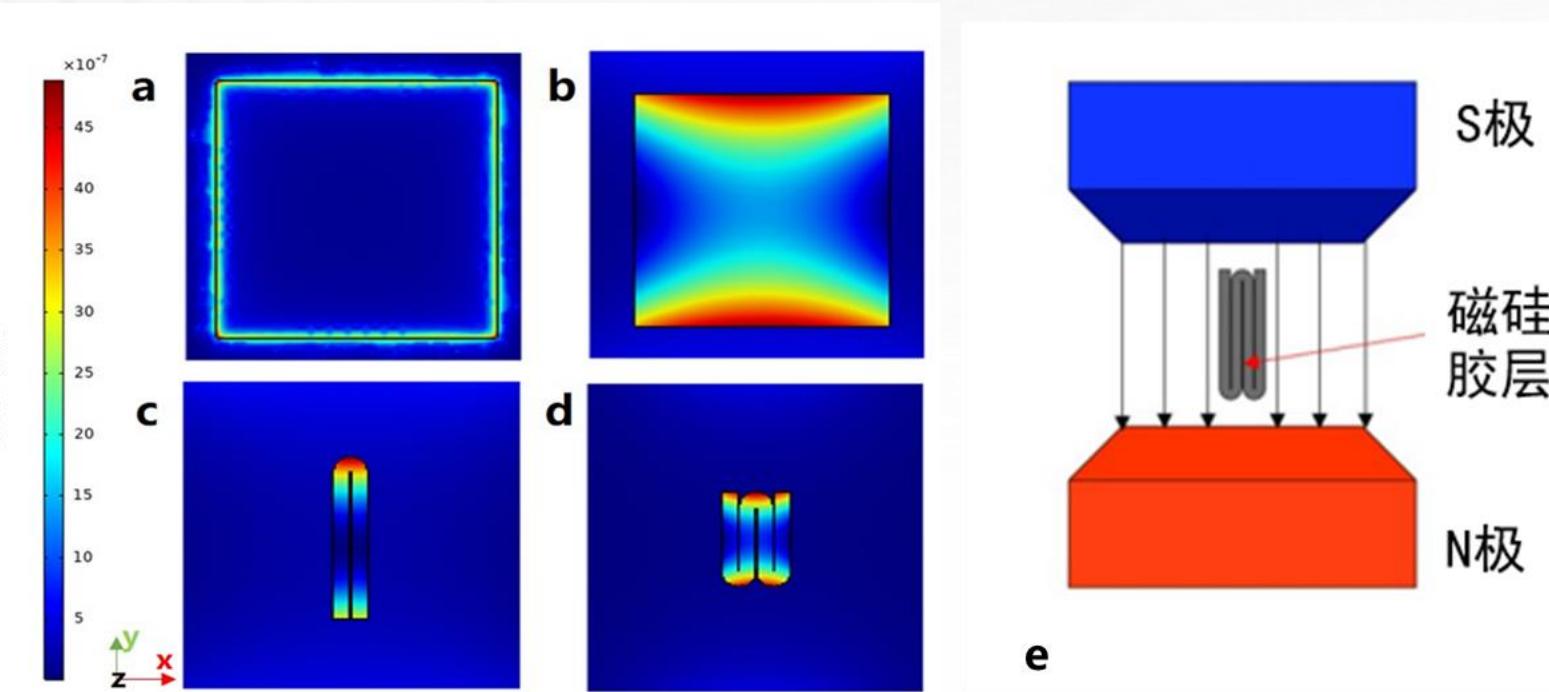


## 主要结构:

- 磁性层: 用于检测接触信号
- 霍尔传感器: 检测磁信号的变化
- 支撑层: 用于霍尔传感器的固定

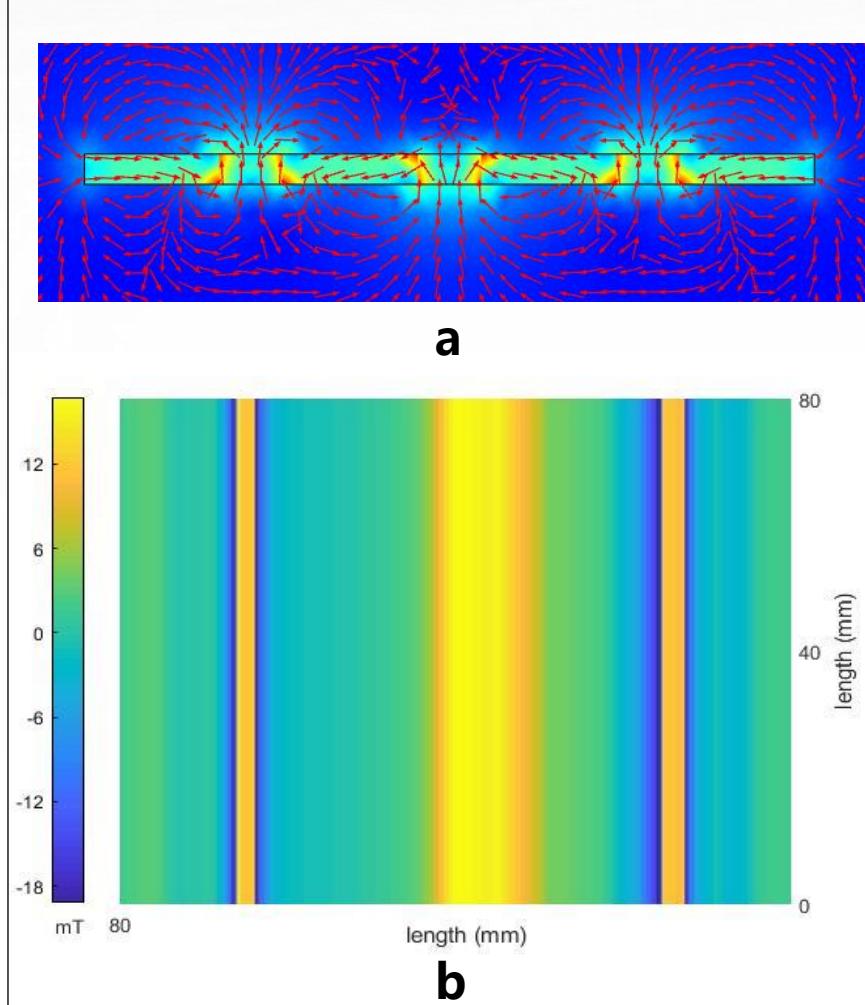


- 传感器的磁场分布: 多磁极磁场
- 响应速度较快: 可以及时响应接触信号

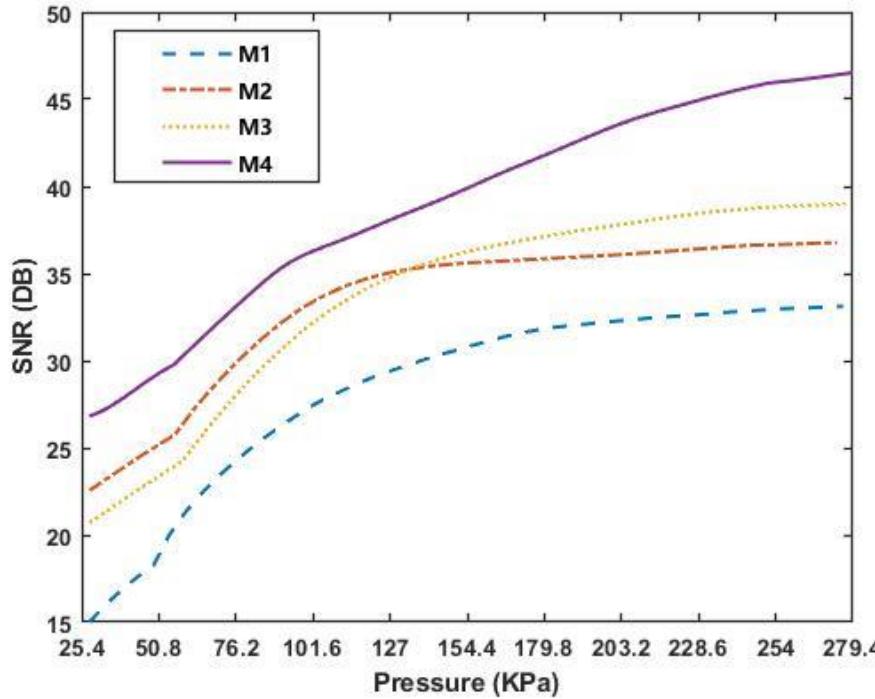


$$\Delta B_{hall} = \iiint_{\Omega} \frac{B_{particle}}{(dx^2 + dy^2 + (z - \Delta z)^2)^{3/2}} dv - \iiint_{\Omega} \frac{B_{particle}}{(dx^2 + dy^2 + z^2)^{3/2}} dv$$

## 磁场分布优化

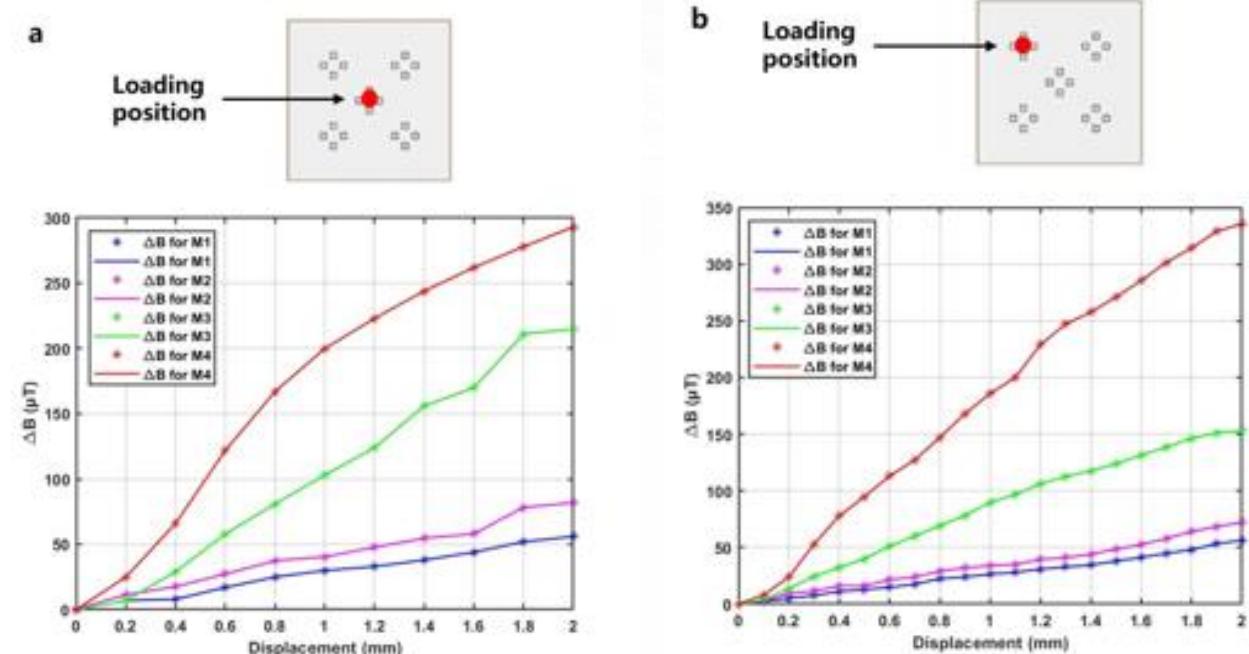


将磁性层采用的传统的单级充磁方式进行了改进及优化：改变充磁方式为多级充磁。  
改良后的传感器表面磁场分布为多磁极分布，磁场强度值也有显著的提升。



**信噪比 (SNR) :**

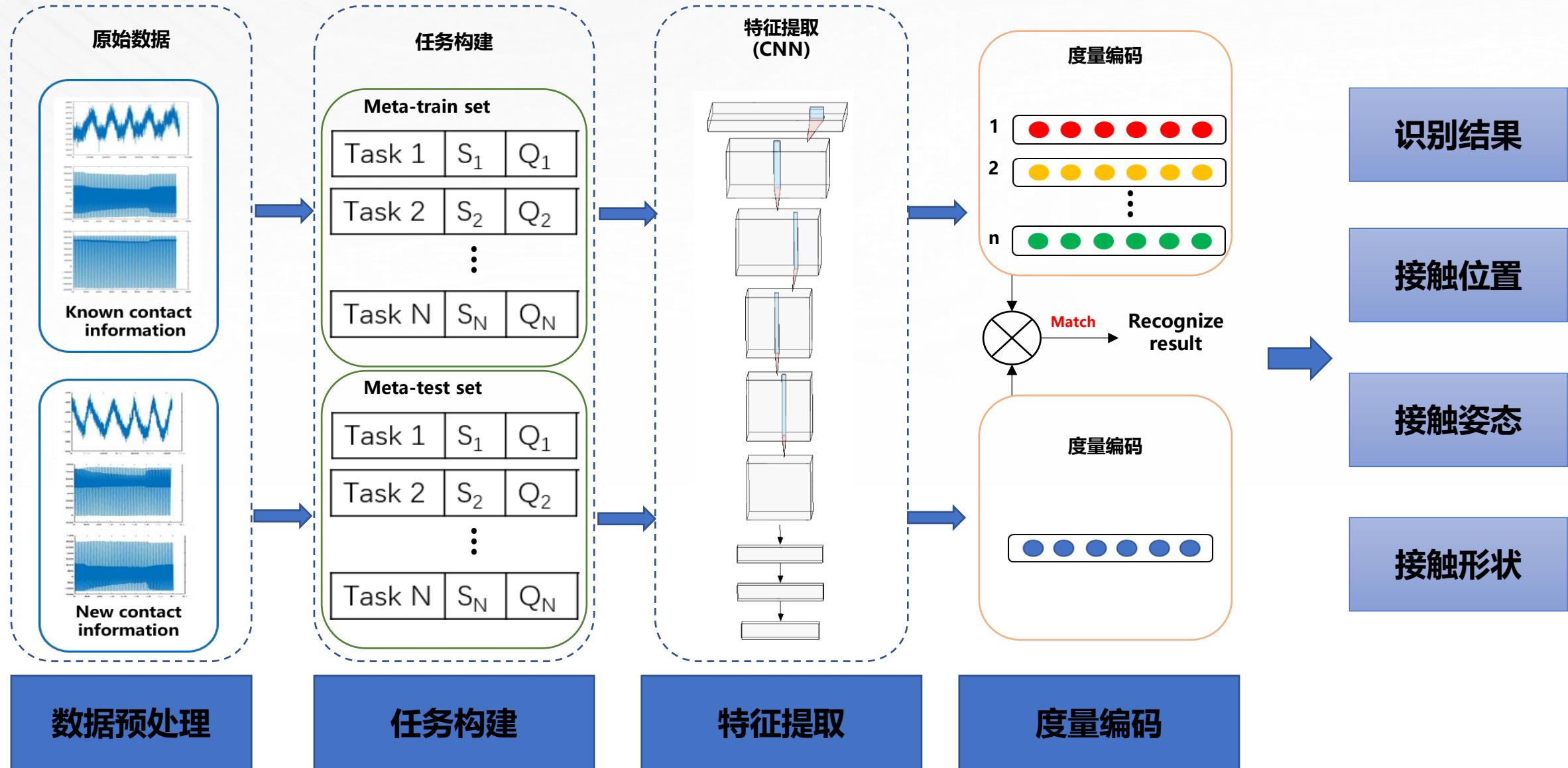
改良后的磁性层制作的传感器，触觉信号所包含的**噪声更少**。

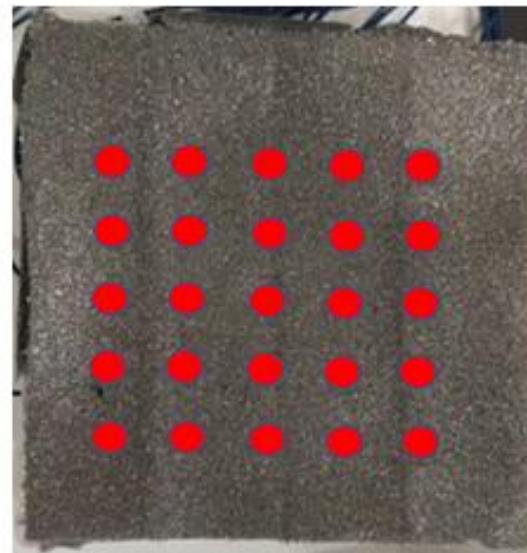
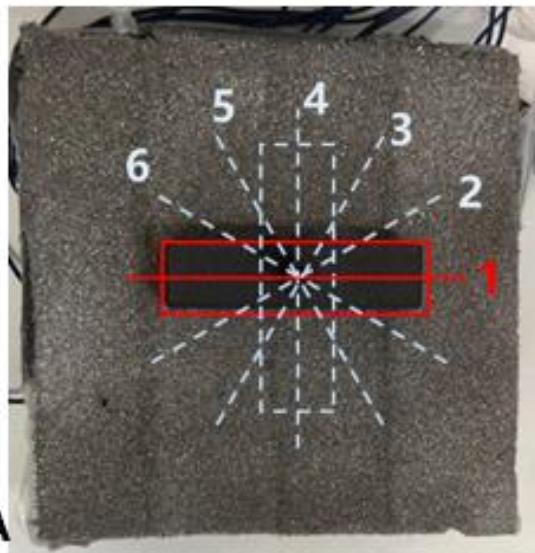
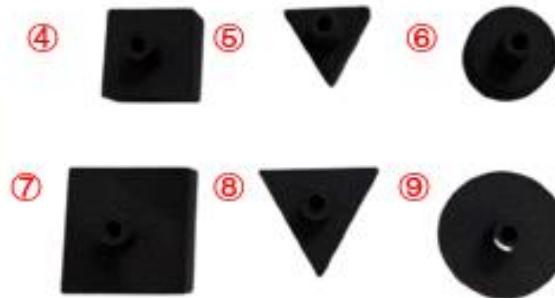


**灵敏度 (Sensitivity) :**

改良后的磁性层制作的传感器，对触觉信号的感知更加**敏感**，更利于**提取触觉特征**。

优化后的传感器在：灵敏度、信噪比等指标方面得到了较大的提升，数据稳定性更高





采集了9类触头的接触信息：包括接触位置、接触姿态两部分内容

测试结果：能较为准确的完成不同触头的接触位置识别任务。  
在姿态、形状两个识别任务上表现良好。

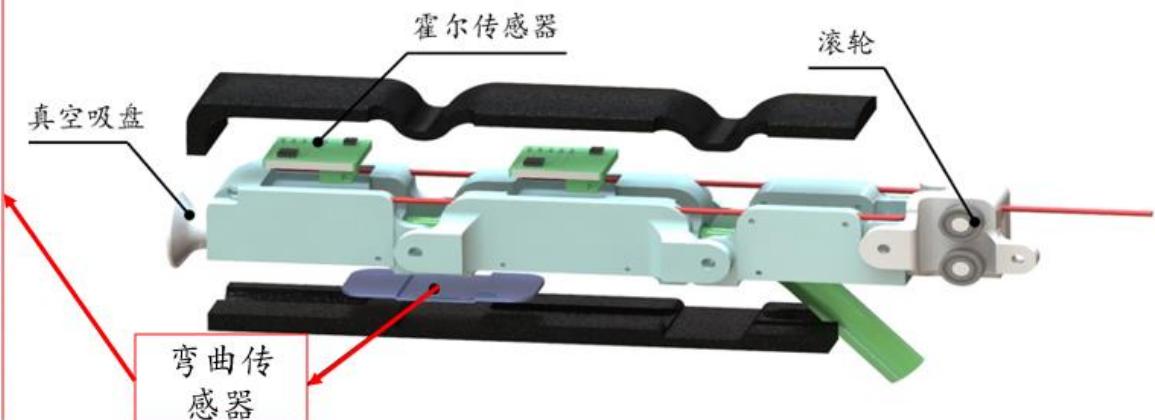
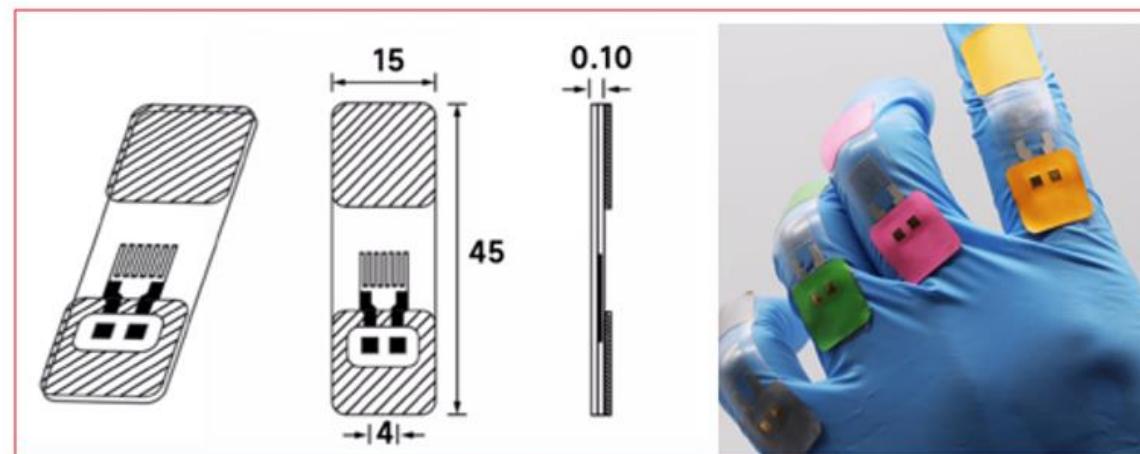
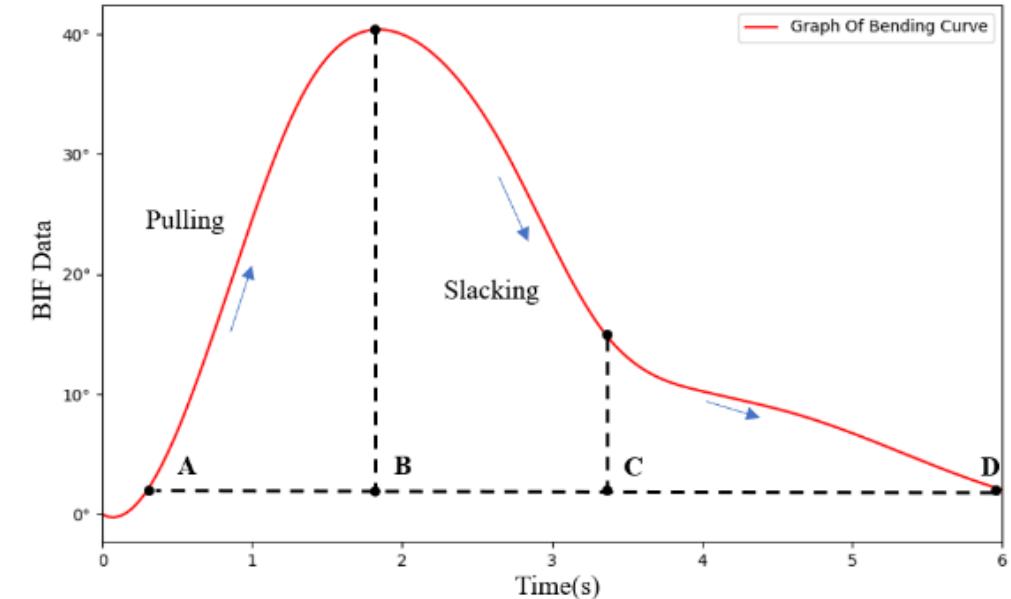
分别对不同的形状、姿态特征进行交叉验证，基于本文提出的方法，相比于传统深度学习方法，触觉特征识别准确率提升了10%，最高可达98%。

6-ways accuracy(%)	1-shot	3-shots	5-shots
Measuring head 1 and 2 → 3	91.25	94.64	97.88
Measuring head 1 and 3 → 2	91.86	95.12	98.14
Measuring head 2 and 3 → 1	91.78	94.76	98.28

accuracy(%)	Measuring head 1 and 2 → 3	Measuring head 1 and 3 → 2	Measuring head 2 and 3 → 1
Pronet(1-shot)	91.25	91.86	91.78
Pronet(3-shot)	94.64	95.12	94.76
Pronet(5-shot)	97.88	98.14	98.28
KNN (K-NearestNeighbor)	92.85	93.54	93.07
CNN	89.15	87.58	90.47



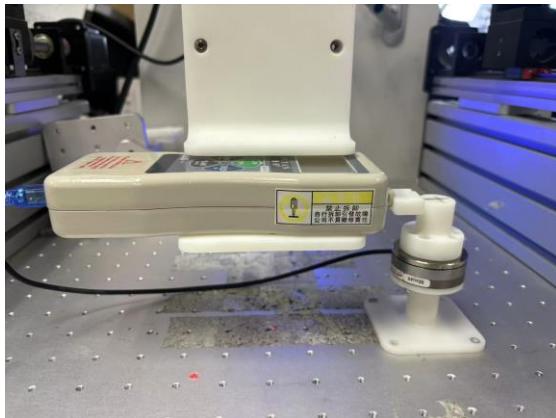
- 优化**磁性层材料和阵列结构**,设计异形分布式触觉阵列,便于不同场合压力感知测量需求。
- 开发了专用**集成数字接口**,降低功耗;设计柔性电路接口,方便与外部处理器通信。
- 多模态集成**,利用薄膜弯曲传感器检测弯曲状态,利用磁触觉传感器检测接触力。



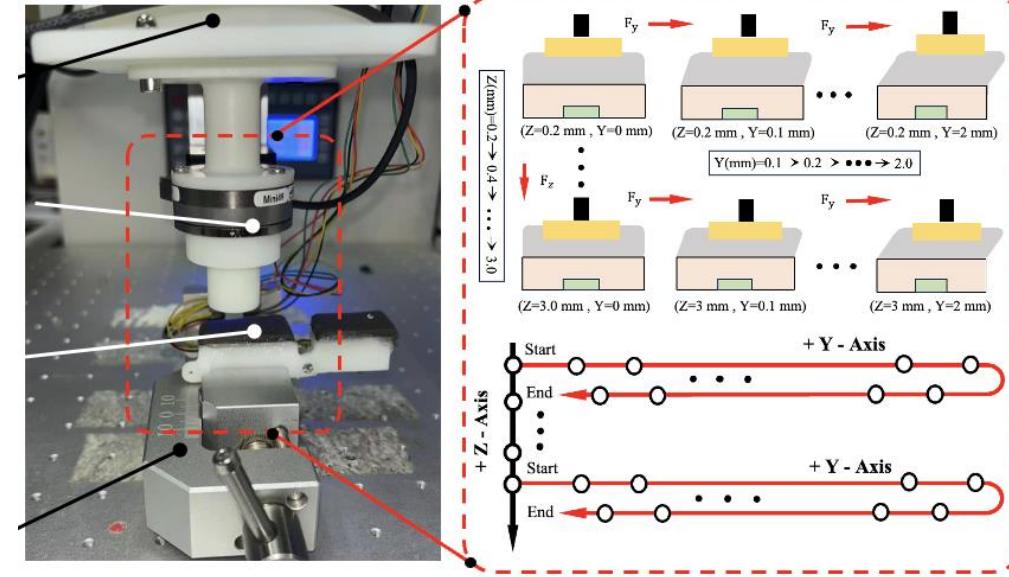
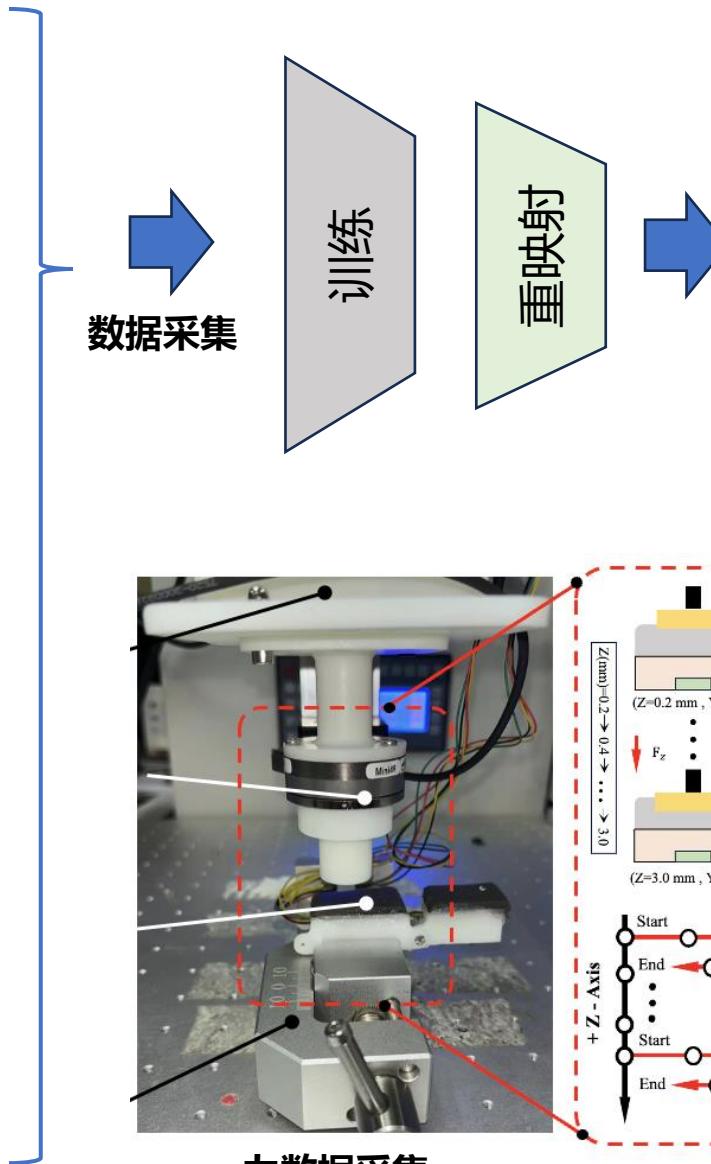
# 磁触觉皮肤——力控感知



法向力校准



切向力校准



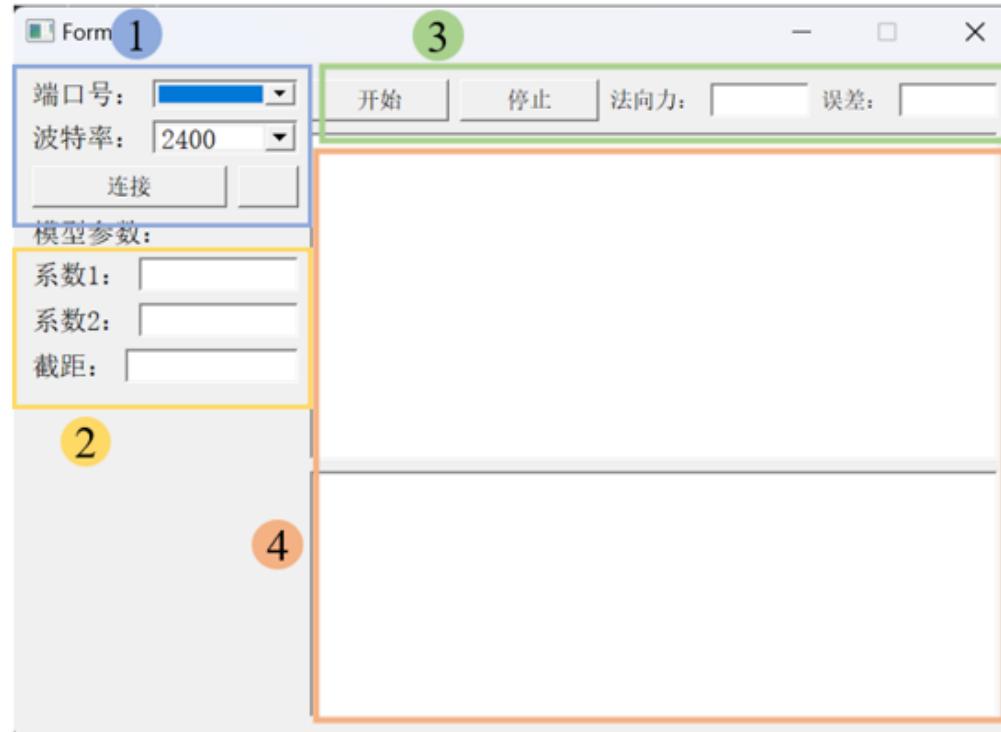
## 采集流程

- 力传感器向下压
  - 切向位移
  - 采集数据

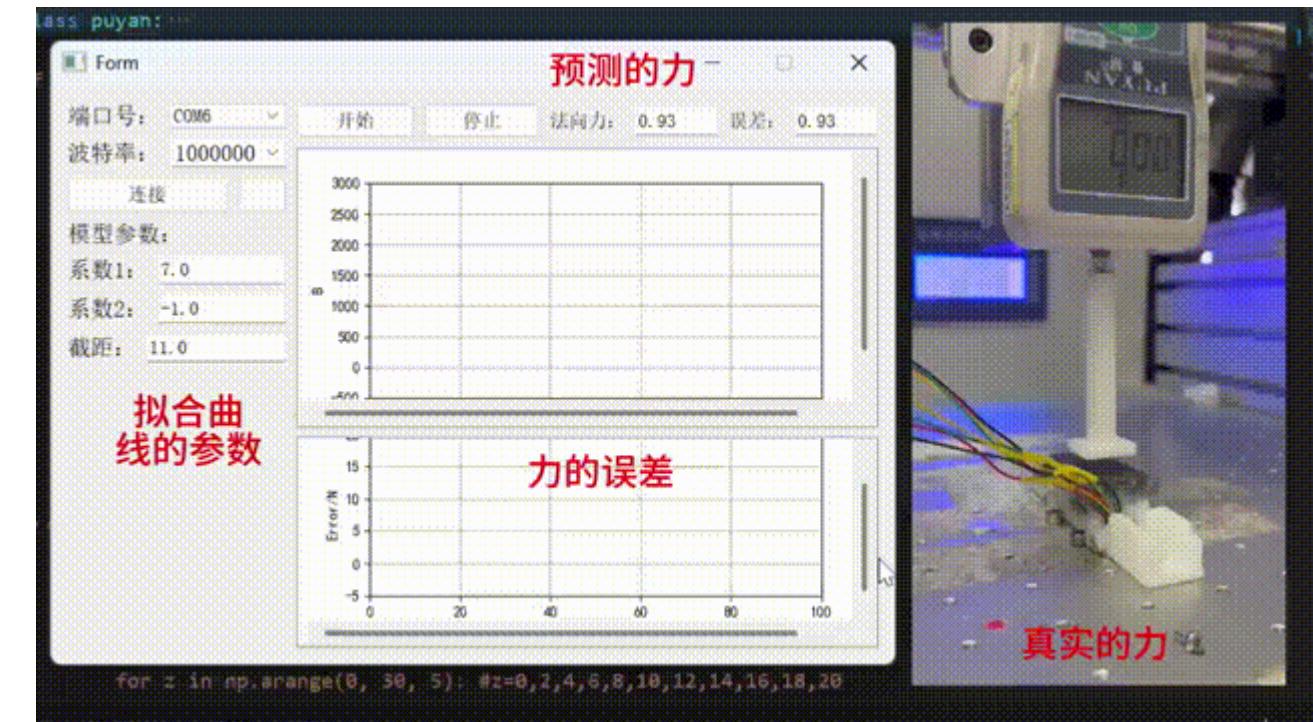
# 磁触觉皮肤——法向力标定



上位机界面



拟合结果



串口通讯

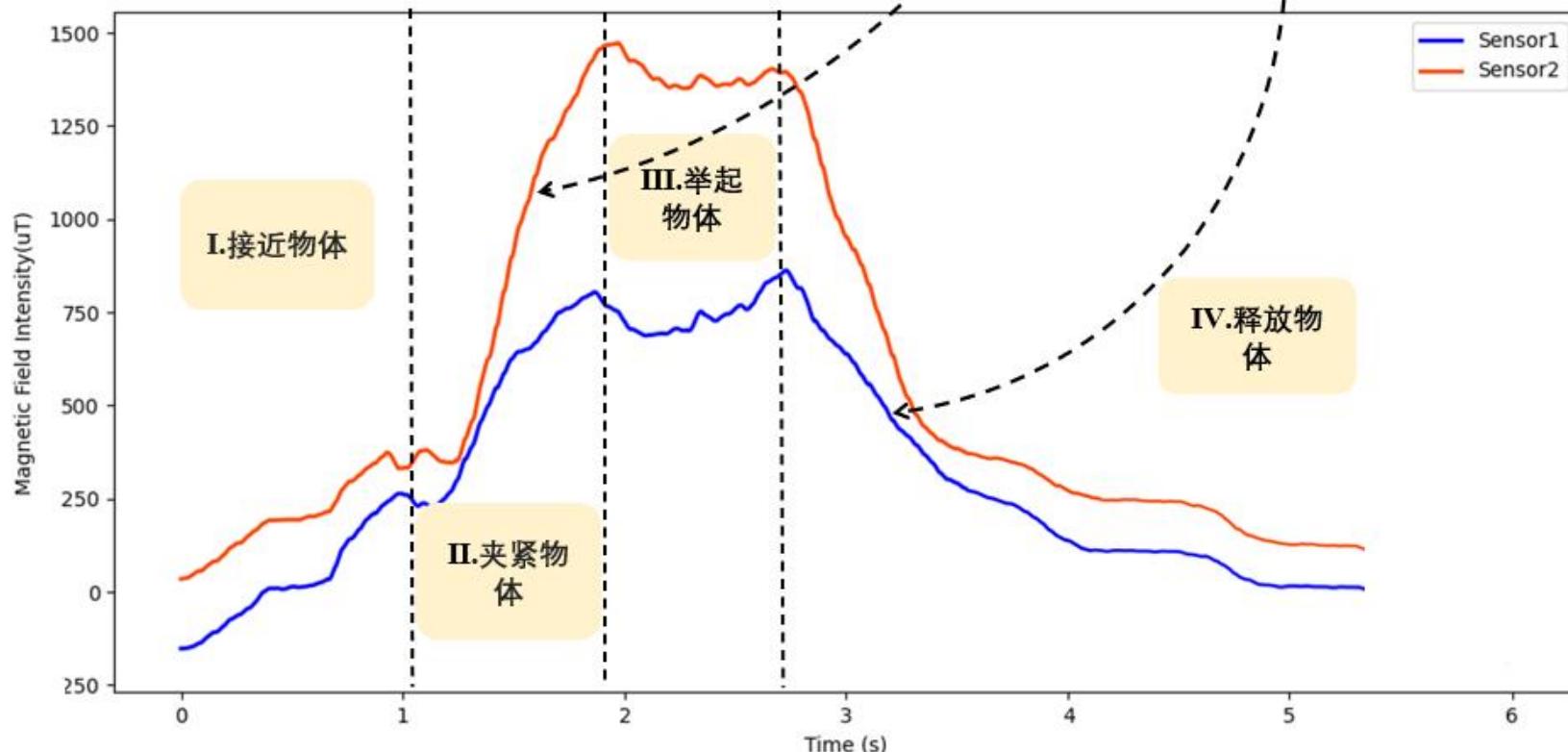
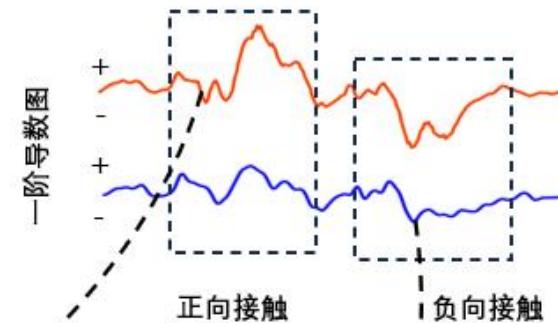
数据采集

感知算法

可视化结果



I. 接近物体 II. 夹紧物体 III. 提起物体 IV. 释放物体

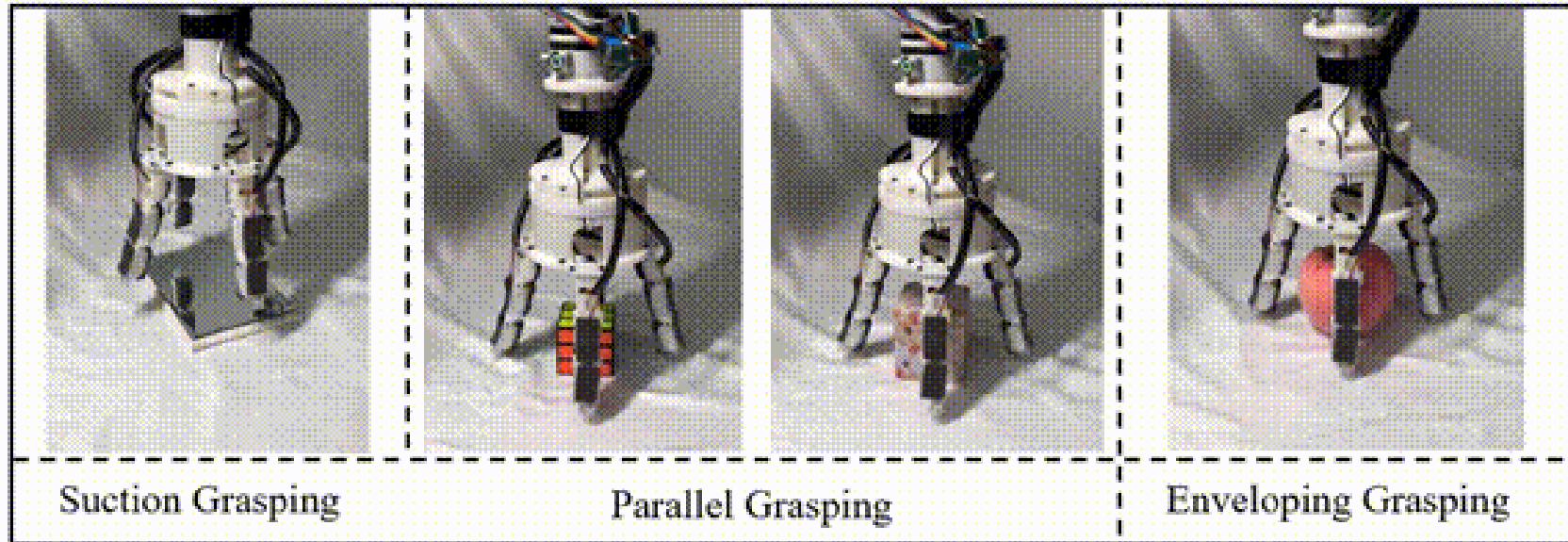


**平行抓取与包围抓取会对磁性硅胶薄膜产生挤压。将平行抓取分为四个阶段：**

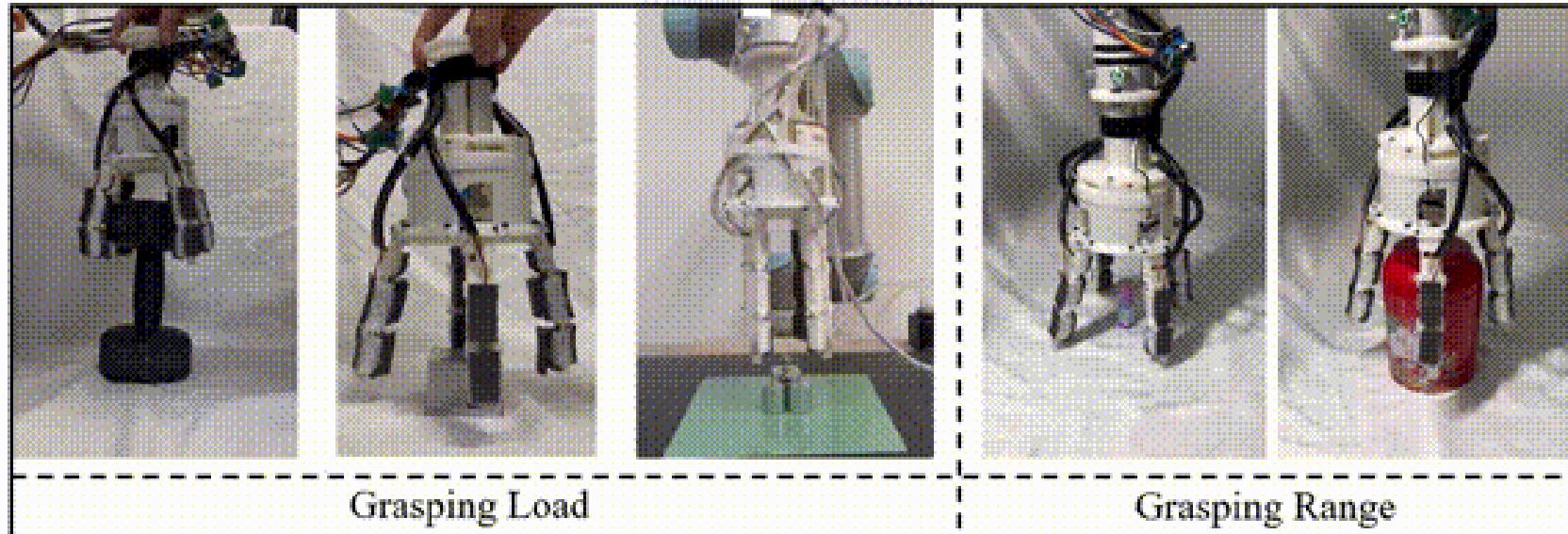
1. 接近物体
2. 夹紧物体
3. 提起物体
4. 释放物体



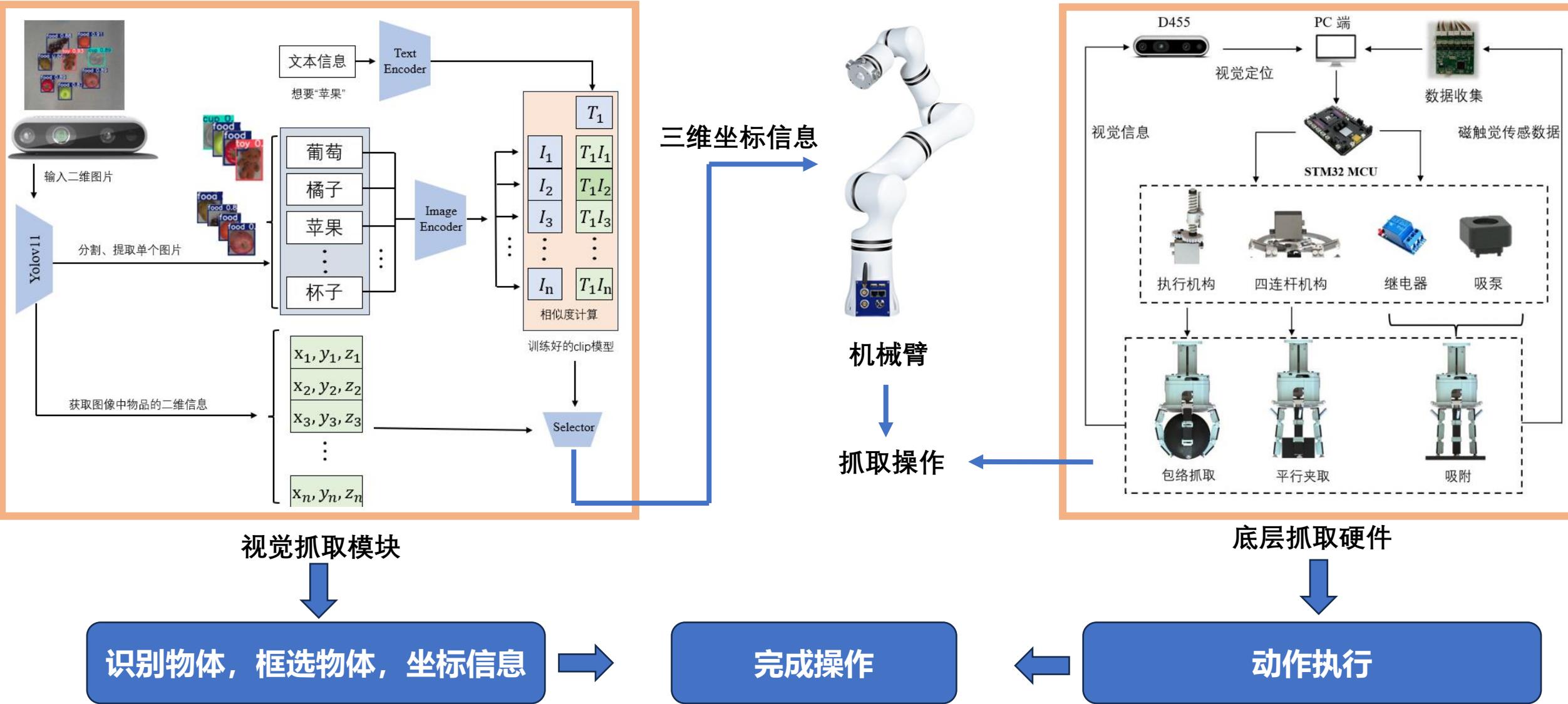
Grasping Mode



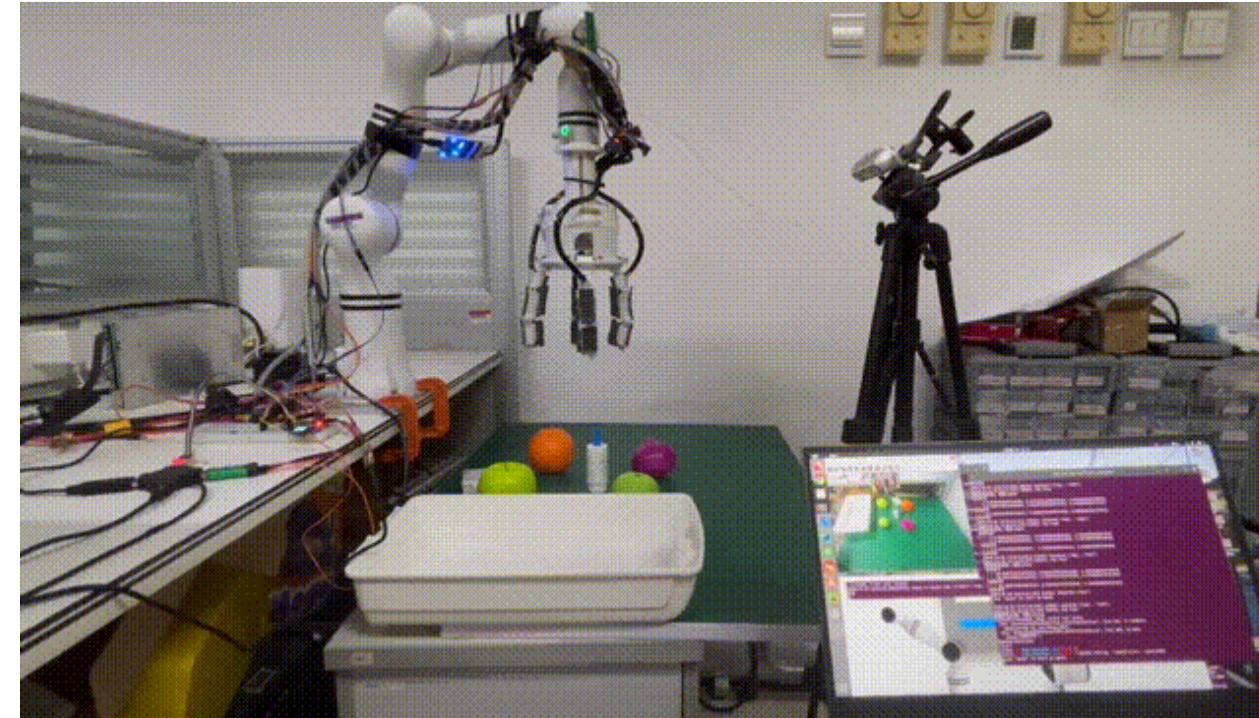
Performance Testing



# 抓取性能测试



# 实验结果



物体识别抓取



擦拭油污实验

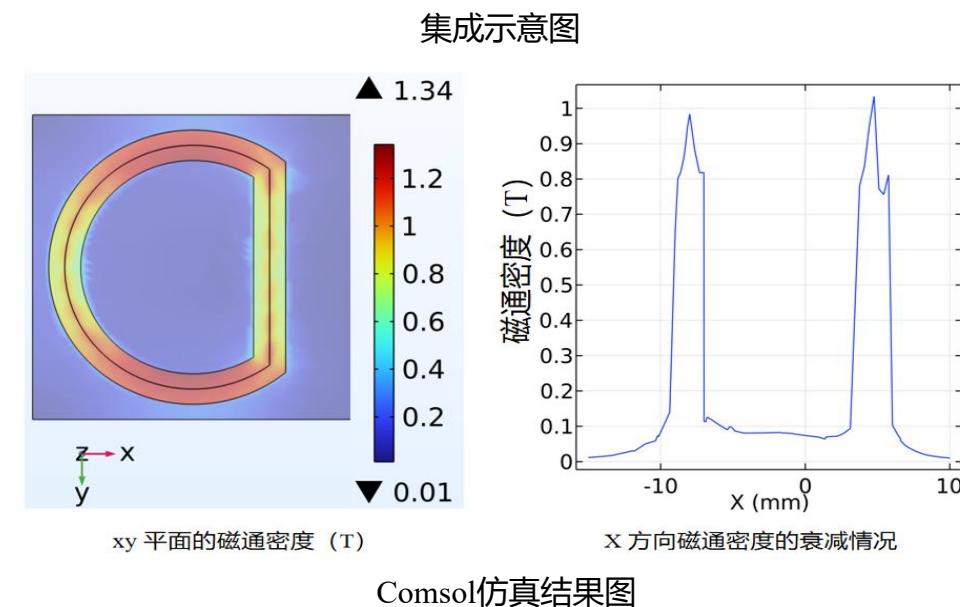
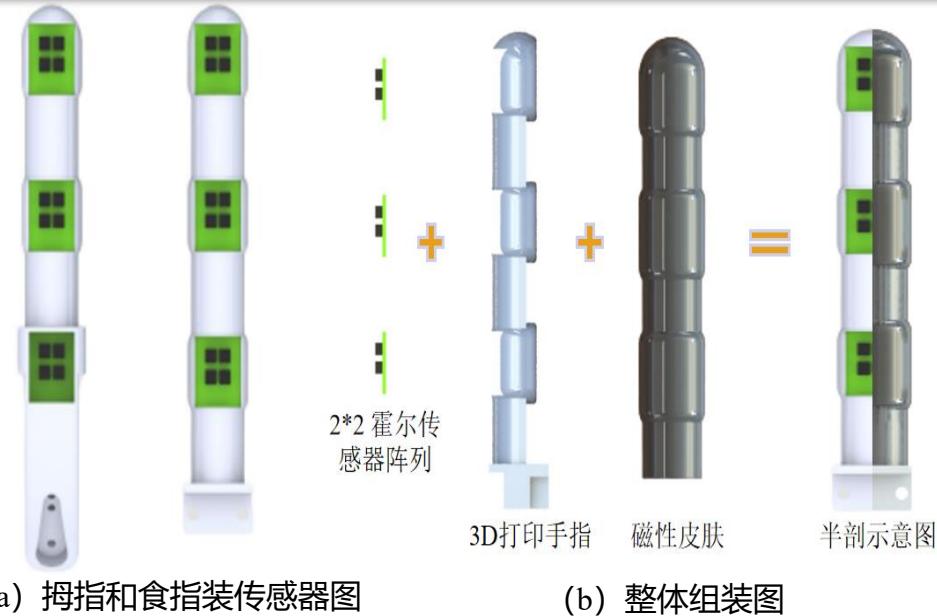
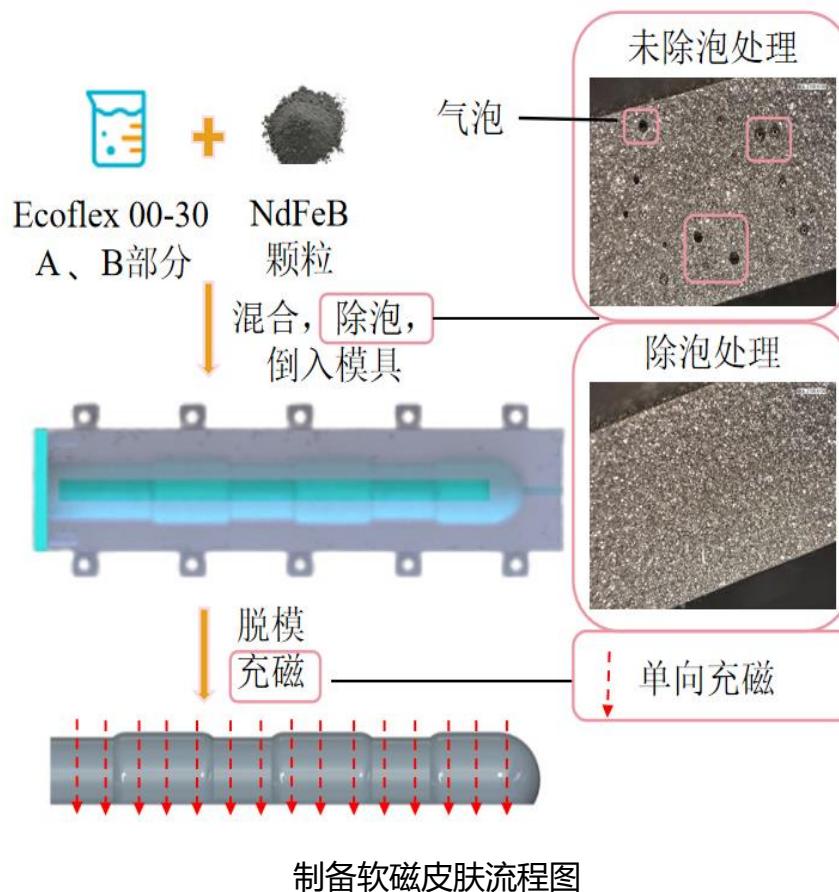
# 磁触觉皮肤——全域感知



北京郵電大學  
Beijing University of Posts and Telecommunications

## 人工智能学院

原理：当皮肤与物体发生接触或产生变形时，内部磁性颗粒发生位移重组，磁场分布发生改变，三维霍尔传感器可以检测出磁场的变化。

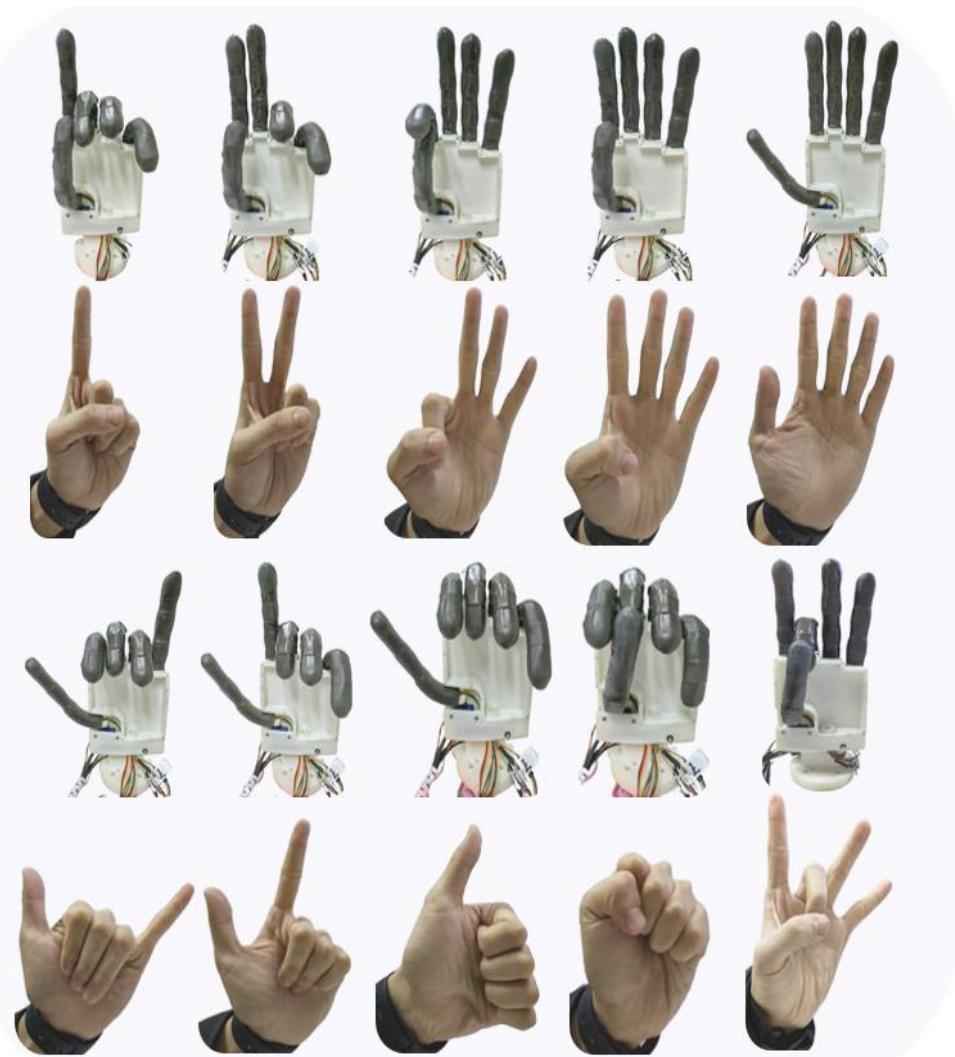


# 磁触觉皮肤——触觉感知及运动感知



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Beijing University of Posts and Telecommunications

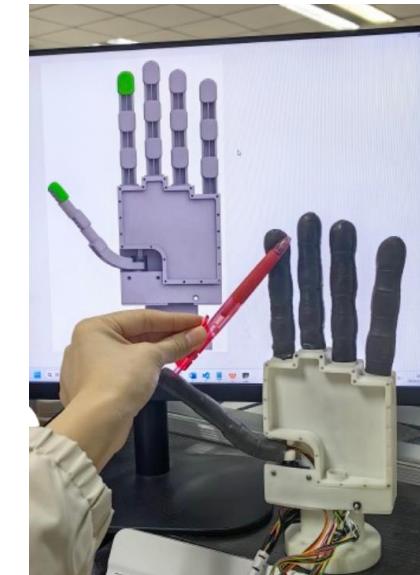
人工智能学院



灵巧手和人手的手势图



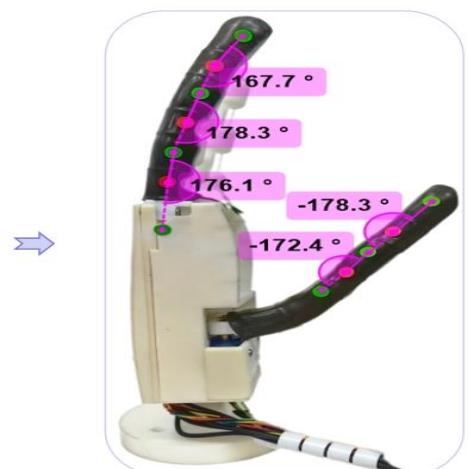
动态显示接触部位图



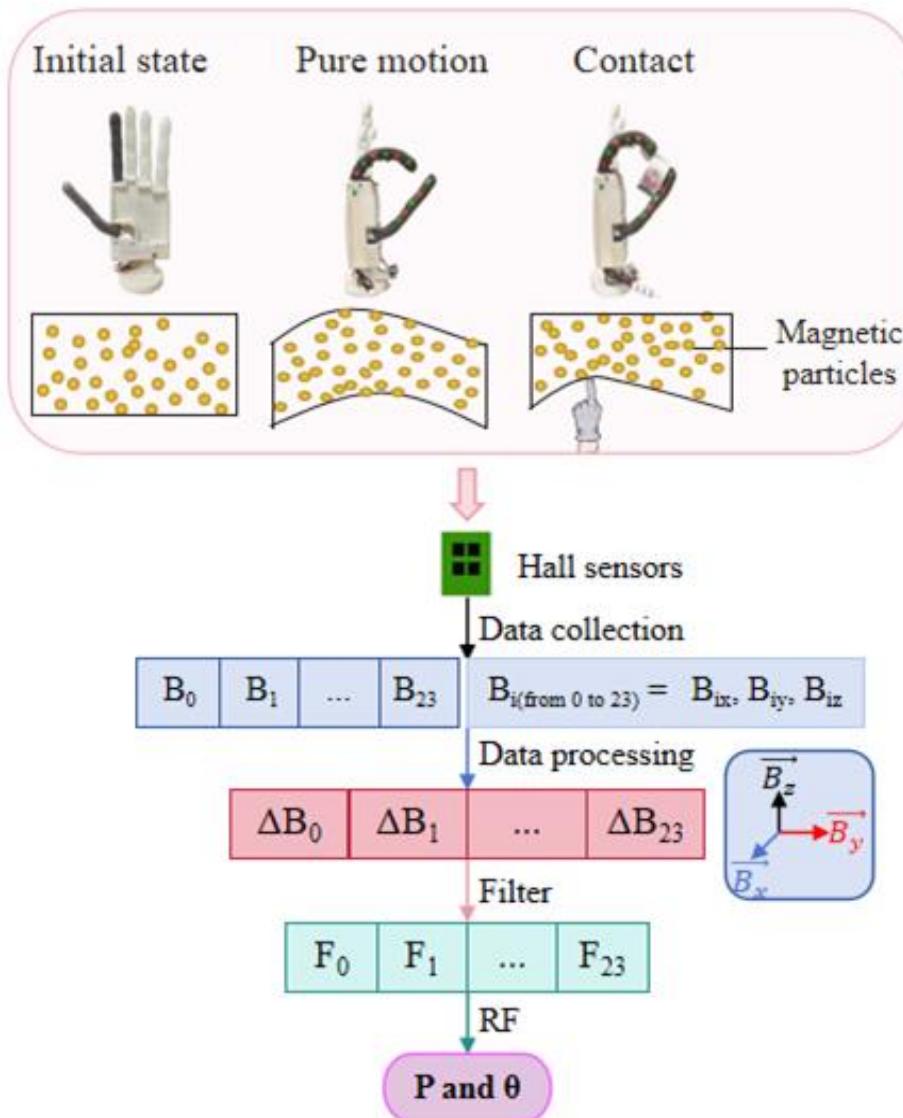
动态显示接触部位实验效果图

接触觉感知

运动觉感知

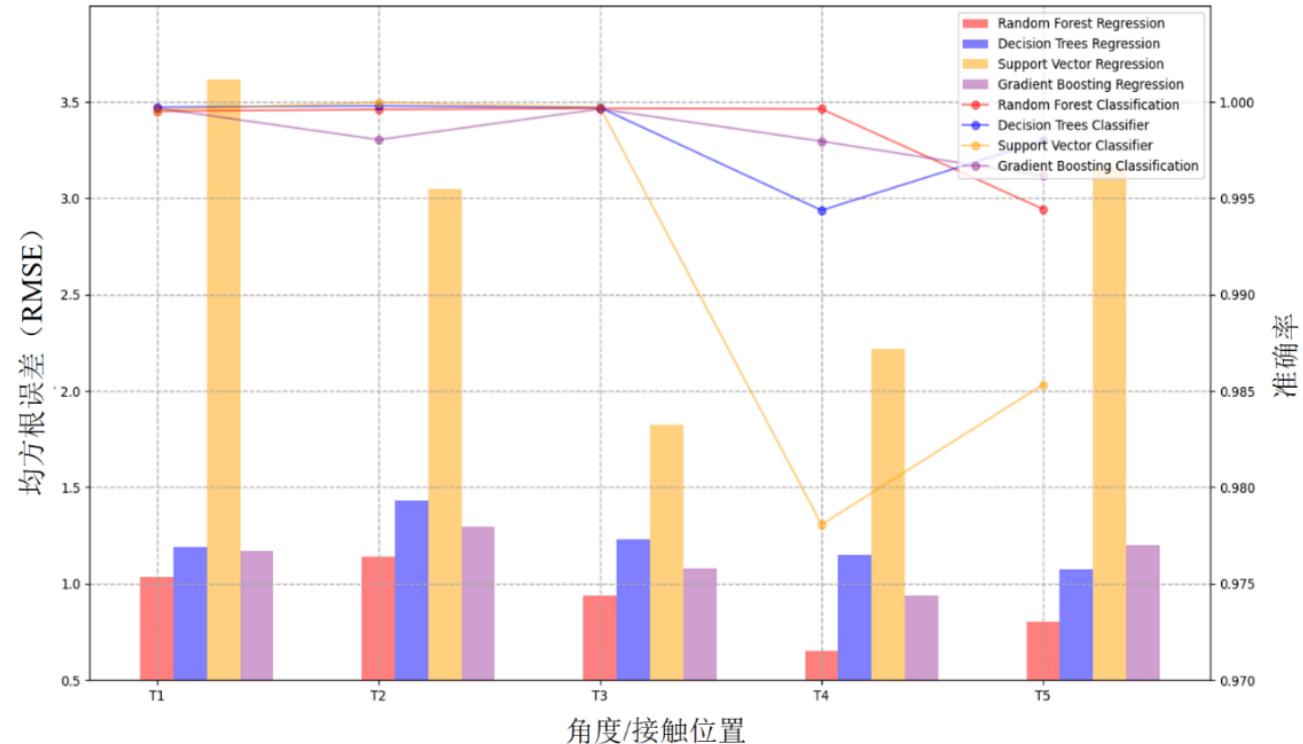


Kinovea标记关节角



接触觉和运动觉的网络框架优化图

对于接触位置分类的正确率最低优于99.4%；对于关节角的拟合， $RMSE = 0.9 \pm 0.2^\circ$ 。



接触觉和运动觉的网络框架优化图



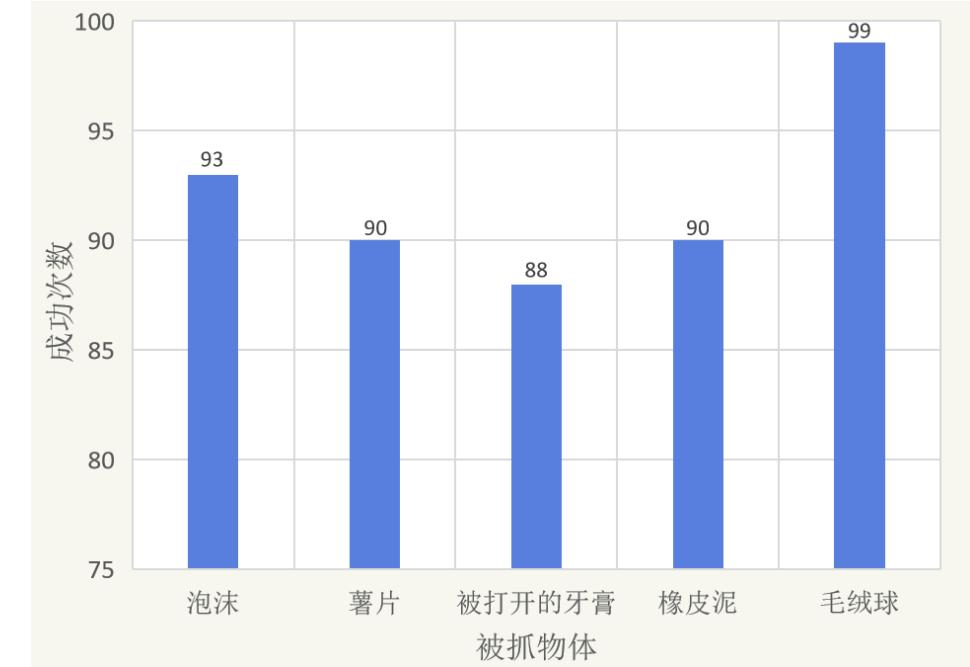
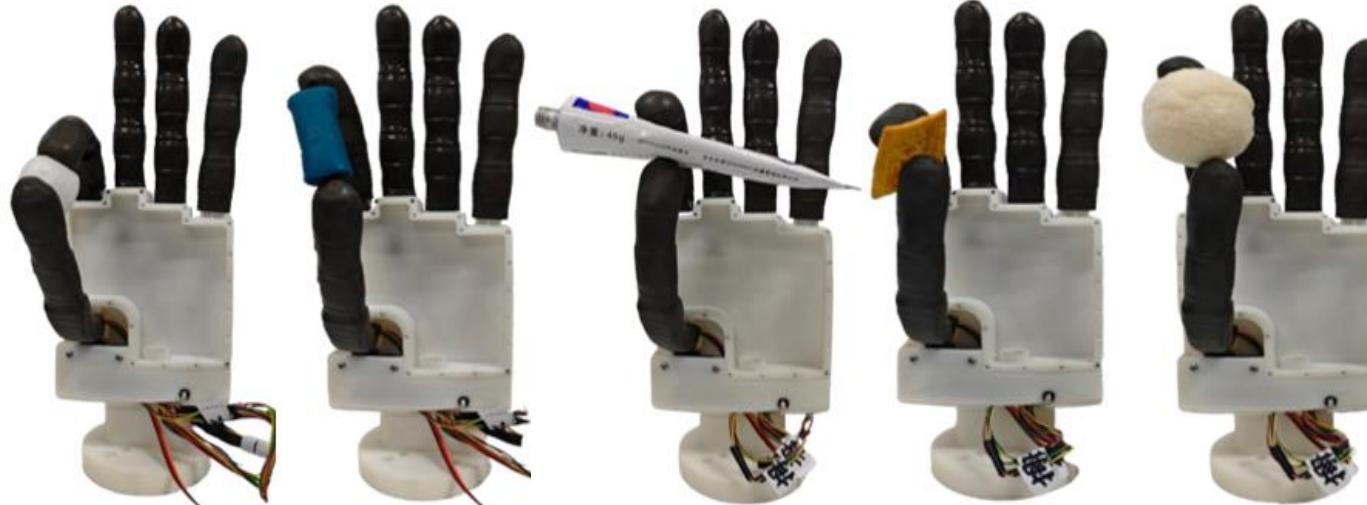
## 灵巧手抓取操作



物体操作分类表

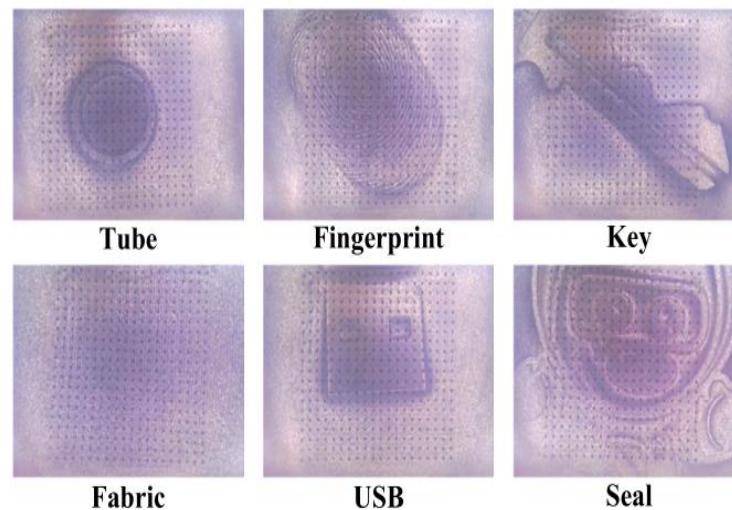
物体	重量 (g)	体积 (cm <sup>3</sup> )	操作类别
剪刀	81.79	214×83×15	勾取
购物袋	222.47	200×100×360	
胶带	16.46	91×91×9	
护手霜	21.46	20×20×117	捏取
长尾夹	1.34	15×7×27	
身份证	6.64	85×54×1	
苹果	304.73	76×82×66	包络
纸杯	3.83	75×75×81	
鼠标	73.59	50×95×45	
笔	12.38	145×16×16	夹取
吸管	1.83	284×14×3	
手套	2.00	65×65×1	

灵巧手表面的皮肤具有柔软、弹性和可变形的特性，能够更好的适应不同形状的物体表面。用相同的按压力接触物体时，软磁皮肤能减小损坏物体的风险，为灵巧手和物体提供一定的保护和缓冲效果。

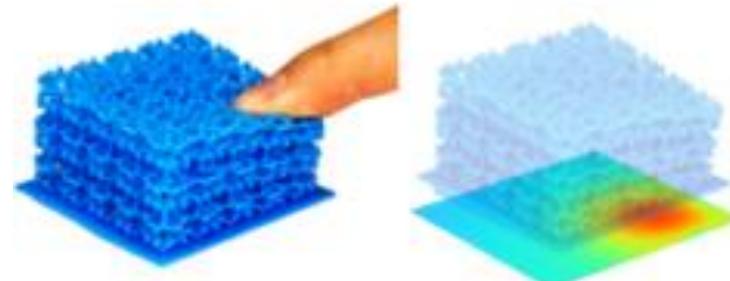


我们对上述五种物体进行抓取操作，每种物体进行100次，以在抓住后轻微摇晃10 s，保持稳定抓握不掉落且平稳放下后无破损、明显或不可逆形变为标准，测试抓取成功率。测试结果如图5.10，对**泡沫、橡皮泥、打开的牙膏、薯片、毛绒球的抓取成功分别为93%、90%、88%、90%和99%**。

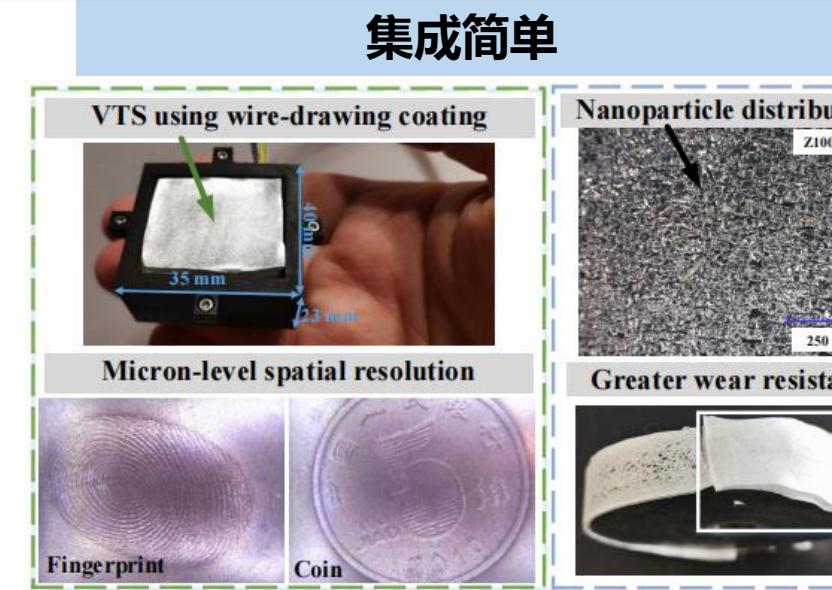
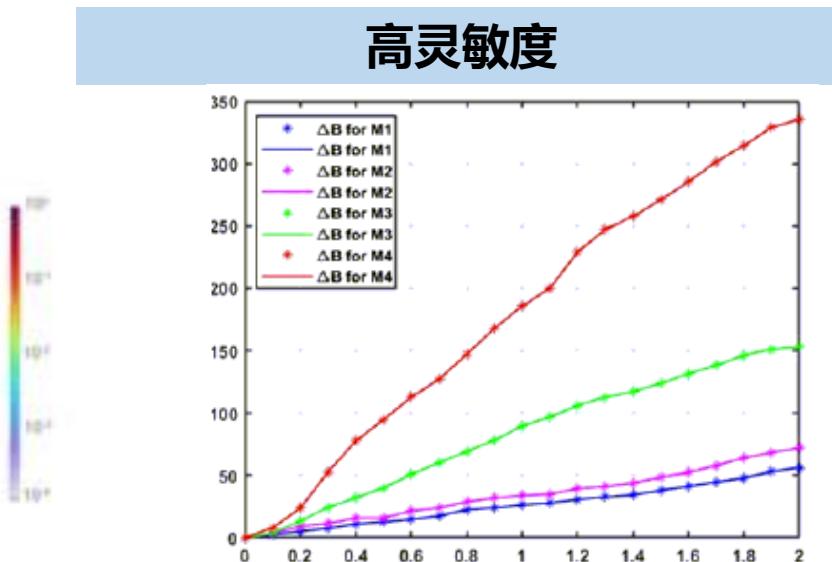
视触觉



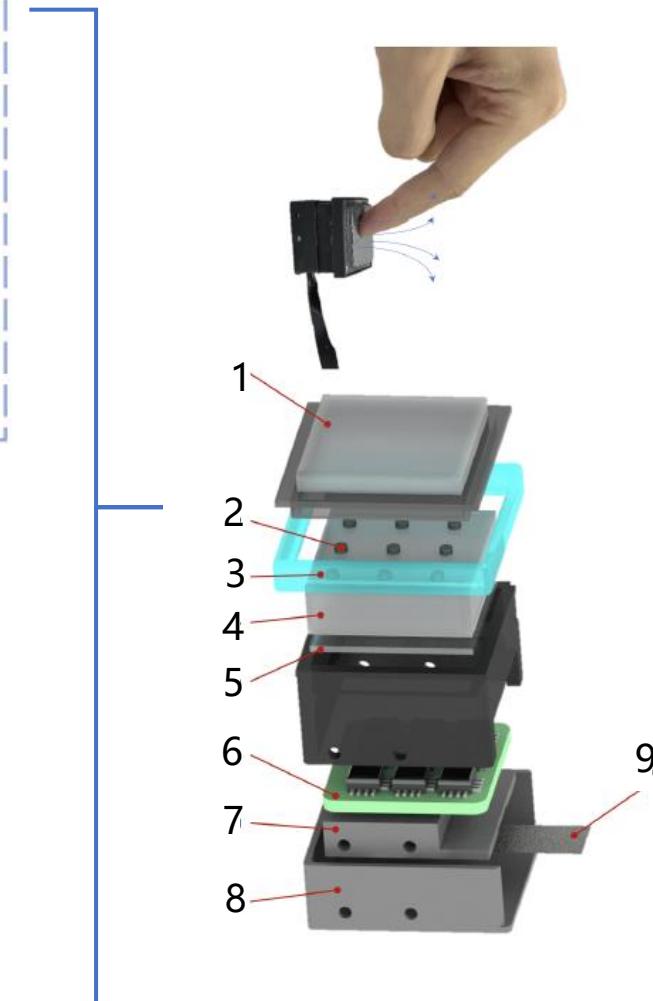
磁触觉传感器



10<sup>-6</sup> 10<sup>-5</sup> 10<sup>-4</sup> 10<sup>-3</sup>



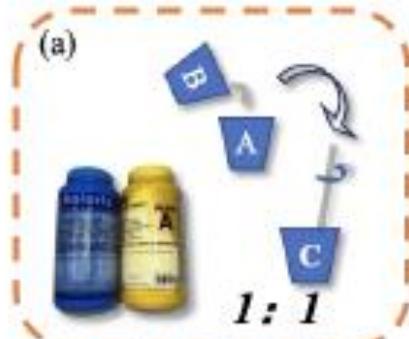
融合



# 磁触觉\_视触觉融合——结构设计



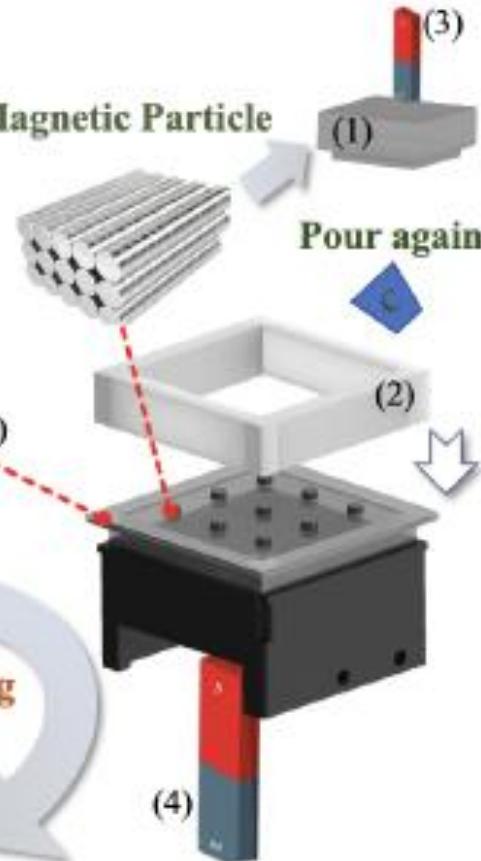
## Material Production:



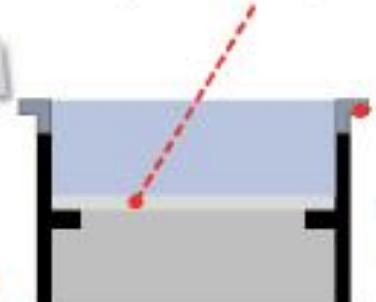
Pour In



Magnetic Particle



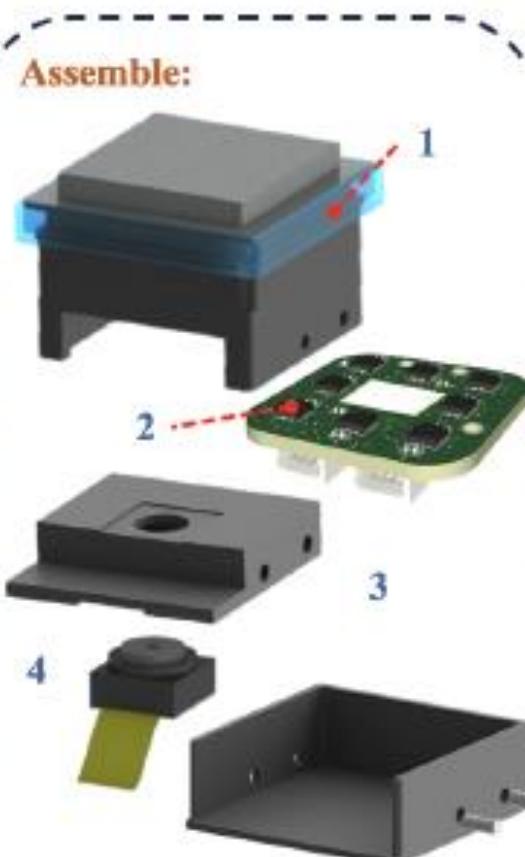
Transparent Acrylic Board



Welding

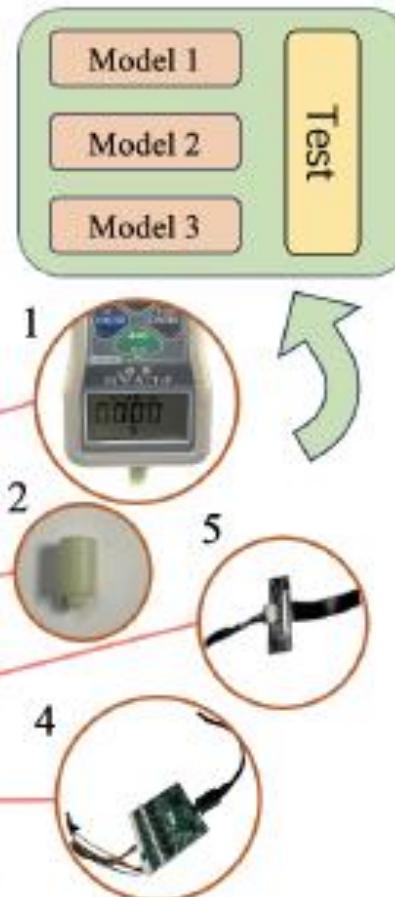
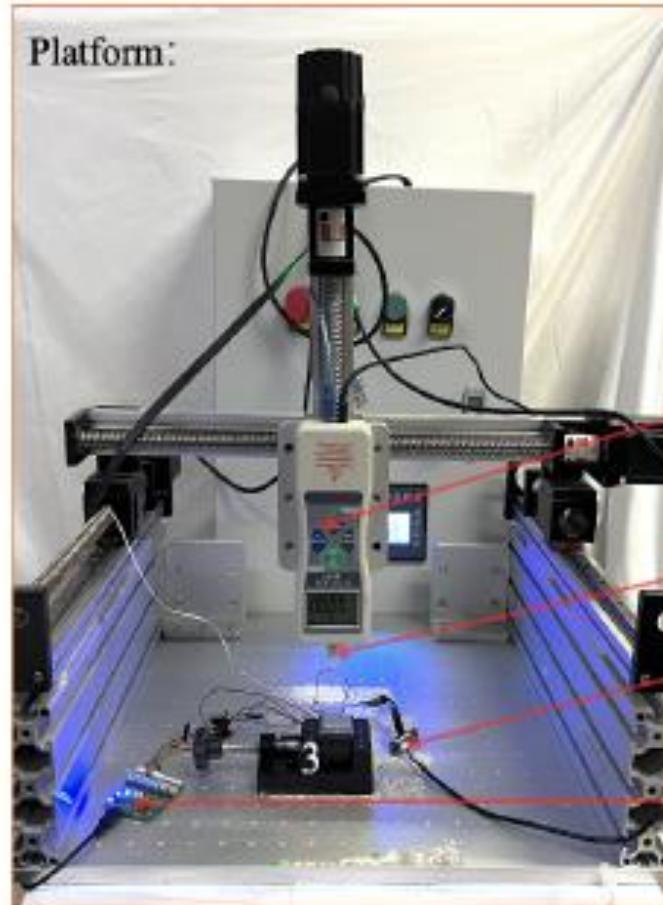


整体结构方案

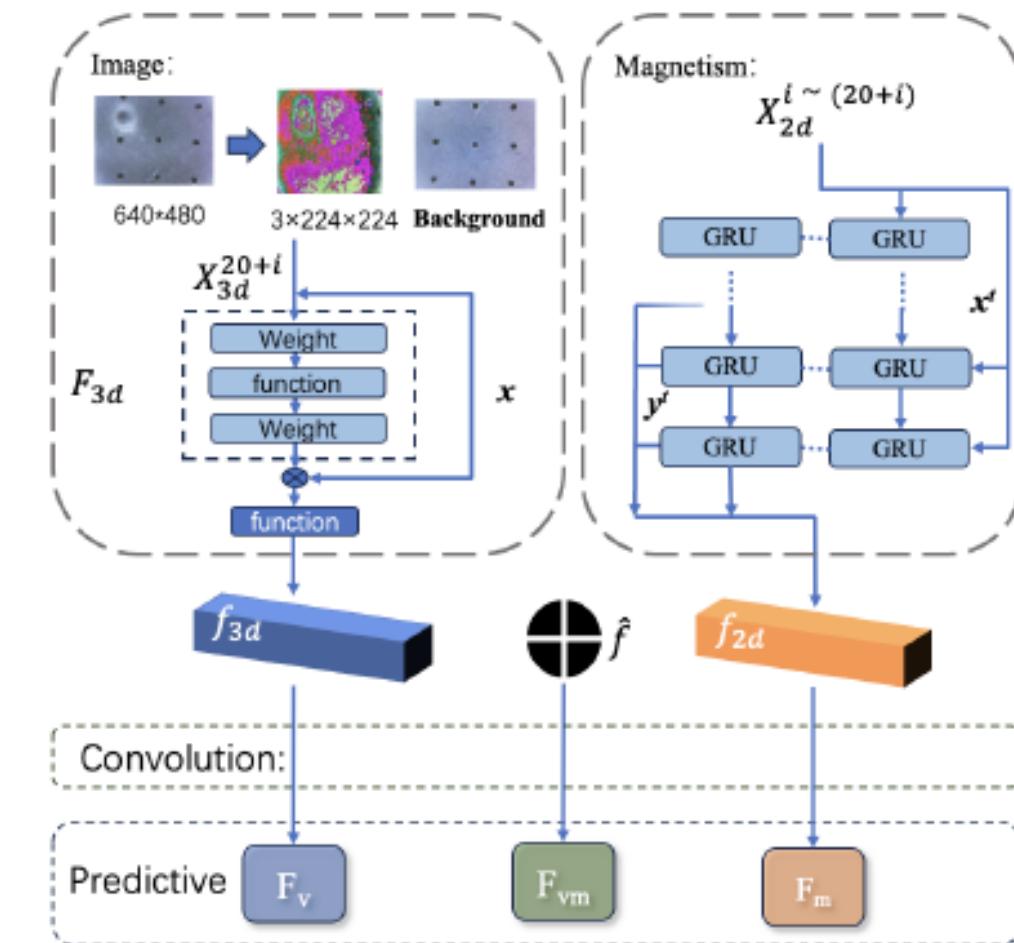


1. Light
2. Hall Sensor
3. Supporting Components
4. Camera

# 磁触觉\_视触觉融合——结构设计



标定试验台

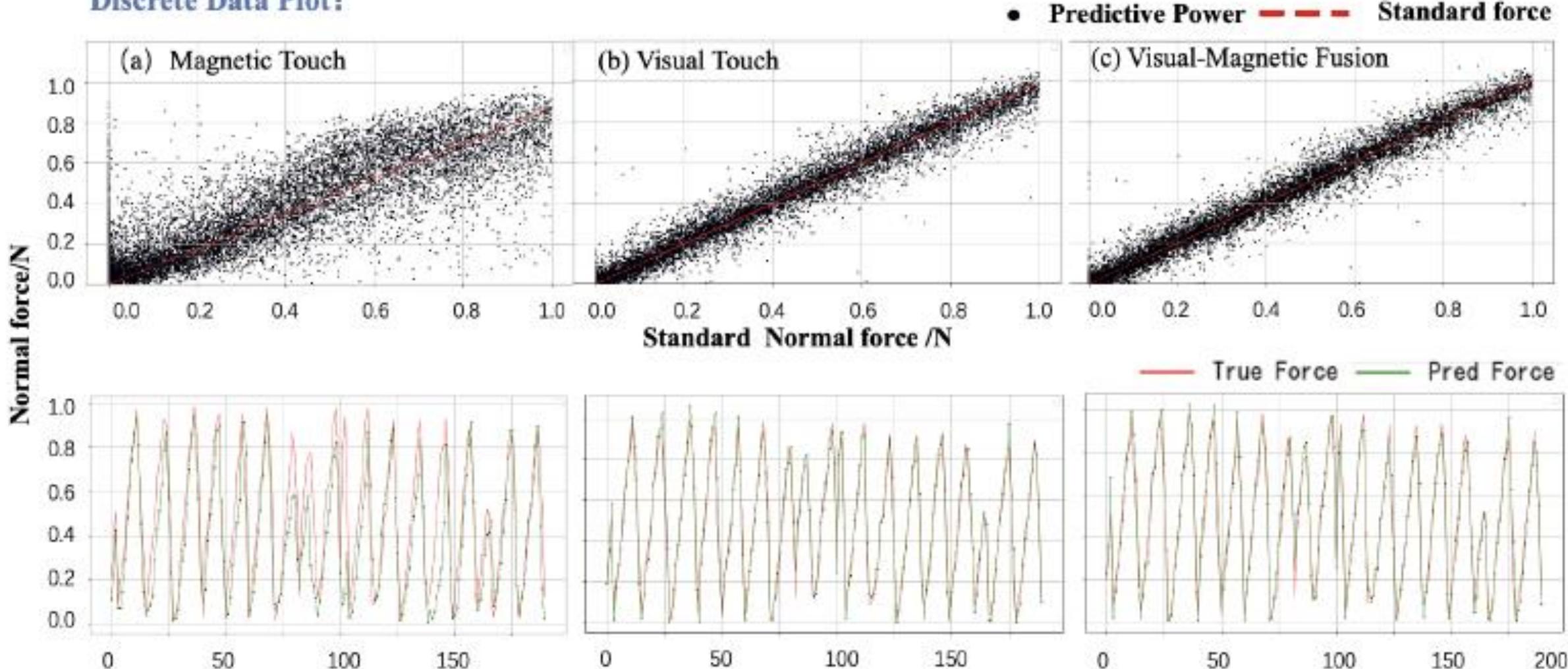


特征融合方法

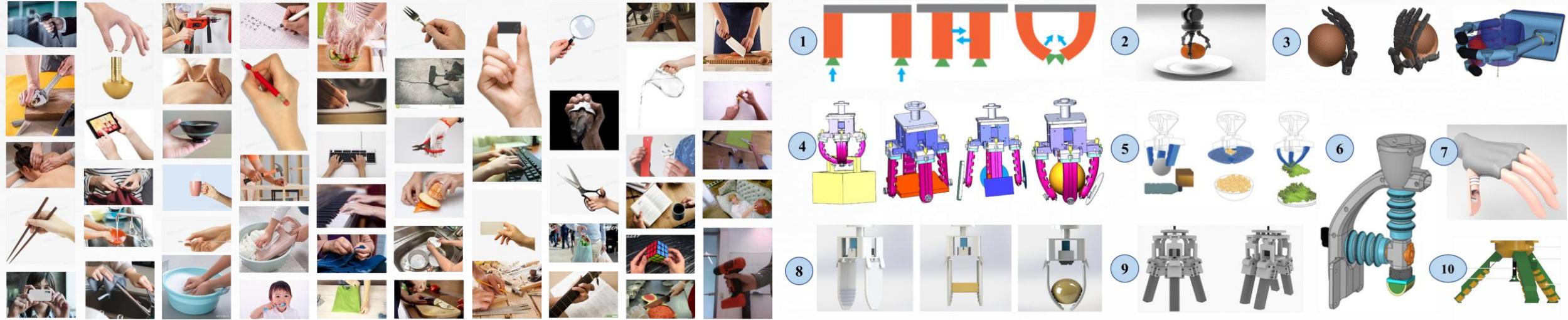
# 磁触觉\_视触觉融合——感知结果



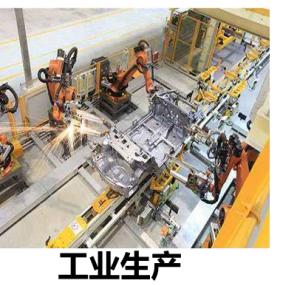
Discrete Data Plot:



# 机器人通用操作大模型，促进机器人服务各行各业，服务千万家庭



通用操作离不开触觉，触觉驱动AI是新的发展点！



# Thanks!