



Soft Robotics and Biodesign Lab
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上海交通大学
SHANGHAI JIAO TONG UNIVERSITY

China 3DV 2025 青年学者论坛

面向智能机器人灵巧操作的视触觉传感器设计与应用

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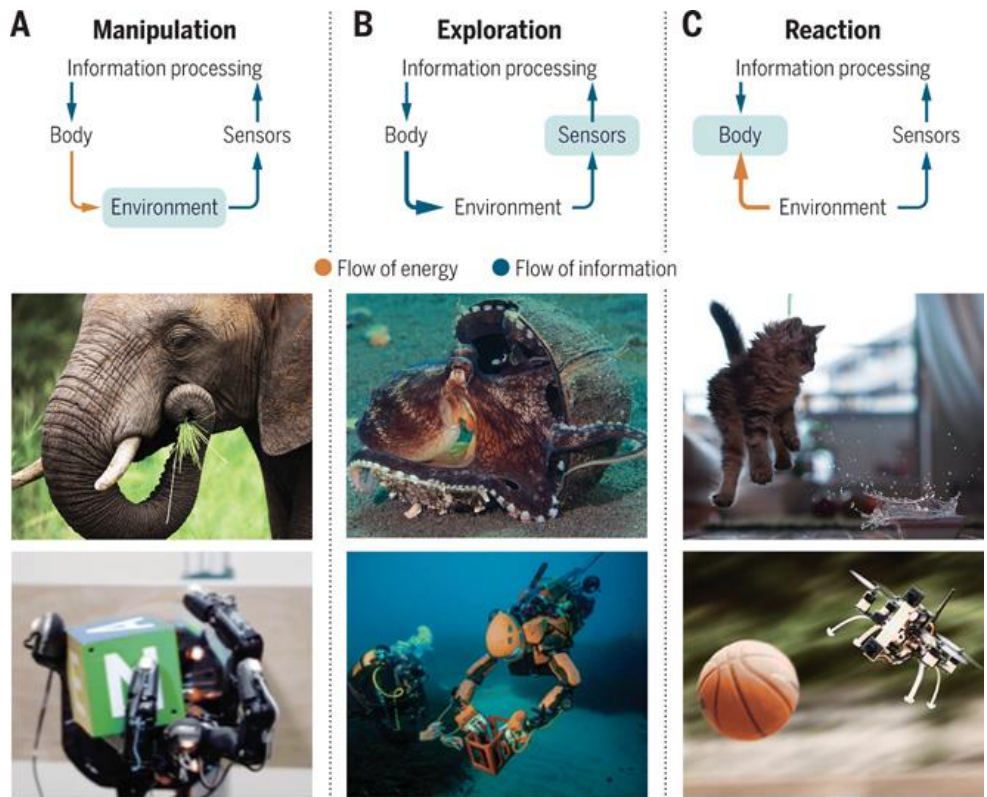
China **3DV**
中国三维视觉大会

2025年04月11日

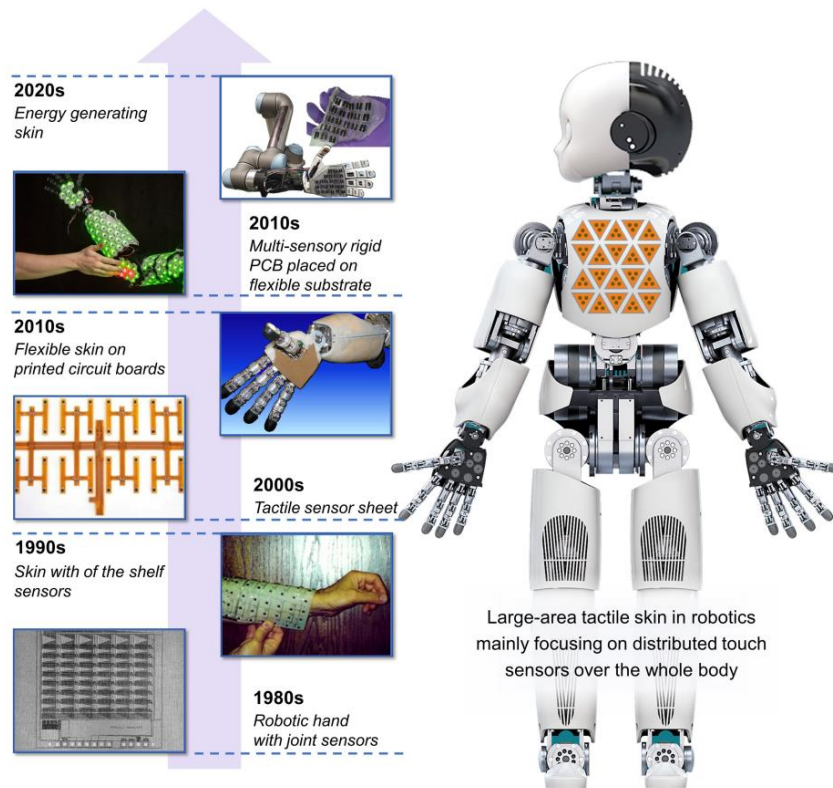
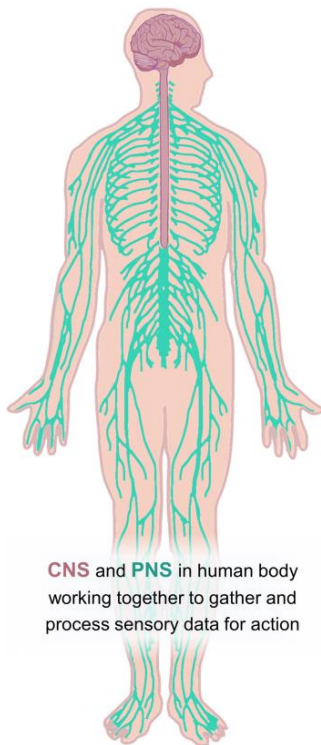
饮水思源 · 爱国荣校

北京 2025.4.11~2025.4.13

触觉感知是机器人与真实世界交互的重要手段，与环境探索、本体感知、认知识别、非结构化抓取、灵巧操作等复杂具身智能任务息息相关。



生物触觉感知 *SciRobotics.aaz9239*

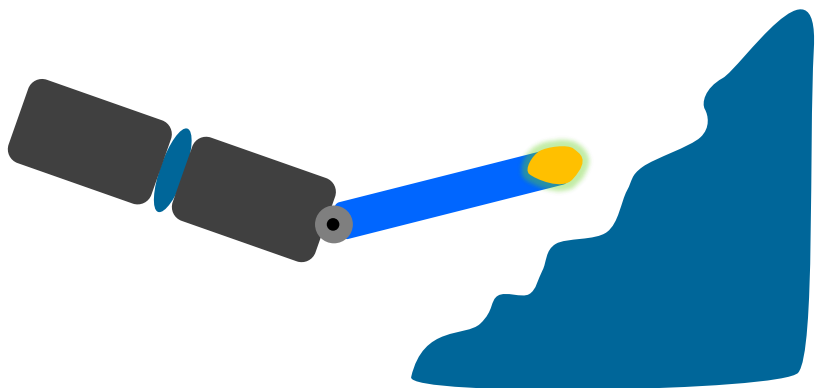


类人触觉感知 *SciRobotics.abl7344*

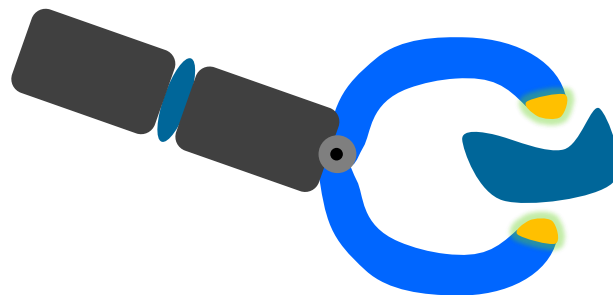
触觉传感器：机器人与具身智能大规模应用落地的必要条件！

触觉传感器可为机器人提供环境与交互对象的几何、材质、软硬、温度等内蕴特征，及交互过程中力分布、形变、滑移、振动、位姿等动态信息。

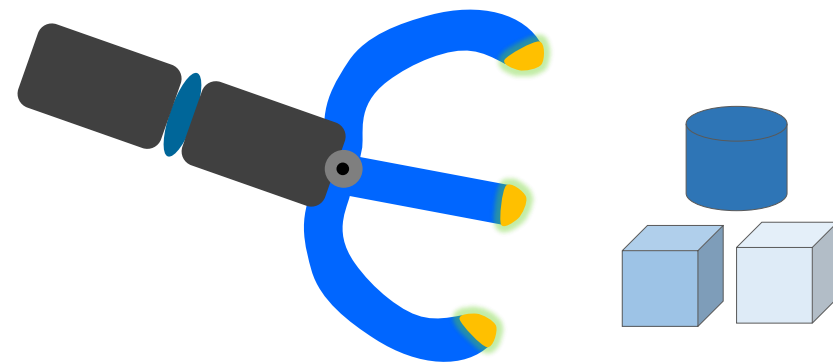
环境探索



灵巧抓取



精细操作



高空间分辨率

高时间分辨率

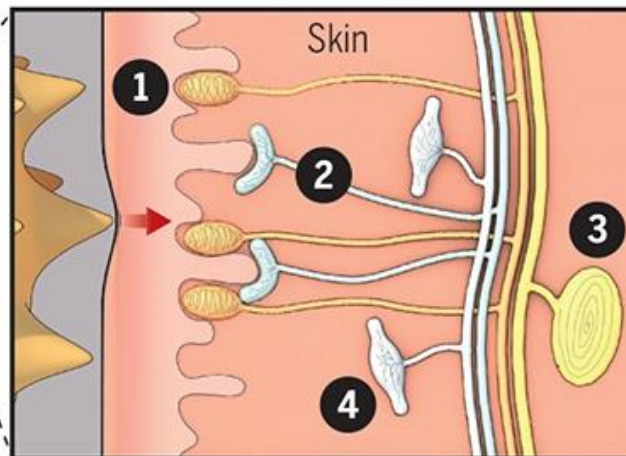
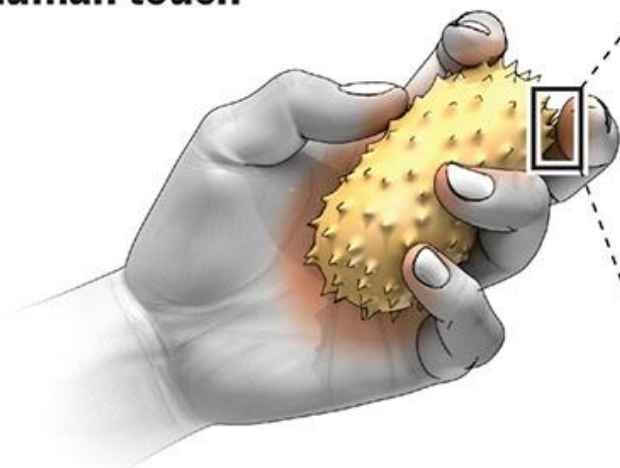
高灵敏度

快速响应

高效神经编码

柔性化顺应性

Human touch



Receptors

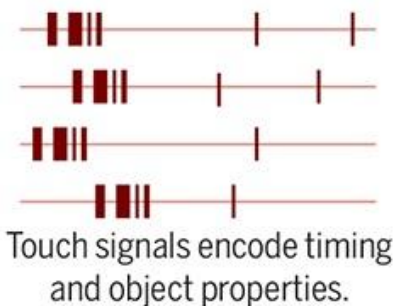
- 1 Meissner corpuscle
- 2 Merkel cell-neurite complex
- 3 Pacinian corpuscle
- 4 Ruffini ending

Mechanoreceptor architecture

Distinct types of mechanoreceptors are arranged in complex architectures in the skin and record specific types of touch stimuli. Sweat can change the elasticity of skin and affect these signals.

FA I FA II SA I SA II

Signal processing
Encoded tactile signals contain rich information about object contact, timing, and movements and collectively reflect object properties.



Neural processing

Tactile signals and proprioception

Distilled information

Object identity
Weight
Feedback control

几何

受力

振动

材质

滑移

动力学

反馈

触觉传感器主要可分为电学传感、视觉传感和其他物理机理的传感器。其中**视触觉传感器**具有空间分辨率高、信号稳定性强等优势。



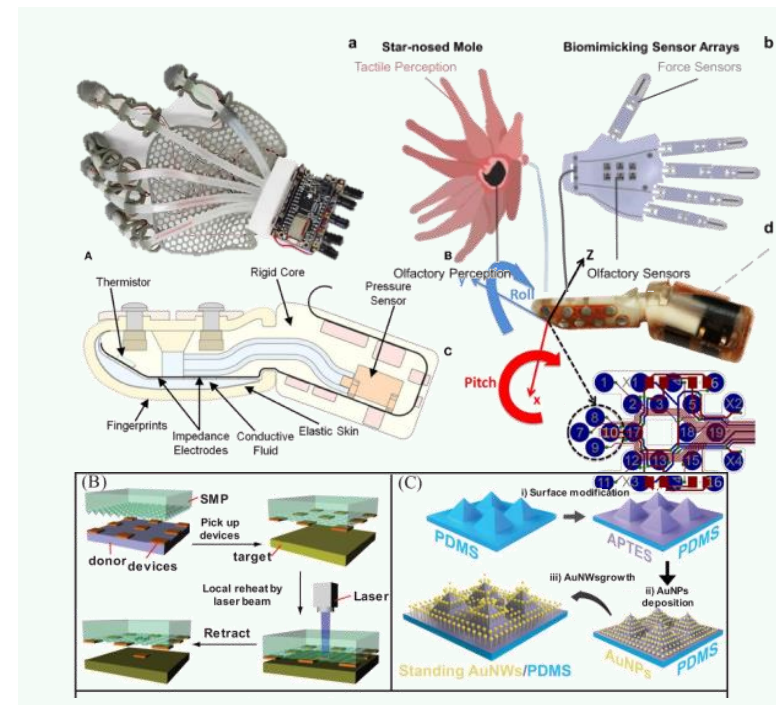
电学传感

高速感知、技术成熟
稀疏传感、电路繁杂



视触觉传感

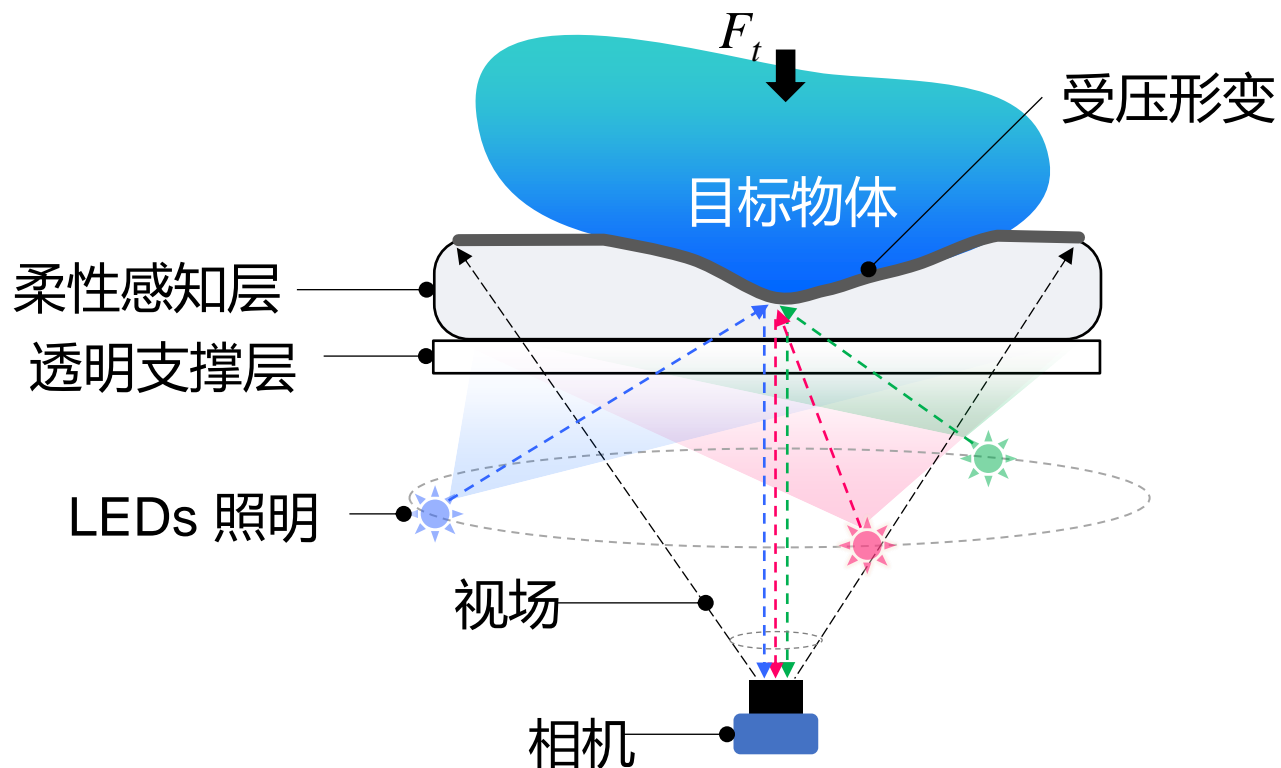
高密度传感、空间一致性
结构简单、算法成熟



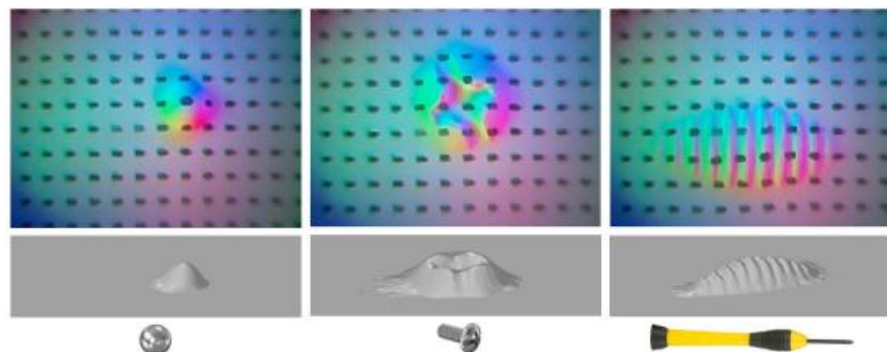
多物理机制传感

机制新颖、模态丰富
稳定不足、解析复杂

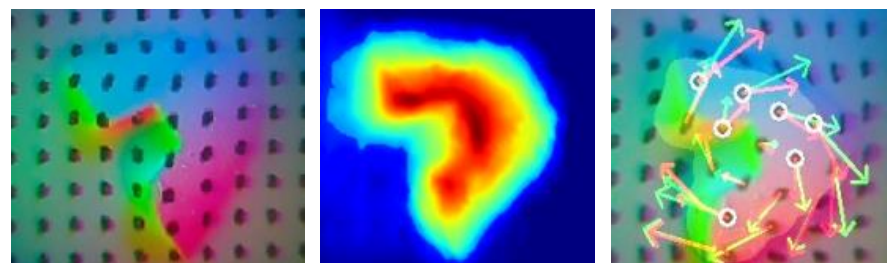
视触觉传感器利用相机捕捉柔性材料层与目标接触过程中的三维形变，通过视觉与力学算法重建出接触面的**形貌与力分布**信息。



视触觉传感器的基本测量原理



视触觉传感器的几何测量结果

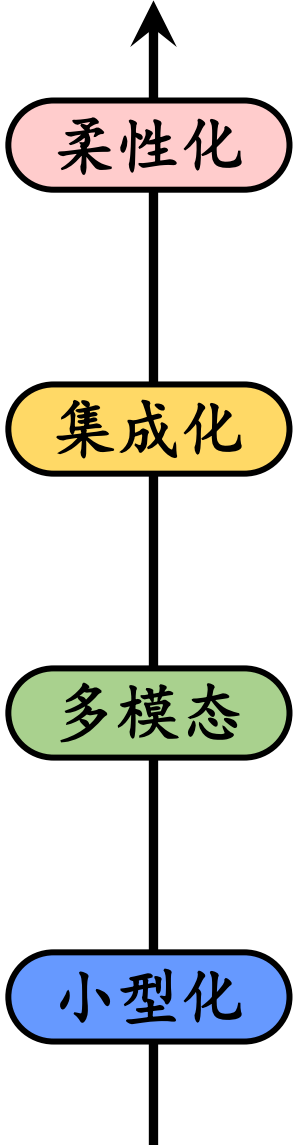


视触觉感知重建结果及其力分布信息

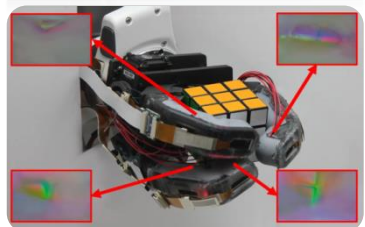
GeISlim3.0 Taylor et al., ICRA 2022

具有感知密度高、稳定可靠、算法成熟、成本低廉、易于集成和小型化等优势。

为机器人进行环境感知与复杂操作提供了高密度触觉信息(几何、受力、运动)



JL. Zhao et al. IROS24



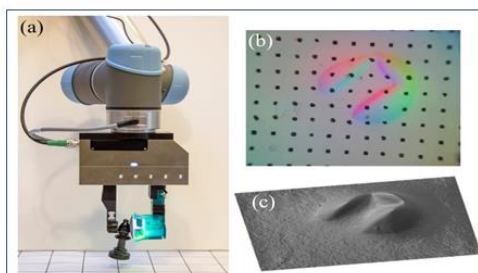
SQ Liu et al. RoboSoft23



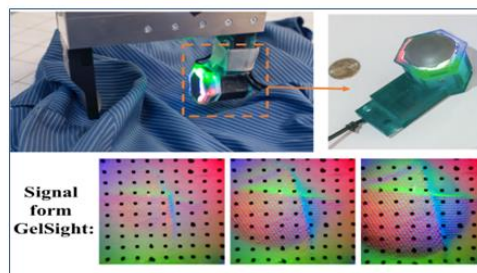
I. Tayler et al. ICRA22



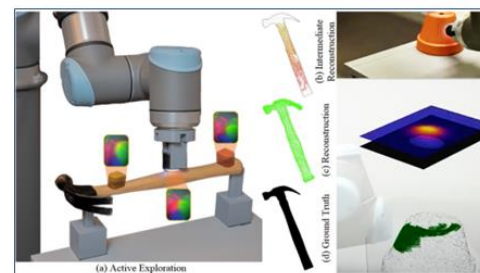
Rui Li et al. IROS14



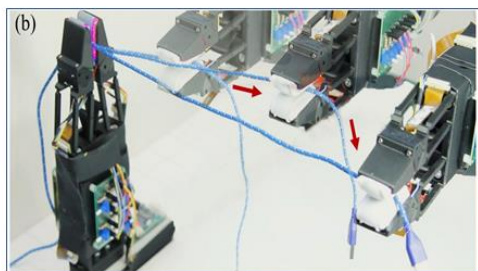
三维形貌感知与抓取
SY Dong et al. IROS (2017)



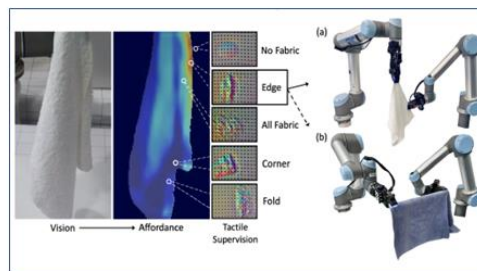
布料纹理感知与分类
W. Yuan et al. ICRA (2018)



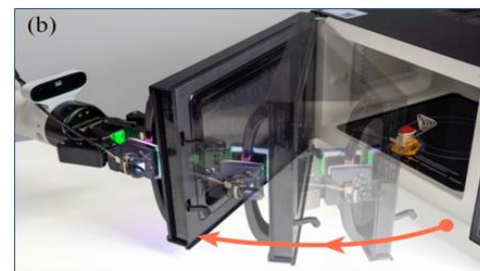
未知物体触觉三维重建
A. Shahidzadeh et al. ICRA (2024)



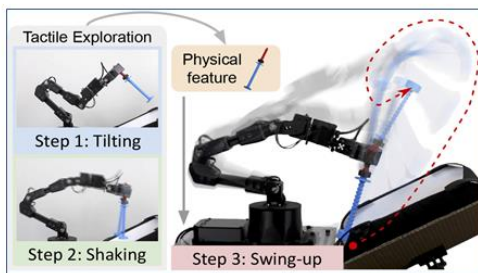
精细触觉感知插入
Y. She et al. RSS (2020)



柔性布料操作与整理
N. Sunil et al. CoRL (2023)



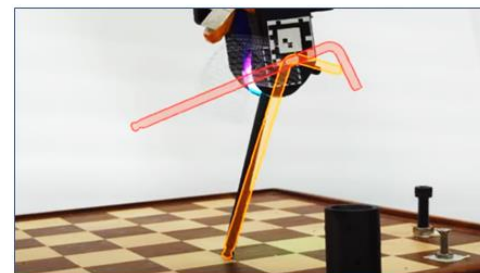
复杂物体通用操作
Z. Zhao et al. Pre-Print (2024)



复杂灵巧触觉操作
C. Wang et al. IROS (2019)

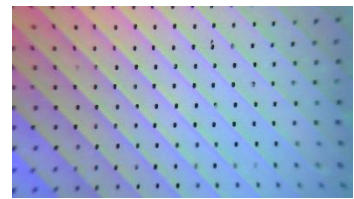
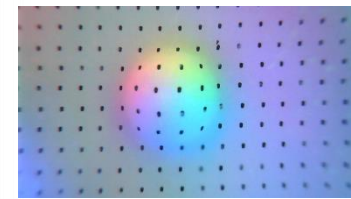
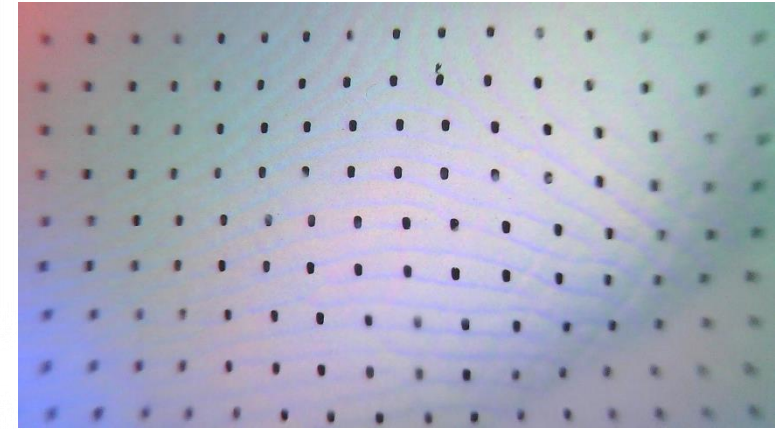
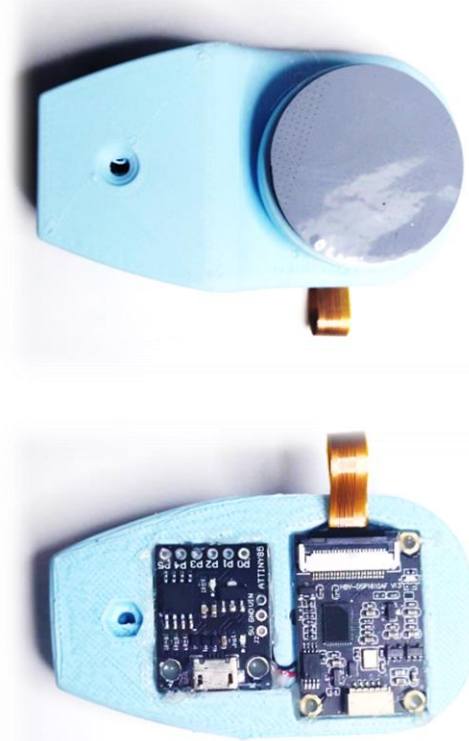
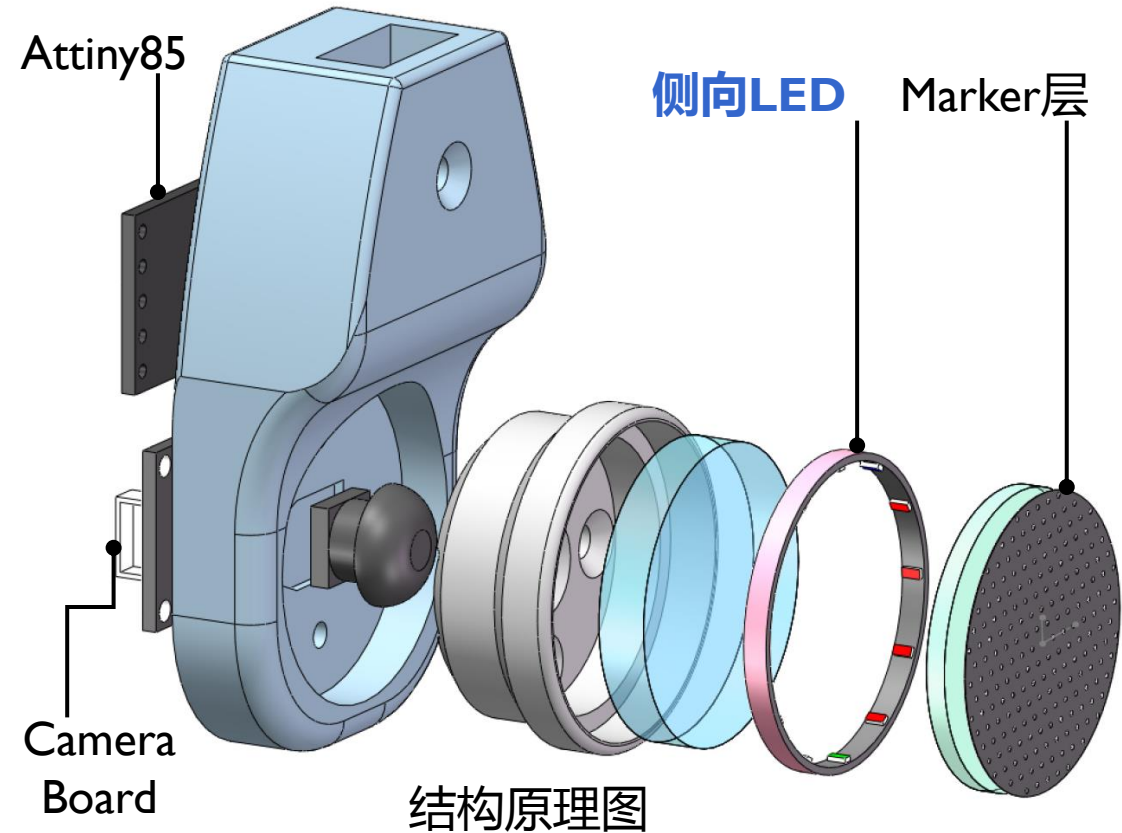


自适应触觉强化学习
P. Piacenza et al. T-MECH (2023)



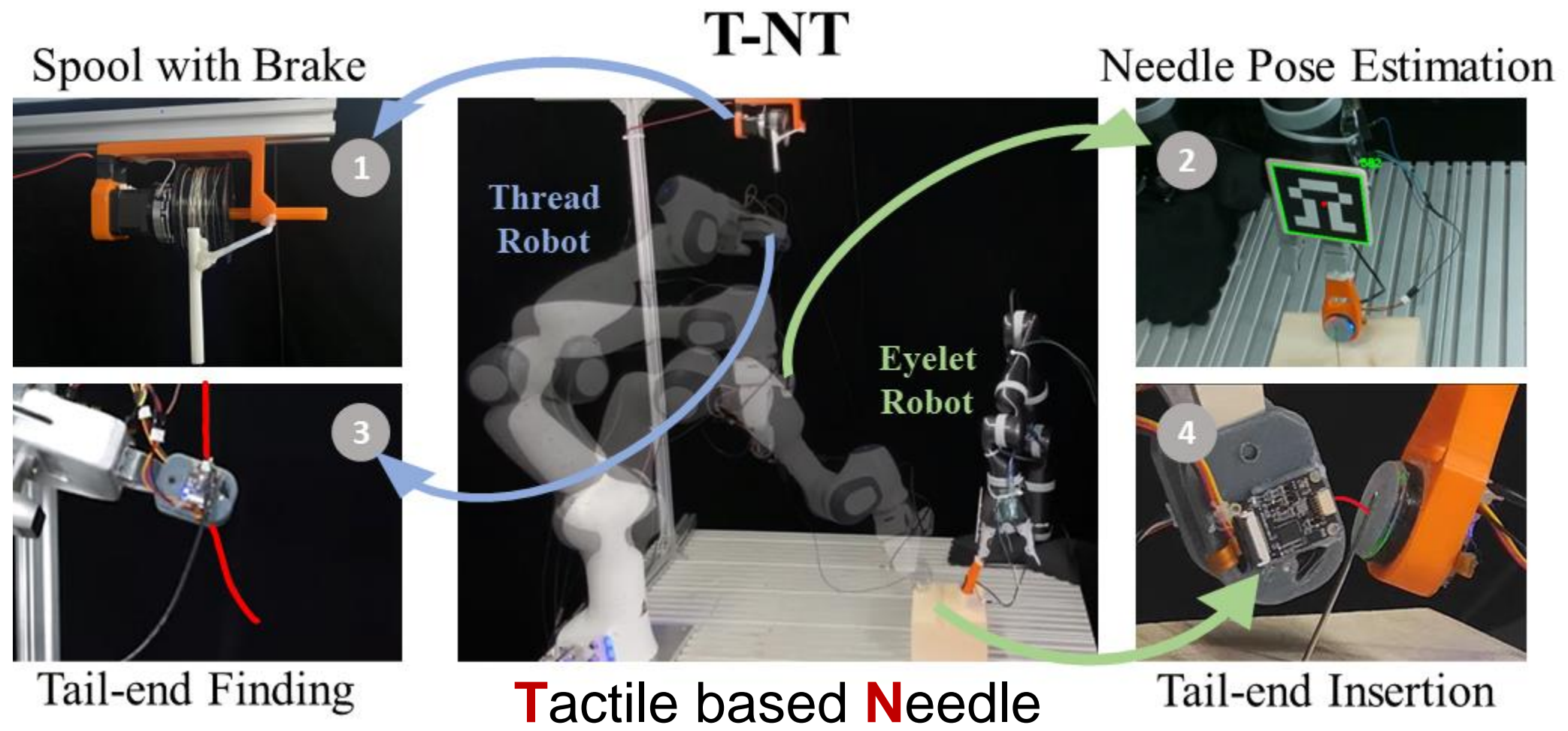
复杂工具触觉反馈操作
A. Bronars et al. ICRA (2024)

一体化设计的小型视触觉传感器模组，优化了照明光路、增加了稠密标注点、集成了采集控制电路、制定了标准化的标定流程。具有空间分辨率高、输出模态丰富、使用便捷、接线简单等优势。

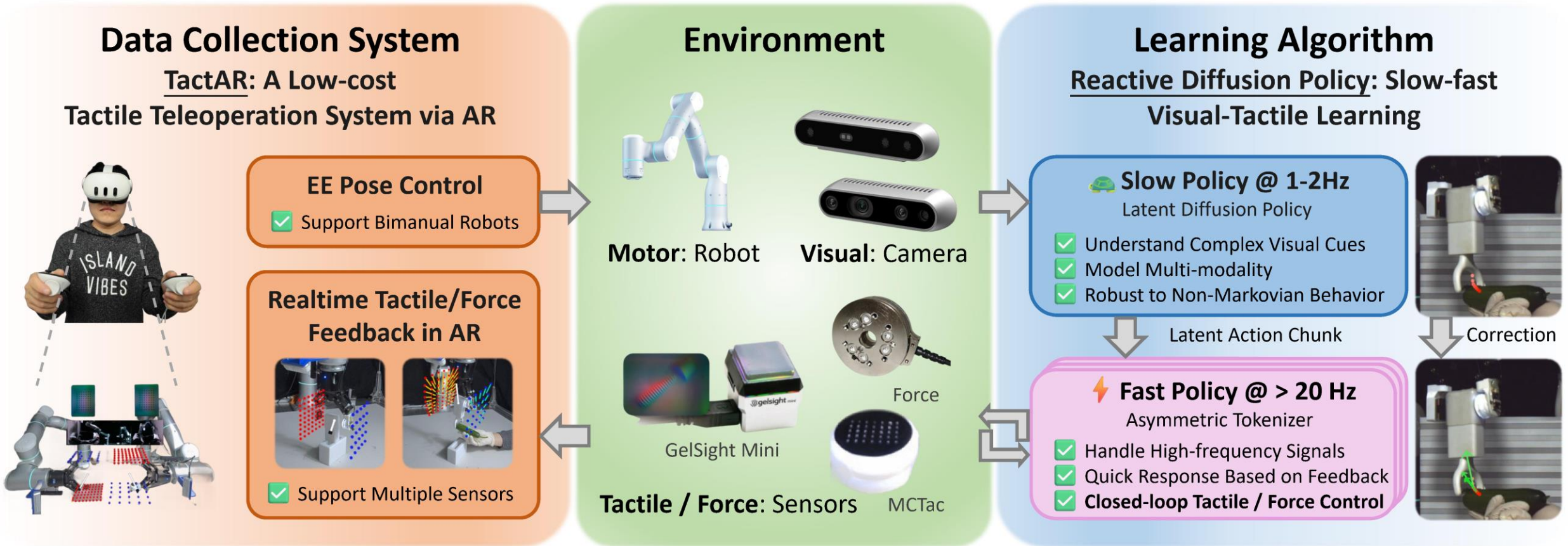


形状编码稳定 + 细节呈现清晰

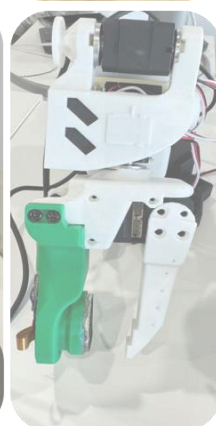
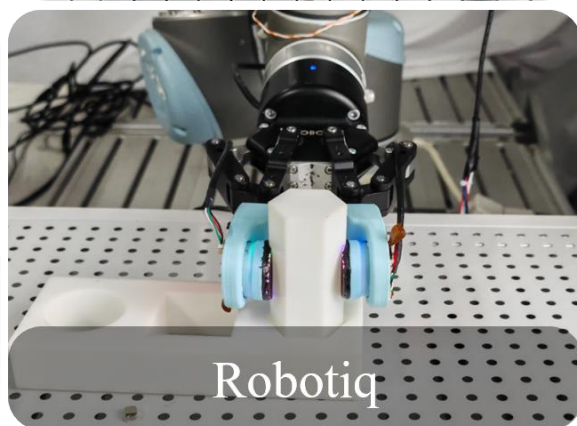
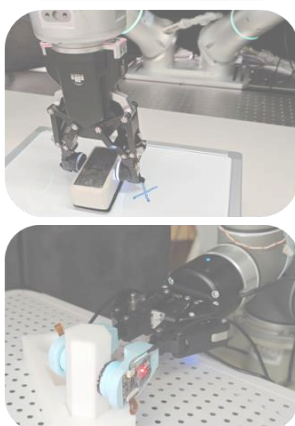
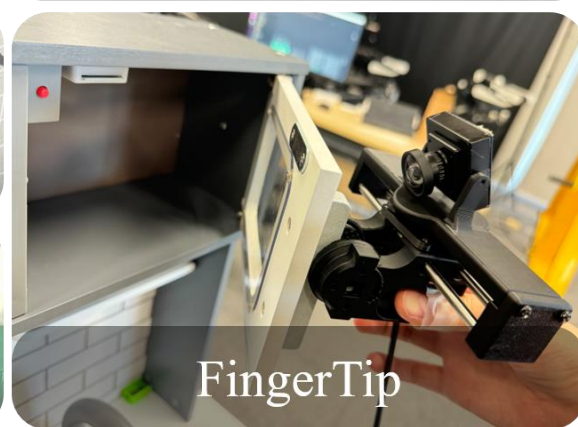
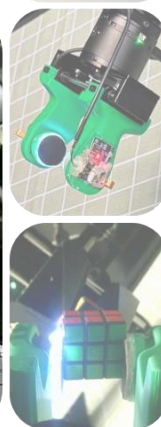
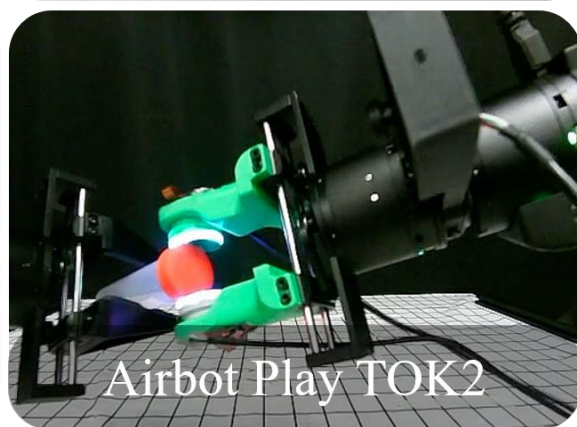
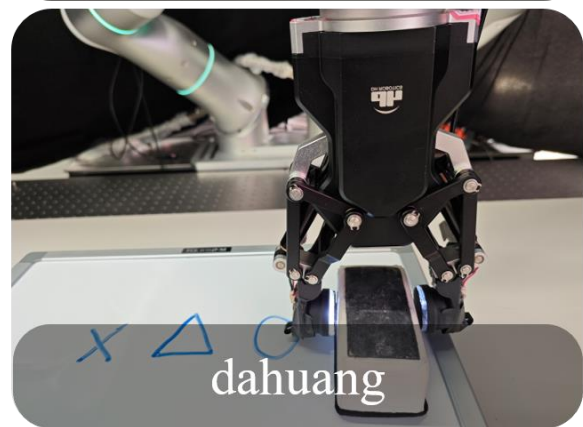
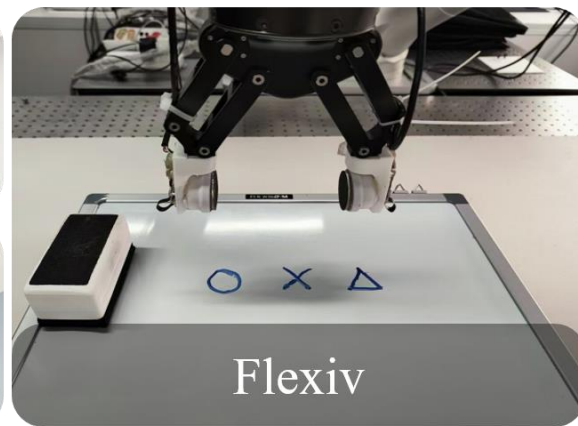
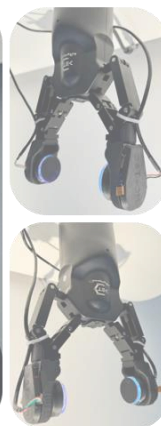
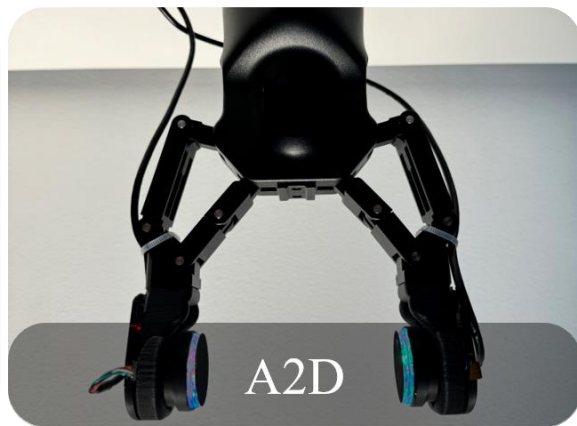
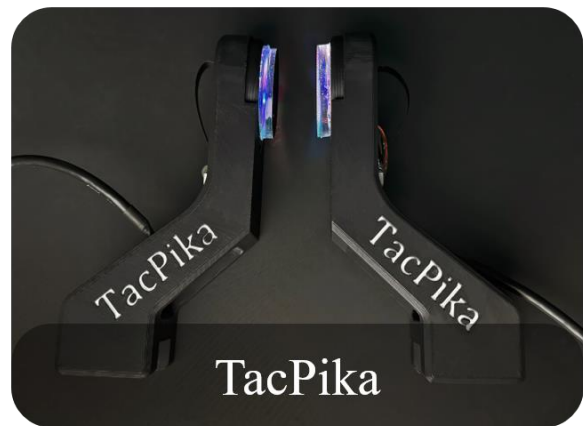
视触觉传感器可为精细操作提供目标丰富的几何与位姿信息，实现**稳定可靠的精细操作（穿针引线）**。



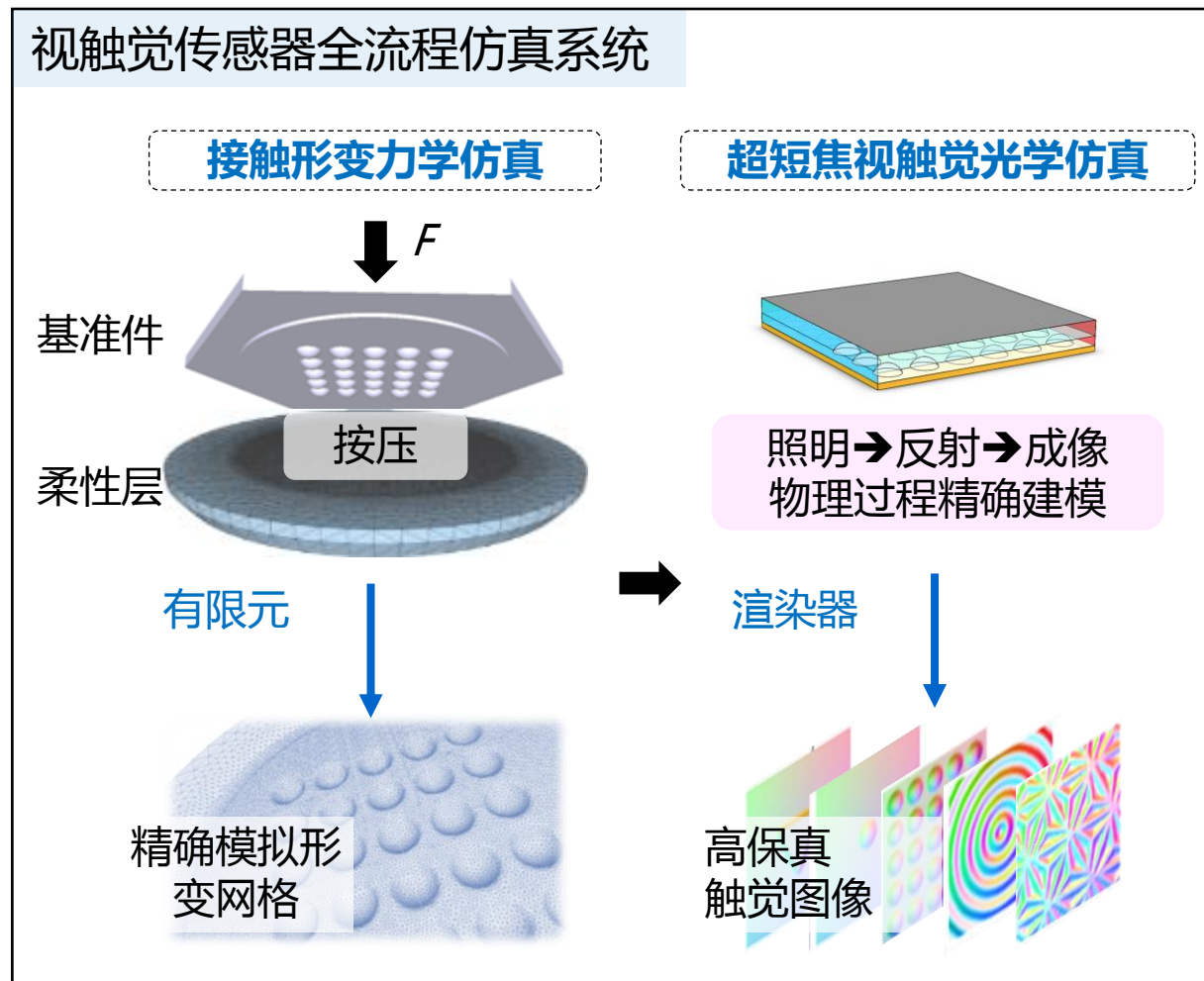
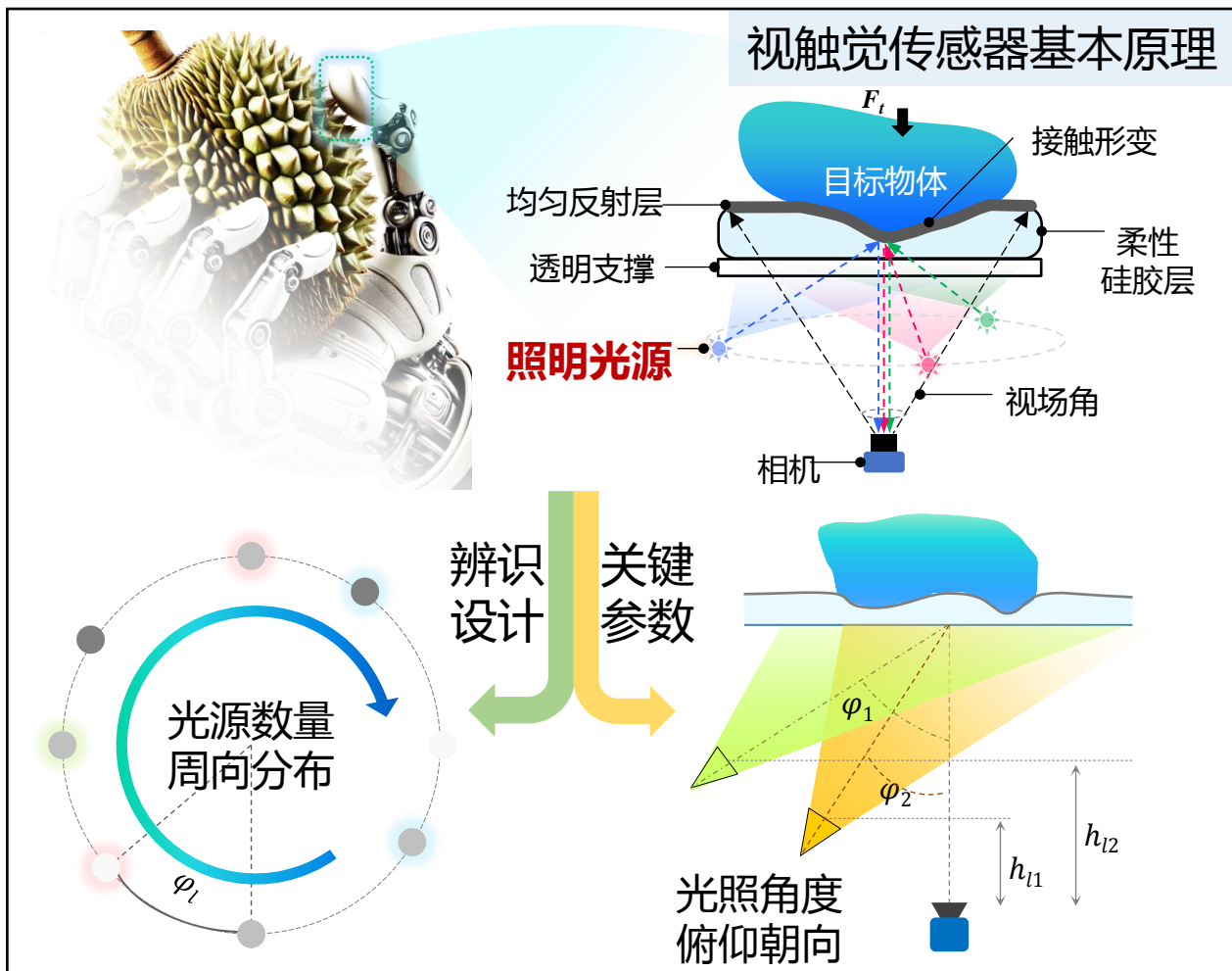
TactAR 系统通过增强现实实现实时触觉反馈与稳定数据采集，结合 RDP 算法实现复杂触觉操控的高效学习，显著提升机器人精细操作性能。



研究进展一：模块化设计的小型视触觉传感模块

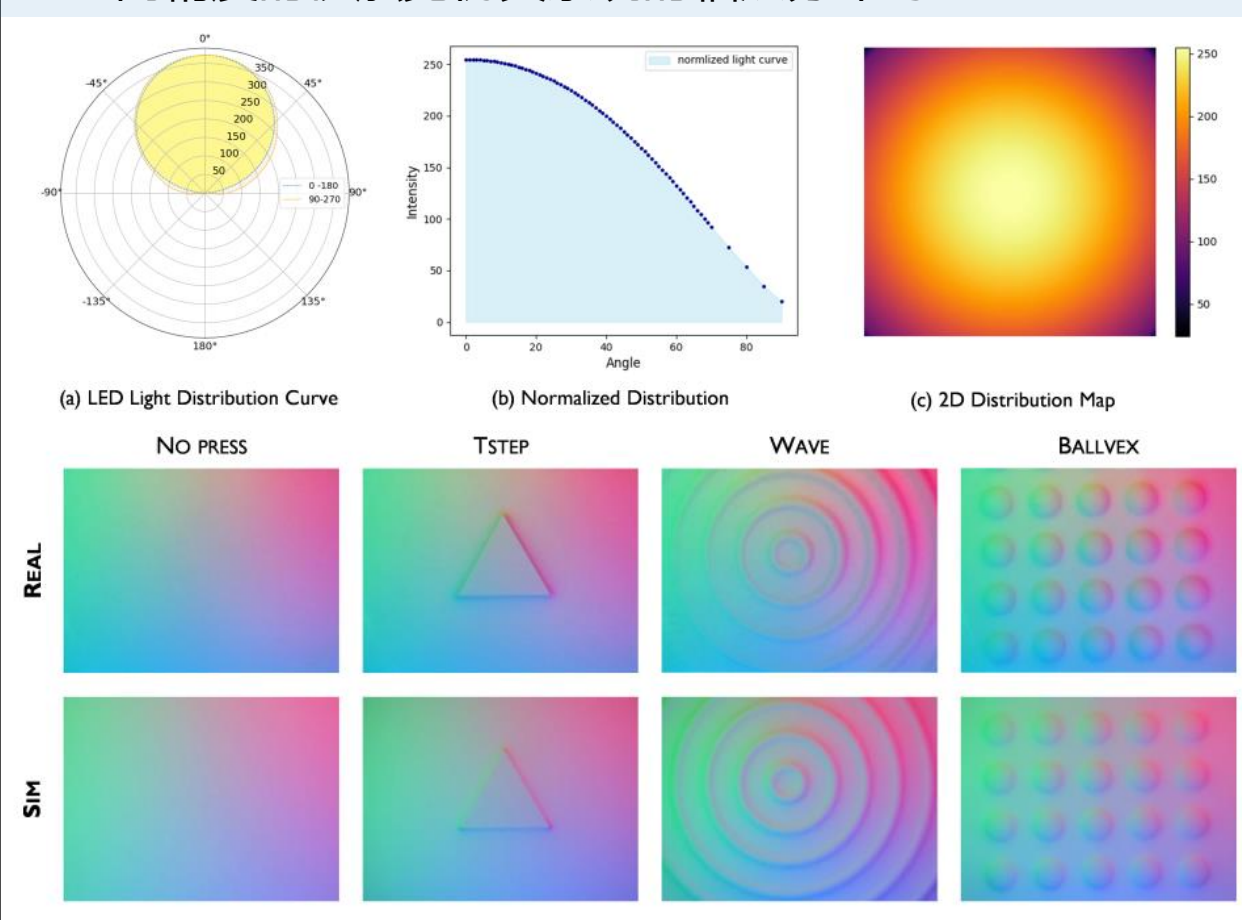


视触觉传感器的感知精度强烈依赖于内部**照明光场**的分布。为了实现较为通用的照明设计，我们提出了一套针对视触觉照明设计的完整**建模、优化与评估系统**。

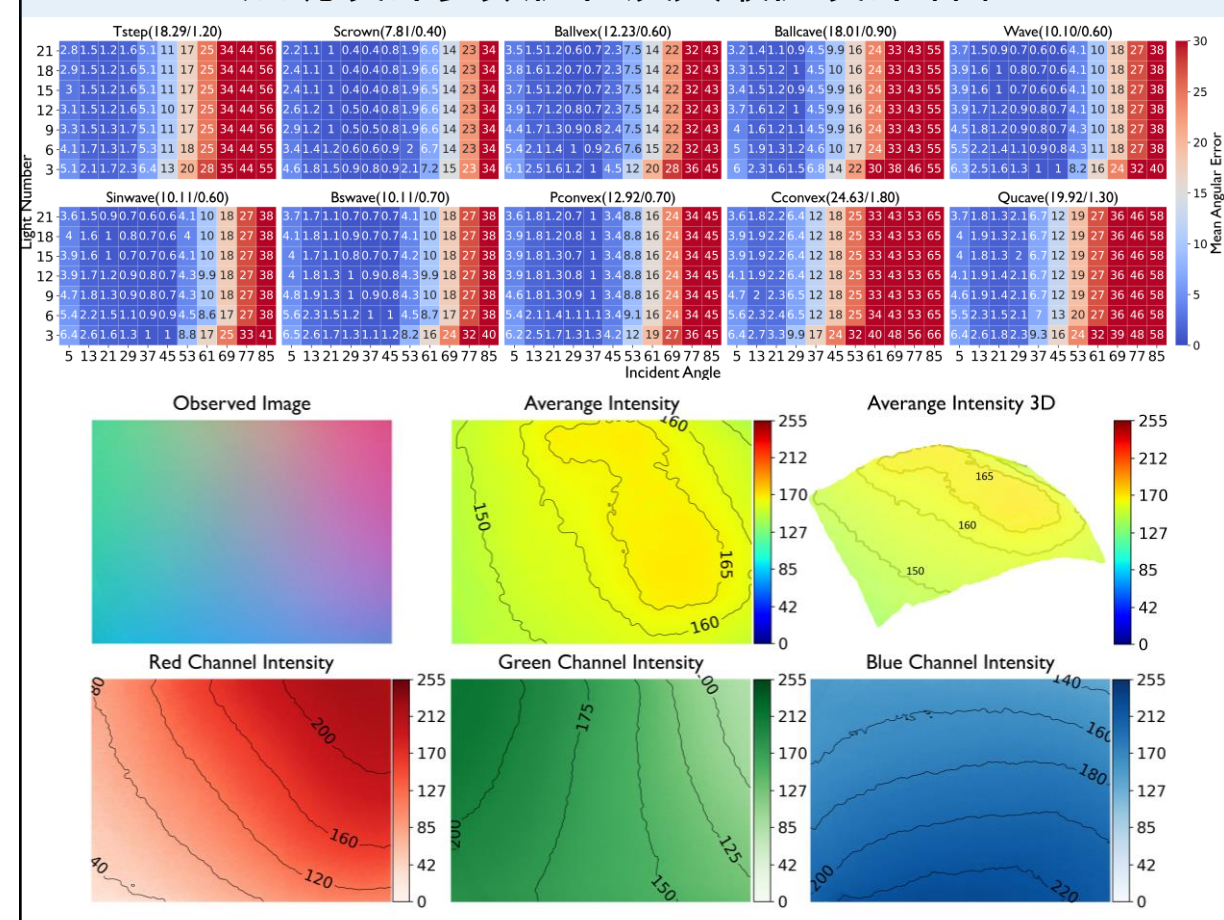


在高精度仿真的支撑下，我们建立了视触觉传感器性能随**照明分布与入射角度的变化关系**，并基于层次优化的方法实现了**最优的照明设计(12光源，29°入射角)**。

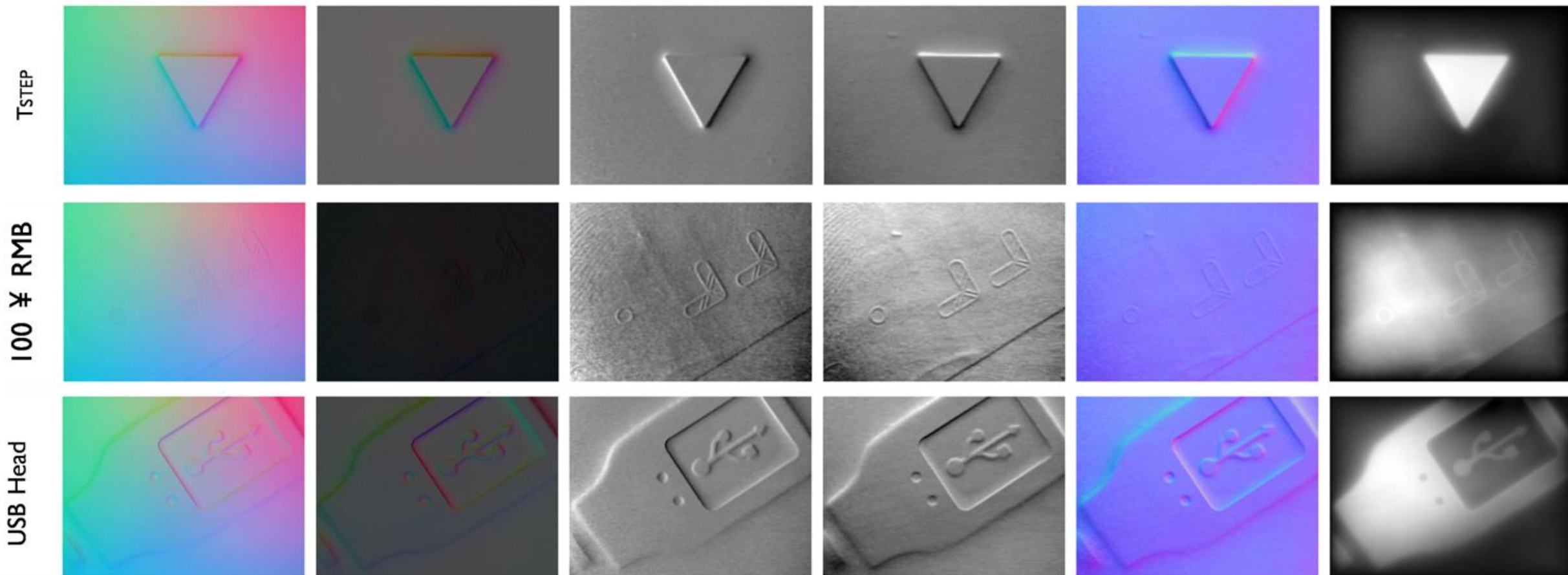
高精度的视触觉仿真系统的辐照分布与Sim2Real



照明设计参数优化及其最优设计结果



优化后的传感器具有高精度与广泛适应性，可以精确感知不同形状、材质、软硬物体表面的**准确精细的几何纹理信息**，为机器人在多领域的应用提供了技术支撑。



原始触觉图像

差分触觉

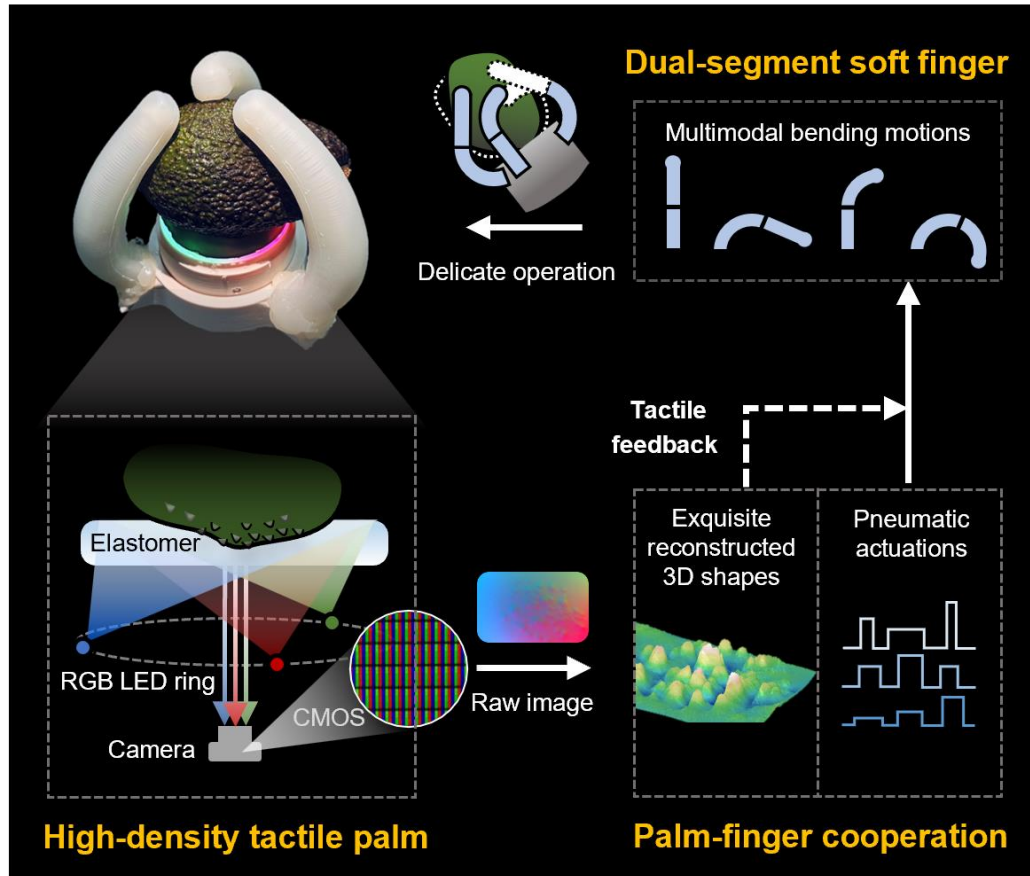
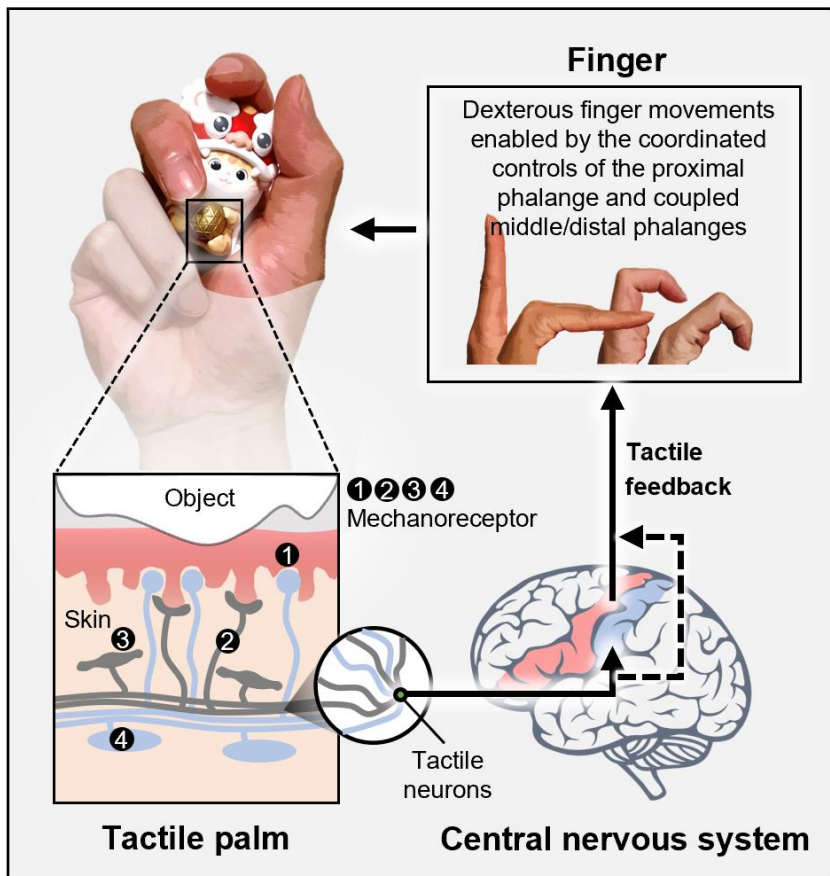
几何触觉梯度X

几何触觉梯度Y

表面法向量

目标深度图

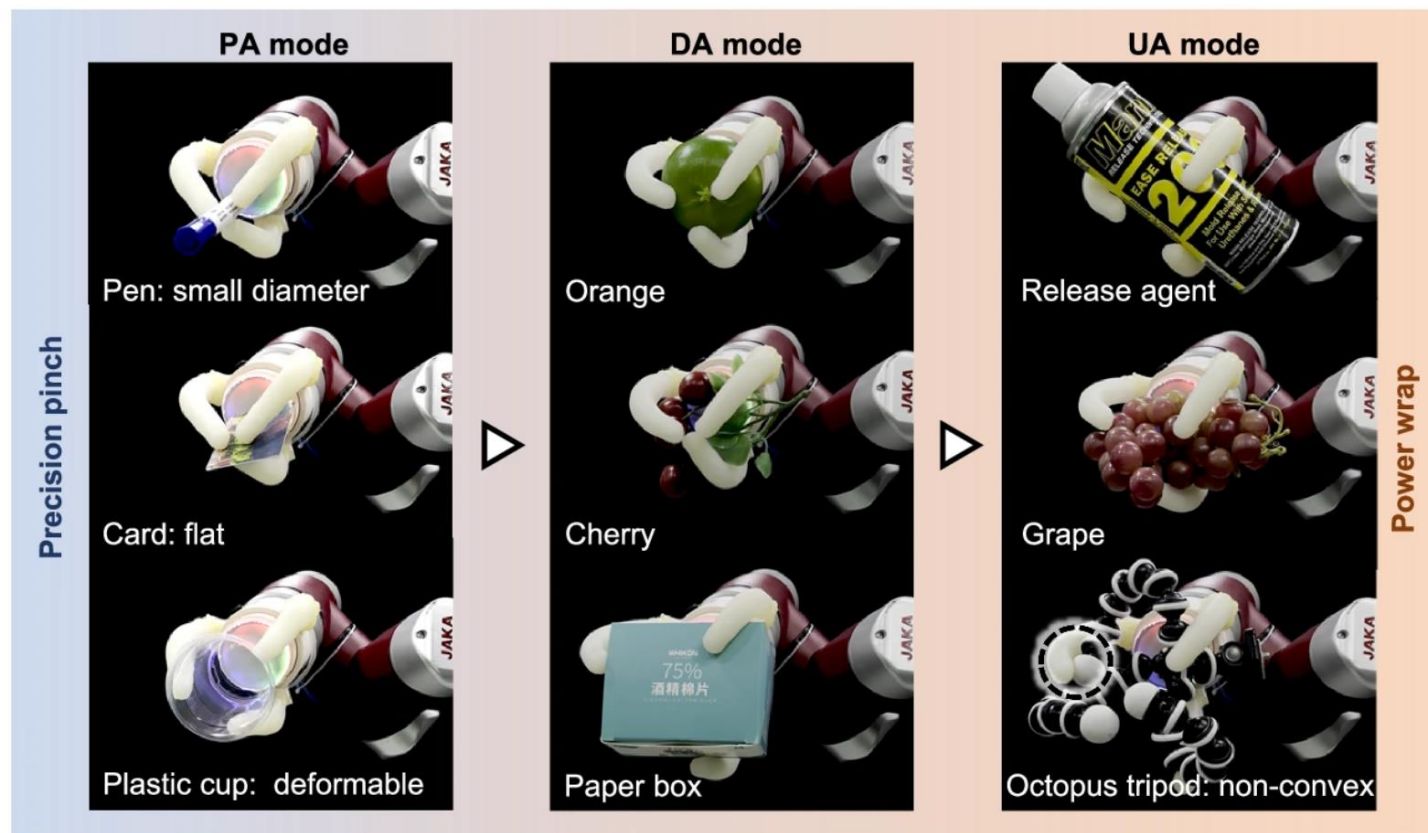
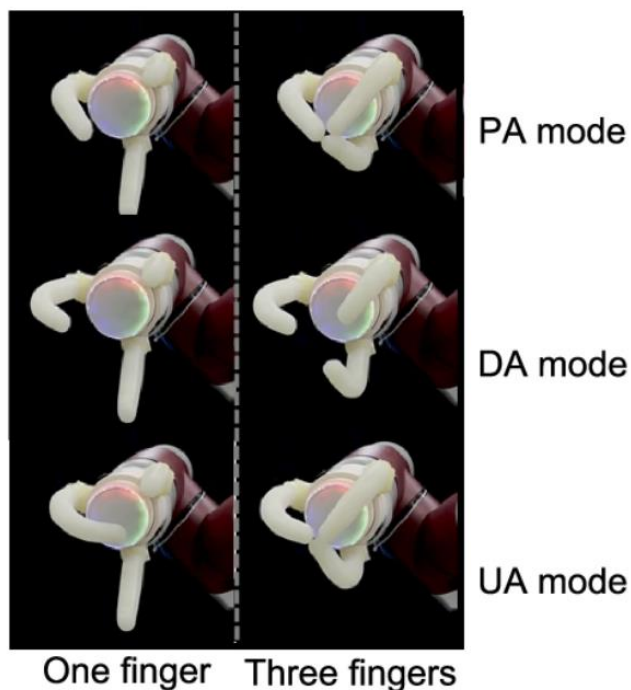
提出了结合高密度视触觉传感与软体手指的**掌指协同**软体灵巧手，实现了仿人触觉感知、纹理分类、多样性抓取以及基于触觉反馈的精细灵巧操作。



生物启发感知

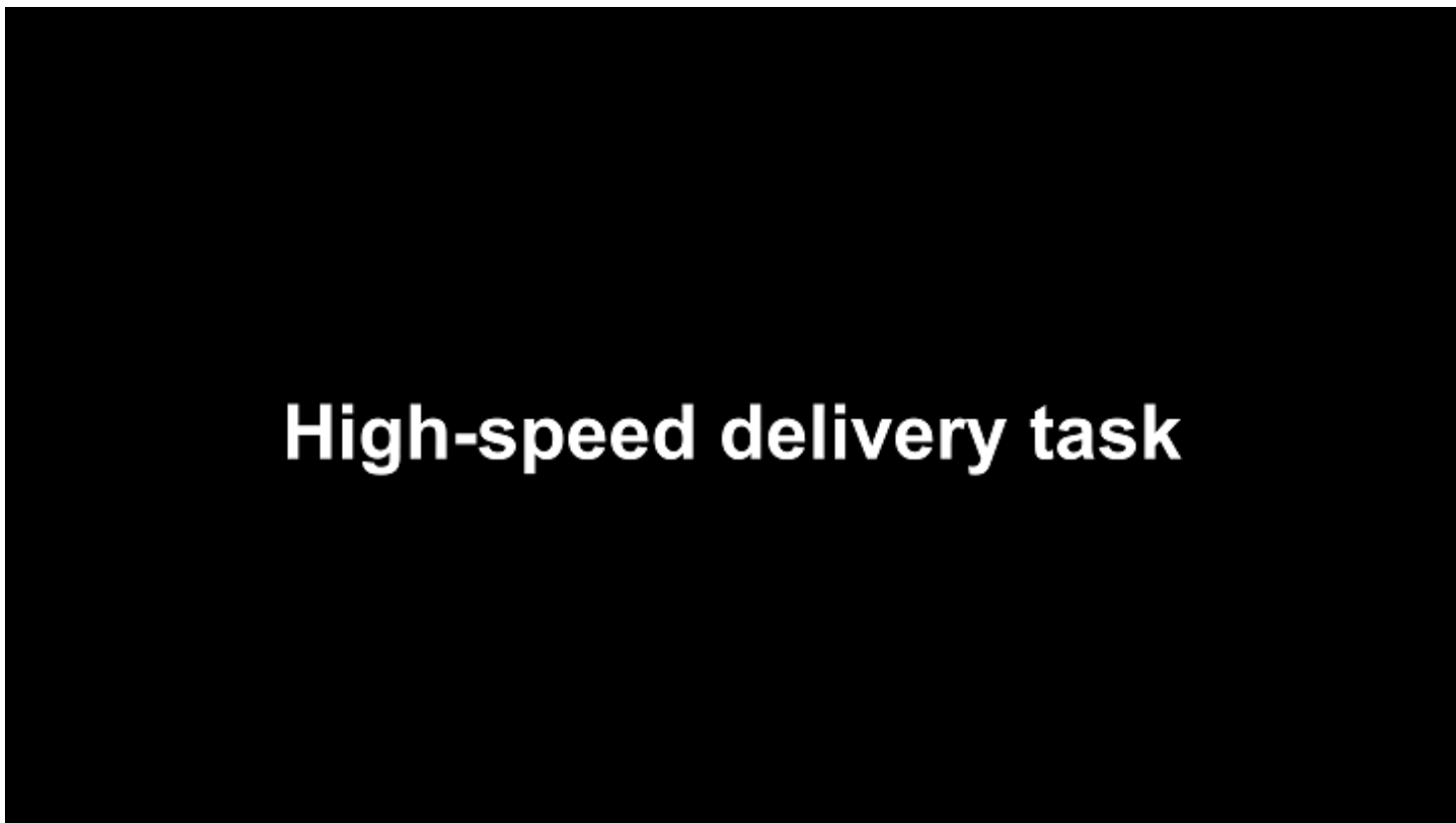
触觉掌部+软体手指=协同操作

双腔体手指可实现多样性物体稳定抓取

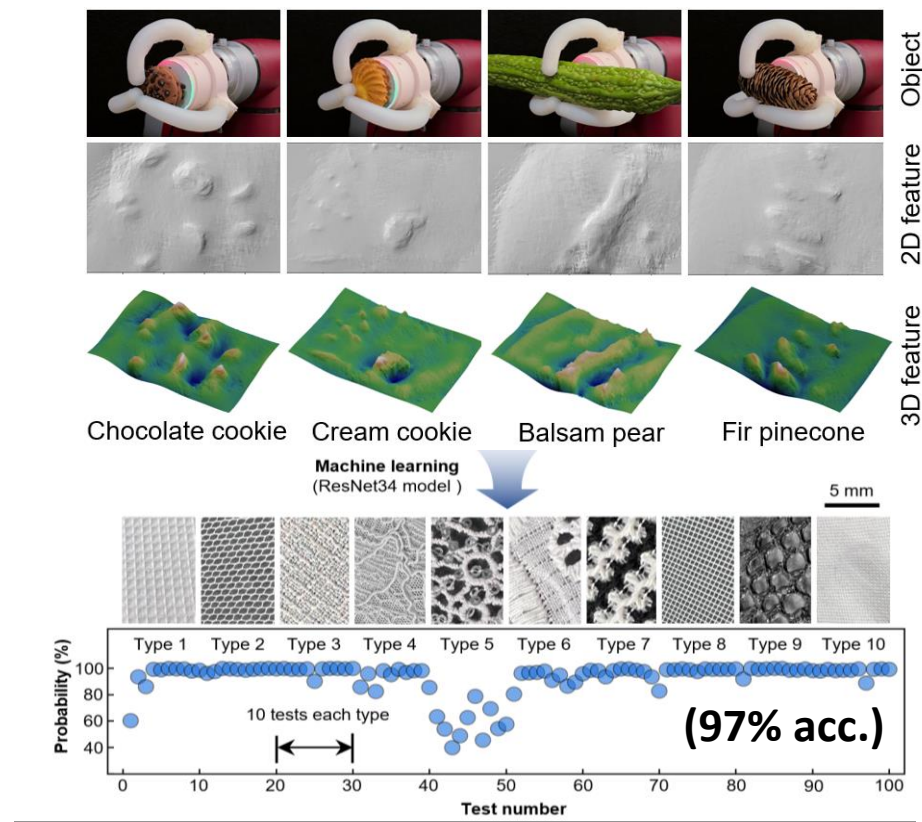


TacPalm-SoftHand 可实现从精细捏取到大力抓取的多模态灵巧抓取

掌部触觉反馈不仅提供了抓取过程中的**感知能力**（三维形貌、材质、软硬等），同时为操作提供了稳定的**支撑**，实现了稳定可靠的触觉传感与**掌指协同**。



基于**视触觉反馈与掌指协同**的稳定高速抓取传送



薄柔脆物体的**顺应性**抓取与感知

基于视触觉掌部实现了液体倾倒过程中的**动态反馈**控制，并通过掌指协同保证操作稳定性，同时探索了视触觉与软体机器人在安全稳定**人机交互**方面的潜力。



利用触觉接触压痕作为**触觉反馈**参数的
闭环手指运动控制，用于茶壶的**精细姿态**调节

集成机械臂与软体手的自动**盲袋识别**（准确率88%）
与安全抓取递送的**人机交互**应用

主要合作者



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Peking University



Dr. Ningbin Zhang
Shanghai Jiao Tong University



Dr. Heng Guo
BUPT University

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Soft Robotics and Biodesign Lab



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Soft wall-climbing robot

Integrating and synchronizing dielectric-elastomer muscles and electroadhesive feet.



Science
Robotics

Welcome to Gu Research Group

The SJTU Soft robotics and biodesign (SRB) lab focuses on design, manufacturing, modeling and control of new bioinspired, soft robots for safe, compatible and adaptive interactions with humans and environments. SRB Lab is part of Robotics Institute, School of Mechanical Engineering in Shanghai Jiao Tong University. Our current research interests include soft robotics, bioinspired robot design and motion control, smart materials actuators and sensors, and additive manufacturing with soft materials. Example applications include soft wearable rehabilitation robots for assisting and restoring the ability of the humans with the upper extremity weakness in activities of daily living, bioinspired robotic systems for grasping and manipulation, and soft sensing systems for human-robot interaction.

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