



上海大学未来技术学院
SCHOOL OF FUTURE TECHNOLOGY, SHANGHAI UNIVERSITY

上海大学人工智能研究院
INSTITUTE OF ARTIFICIAL INTELLIGENCE, SHANGHAI UNIVERSITY

人工智能导论

——第5课：具身智能

叶林奇

未来技术学院（人工智能研究院）

2024秋季学期



提纲

一、具身智能概念

二、具身智能本体

三、具身智能感知

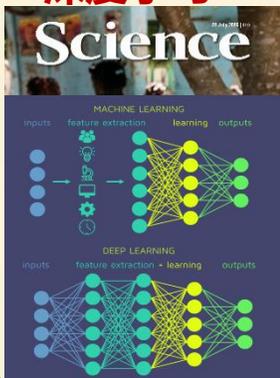
四、具身智能控制

五、具身智能展望



具身智能概念

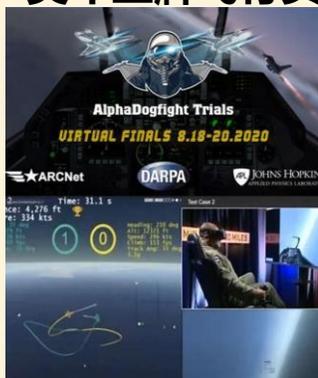
Hinton提出
深度学习



四足机器人强化
学习超越传统控制



模拟空战AI打败
美军王牌飞行员



无人机竞速AI战胜
人类世界冠军



智能
无人系统

2006

2016

2019

2020

2022

2023

游戏
AI

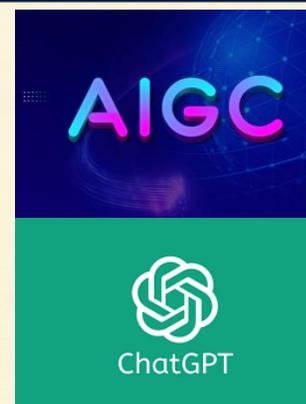


AlphaGo战胜
人类最强围棋选手



AI星际争霸超越
99.8%人类玩家

大
模型



ChatGPT横空出世,
AIGC火爆全球



谷歌发布具身多模态
大语言模型PaLM-E

具身智能概念

非具身智能依赖已有数据进行学习，被动接收知识

具身智能通过交互获取直接经验，**学习和主动探索**

读万卷书



非具身智能

具身智能



行万里路

知识

理论抽象

数据

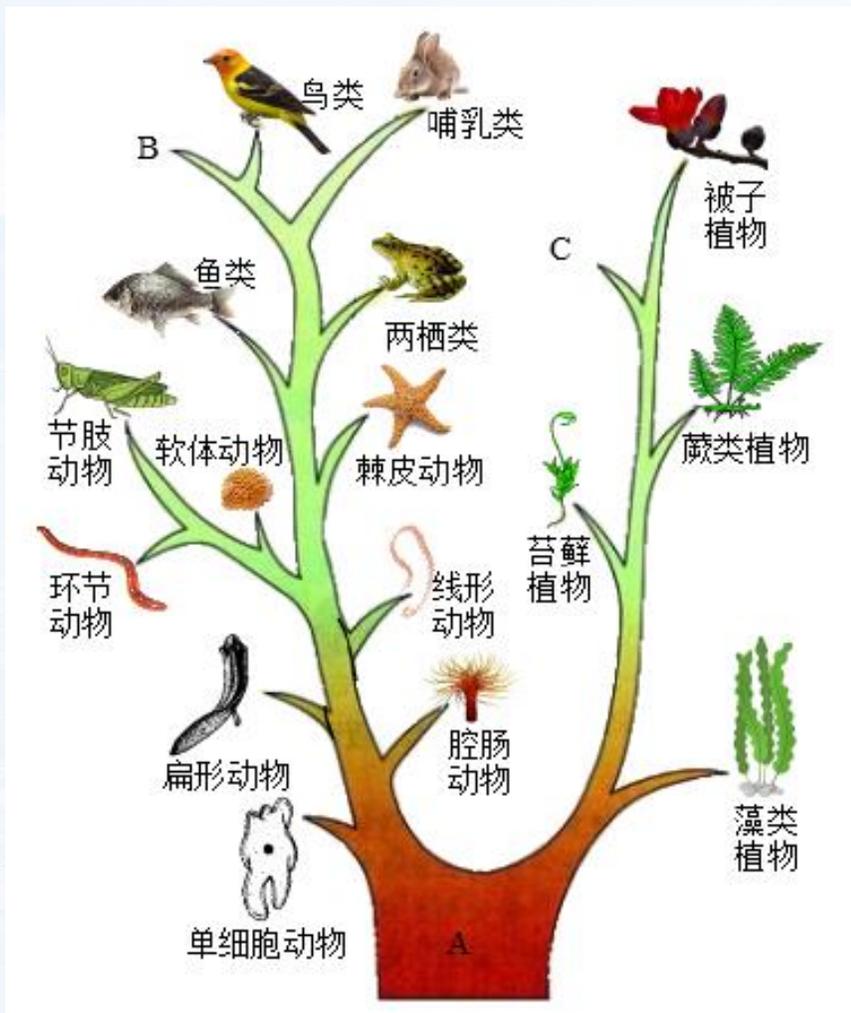
实践总结

经验

具身智能的核心是智能体与环境的交互——
智能体通过**感知**环境、采取**行动**并从环境中获得**反馈**来调整、优化自身行为



什么样的身体和环境，发展出什么样的智能
身体不仅是感知和改变世界的工具，更是影响和塑造认知结构的**主体**



草履虫



捕蝇草



水母



海豚

具身智能概念

2024年3月，CAAI监事长蒋昌俊院士**具身智能**大会上表示，要实现真正的**通用人工智能**，需要赋予它们在真实物理世界中的**交互能力**，这就意味着需要让AI 拥有**实体**，让它们像人类一样具备**感知、思考和行动**的能力。



2023年，NVIDIA创始人黄仁勋，AI的**下一波浪潮**被称为具身智能，它指的是能够理解、推理和与物理世界互动的**智能系统**。



2021年，李飞飞教授提出，具身的含义不是身体本身，而是与环境**交互**并在环境中发挥作用的**整体需求和功能**。



1986年，布鲁克斯从控制论角度出入，强调智能是**具身化和情境化**。



Computing Machinery and Intelligence

1950年，图灵在论文**COMPUTING MACHINERY AND INTELLIGENCE**有了**具身智能的思想萌芽**。

- Published in "Mind: A Quarterly Review of Psychology and Philosophy", in 1950.
- "I propose to consider the question, 'Can machines think?'"



We may hope that machines will eventually compete with men in all purely intellectual fields. But which are the best ones to start with? Even this is a difficult decision. Many people think that a very abstract activity, like the playing of chess, would be best. It can also be maintained that it is best to provide the machine with the best sense organs that money can buy, and then teach it to understand and speak English. This process could follow the normal teaching of a child. Things would be pointed out and named, etc. Again I do not know what the right answer is, but I think both approaches should be tried.

具身智能是一个与传统人工智能有所区别的概念，它强调的是有物理身体的智能体与环境的紧密交互以及通过这种交互所形成的自进化行为。

提纲

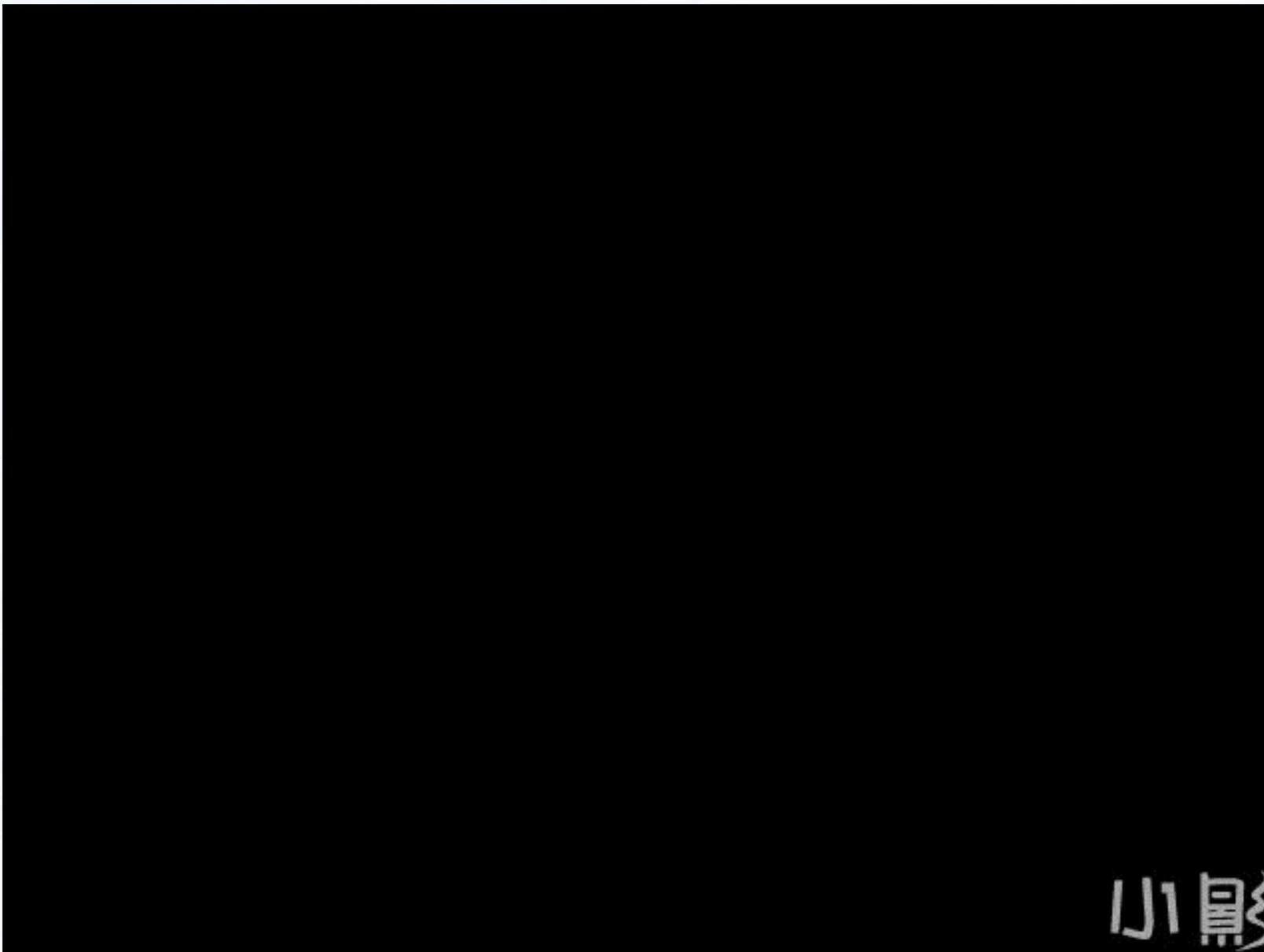
- 一、具身智能概念
- 二、**具身智能本体**
- 三、具身智能感知
- 四、具身智能控制
- 五、具身智能展望



上海大学
SHANGHAI UNIVERSITY

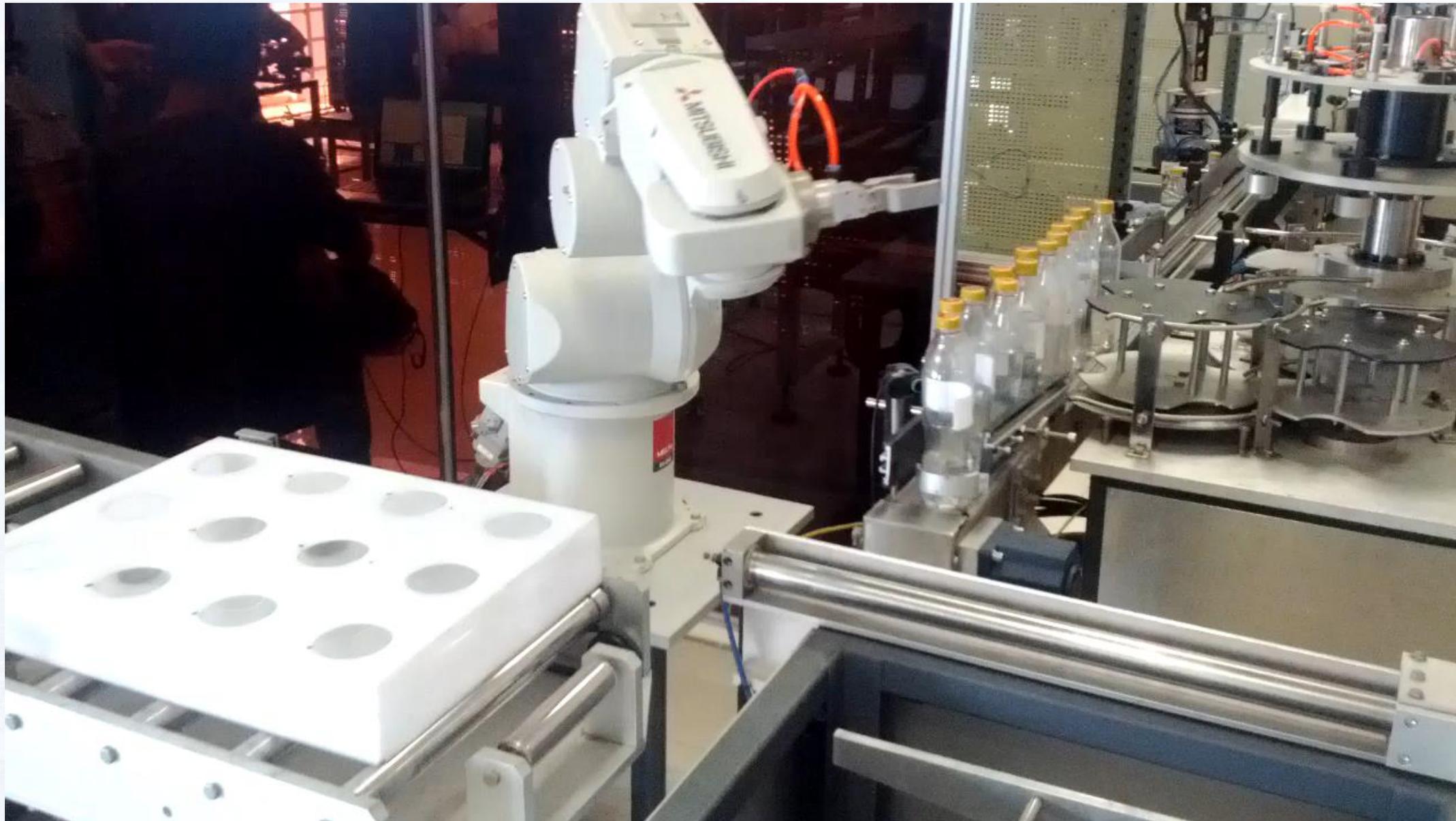
小王子与玫瑰107 bilibili





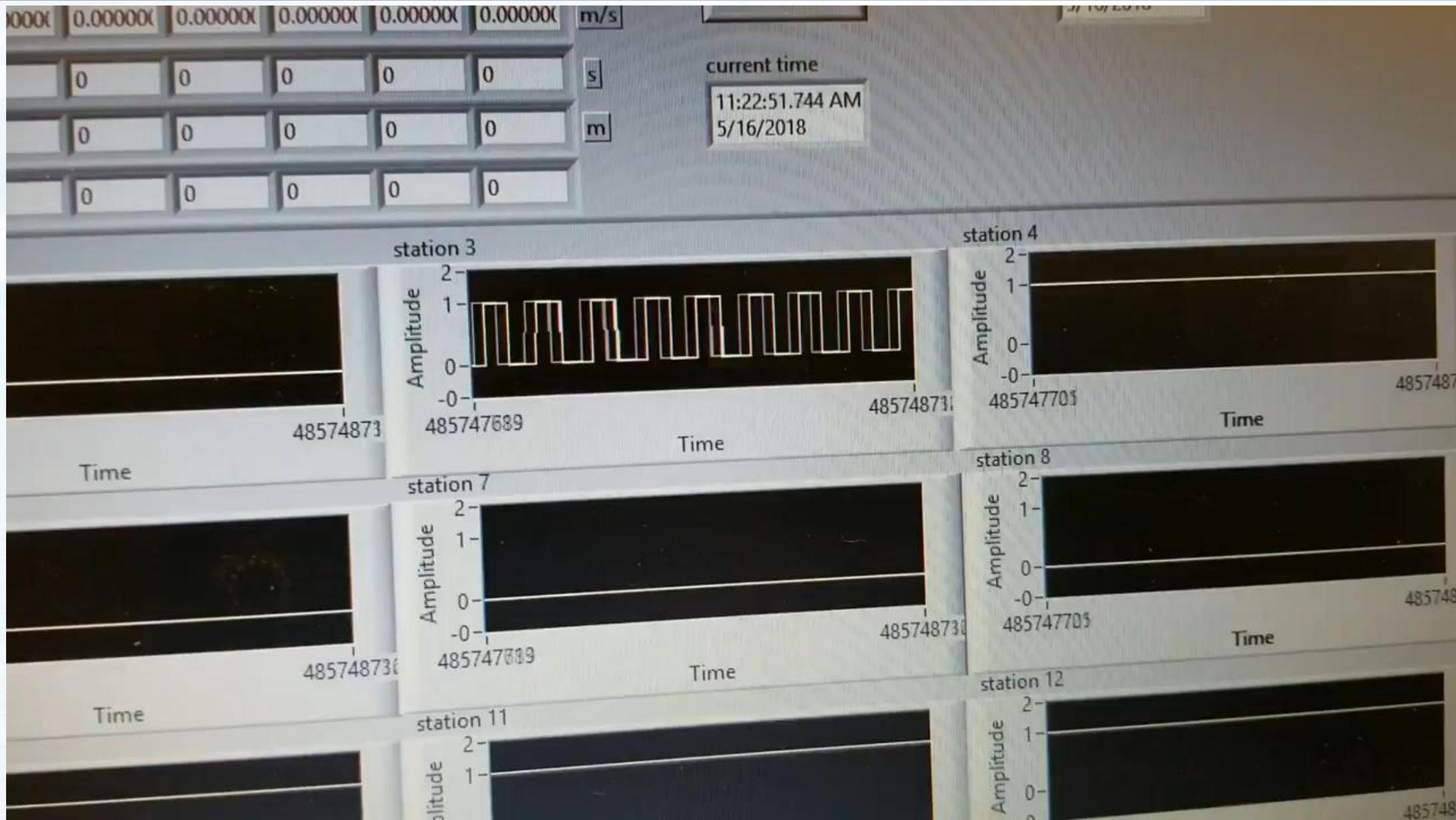
具身智能本体

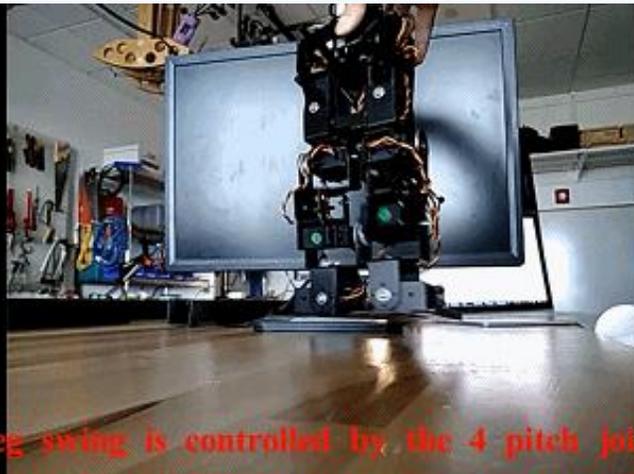
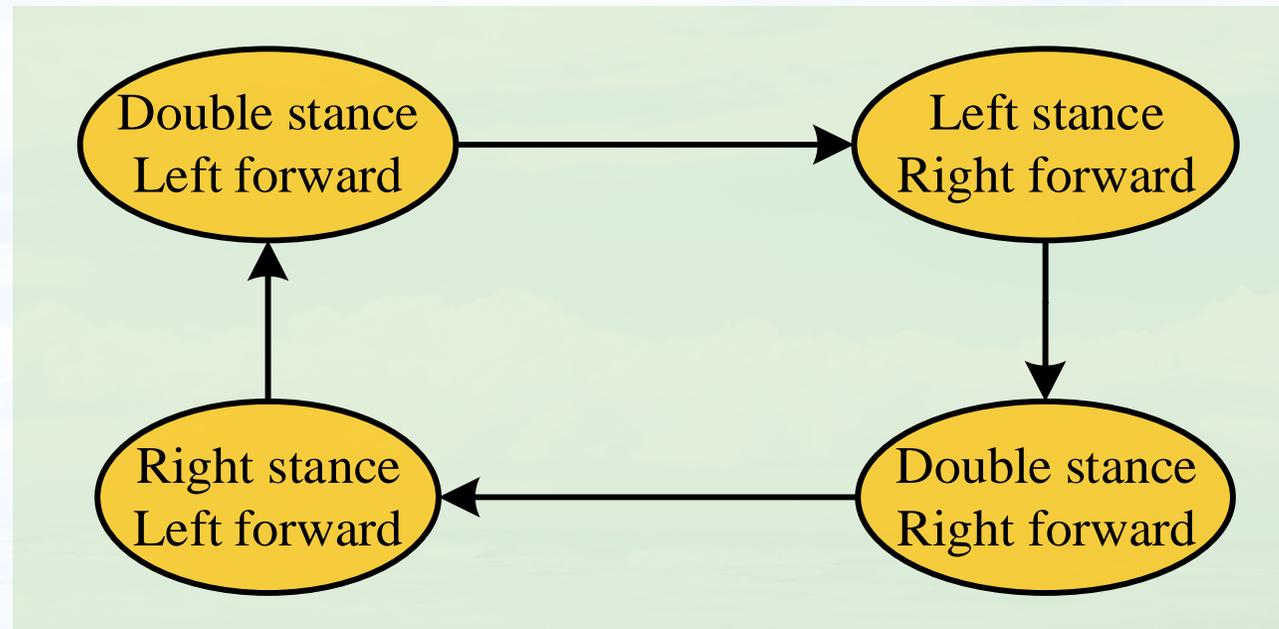
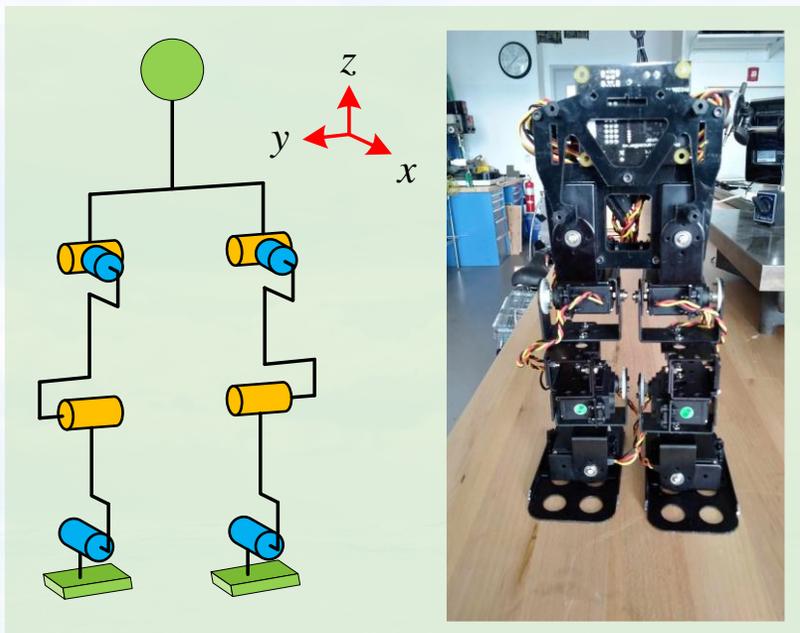
➤ 本科毕设：三菱六自由度机械臂装瓶系统



具身智能本体

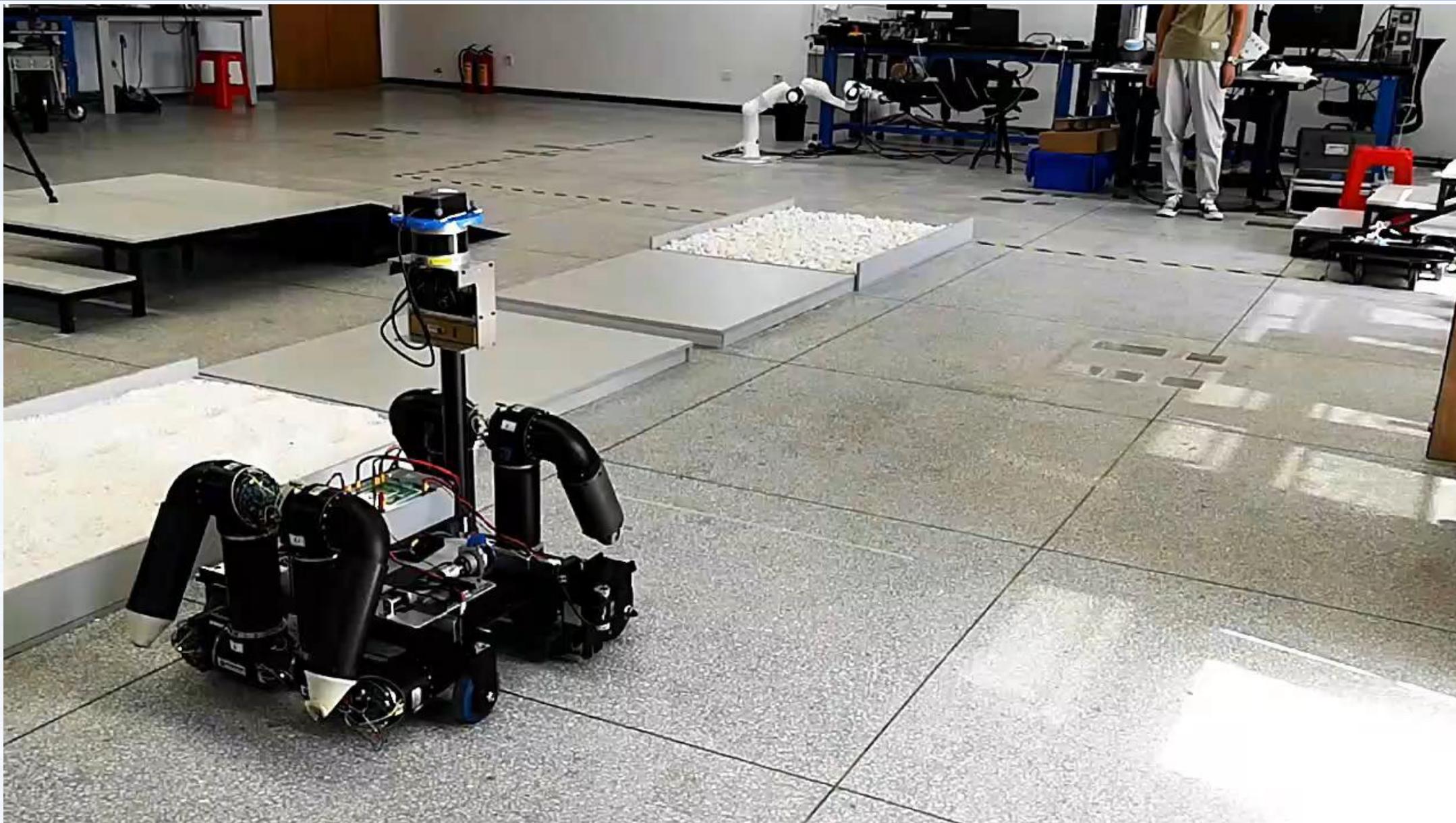
➤ 康奈尔大学：昆虫磨项目“Flight Mill”





具身智能本体

➤ 可重构四足机器人







提纲

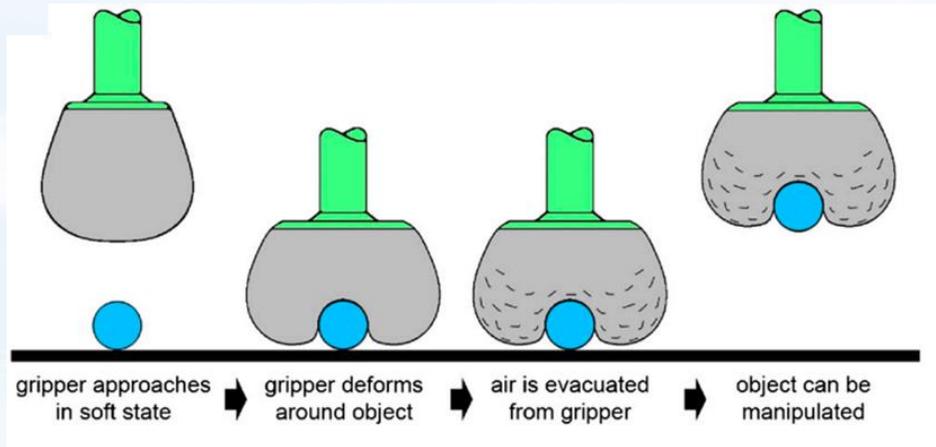
- 一、具身智能概念
- 二、具身智能本体
- 三、具身智能感知
- 四、具身智能控制
- 五、具身智能展望



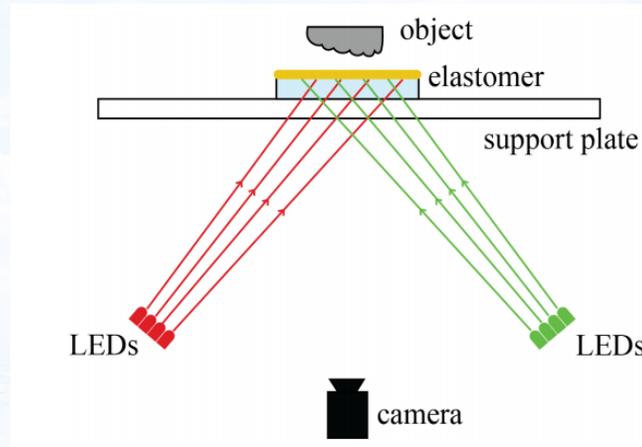
上海大学
SHANGHAI UNIVERSITY

视触觉抓取机器人 (ICRA 2022 最佳设计论文提名)

将负压阻塞抓取与视触觉感知巧妙融合，实现感知抓取一体化



+



GelSight

Retrographic sensing for touch, texture and shape

Micah K. Johnson, Edward H. Adelson and Alvin Raj

MIT Department of Brain and Cognitive Sciences
MIT Computer Science and Artificial Intelligence Lab

视触觉抓取机器人 (ICRA 2022 最佳设计论文提名)

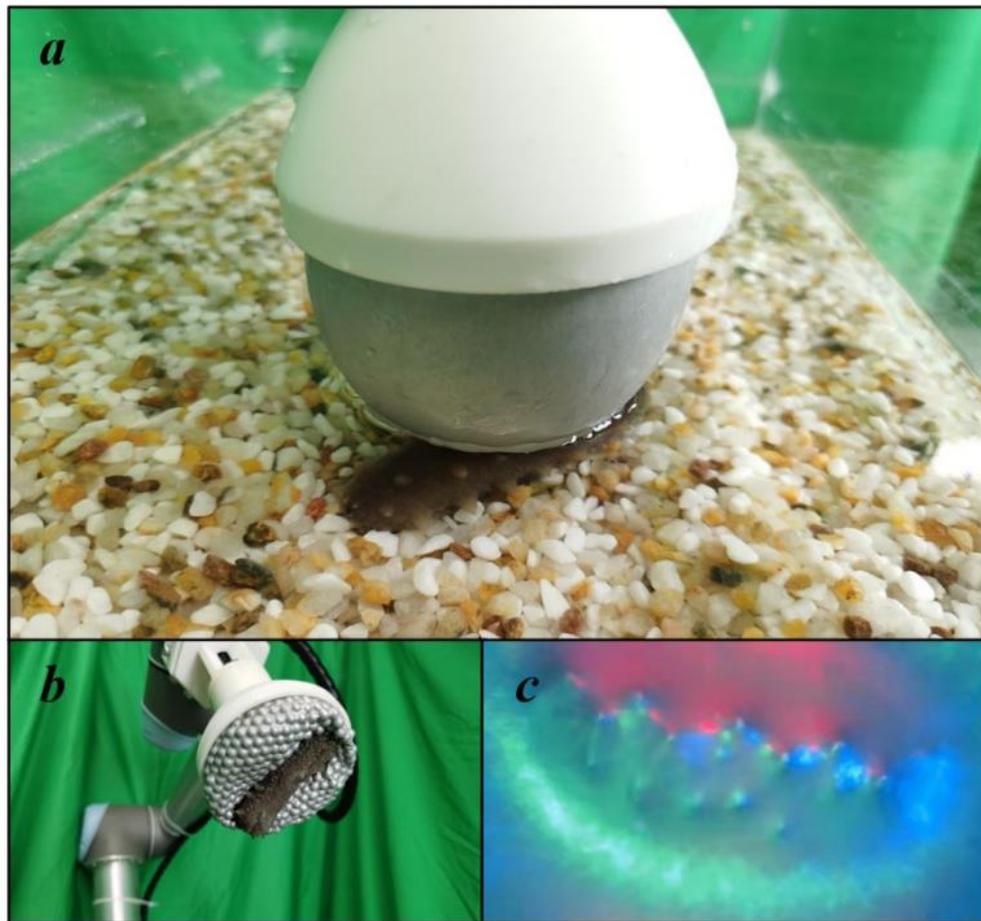


Fig. 1. (a) The picture of TaTa perceiving a trepang; (b) TaTa gripping a trepang; (c) Membrane deformation seen from the inside camera.

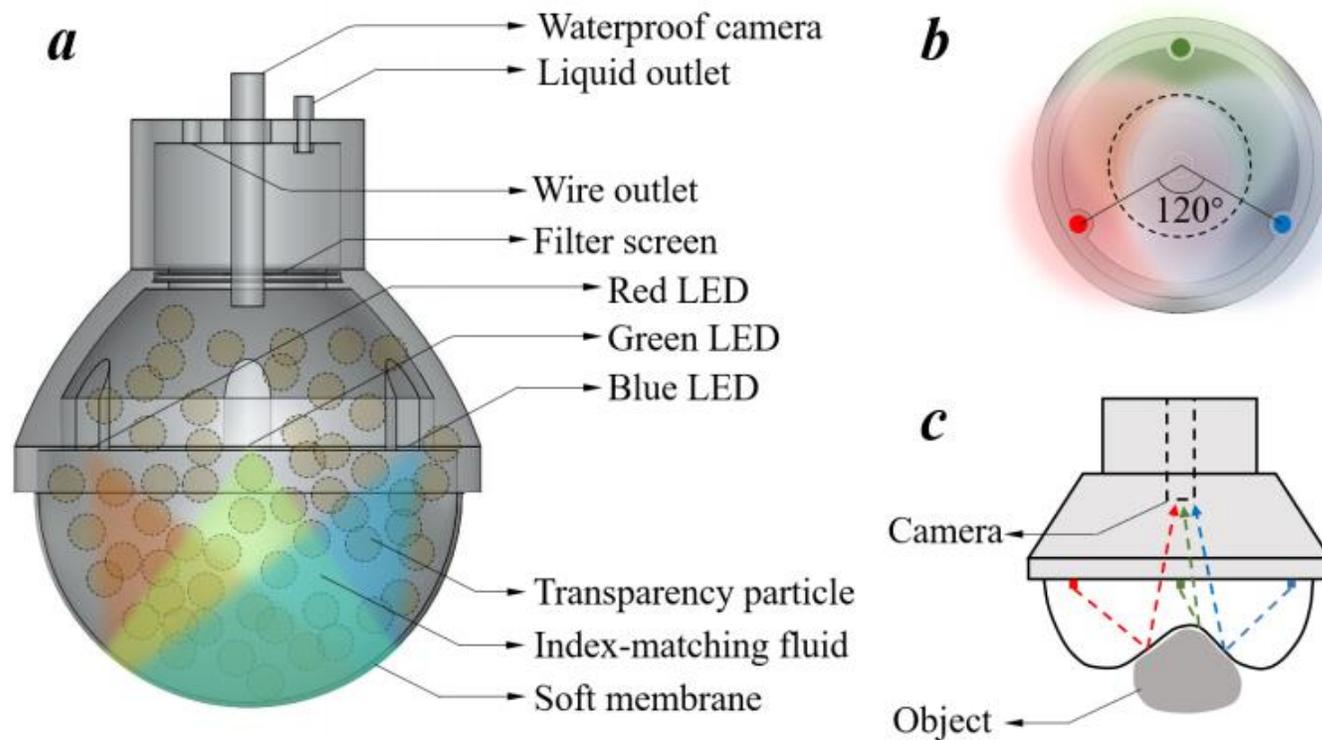


Fig. 3. (a) The schematic diagram of the gripper; (b) The layout of the LEDs plane; (c) The schematic diagram of the light path.

视触觉抓取机器人 (ICRA 2022 最佳设计论文提名)

Composition of the liquid	Composition of the particle	Refractive index	Defect
59% NaI solution [23]	High borosilicate glass	1.473	Oxidized to brown
Water	Super-absorbent resin	1.333	Particle is too soft
59.37% tetrachloromethane-tetrahydrofuran solution	Fluorine crown glass [24]	1.438	Generate virulent phosgene
77.26% trichloromethane-tetrahydrofuran solution			
30.2% gasoline-benzene solution	Barium fluoride	1.474	Dissolve the rubber soft film
12.4% engine oil-benzene solution	Organic glass	1.49	
p-cymene	Organic glass		
43.99% tetralin-ethanol solution	Fluorine crown glass (CDGM mark: H-FK95N)	1.438	Dissolve most organics
54.46 % tetralin-ethanol solution	Fluorine crown glass (CDGM mark: H-FK71)	1.457	
76.64 % tetralin-ethanol solution	Fluorine crown glass (CDGM mark: H-FK61)	1.497	
78% tetralin-ethanol solution	Fluorine crown glass (CDGM mark: H-K1)	1.499	
87.25% tetralin-ethanol solution	Fluorine crown glass (CDGM mark: H-K9)	1.517	

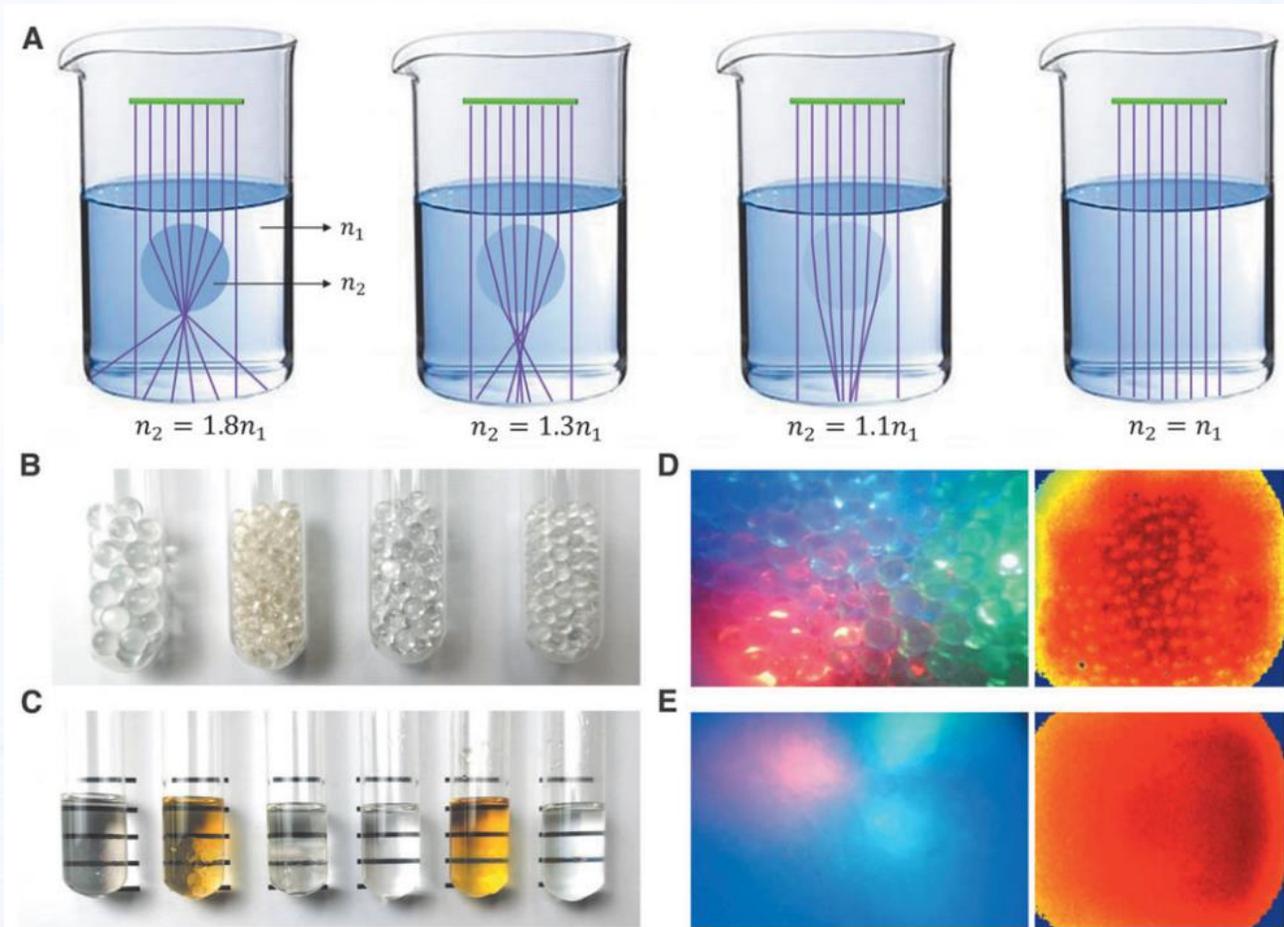


FIG. 3. Particles, solutions, and camera views. (A) Light rays pass through liquid with solid beads. As the refractive index of the bead gets closer to that of the liquid, the light is less deflected and the bead becomes less visible. Particularly, when $n_2 = n_1$, the bead becomes invisible. (B) The particles alone. Left to right: H-K9 glass, organic glass, high borosilicate glass, super absorbent resin. (C) The mixture of particles and liquid. Left to right: 87.25% tetralin-ethanol solution and H-K9 glass, 12.4% engine oil-benzene solution and organic glass, water and super absorbent resin, 59% NaI solution and high borosilicate glass, 59% NaI solution and high borosilicate glass with $\text{Na}_2\text{S}_2\text{O}_3$ as a decolorizer. (D) The RGB and depth images captured from inside the gripper when there is no liquid. (E) The RGB and depth images from inside the gripper are clean when there is index-matching liquid.



清华大学
Tsinghua University



TaTa: A Universal Jamming Gripper with High-Quality Tactile Perception and Its Application to Underwater Manipulation

Shoujie Li*, Xianghui Yin*, Chongkun Xia, Linqi Ye,
Xueqian Wang, Bin Liang

The Center for Intelligent Control and Telescience, Tsinghua Shenzhen International Graduate School, Tsinghua University

The Navigation and Control Research Center, Department of Automation, Tsinghua University

*These authors contributed equally to this work.

浑浊水下打捞机器人 (Soft Robotics 2023)

基于视触觉的世界首款可在浑浊水下进行物体搜索和打捞的机器人

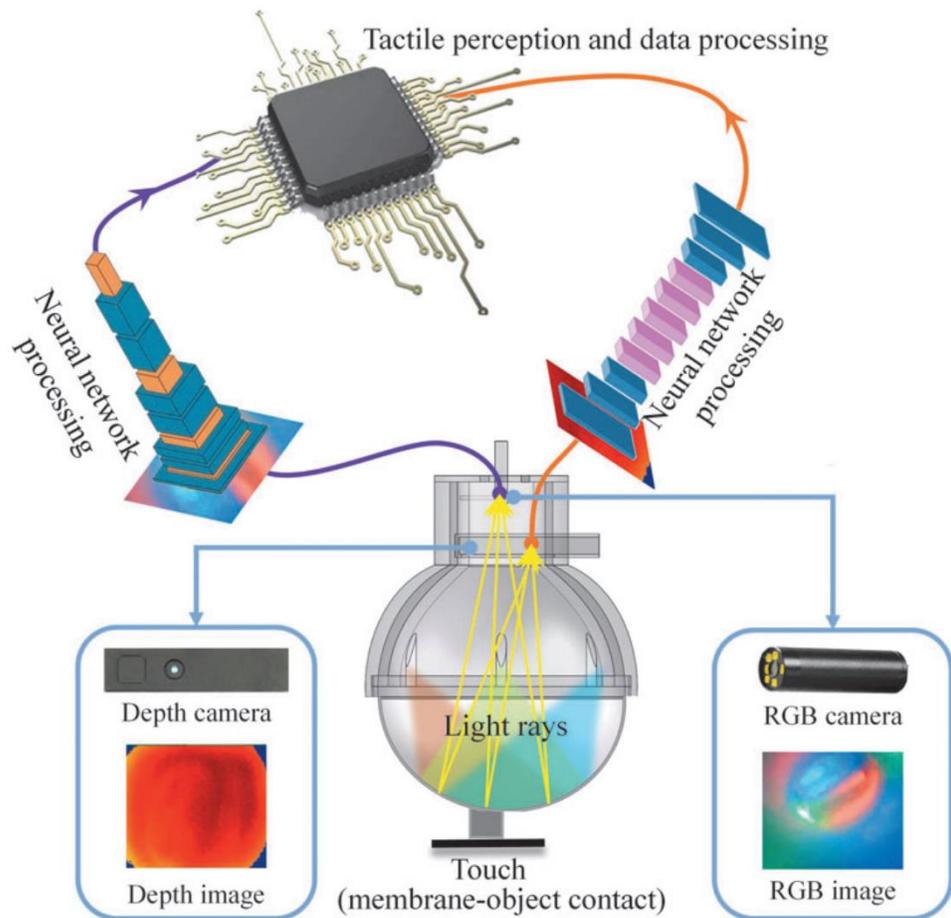
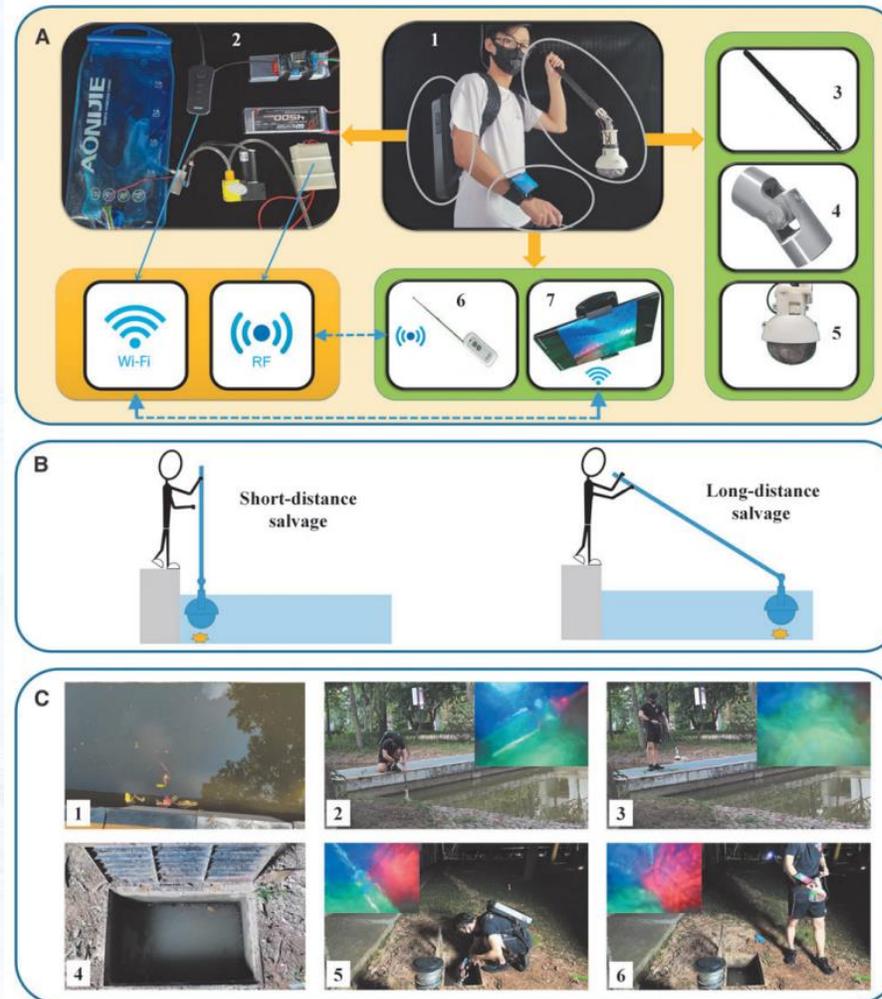


FIG. 1. Basic principle of JamTac. Color and depth images are obtained simultaneously inside the gripper to output tactile sensing information.



Searching and grasping in low-visibility environments
using a tactile jamming gripper

Underwater salvage in a pool

Searching and grasping in low-visibility environments
using a tactile jamming gripper

Underwater salvage in a sewer

视触融合透明物抓取 (IEEE TRO 2023)

基于深度学习实现视觉、触觉融合的透明物抓取，达到人类水平

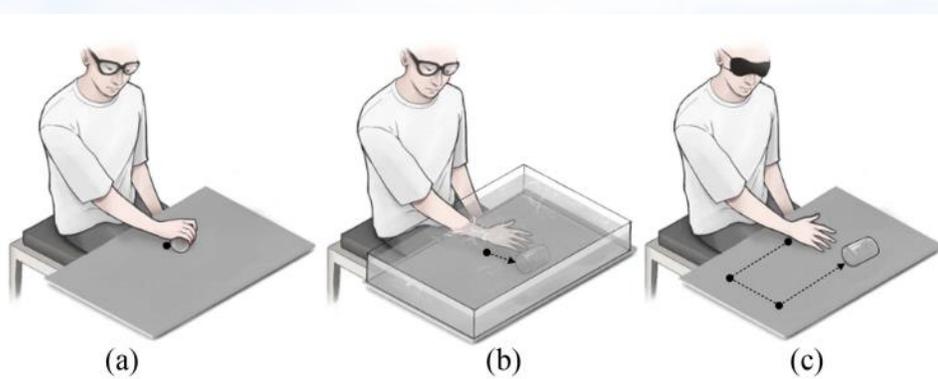
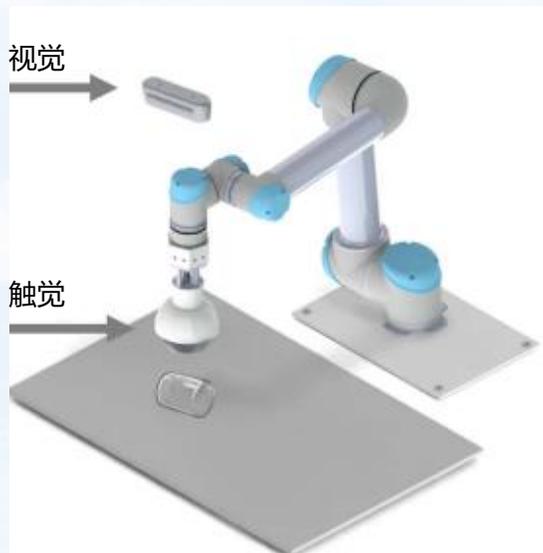


Fig. 12. Human grasping strategies in different scenes (The black curve indicates the movement path of the hand). (a) Grasping objects in clear view. (b) Grasping transparent objects underwater. (c) Grasping objects in visually undetectable scenes.

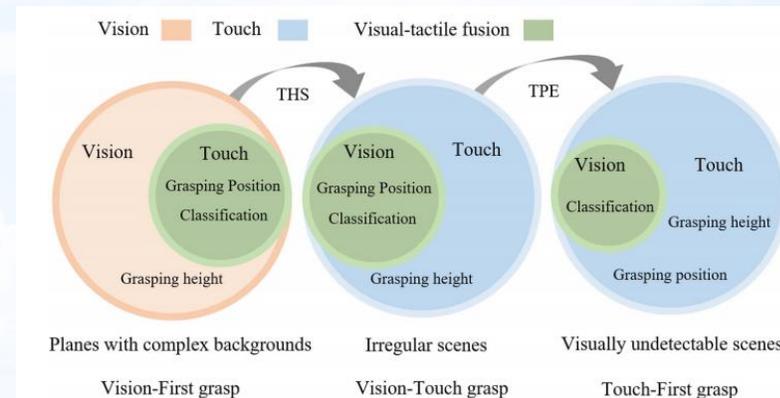
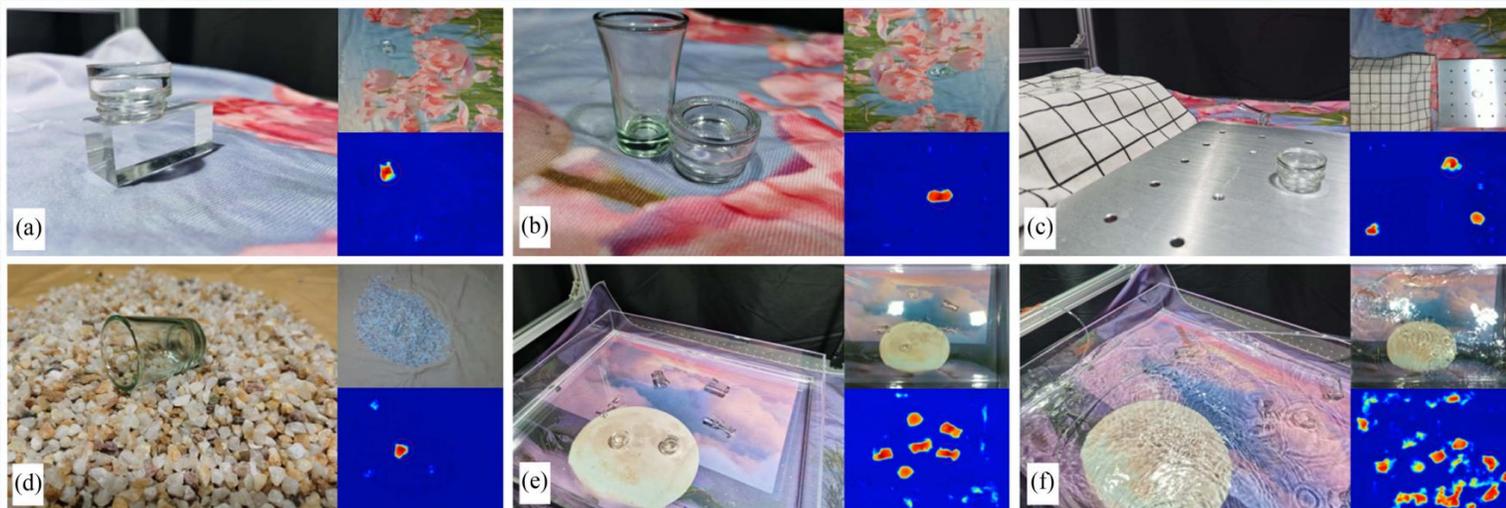
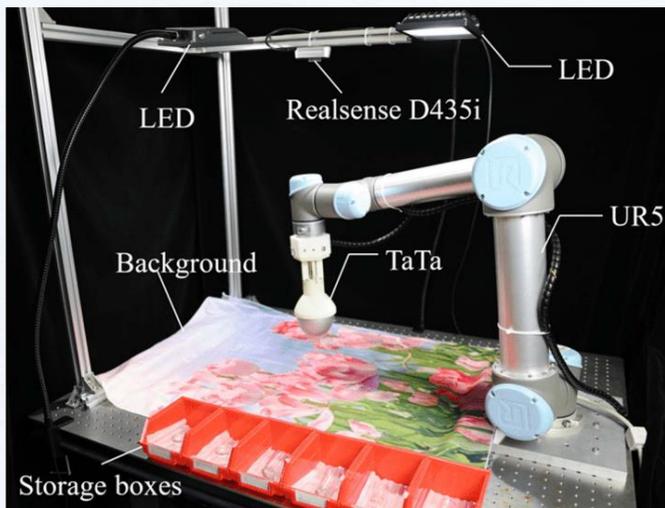


Fig. 13. Grasping strategies in different scenes. The orange, blue, and green colors represent the functions of visual detection, tactile, and visual-tactile fusion, respectively. The framework can be adapted to different scenes by adjusting the grasping strategies.

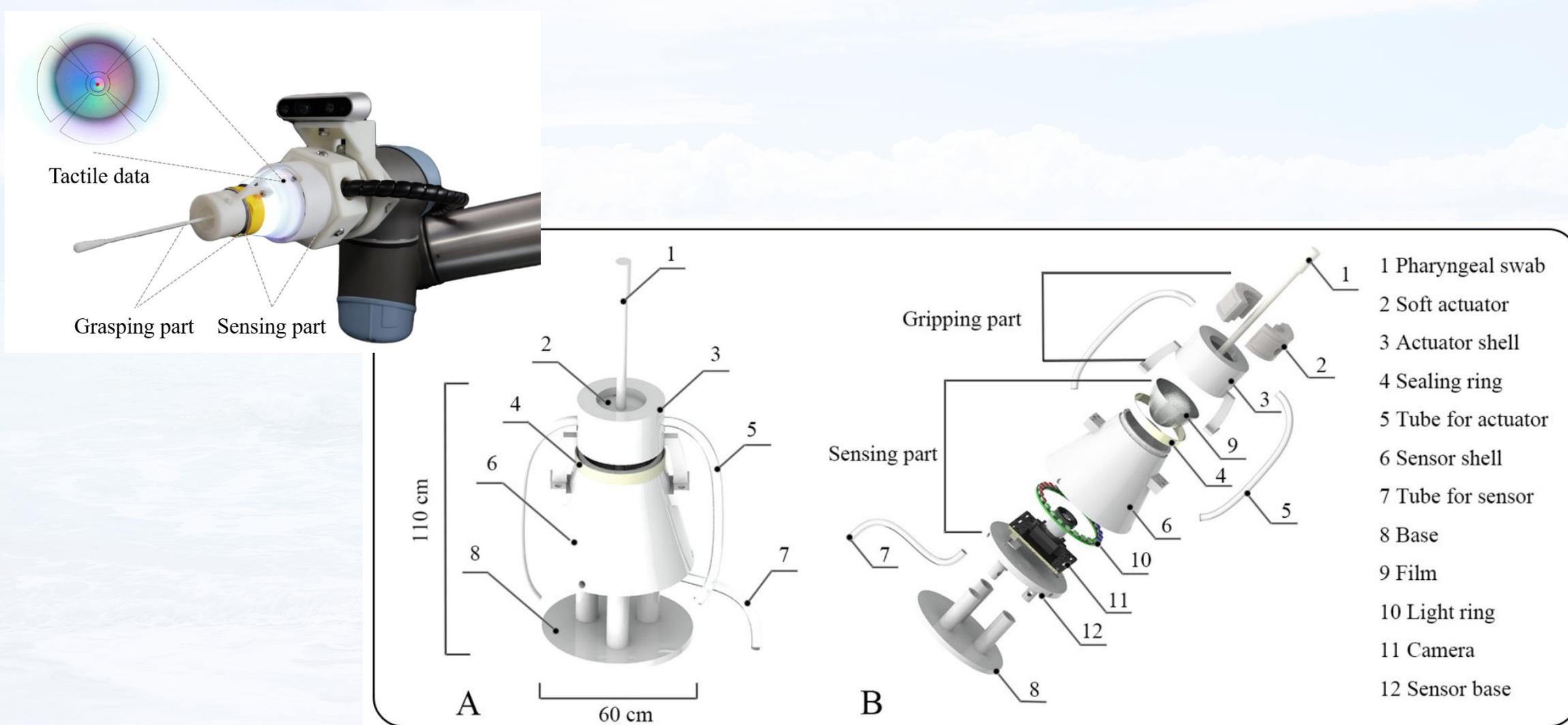


Transparent Object Grasping in Undulating Scenes

Transparent Object Grasping in High-dynamic Underwater Scenes

咽拭子采样机器人 (IROS 2023最佳应用论文提名)

基于视触觉和深度学习实现精准柔顺采样，大幅提升安全和舒适性





Visuo-Tactile Sensor Enabled Pneumatic Device Towards Compliant Oropharyngeal Swab Sampling

Shoujie Li¹, Mingshan He², Wenbo Ding¹, Linqi Ye³, Xueqian Wang¹, Junbo Tan¹, Jinqiu Yuan⁴, Xiao-Ping Zhang^{1,5} *IEEE Fellow*

1 Tsinghua Shenzhen International Graduate School, Tsinghua University, Shenzhen, China.

2 The Department of Mechanical Engineering, Seoul National University, Korea.

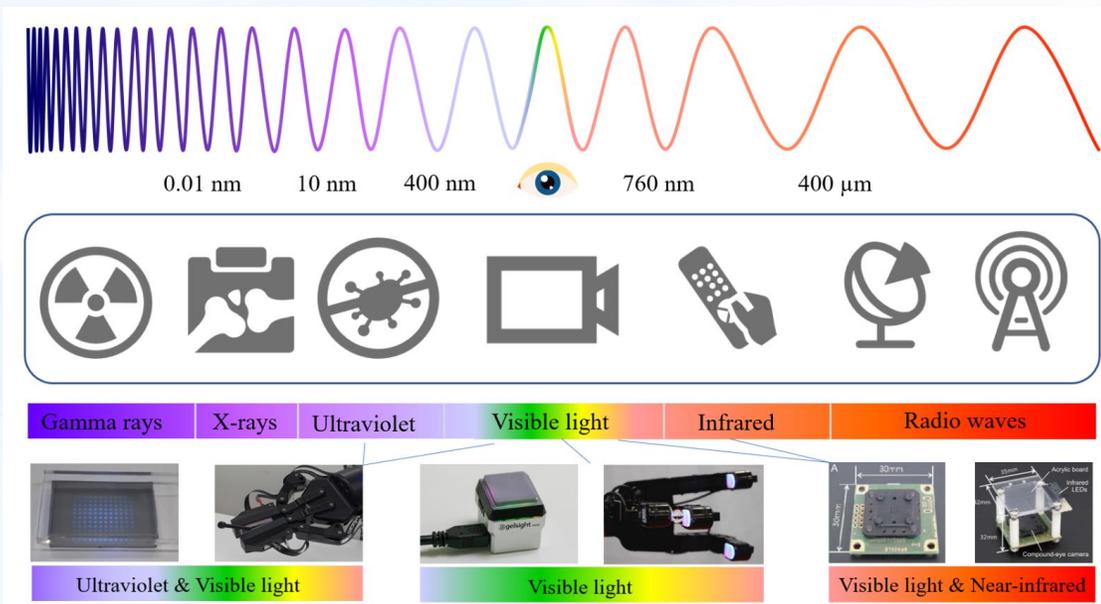
3 The Department of Intelligent Control, Qianyuan Institute of Science, Hangzhou, China.

4 The Clinical Research Center, The Seventh Affiliated Hospital, Sun Yat-sen University, Shenzhen, Guangdong, China

5 The Department of Electrical, Computer and Biomedical Engineering, Ryerson University, Toronto, Canada.

多光谱视触觉感知 (IEEE TRO 2024)

融合可见光、近红外、中红外的多光谱感知，实现超越人类的感知能力



(可见光) 基于投影光强度的距离感知算法 → **精度3.8 mm**

(近红外) 基于有限元的力感知神经网络 → **精度0.023 N**

(近红外) 基于生成式模型的三维重建算法 → **精度0.33mm**

(中红外) 基于卷积网络的超分辨率温度感知 → **精度0.3°C**

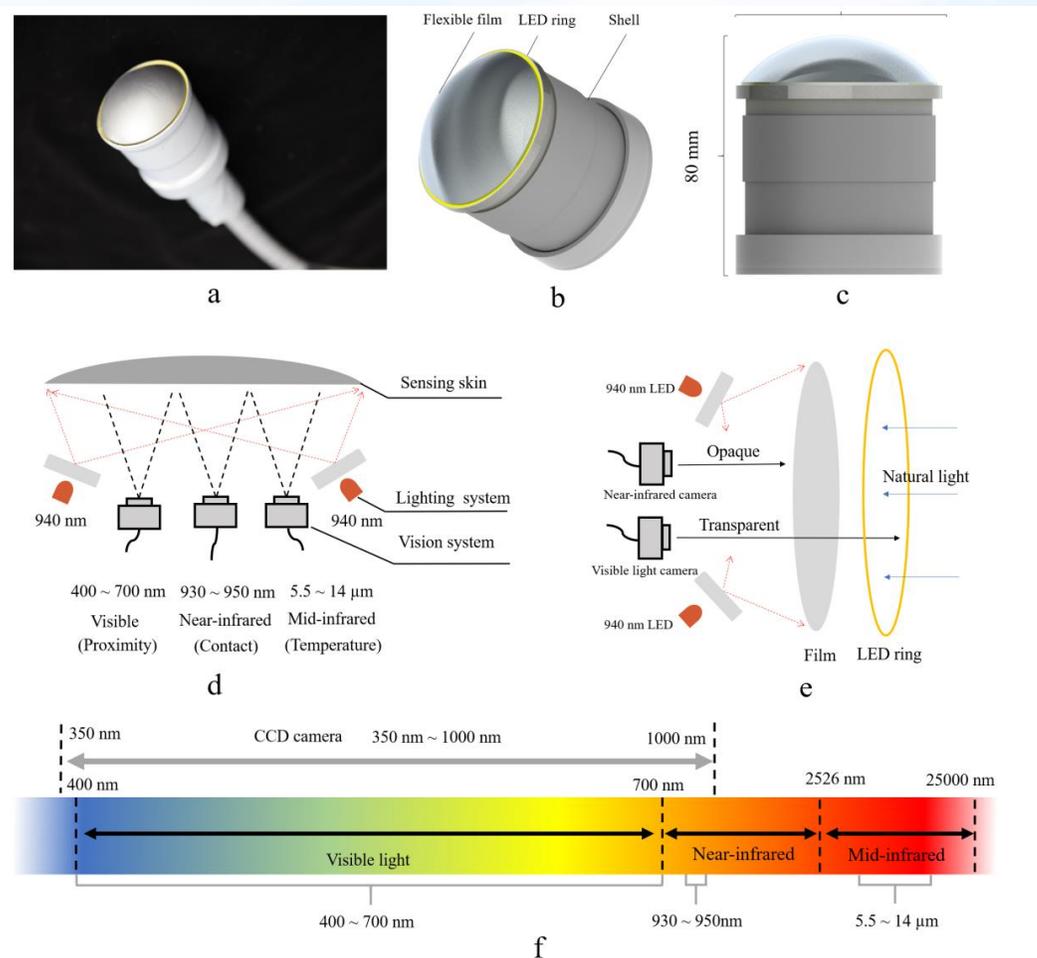


Fig. 2. Sensor overall design structure diagram. (a) The physical picture of M³Tac; (b) Overall structure of M³Tac; (c) Dimensions of M³Tac; (d) M³Tac optical imaging schematic; (e) Unidirectional perspective latex film transmission schematic; (f) Optical bands used in M³Tac.

Video 1: M³Tac Tactile Perception Performance Test

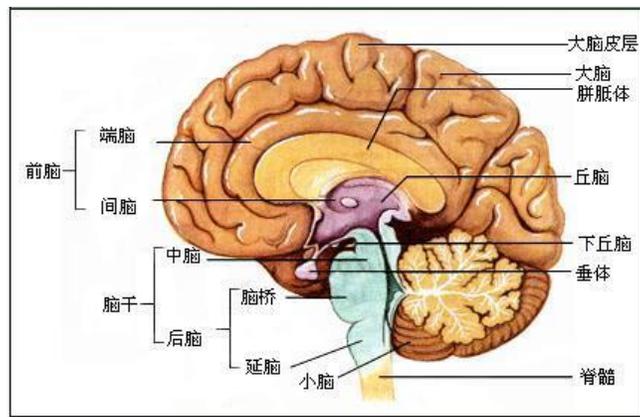
提纲

- 一、具身智能概念
- 二、具身智能本体
- 三、具身智能感知
- 四、具身智能控制**
- 五、具身智能展望

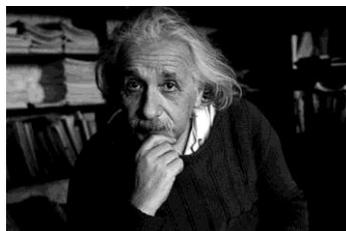


上海大学
SHANGHAI UNIVERSITY

人的大脑和小脑协同合作，分工配合



- **大脑**支配人的生命活动：语言、运动、听觉、视觉、情感表达等。它能够调节消化、呼吸、循环、泌尿、生殖、运动等中枢。
- **智力**：观察力、注意力、记忆力、思维力、想象力，大脑是一切思维活动的物质基础。
- **能力**：思维记忆、学习获得、认识理解、判断推理、综合分析、语言表达、社会活动能力、意识情绪



大脑（认知，知道怎么游泳）



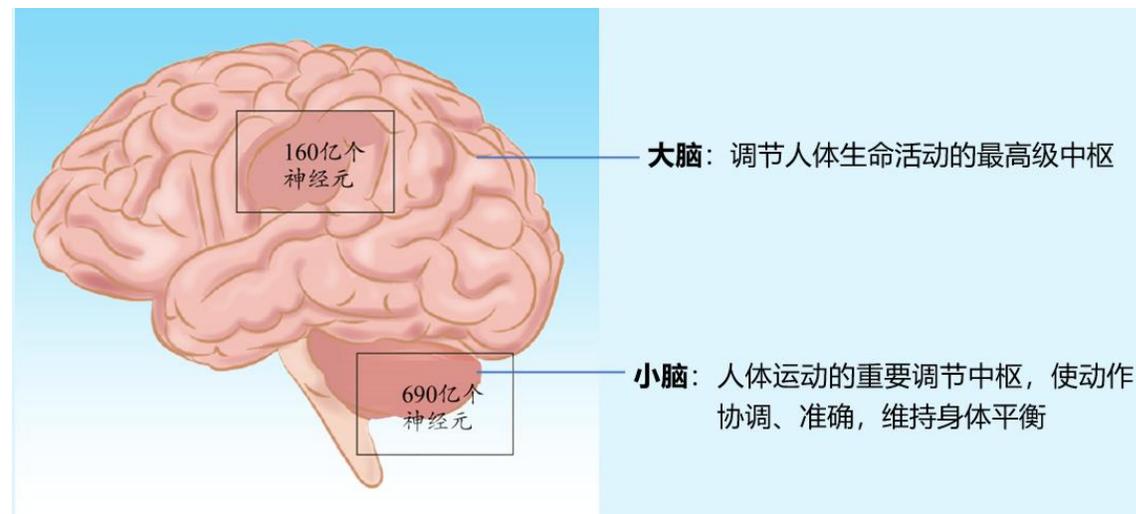
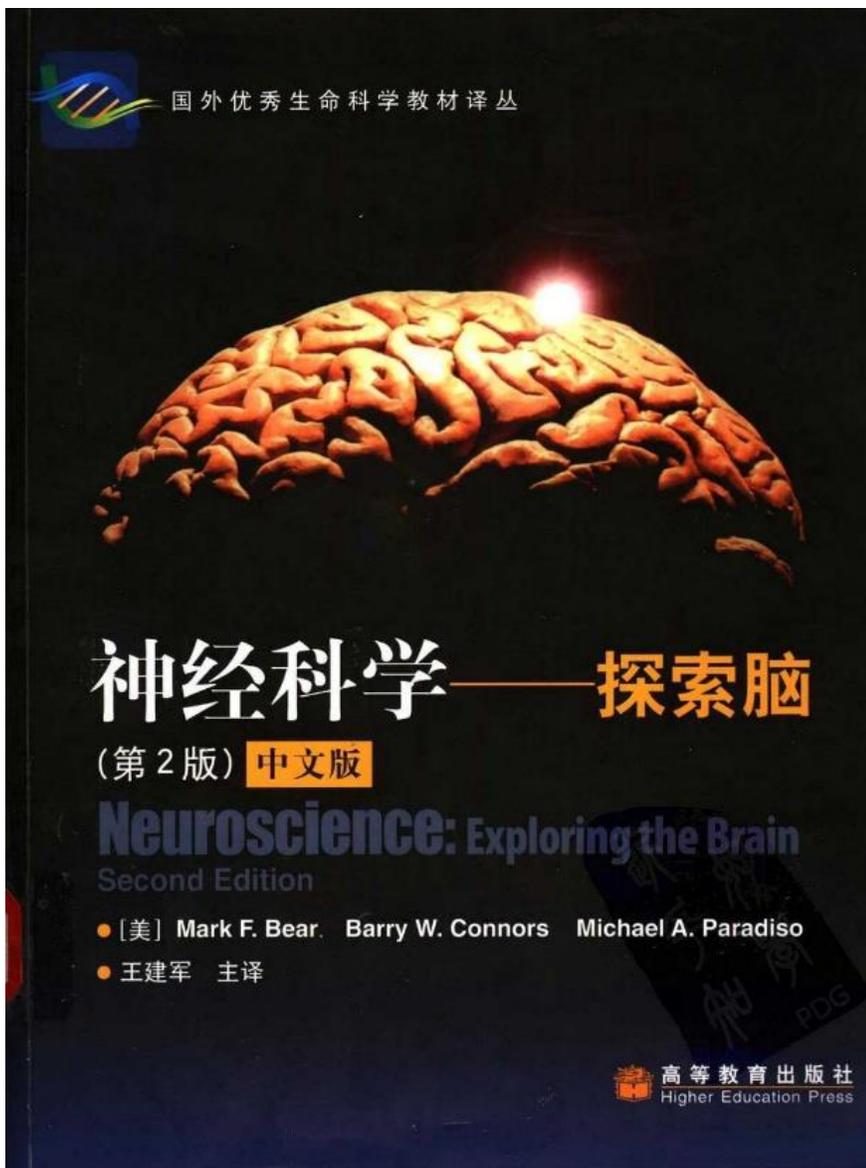
小脑（技能，会游泳）

- **小脑**通过复杂的调节和反馈机制成为维持平衡和肌张力的协调中枢（**运动协调**），它还能使躯体肌肉系统完成精细的技巧性运动（**运动学习**）。小脑像计算机一样能扫描和协调感觉传入并调节运动传出。

大脑是总司令,小脑就是参谋长。大脑在发出指令时,先将信息传递给小脑,小脑分析校正,确保准确性后,再传回到大脑,由大脑做出最终的指令。



人的小脑仅占全脑体积1/10，但神经元数量却是大脑的4倍

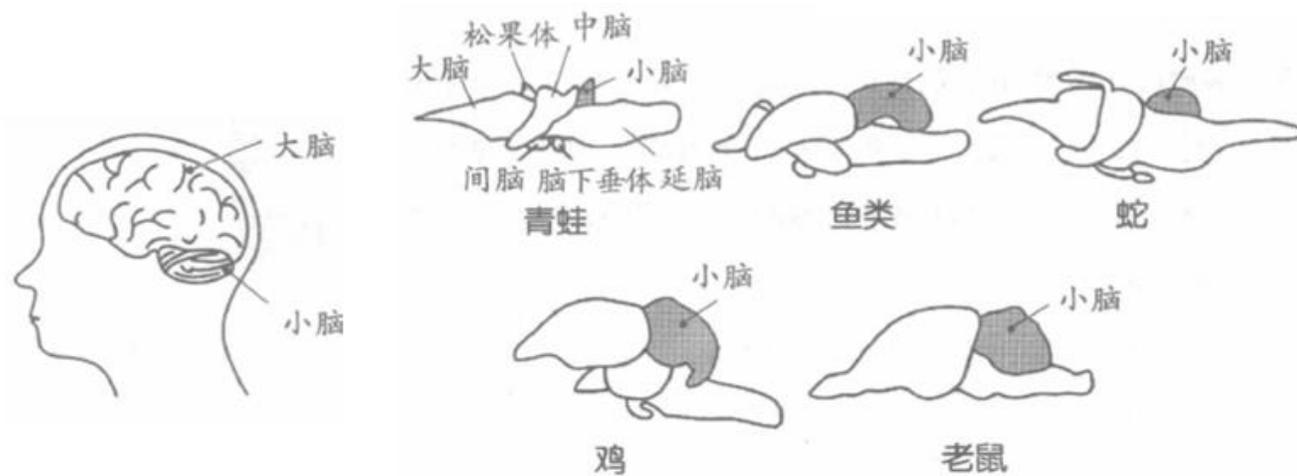


运动控制的等级

水平	功能	结构
高	运动战略	新皮层联络区、基底神经节
中	运动战术	运动皮层、小脑
低	运动执行	脑干、脊髓

动作越灵活的动物，小脑越发达

鸟类、鱼类、哺乳类的小脑占脑部的比例很大，而两栖类或爬虫类的就很小。研究表明，小脑受损患者运动控制变得粗糙、不精细、控制不足。借鉴小脑功能机制，建立机器人运动控制小脑，将有可能使机器人运动能力实现质的飞跃。



小脑在精细运动控制、身体平衡、多关节运动协调和运动学习方面扮演至关重要的作用。

运动精确性和协调性的控制

- 平衡**：姿势控制，对外部干扰做出反应，提供前瞻性控制
- 移动**：躲避障碍和适应新环境，保持双眼凝视的稳定性
- 抓握**：握力的控制，不同目标物体的适应
- 时序**：运动协调，为肌肉活动提供正确时序
- 多关节运动控制**：对跨关节肌肉进行复合协同，调节互动力矩
- 感觉运动同步化**：参与获取序列运动的最佳内在模式，优化感觉运动参数

运动学习

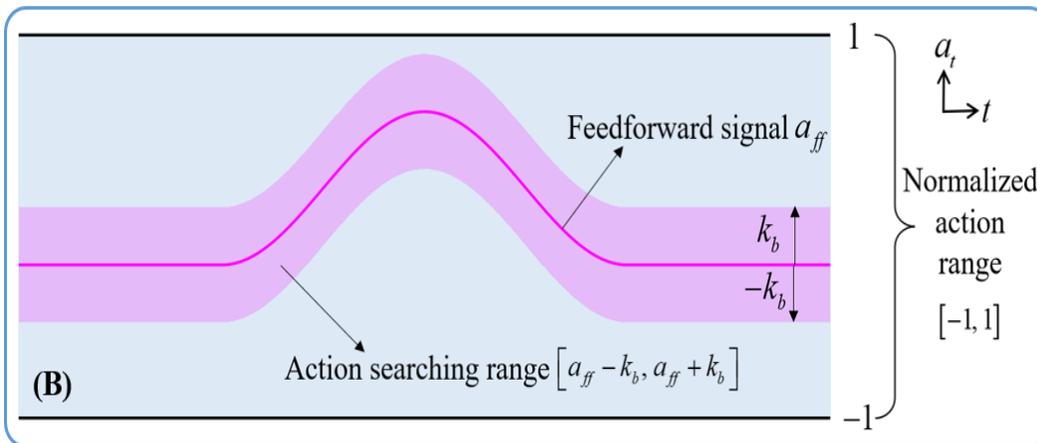
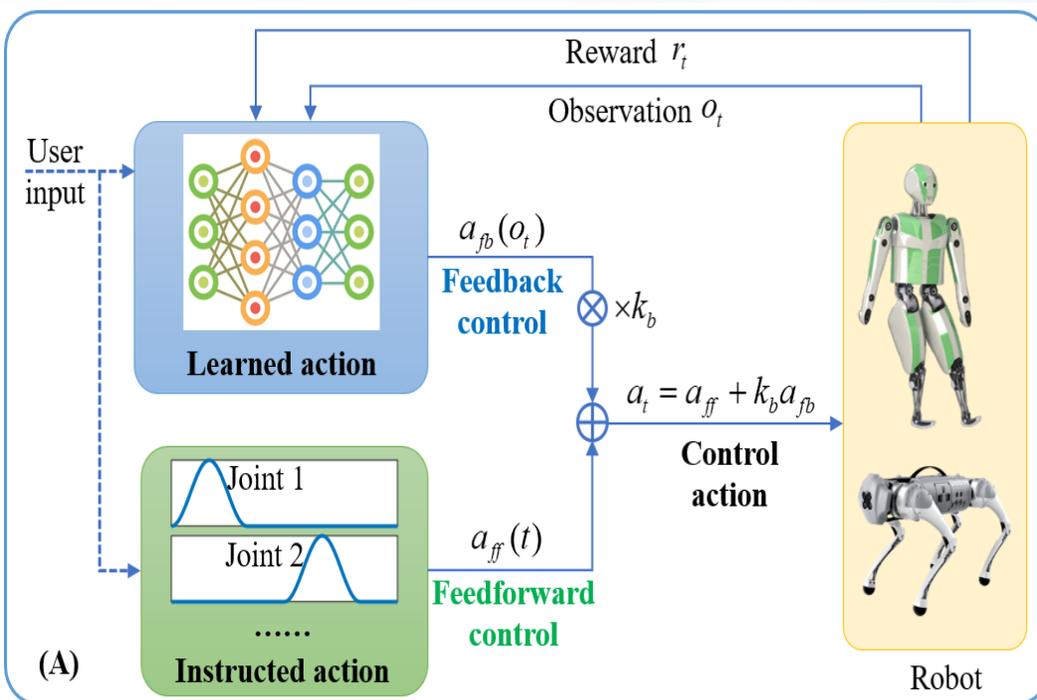
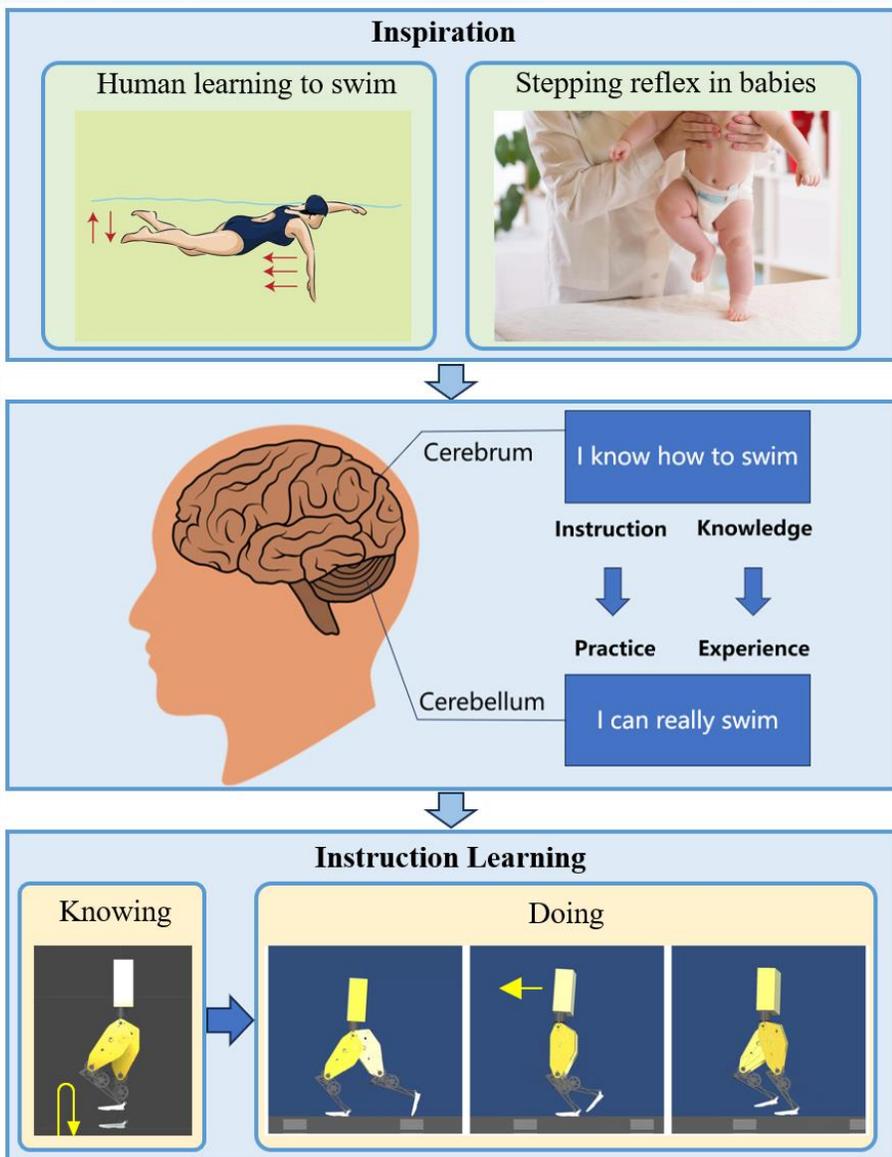
- 建模**：建立运动器官和运动环境的神经内在模型并不断更新改进
- 预测**：内在模型预测产生运动指令，克服感觉反馈的延迟现象
- 自主**：让运动转变成更加自主的运动，减少运动细节对注意力的需求

知识引导的模仿学习 (ICRA 2024)

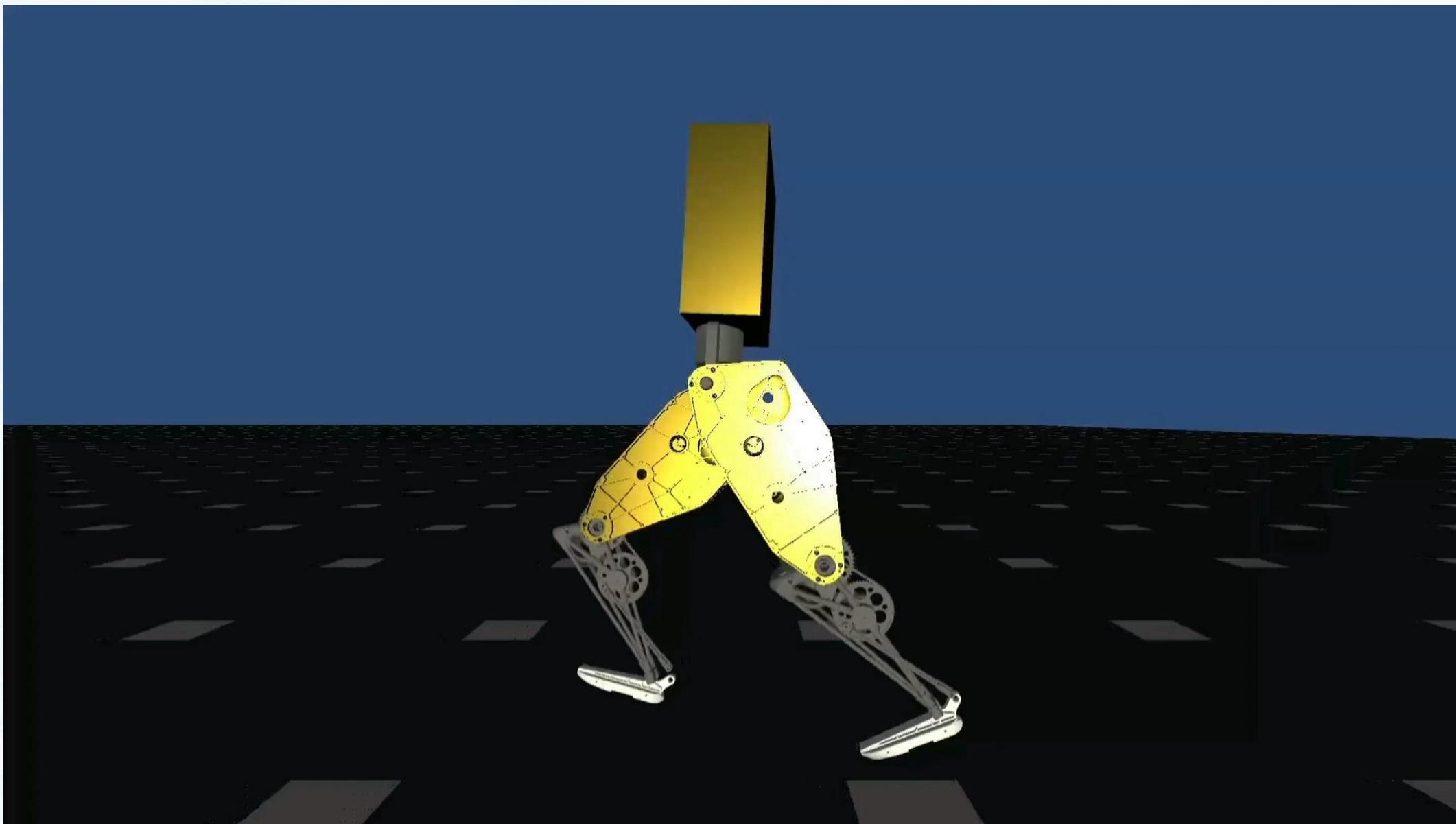
提出知识引导的模仿学习方法，学习速度比传统模仿学习提升数倍



知识引导的模仿学习 (ICRA 2024)



知识引导的模仿学习 (ICRA 2024)





Home Environment Simulation

We built a two-story room scenario to test the robot's ability to move in a narrow and obstructed environment. Ankle and trunk target trajectories are manually set and we focus on verifying the tracking capabilities of our controllers.

四足强化学习盲走越障 (IROS 2024)

基于碰撞感知判断障碍物类型并选择控制策略，实现超强越障能力



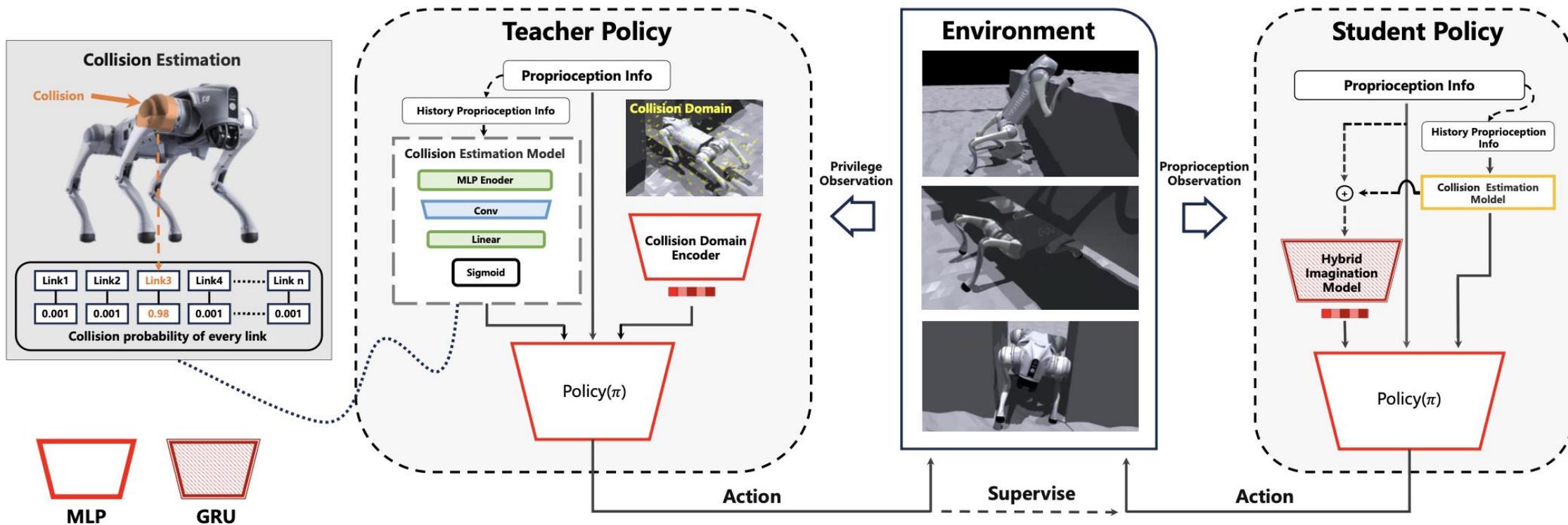
历史状态信息

长短期
记忆网络

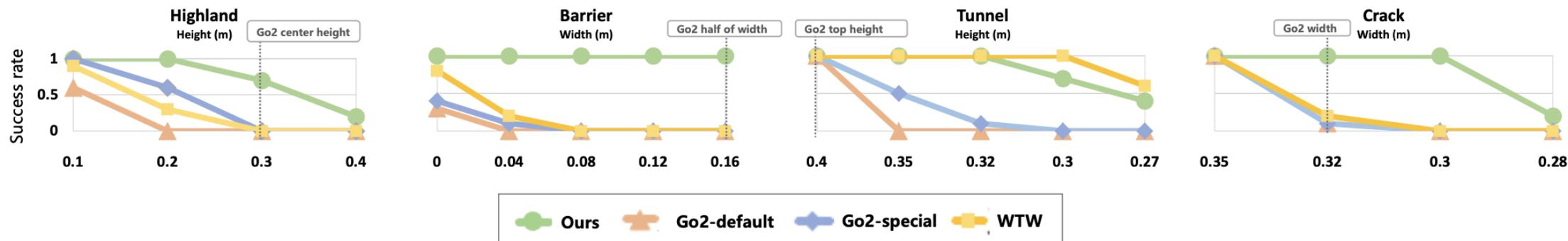
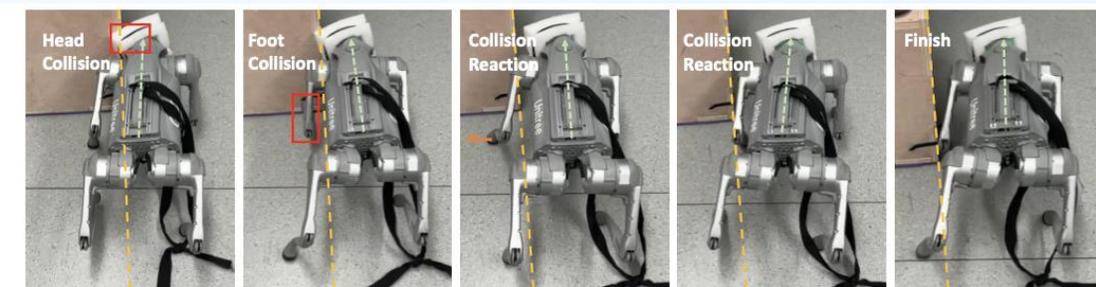
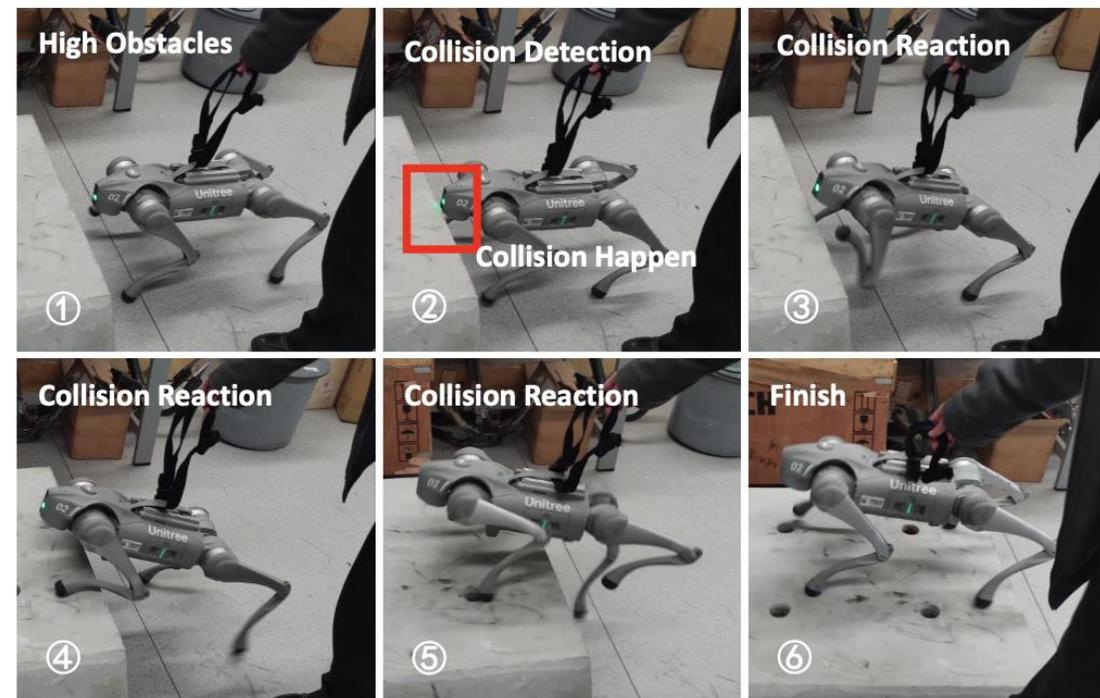
碰撞检测模型

环境
特征向量

越障控制策略



四足强化学习盲走越障 (IROS 2024)



四足强化学习盲走越障 (IROS 2024)



Quadruped robot traversing 3D complex environments with limited perception

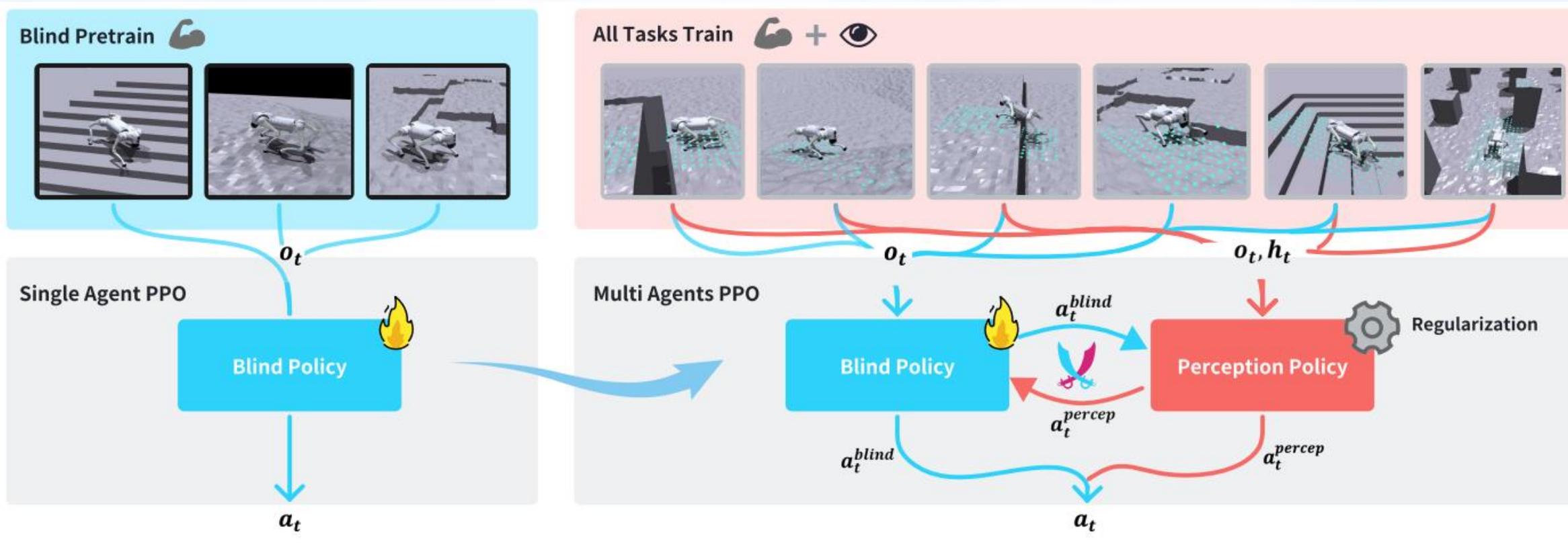
Yi Cheng*, Hang Liu*, Guoping Pan, Linqi Ye, Houde Liu, Bin Liang

Abu Dhabi 2024
IROS



四足多脑协同强化学习 (CoRL 2024)

有视觉、无视觉策略协同强化学习，视觉受损时仍能保持最佳性能



无视觉强化学习训练

无视觉、有视觉博弈对抗
强化学习训练

多脑协同
控制策略

四足多脑协同强化学习 (CoRL 2024)

Robustness test

Lidar damage

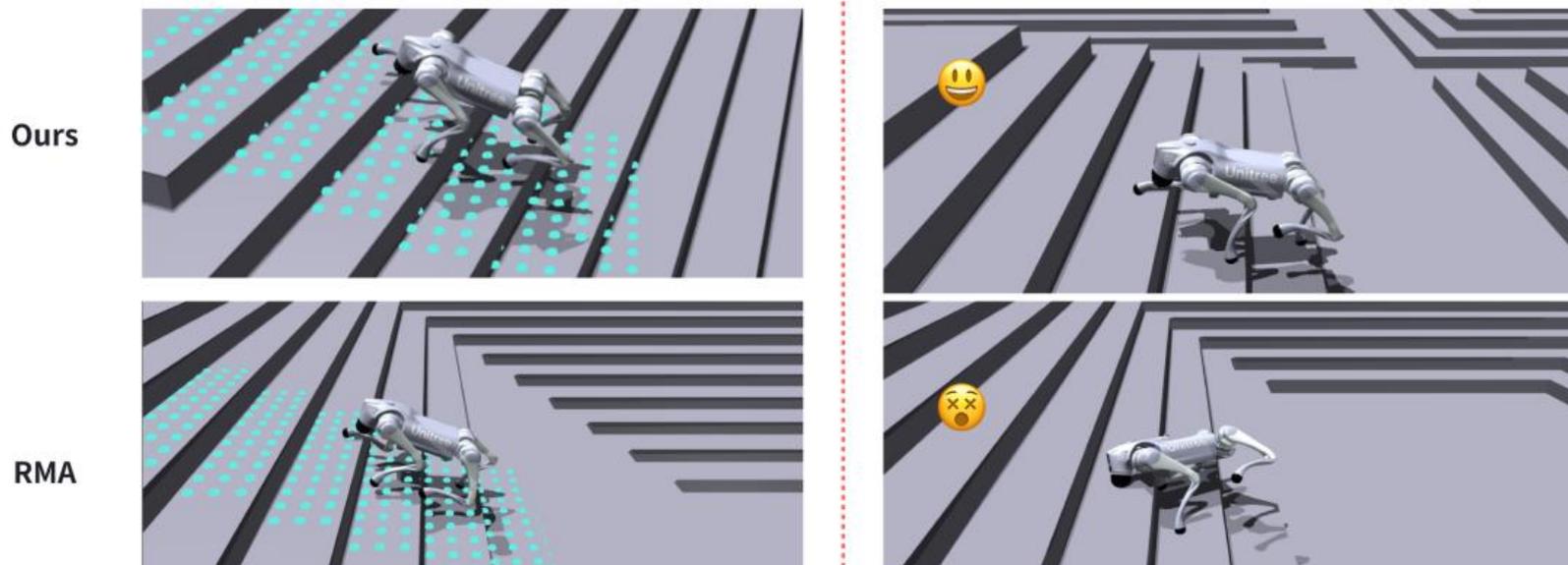


Figure 3: Robustness testing In simulation, the perception-based RMA mode collapses when the height map is corrupted while our policy works well.

Method	Up Stair Success	Down Stair Success	Discrete Success	Stair XMD	Discrete XMD
Ours	97%	100%	90%	19.97	17.04
RMA	0%	100%	81%	8.2	12.38
Baseline	0%	100%	76%	7.8	11.53
Ours w/o VAE	87%	100%	90%	16.42	14.99

四足多脑协同强化学习 (CoRL 2024)

Multi-Brain Collaborative Control for Quadruped Robots



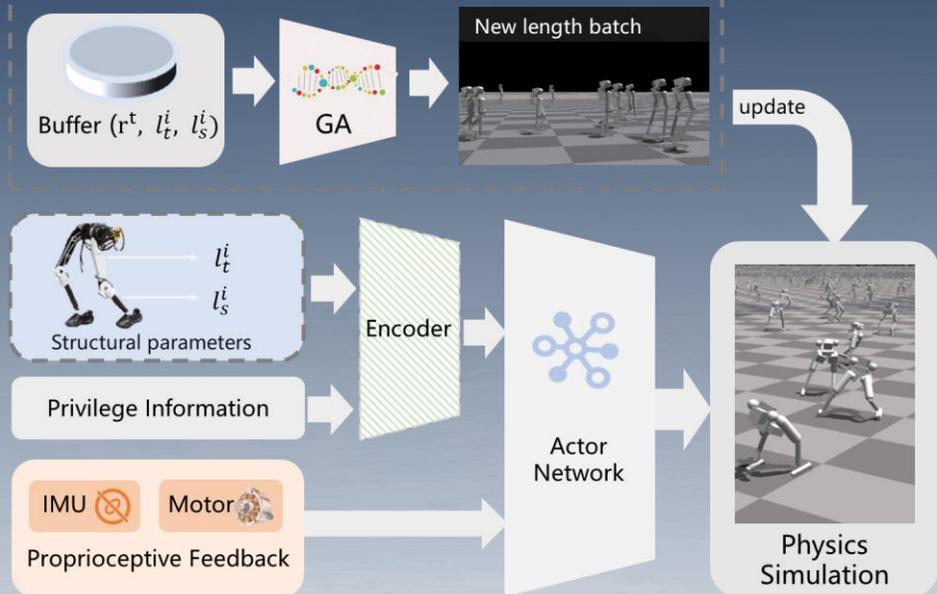
Submission Number: 681

双足形态策略协同进化 (IROS 2024)

利用遗传算法和强化学习，实现机器人结构参数和控制策略的协同进化

基于遗传算法的机器人结构参数更新

Structure Evolution



基于强化学习的机器人运动控制

Evolution: 10 iterations



Evolution: 310 iterations

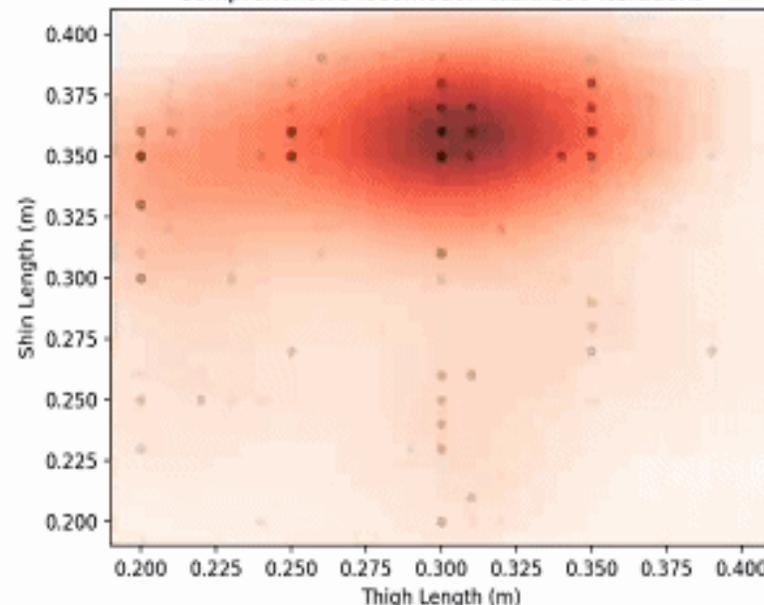


Evolution: 830 iterations

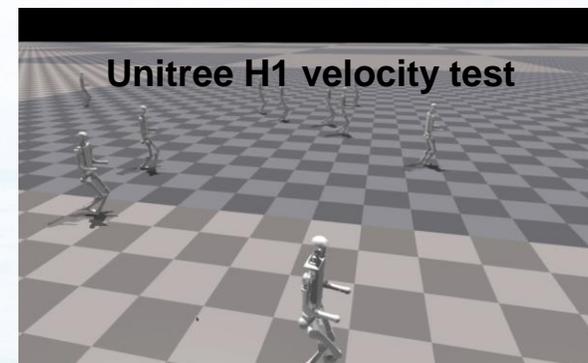
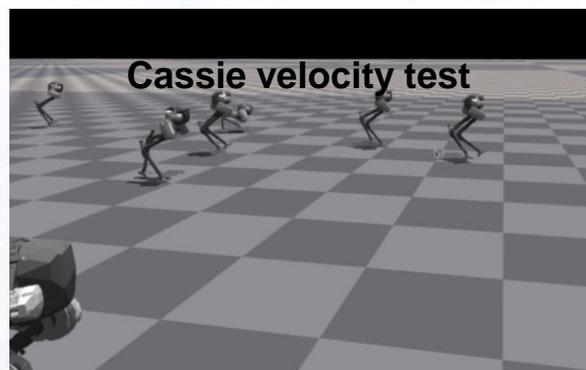
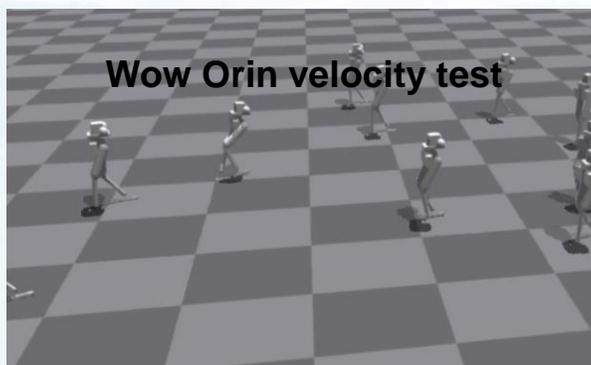
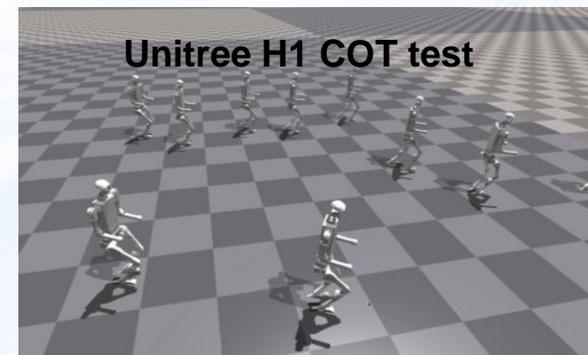
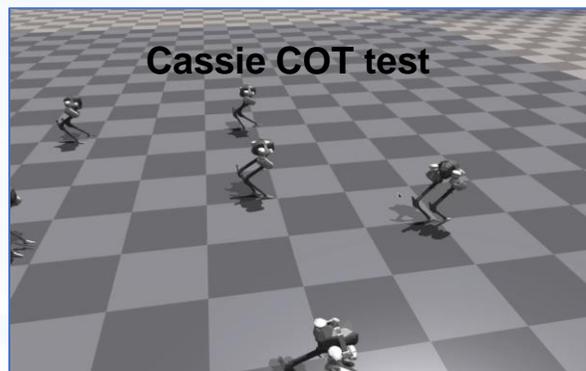
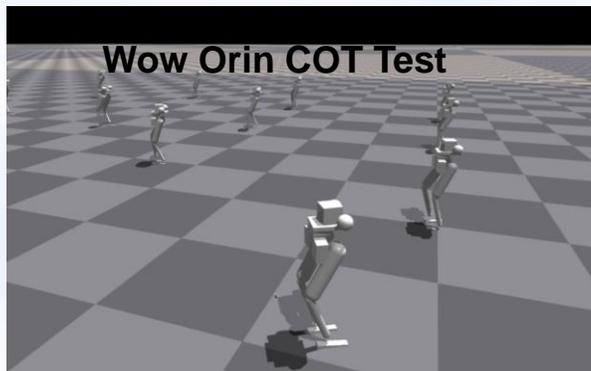


SERL Optimization Process Comprehensive locomotion Task

Comprehensive locomotion task: 190 iterations



双足形态策略协同进化 (IROS 2024)



Performance Test

Energy Efficiency And Velocity

The COT is used to gauge the efficiency of legged robots, calculated as: $COT = P/(mgv)$

The Froude number is used to compare the dynamic similarity of robots, calculated as: $F_r = v^2/gl$

	Wow Orin	Cassie	Unitree H1
Weight (kg)	10.5	31	47
Joint Maximum Torque ($N \cdot m$)	67	195	360
COT	0.407	0.762	0.718
Leg Length(m)	0.7	1.0	0.8
Max Velocity (m/s)	2.1	3.2	1.9
Froude number	0.75	1.04	0.46

双足形态策略协同进化 (IROS 2024)



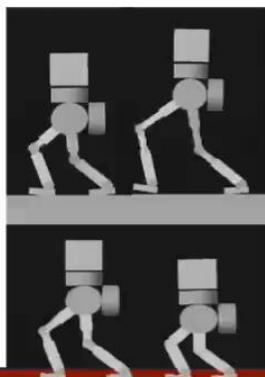
Abu Dhabi 2024
IROS

2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
October 13 – 17, 2024 | Abu Dhabi, UAE



Structural Optimization of Lightweight Bipedal Robot via SERL

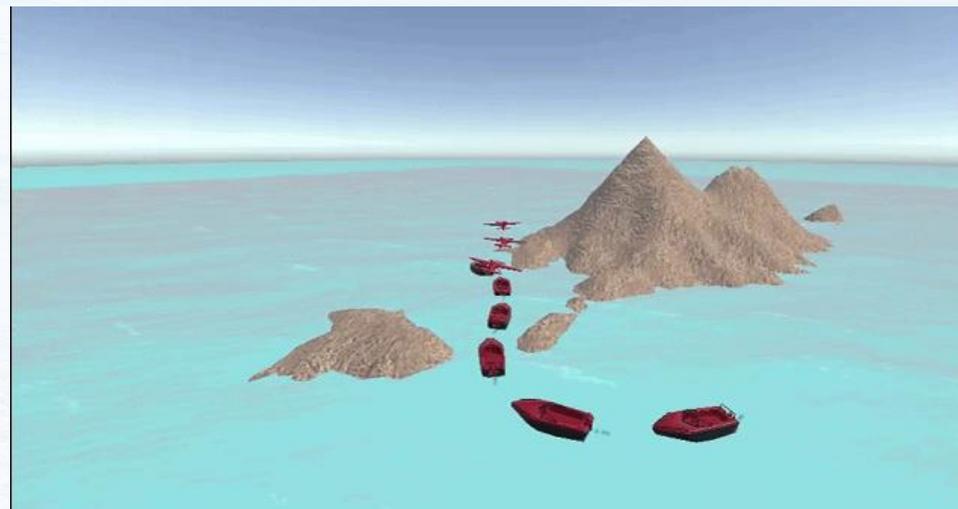
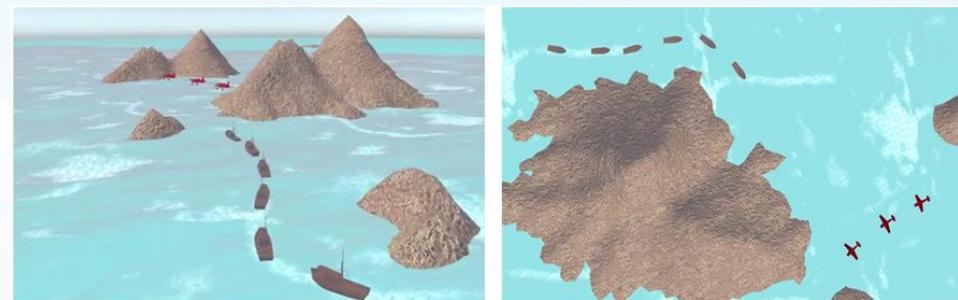
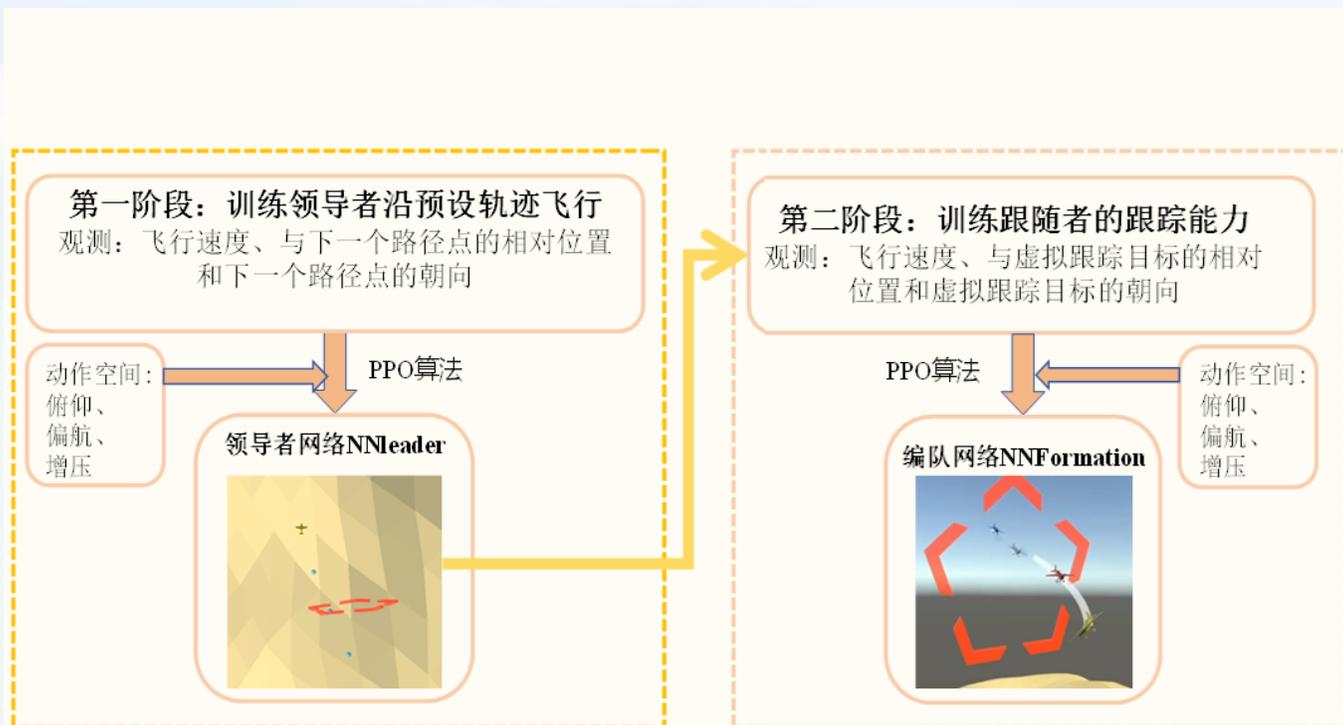
Yi Cheng*, Chenxi Han*, Yuheng Min, LinQi Ye, Houde Liu, Hang Liu, Bin Liang



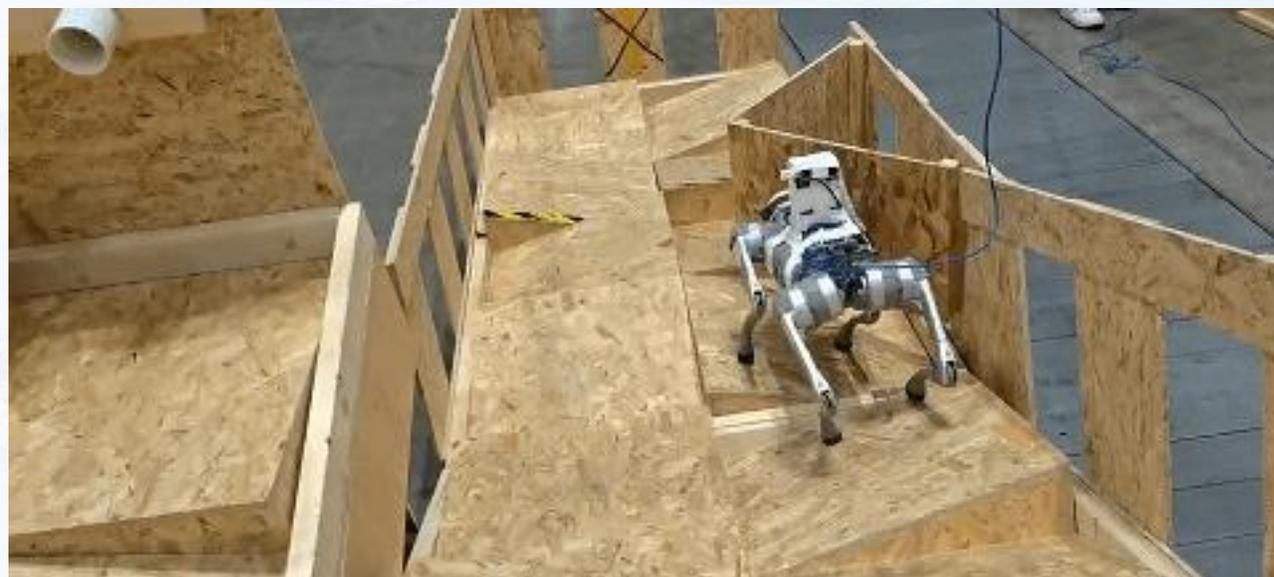
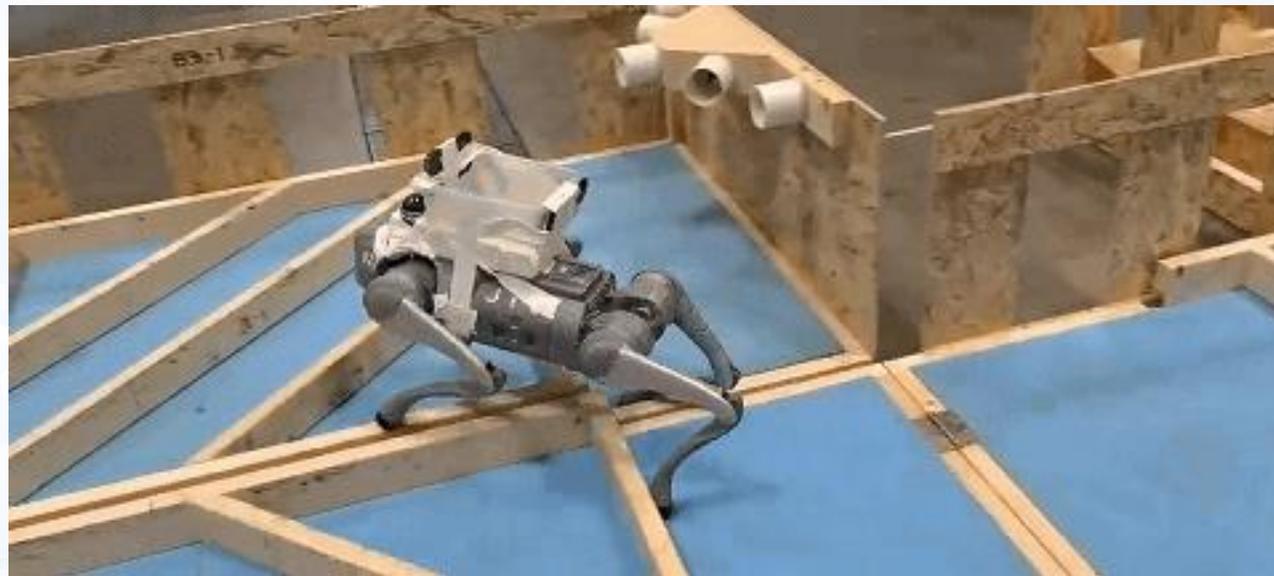
This video introduces a lightweight bipedal robot

海空跨域协同编队 (ARCAI 2024)

基于多智能体强化学习实现无人机、艇复杂环境自适应编队巡逻



四足机器人强化学习挑战赛



 **IEEE**
IEEE ROBOTICS AND AUTOMATION SOCIETY

Quadruped Robot Challenges

IEEE International Conference on Robotics and Automation – ICRA 2024

The Fourth Placement in Tele-operation

Tsinghua University:

Houde Liu, Linqi Ye, Yi Cheng, Guoping Pan, Hang Liu,
Xueqian Wang, Yuheng Min, Chenxi Han, Han Zheng, and Jiayi Li



May 2024


Zhidong Wang
ICRA General Chair


Hyungpil Moon
Quadruped Robot Challenges, Chair



人形机器人强化学习挑战赛

获奖证书

CERTIFICATE OF AWARD

江淮前沿技术协同创新中心、清华大学、上海大学 代表队：

在第二十六届中国机器人及人工智能大赛全国总决赛中，表现优异，成绩突出，荣获 人形机器人创新挑战赛（仿真赛）

一等奖

团队成员：郑函、程颐、张辉

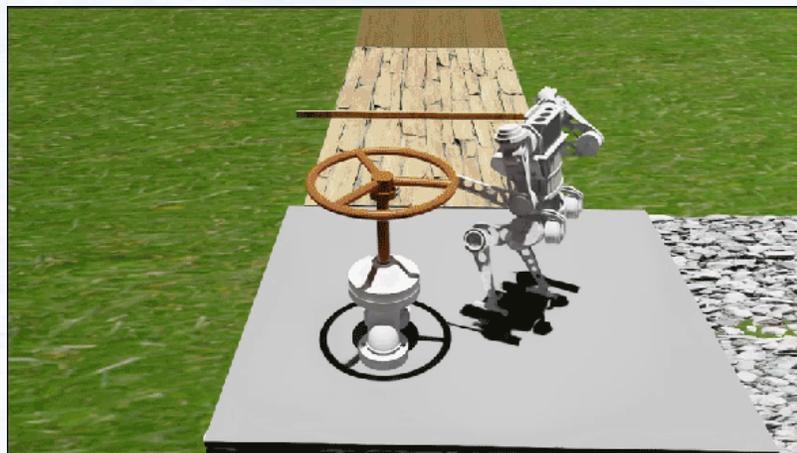
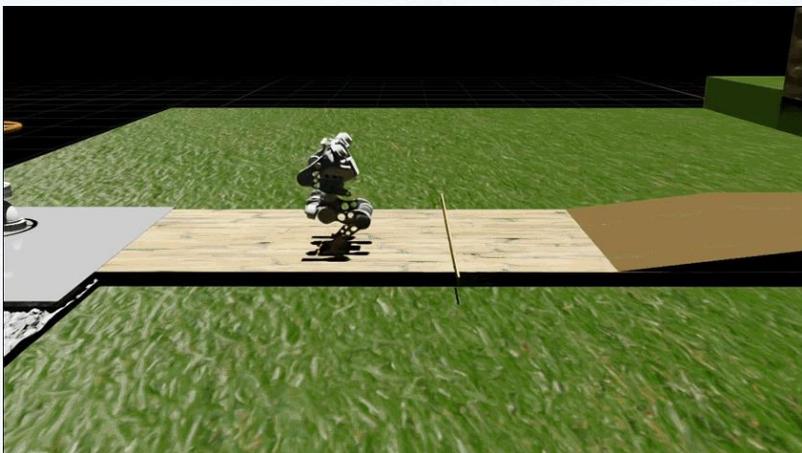
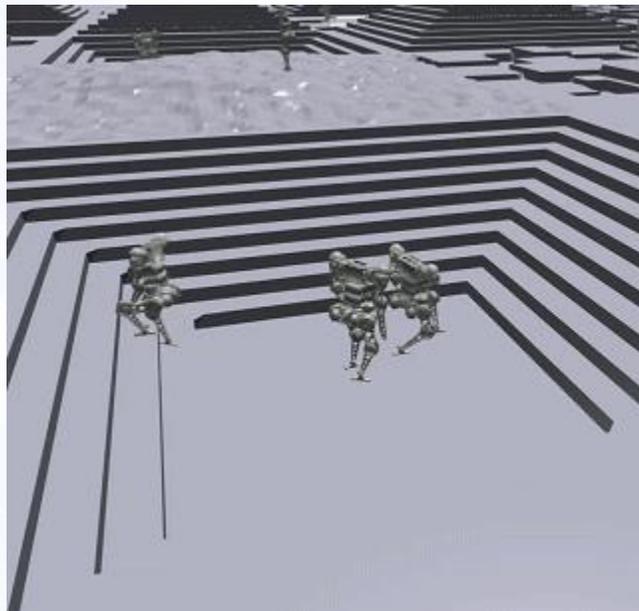
指导老师：刘厚德、叶林奇

特发此证，以资鼓励。

证书编号：CRAIC2024-NF-BWZFS

中国机器人及人工智能大赛组委会

二〇二四年八月



人形机器人强化学习实物试验



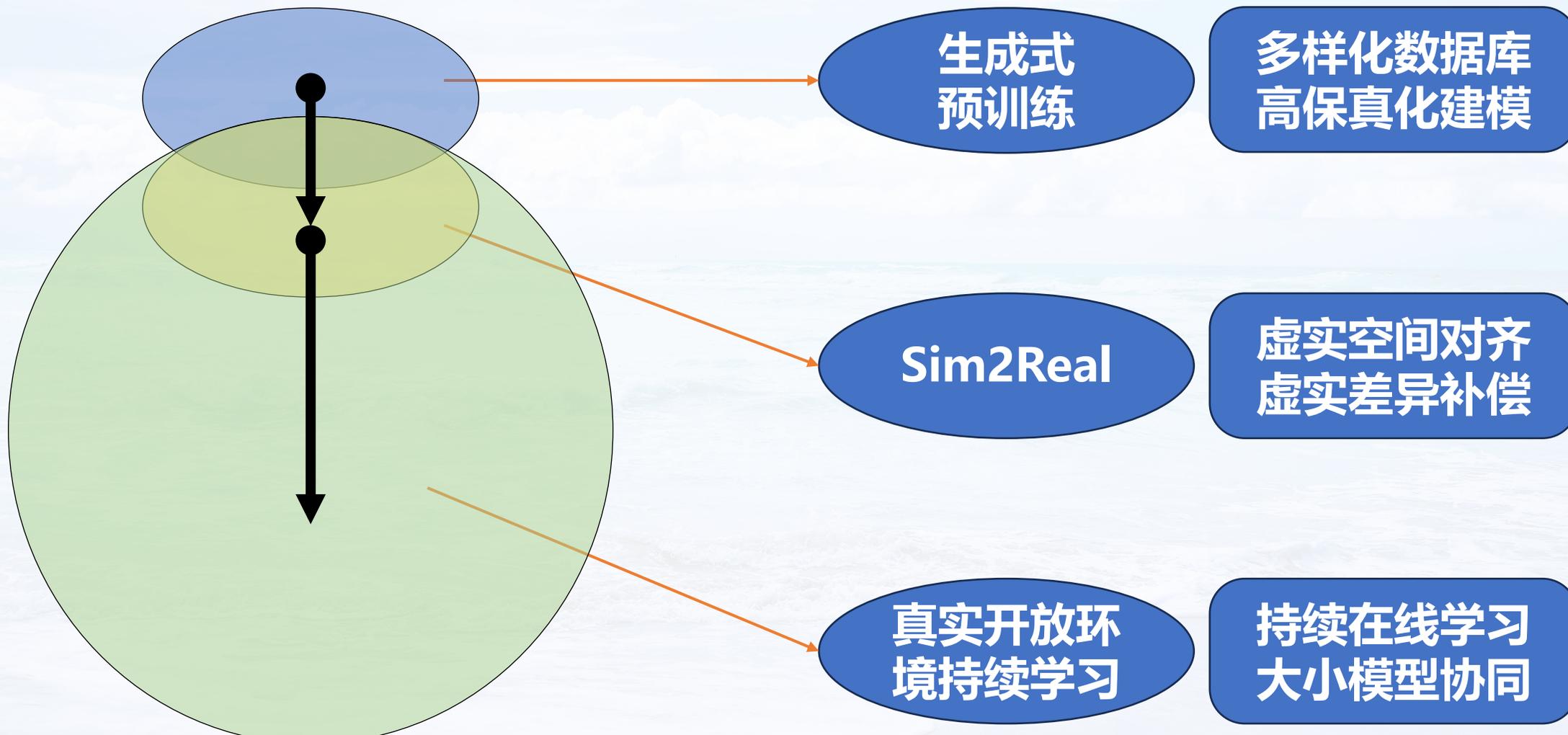
提纲

- 一、具身智能概念
- 二、具身智能本体
- 三、具身智能感知
- 四、具身智能控制
- 五、具身智能展望

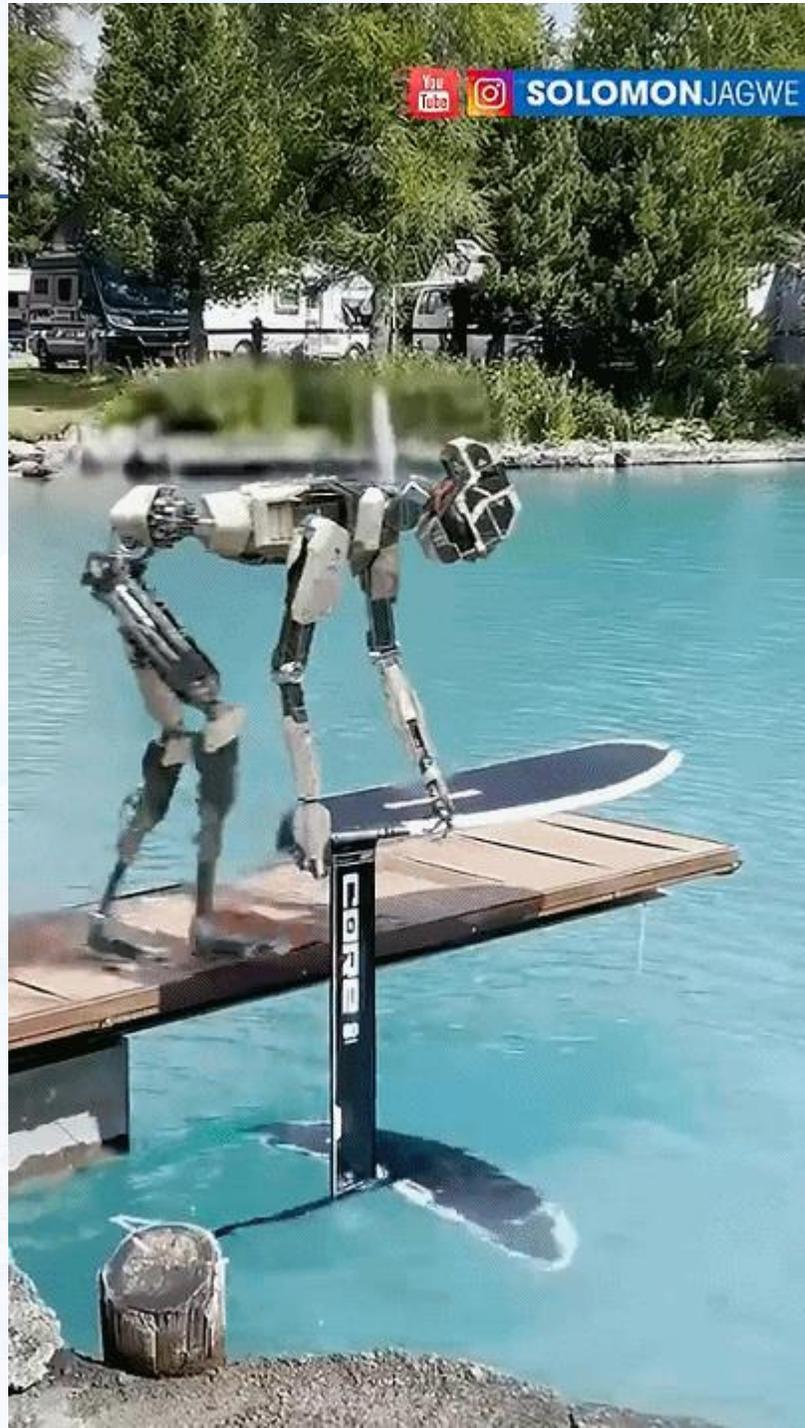


上海大学
SHANGHAI UNIVERSITY

具身智能未来发展范式：**生成式预训练** + **实物在线学习**



具身智能展



YouTube Instagram SOLOMONJAGWE



具身智能展望

机器人环游世界



具身智能小镇



斯坦福小镇





谢谢大家