make history.

THE UNIVERSITY of ADELAIDE

Consensus and Formation Control for Multi-agent Systems

International Symposium on Applied Computational Intelligence and Informatics

22-24 May 2025, Timisoara, Romania

Peng Shi

Adelaide University, Australia

make history.

THE UNIVERSITY of ADELAIDE

Consensus and Formation Control for Multi-agent Systems

International Symposium on Applied Computational Intelligence and Informatics

22-24 May 2025, Timisoara, Romania

Peng Shi

Adelaide University, Australia

Outline

1) Introduction and applications of multiagent systems (MAS)

2) Critical problems and challenges of MAS collaboration

3) Key control and AI technologies in MAS

4) Future research directions in MAS

Outline

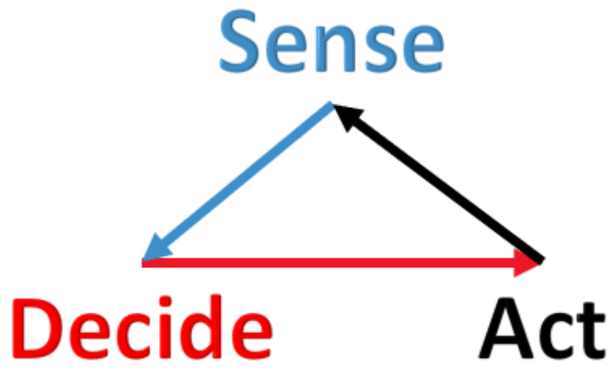
1) Introduction and applications of multiagent systems (MAS)

2) Critical problems and challenges of MAS collaboration

3) Key control and AI technologies in MAS

4) Future research directions in MAS

What is Agent?



= **Agent, an autonomous entity**

UAV

Self-driving vehicle

Satellite

Controller

Software

THE UNIVERSITY of ADELAIDE

What is MAS?

MAS = a group of agents in a shared environment

UAV formations

Heterogeneous satellite system

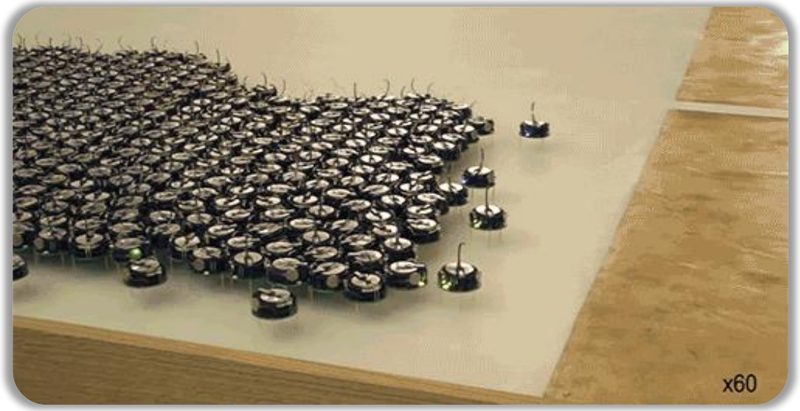
Autonomous cars in intersection

Network systems

THE UNIVERSITY of ADELAIDE

Classification of MAS

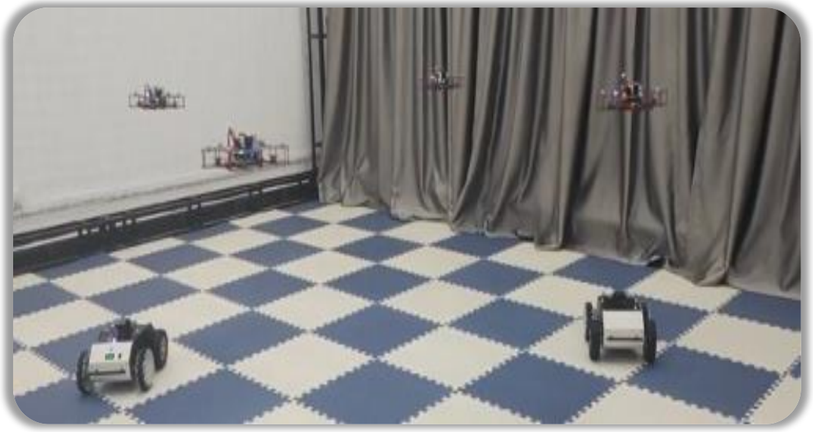
Homogeneous MAS



Bio-inspired Kilobots

Self-organizing robots

Heterogeneous MAS



Air-ground collaboration

Human-machine collaboration

Source from: https://ssr.seas.harvard.edu/kilobots

THE UNIVERSITY of ADELAIDE

Advantages of MAS

Save average energy

Improve survivability

Complete complex tasks

Extend functions

Source from: https://www.youtube.com/watch?v=i3ernrkZ91E

THE UNIVERSITY of ADELAIDE

Significance - Frontier Field

125 Questions from Science

125 QUESTIONS: EXPLORATION AND DISCOVERY

Artificial Intelligence

Could we integrate with computers to form a human–machine hybrid species?

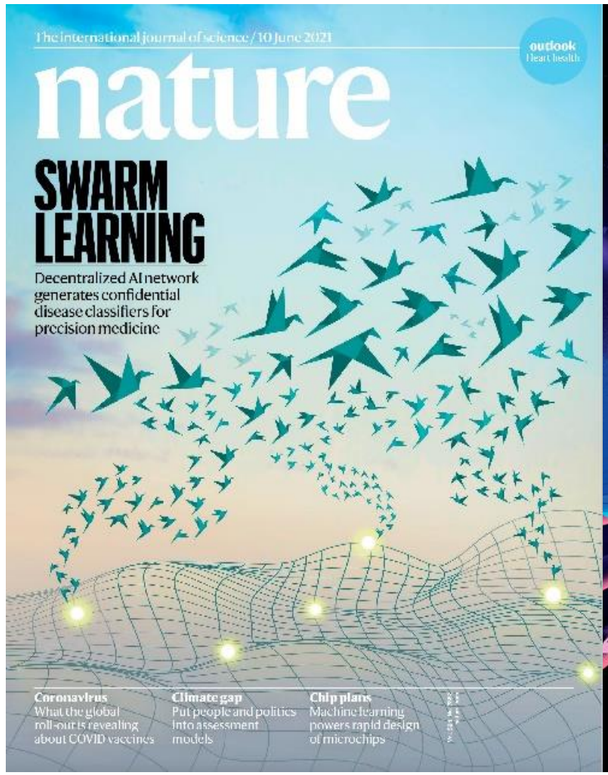
We are on the cusp of human-machine hybrids, especially given advancements in smart exoskeletons and prosthetics, implantable sensors and chips, AI, and genomic editing technologies.

How does group intelligence emerge?

Group or collective intelligence occurs when individuals come together and collaborate. In his book *Social Media Security*, Michael Cross discusses how groups collectively solve problems through interaction and competition between individuals within the group. Through consensus, ideas that detract from the solution are resolved and discarded. This phenomenon is not limited to human-human interaction. Scientists at the MIT Center for Collective Intelligence are exploring "how people and computers can be connected so that–collectively–they act more intelligently than any person, group, or computer has ever done before." The team's multidisciplinary insights can offer a window into how group intelligence emerges, using methods

How does group intelligence emerge?

Covers from Science and Nature



Swarm learning, AI, etc.

THE UNIVERSITY of ADELAIDE

Significance - Strategic Needs

China

USA

Australia

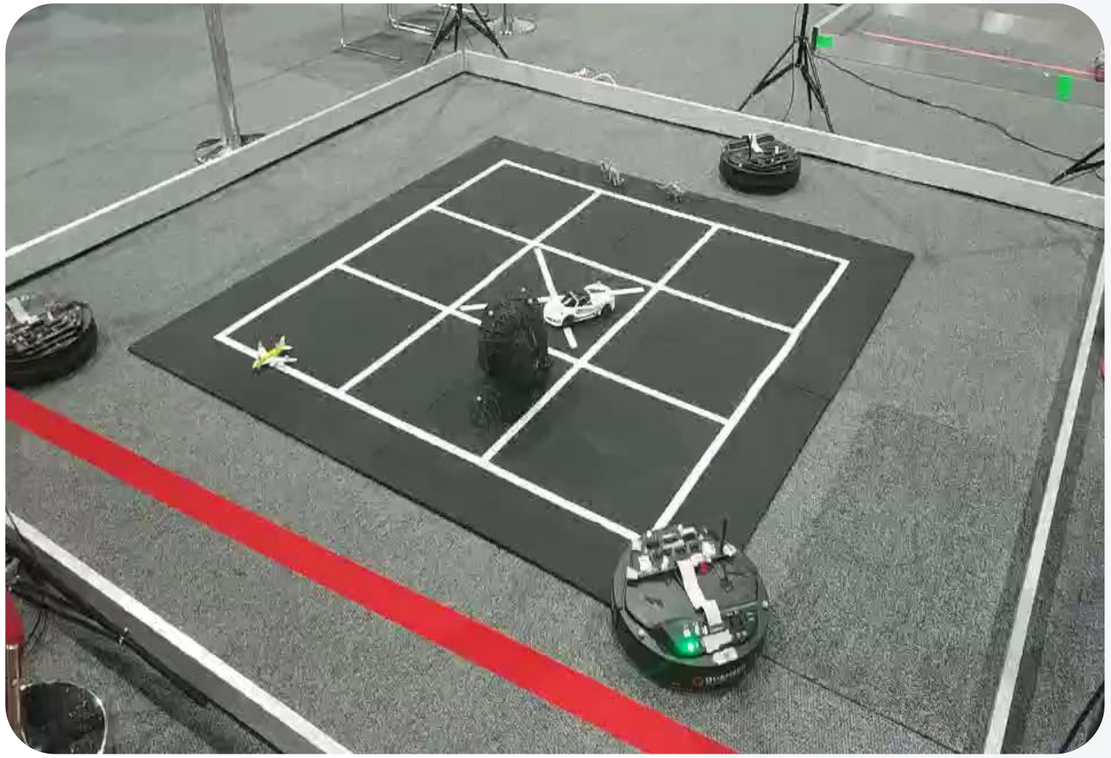
UK

THE UNIVERSITY of ADELAIDE

Applications - Intelligent Transportation

Traffic signal control, reducing congestion and optimizing traffic flow
Autonomous parking systems, optimizing making desicion

Intelligent transportation systems-self-drive AlphaBus



Autonomous parking system (University of Adelaide (UoA))

Source from: https://news.sina.cn/2017-12-05/detail-ifyphtze4406603.d.html

THE UNIVERSITY of ADELAIDE

Applications - Defence

Autonomous attack and defense, enhancing combat efficiency while reducing human involvement in dangerous environments

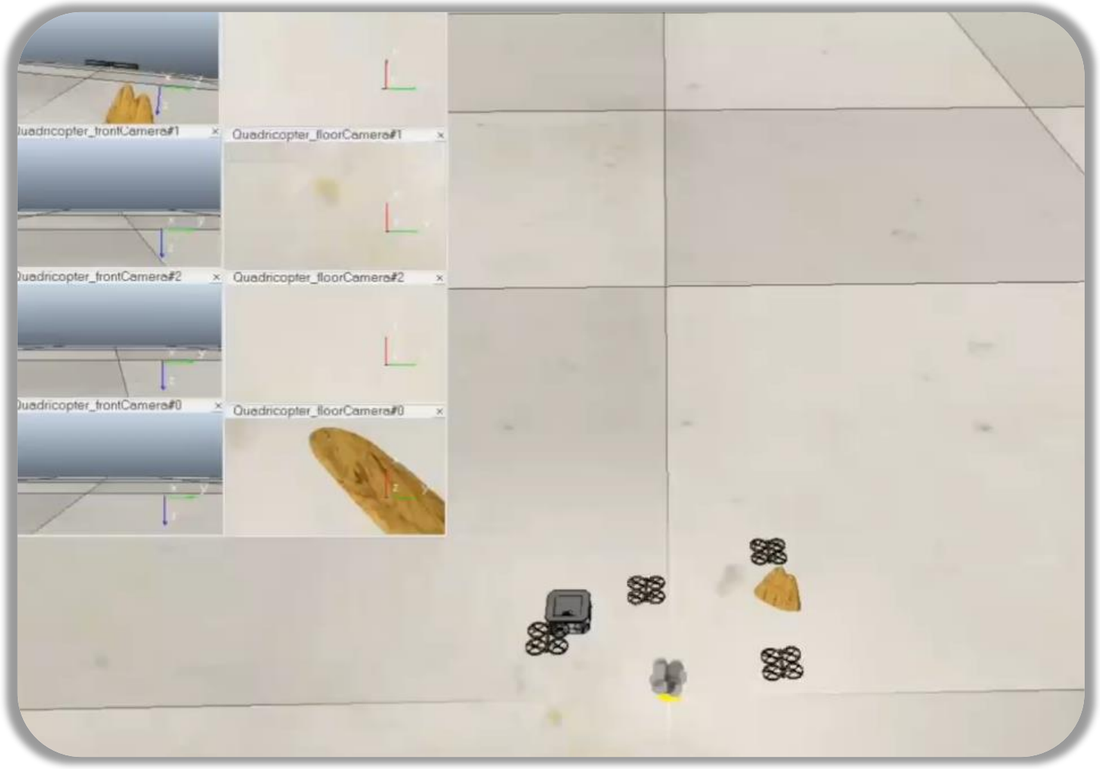
Unmanned vehicle formations for attack and defence

Russia-Ukraine conflict

Source from: https://news.sina.cn/2017-12-05/detail-ifyphtze4406603.d.html

Applications - Environmental Monitoring

Collaborative environmental data collection, disaster assessment, improving real-time monitoring performance and area coverage



Australian bushfire disaster monitoring

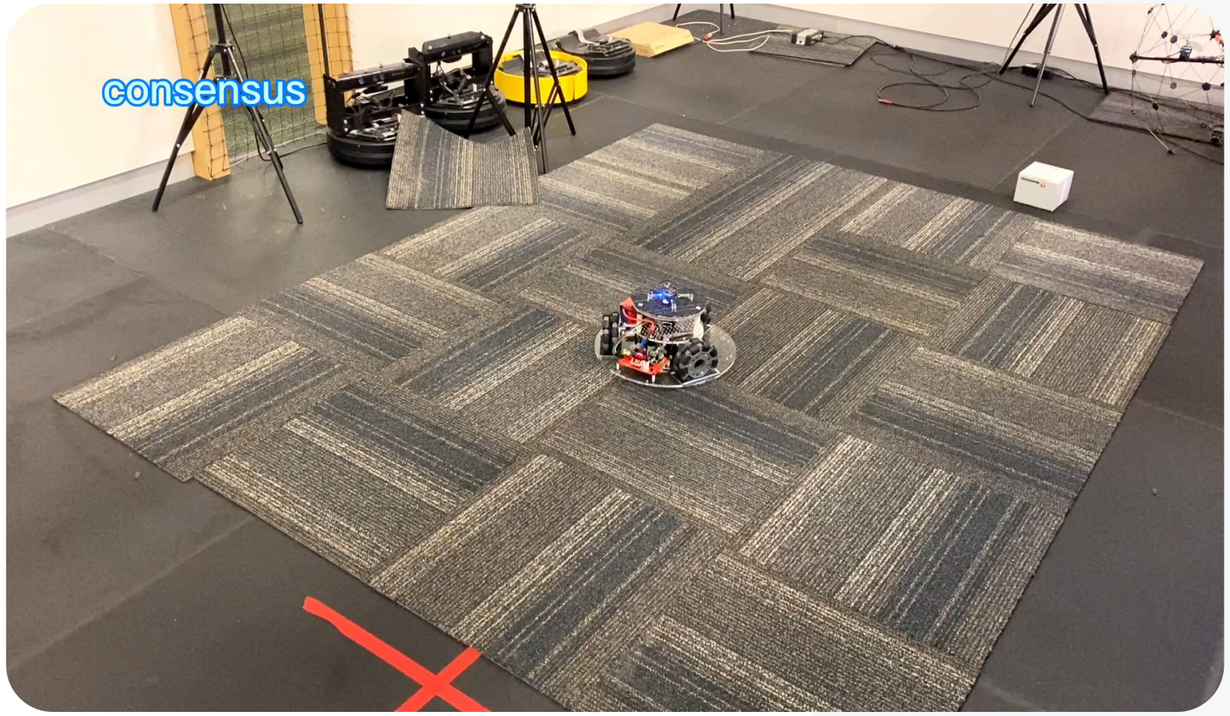
Insect-inspired flapping-wing drones for monitoring Australian bushland (UoA)

THE UNIVERSITY of ADELAIDE

Applications - Smart logistics

Collaborative logistics, optimizing goods distribution and logistics operations

Unmanned warehouse



UAV-UGV consensus
(UoA)

THE UNIVERSITY of ADELAIDE

Outline

1) Introduction and applications of multiagent systems (MAS)

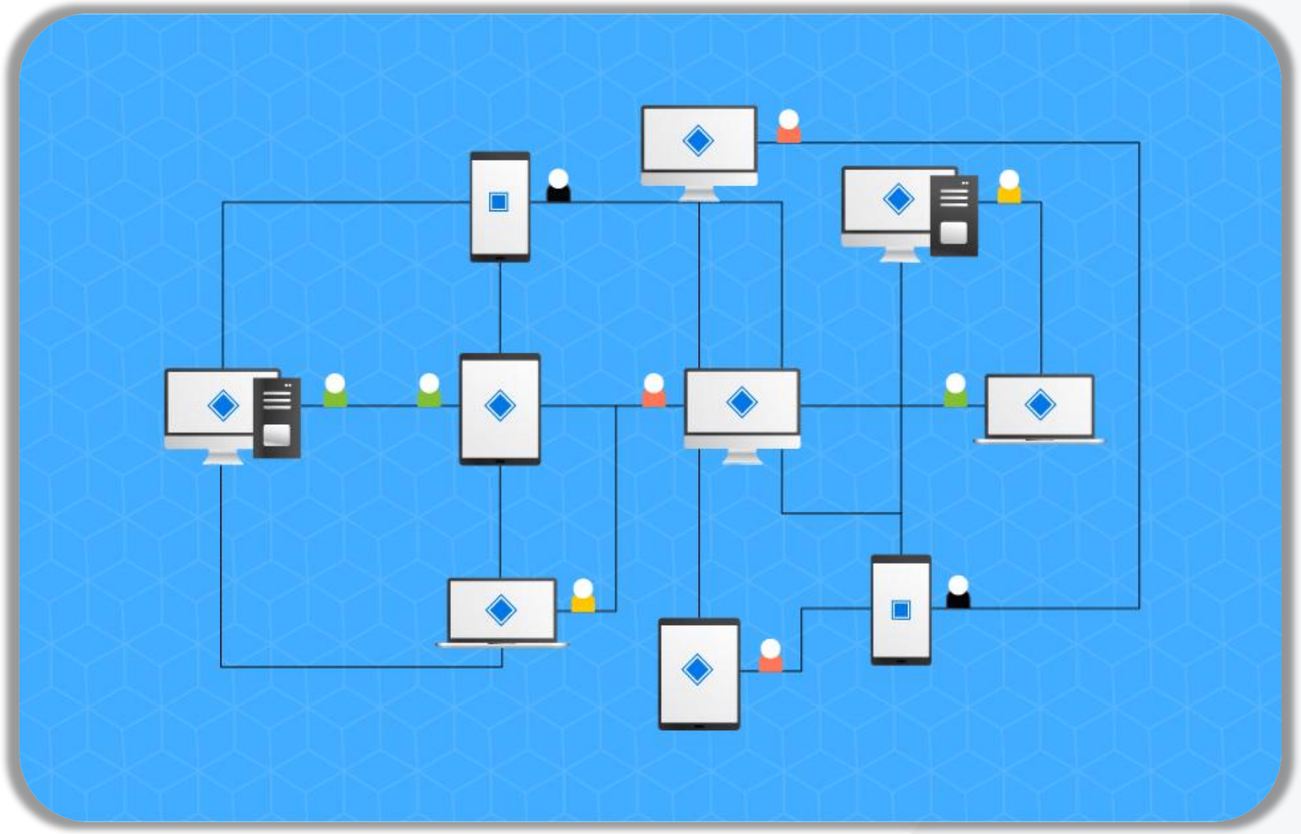
2) Critical problems and challenges of MAS collaboration

3) Key control and AI technologies in MAS

4) Future research directions in MAS

Three Critical Problems in MAS Collaboration

- **Consensus**

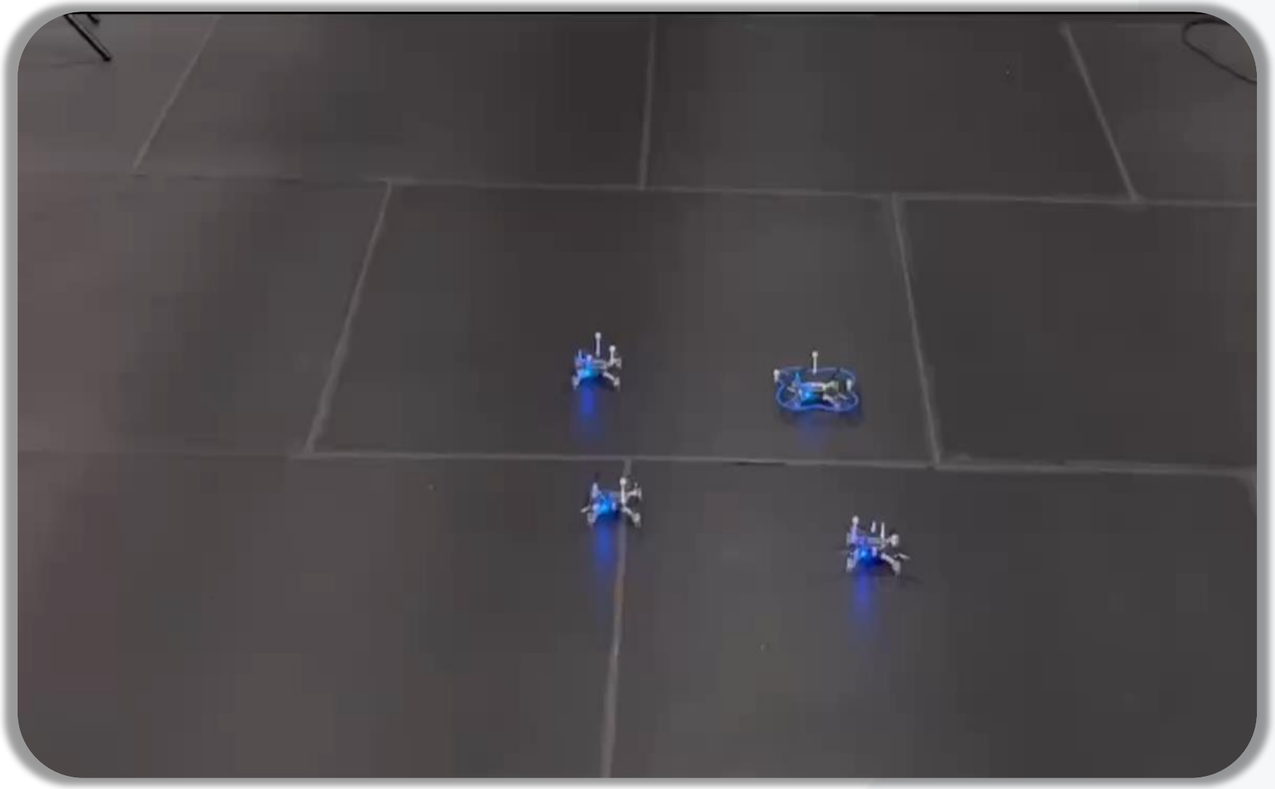


Reaching consensus in networked MAS

THE UNIVERSITY of ADELAIDE

Three Critical Problems in MAS Collaboration

- **Consensus**
- **Formation Control**

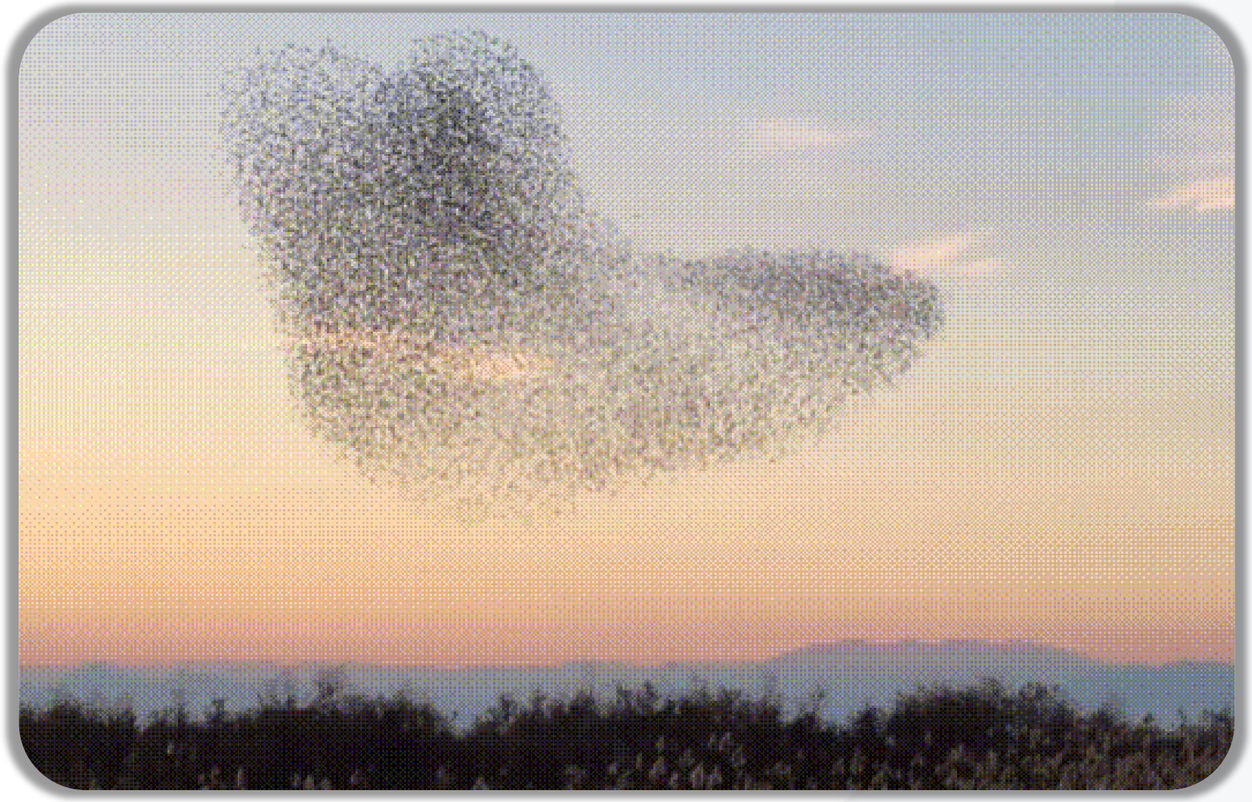


Formation changing for U, O and A, stands for the University of Adelaide

THE UNIVERSITY of ADELAIDE

Three Critical Problems in MAS Collaboration

- Consensus
- Formation Control
- Flocking and Swarming



Swarm behavior of bird flocks

THE UNIVERSITY of ADELAIDE

Current Challenges

- Unstable communication networks

→ **Distributed resilient consensus**

Partial failure in a drone swarm performance in Xi'an

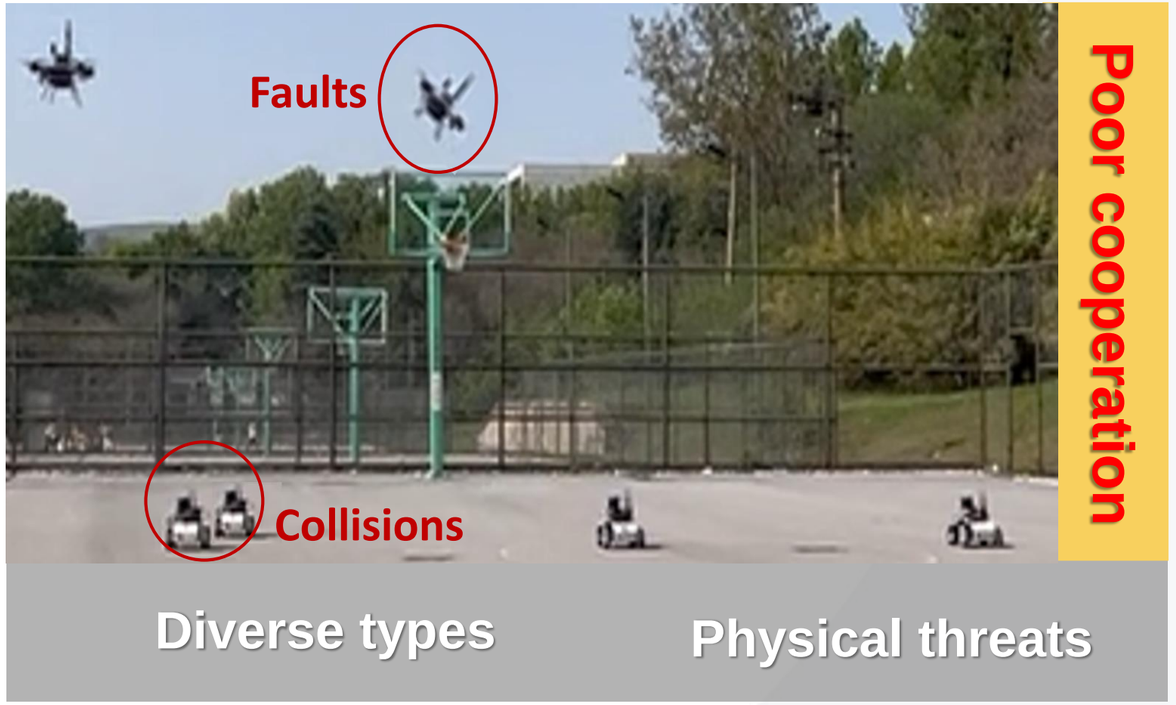
Source from： https://www.youtube.com/watch?v=YQK6_2Brnqk

Current Challenges

- Unstable communication networks

- Numerous constraints in heterogeneous operational

→ Safe cooperative control



Air-ground heterogeneous cooperation systems

Source from：https://blog.csdn.net/FEISILAB_2022/article/details/130678377

Current Challenges

- Unstable communication networks
- Numerous constraints in heterogeneous operational
- Complex and dynamic environment

→ Learning-based optimization

Swarm of micro flying robots in the wild

Source from：http://www.szuavia.org/news_cen.php?cid=27&id=5228

THE UNIVERSITY of ADELAIDE

Outline

1) Introduction and applications of multiagent systems (MAS)

2) Critical problems and challenges of MAS collaboration

3) Key control and AI technologies in MAS

4) Future research directions in MAS

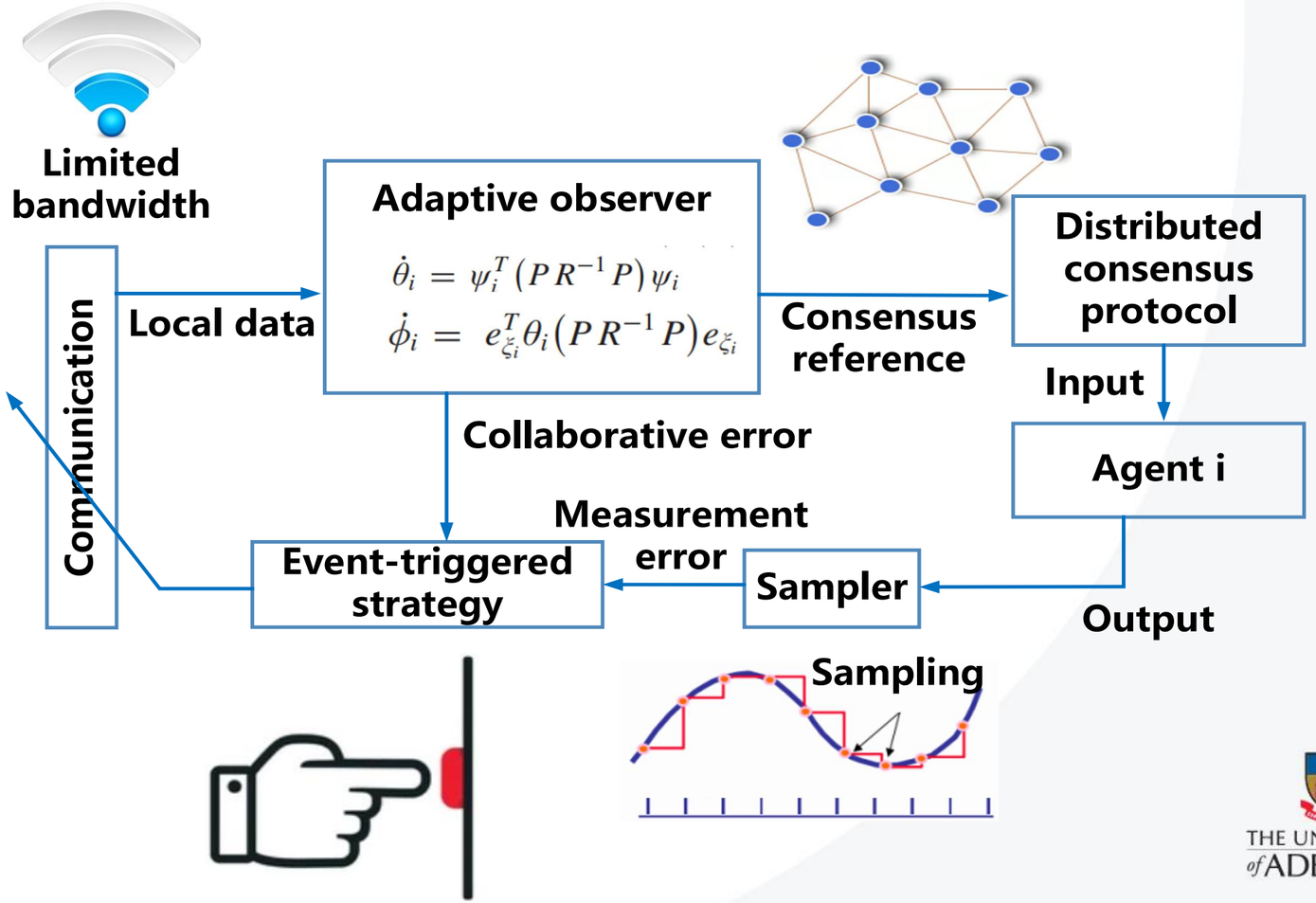
THE UNIVERSITY of ADELAIDE

1. Distributed Resilient Consensus

- **Adaptive event-triggered observer and consensus protocol**
  — Efficient interaction under limited communication

Core idea ➡ **Overcome**

Event trigger	**Limited bandwidth**
Adaptive law	**Local data**



Automatica, 2020, 122, 109223; IEEE TASE, 2022,19(4): 2788-2800; IEEE TCYB, 2022, 52(7), 6391-6405

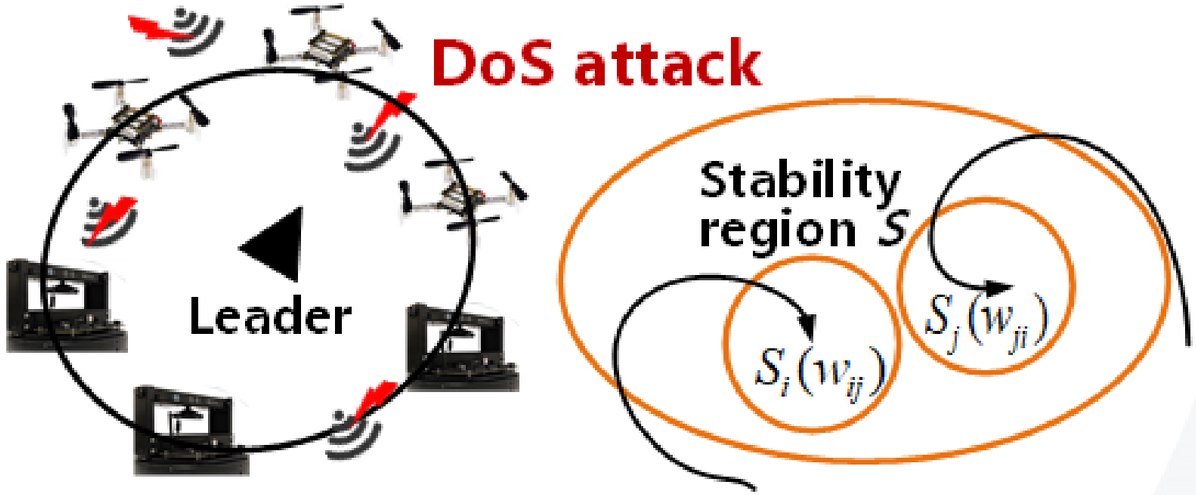
1. Distributed Resilient Consensus

- **Distributed observation mechanism**
  — secure interaction under cyber-attacks

Core idea ➡ **Overcome**

Resilient CLF **Cyber-attacks**

Distributed observation **Information coupling**



Distributed convergence to each stability regions

$$\dot{V}_i(x_i, x_j, u_i, \mathrm{w}_{ij}) + \mathrm{w}_{ij}\,\beta_1 V_i < \boxed{\mathrm{w}_{ij}}\,\varepsilon \quad \textbf{Under DoS}$$

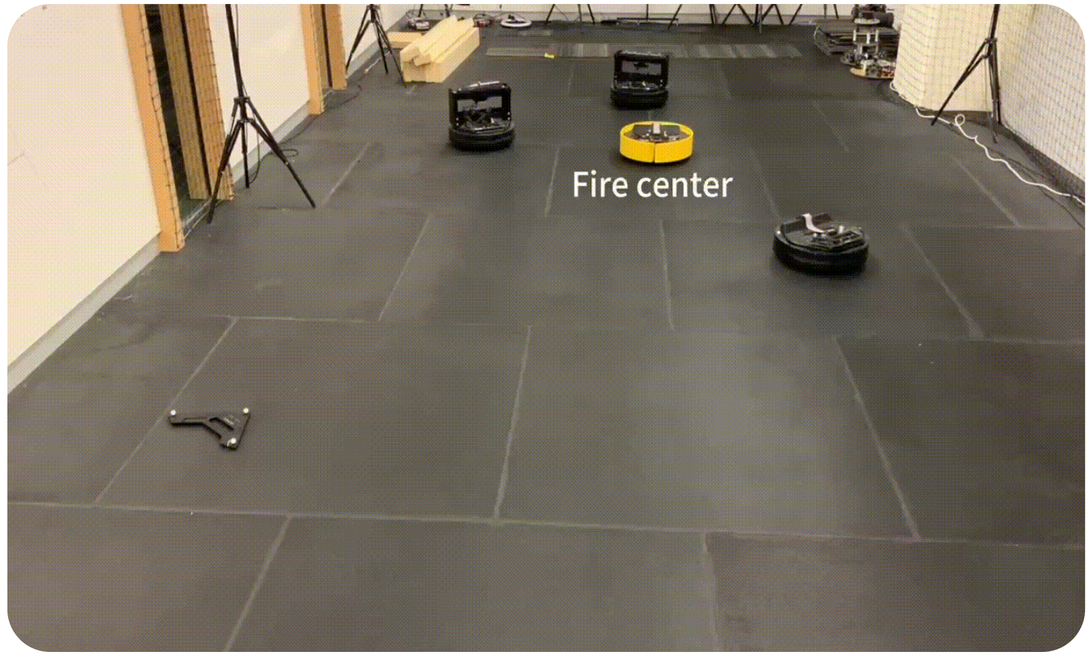
$$\dot{V}_i(x_i, x_j, u_i, \mathrm{w}_{ij}) - \mathrm{w}_{ij}\,\beta_2 V_i < \boxed{\mathrm{w}_{ij}}\,\varepsilon \quad \textbf{Without DoS}$$

THE UNIVERSITY of ADELAIDE

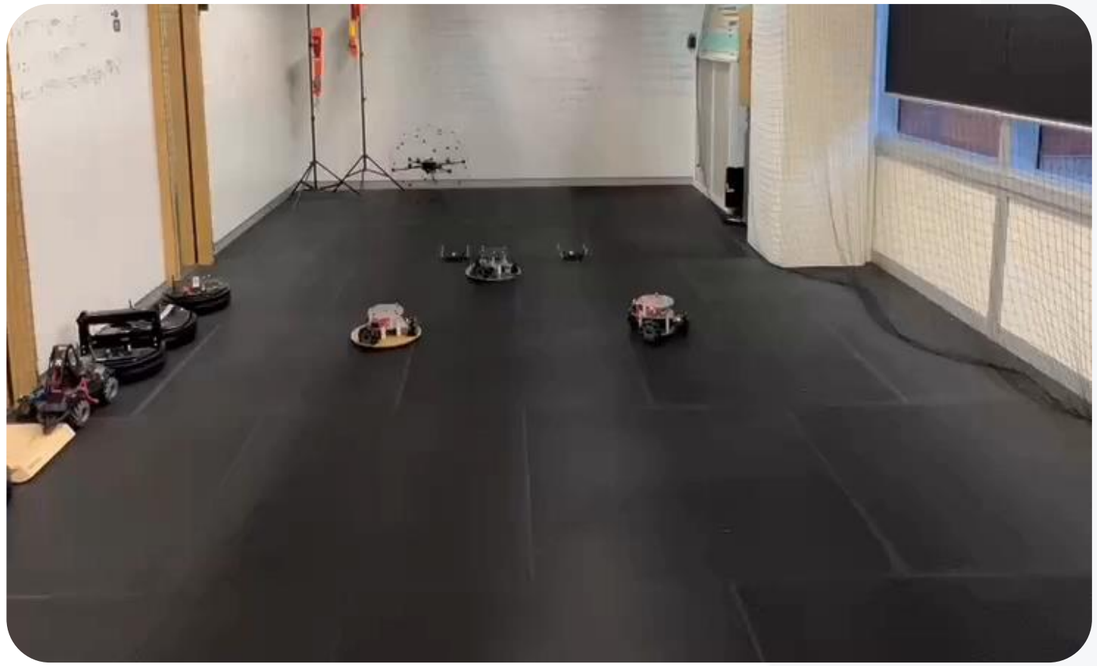
IEEE TAC, 2021, 66(11):5369-5376; IEEE TNSM, DOI: 10.1109/TNSM.2024.3405974; IEEE TCYB, 2023, 53(4): 2600-2609

1. Distributed Resilient Consensus

- **Verifications — applied to build information security for unmanned systems**



Collaborative target tracking and patrolling under communication constraints



Bipartite consensus tracking under DoS attacks

Efficient Interaction

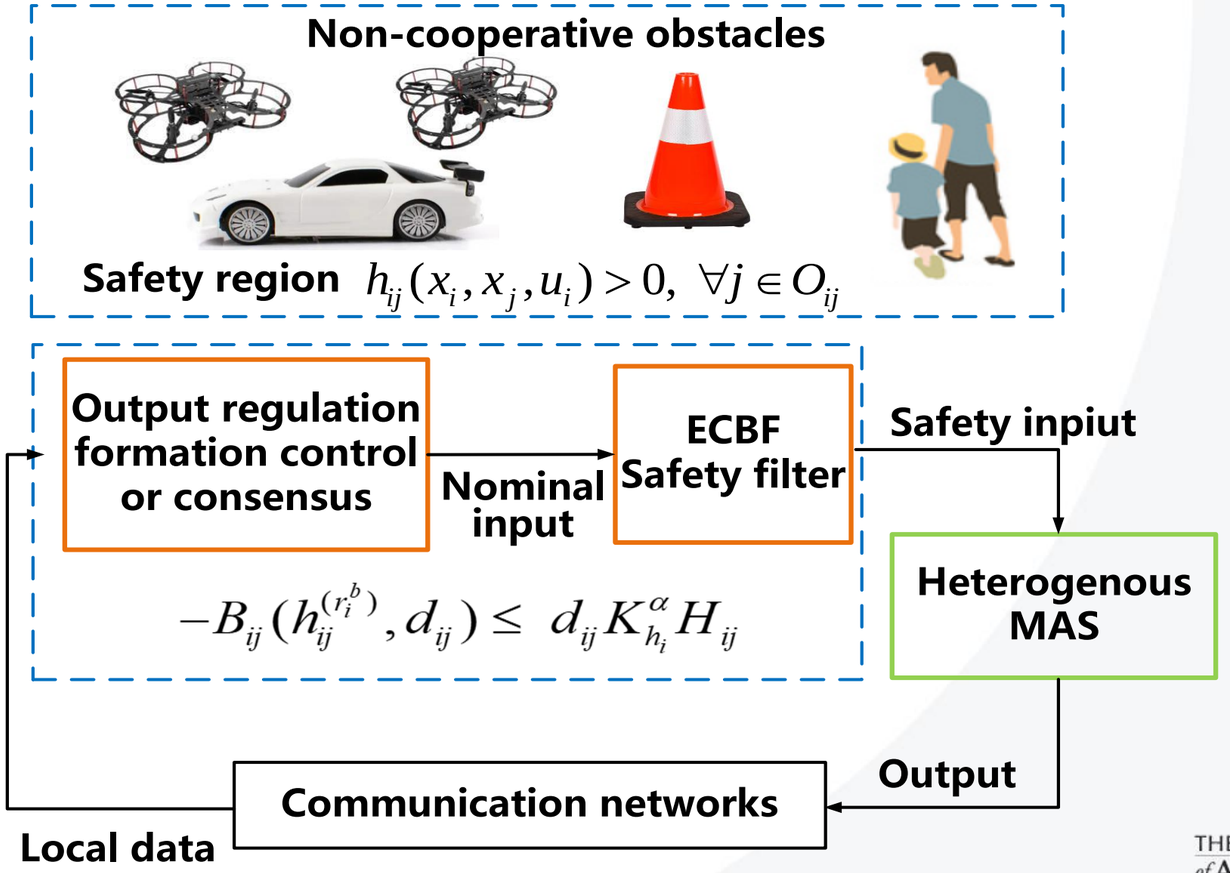
THE UNIVERSITY of ADELAIDE

2. Safe cooperative control

- **Control barrier function-based heterogeneous cooperative control — safe cooperation under non-cooperative obstacles**

Core idea ➡ **Overcome**

Output regulation	**Heterogenous coupling**
Distributed CBF	**Dynamic obstacles**



IEEE TFUZZ, 2021, 29(5):1008-1022; IEEE TCYB, DOI: 10.1109/TCYB.2024.3418973; IEEE TNNLS, 2021, 32(2):763-776

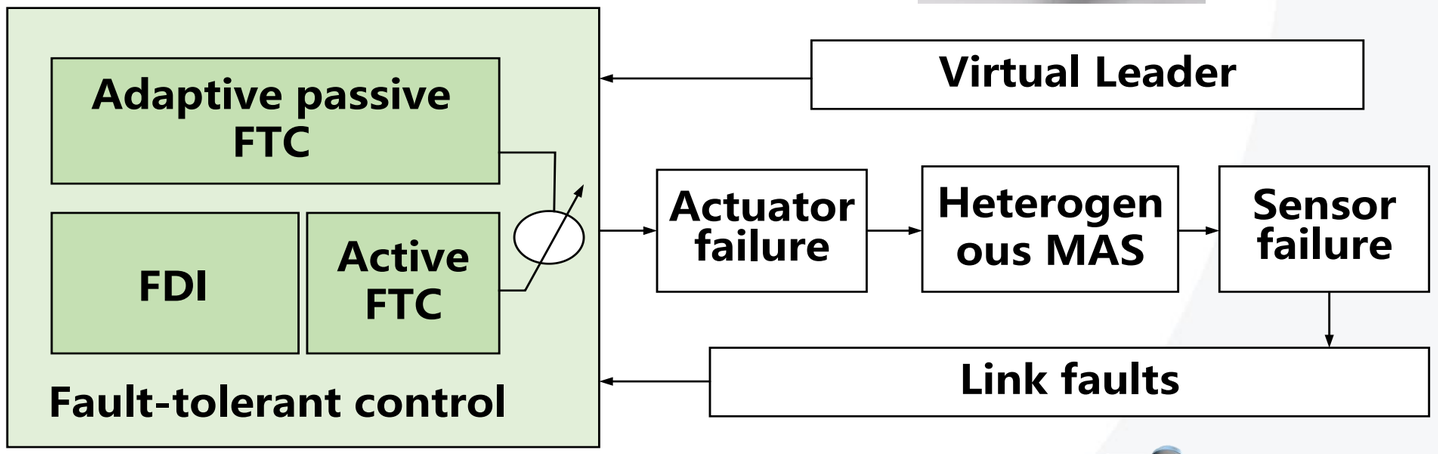
2. Safe cooperative control

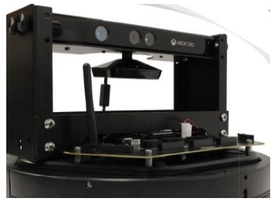
- **Robust fault-tolerant cooperative control**
  — safe cooperation under physical faults

Core idea ➡ **Overcome**

Passive FTC **Sudden faults**

Active FTC **Multi-faults**



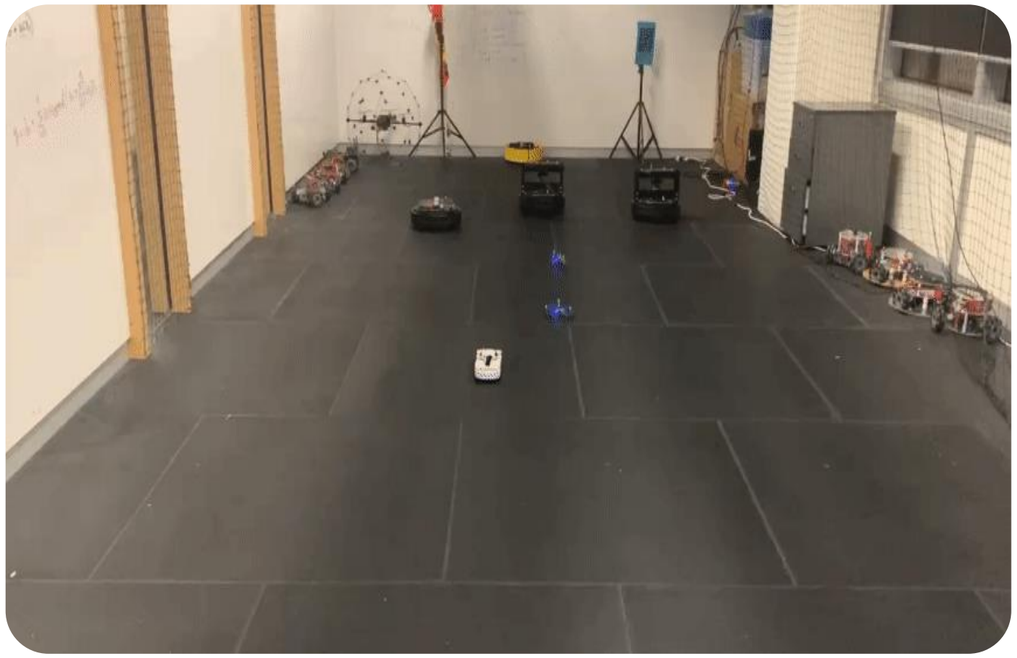


THE UNIVERSITY of ADELAIDE

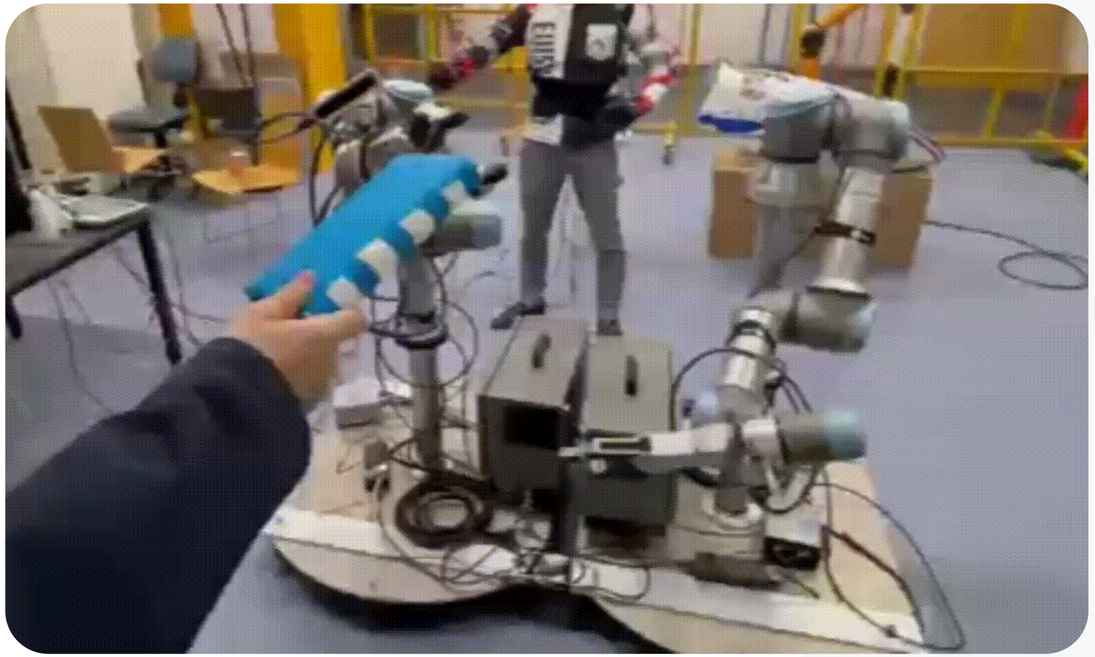
IEEE TCNS, 2022, 9(2):845-855; IEEE TNNLS, 2020, 31(11):4831-4841; JFI, 2019, 356(12):6547-6570

2. Safe cooperative control

- **Verifications — applied to machine-to-machine and human-machine collaborative systems**



UAV-UGV collaborative area scanning under non-coopartive obstacles



Shadow robots—human-machine cooperation for manufacturing tasks

Reliable Cooperation

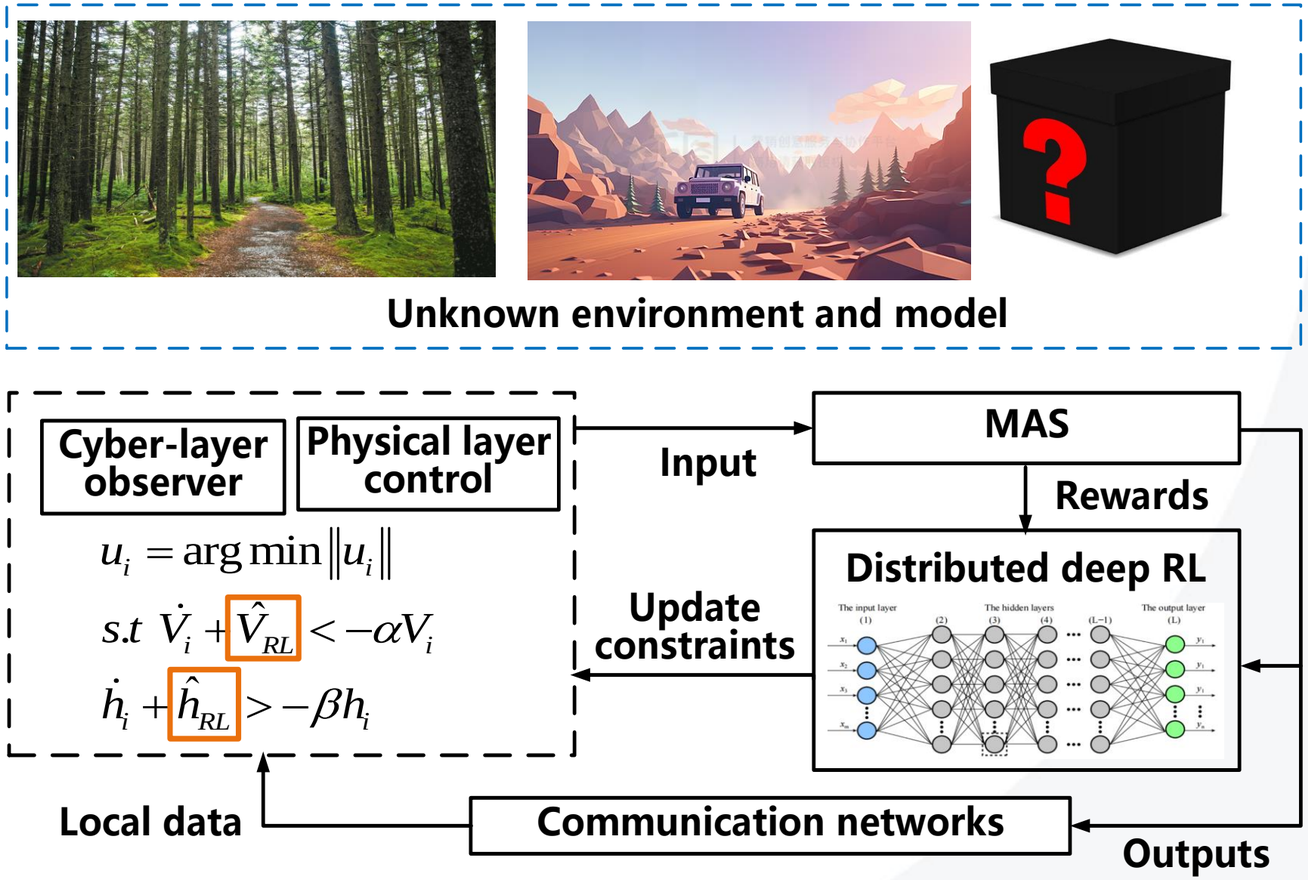
THE UNIVERSITY of ADELAIDE

3. Learning-based optimization

- **Distributed deep reinforcement learning optimal control**
  — model-free optimization

Core idea ➡ **Overcome**

DDRL-based control	**Unknown model**
Two-layer design	**Uncertain environment**



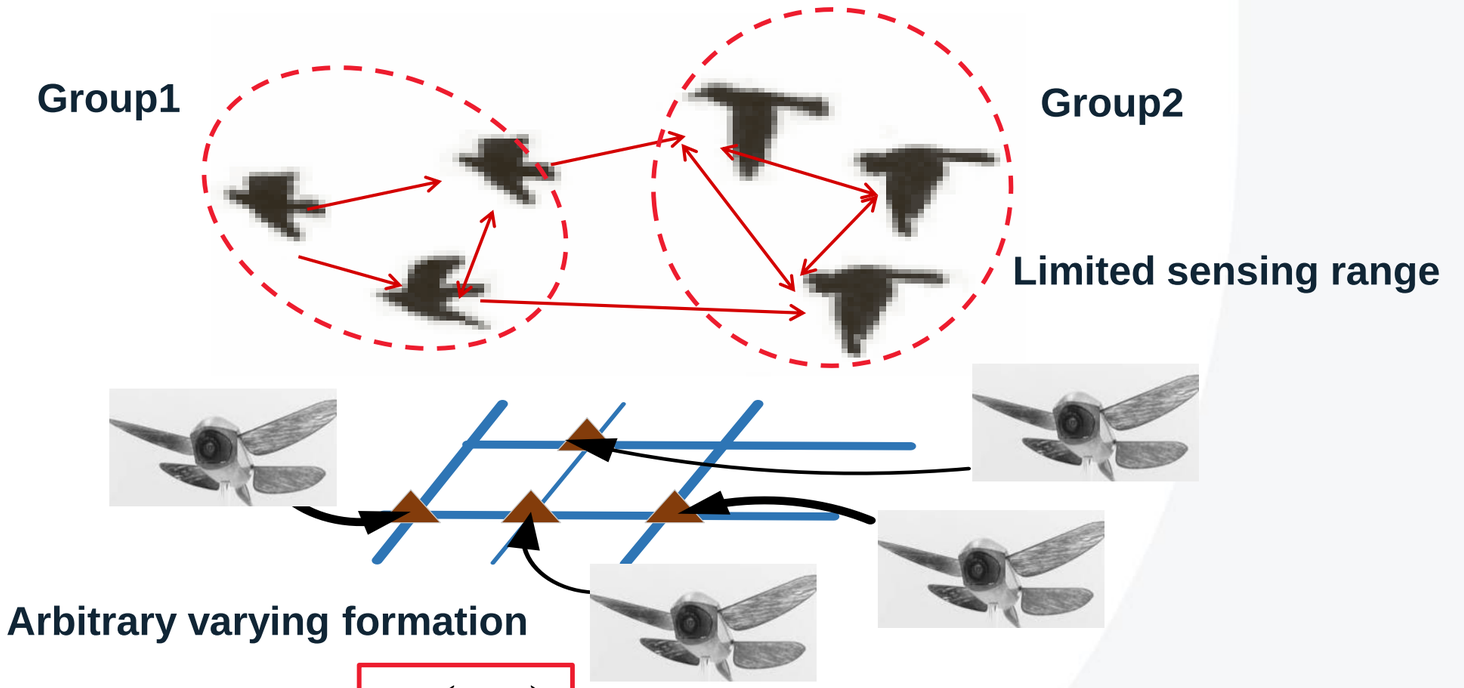
IEEE TNNLS, DOI: 10.1109/TNNLS.2024.3350679; 51(1):161-175; IJRNC, 2022, 32(5), 2683-2704; IEEE TNNLS, 2023, 34(8), 4286-4295

3. Learning-based optimization

- **Bio-inspired swarm optimal decision-making**
  — scalable optimization

Core idea ➡ **Overcome**

Self decision-making	**Scalable size in MAS**
Autonomous learning	**Varying tasks**



$$P_i \rightarrow \boxed{d(P_i)}$$

$$d(g(P_i)) = \arg\min_{d(g(P_i))\in F} L^F(g(P_i))$$

THE UNIVERSITY of ADELAIDE

IEEE TSMC, 2021, 51(1):161-175; IJRNC, 2017, 27(3): 410-433; AIAA Scitech 2019, 1619.

3. Learning-based optimization

- **Verifications — applied to bio-inspired unmanned systems**

Collision-free formation control for done swarm to pass through a bounded window

Insect-inspired flapping-wing drones for monitoring Australian bushland

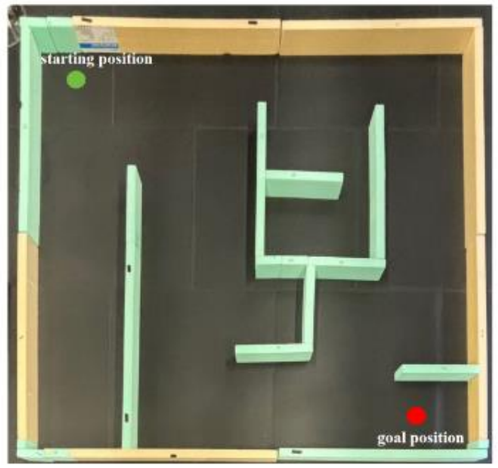
Autonomous optimization

THE UNIVERSITY of ADELAIDE

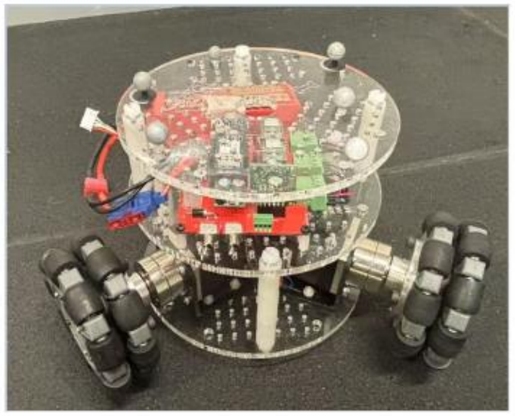
3. Learning-based optimization

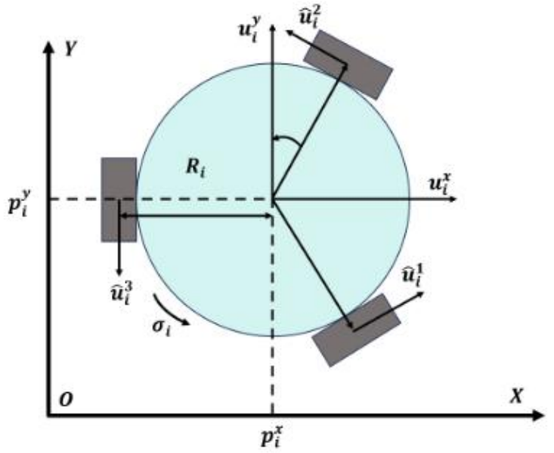
- **Other AI-enabled approaches**

  - **A hybrid Particle Swarm Optimization–Genetic Algorithm (PSO-GA) for local path planning.**
    - **Leverages fast convergence of PSO.**
    - **Utilizes the global search ability of GA.**
    - **Offers both efficiency and adaptability.**



Physical environment-maze





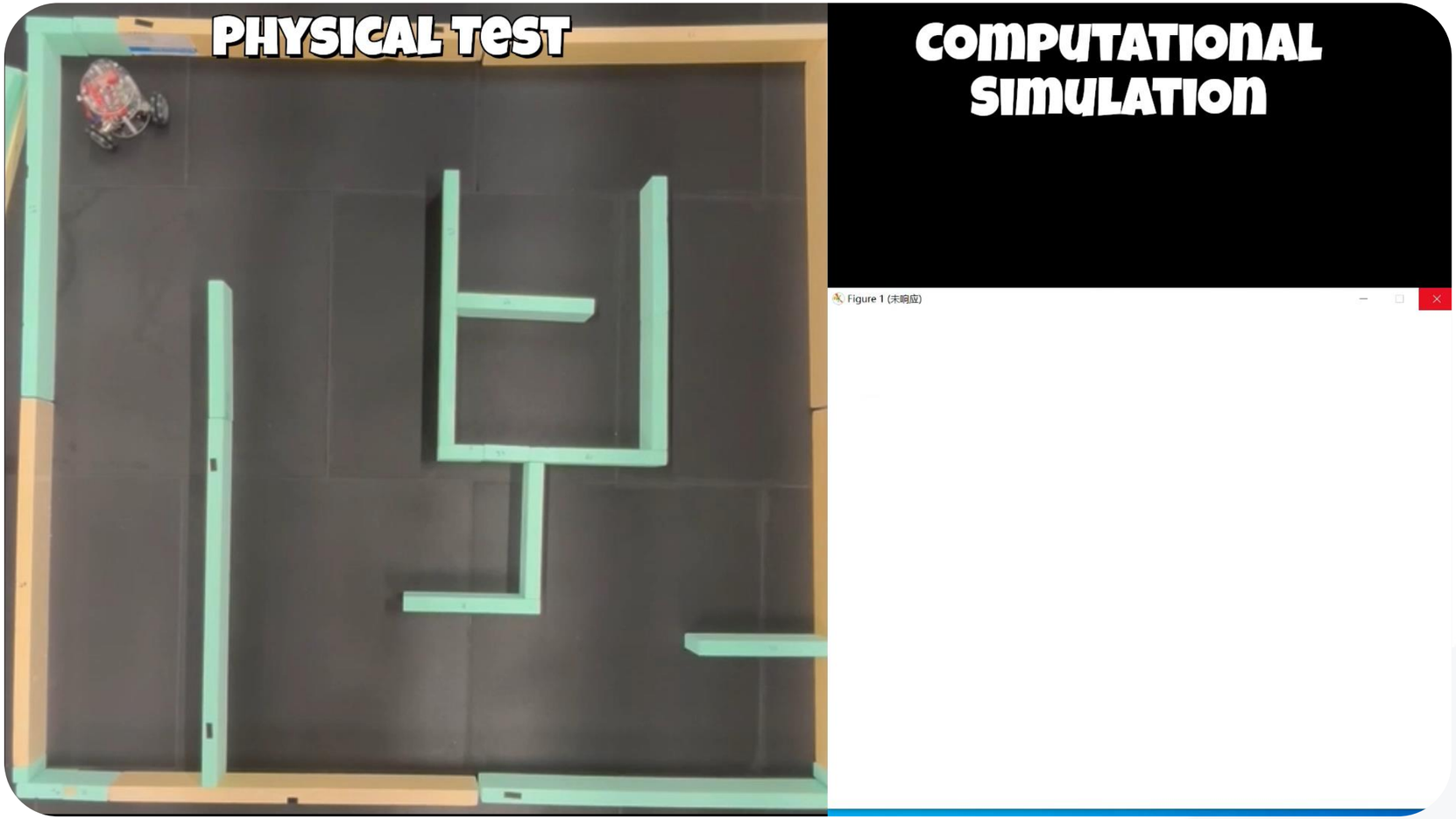
Rover system and model representation

THE UNIVERSITY of ADELAIDE

3. Learning-based optimization

- **Other AI-enabled approaches**

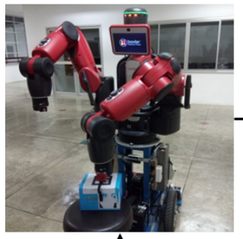
PSO-GA Verification

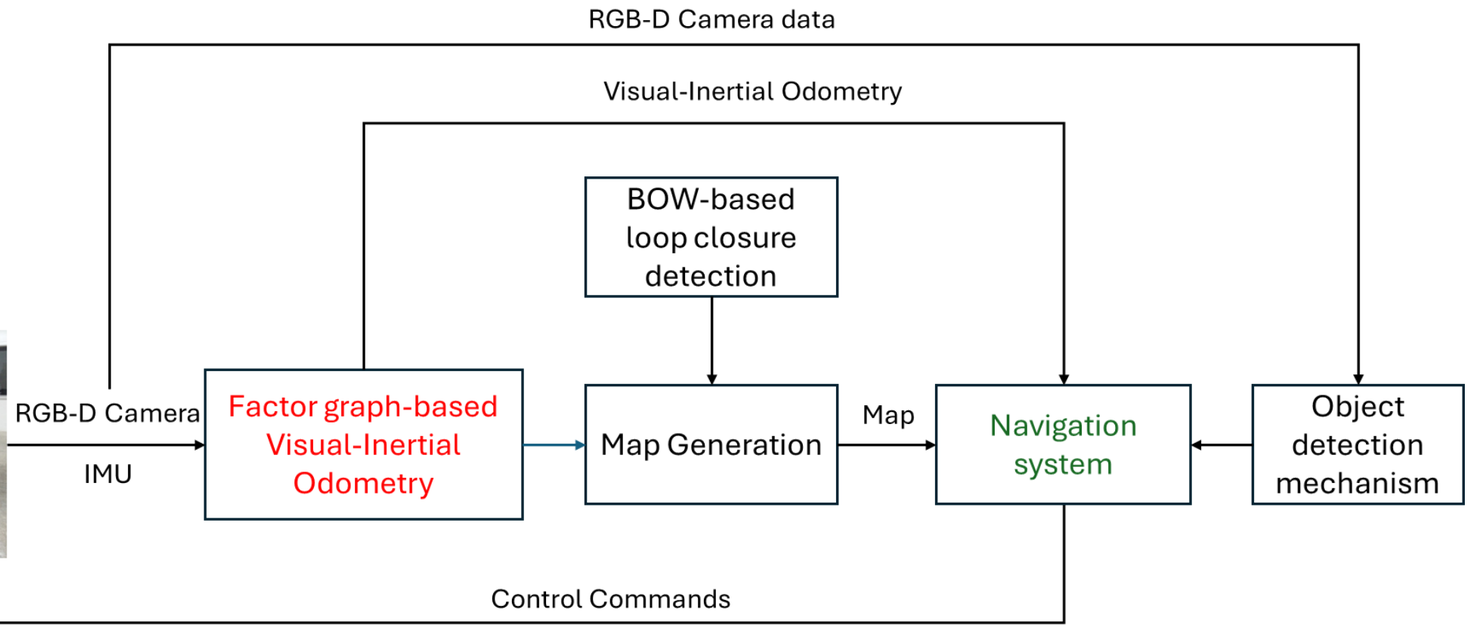


THE UNIVERSITY of ADELAIDE

3. Learning-based optimization

- **Other AI-enabled approaches**
  - ➢ **Visual-inertial SLAM-based navigation system**





The proposed system can be easily adapted to various mobile robotic platforms without significant fine-tuning.

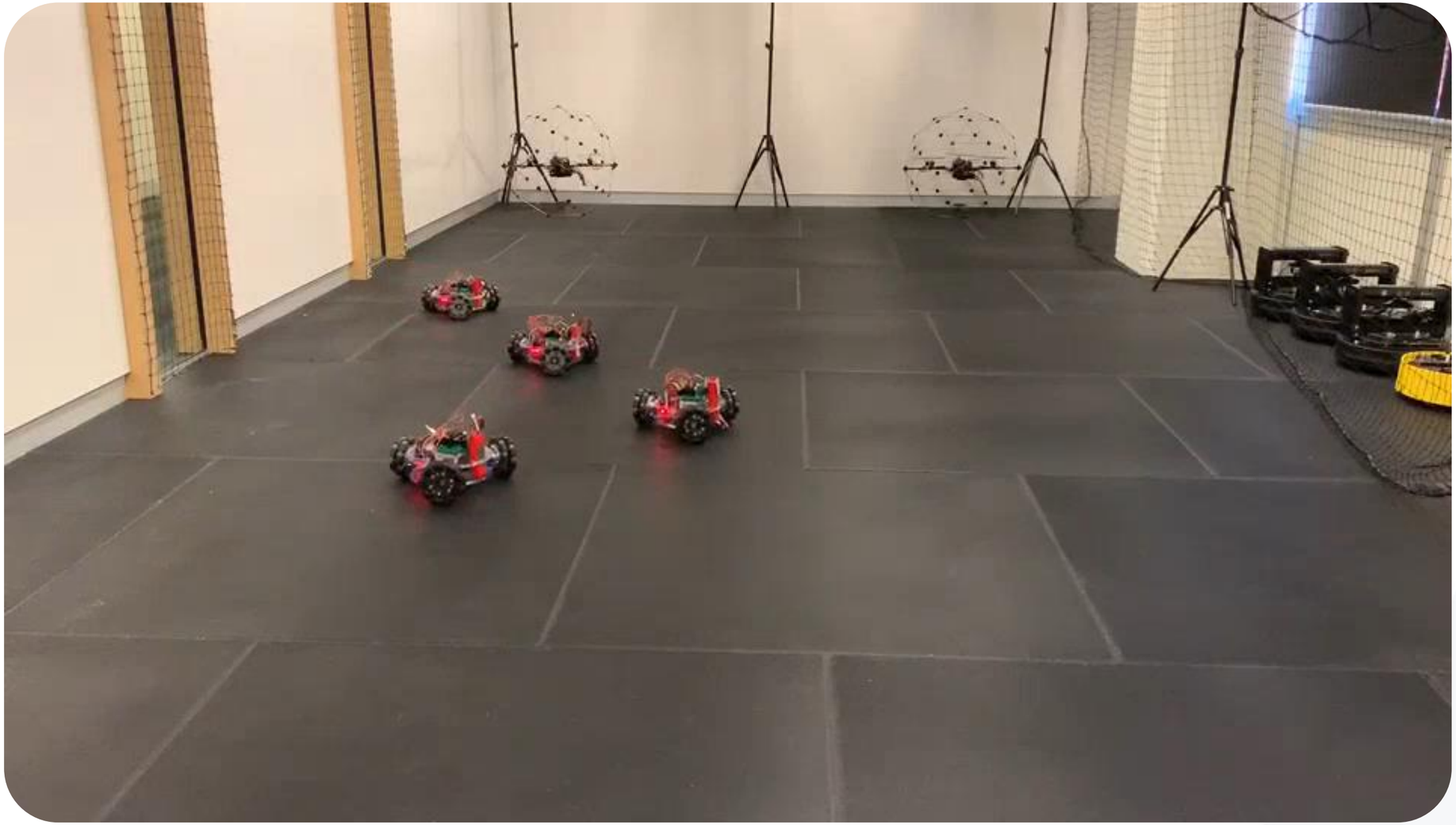
THE UNIVERSITY of ADELAIDE

More experimental demonstrations

Writing rover with arm

THE UNIVERSITY of ADELAIDE

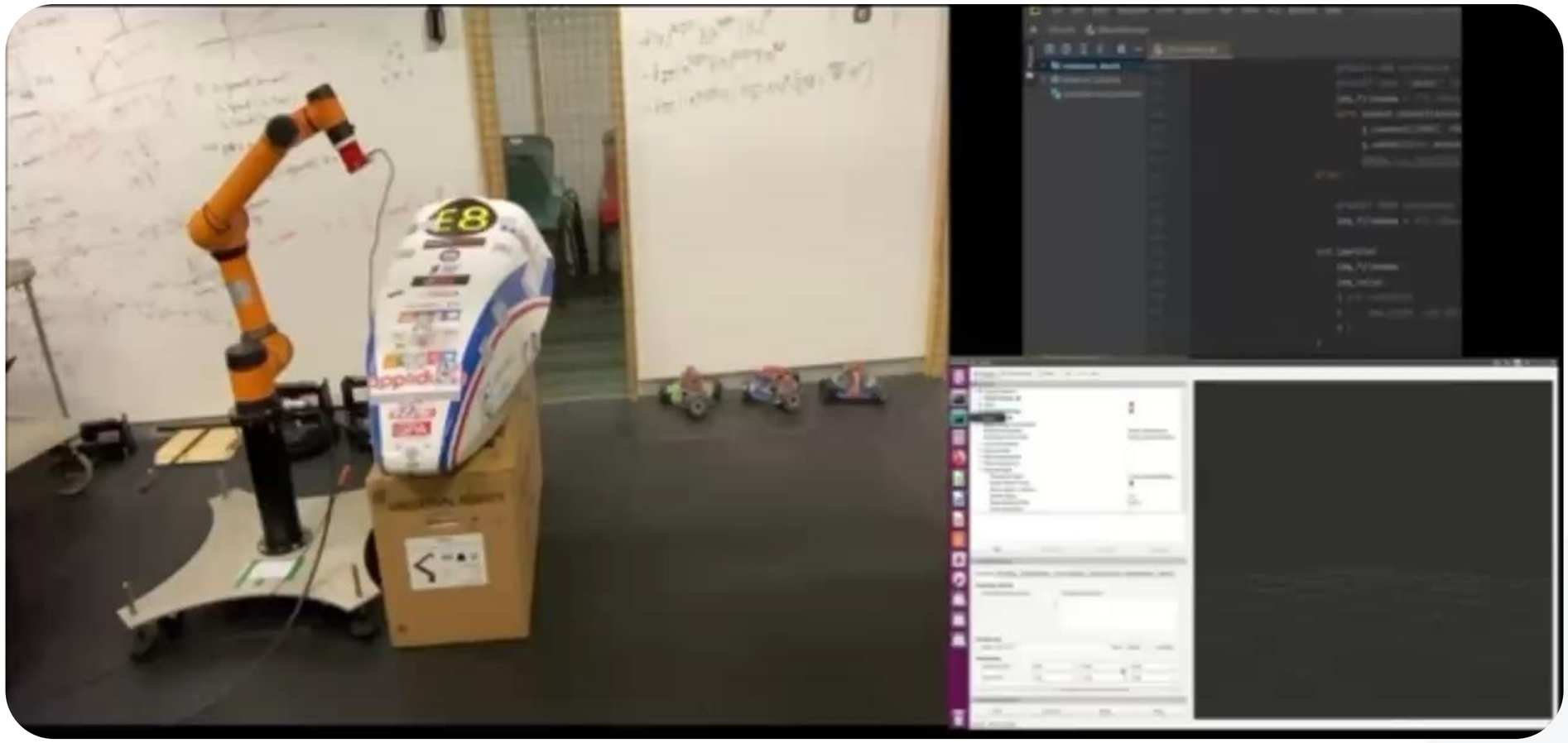
More experimental demonstrations



Different formations for area search

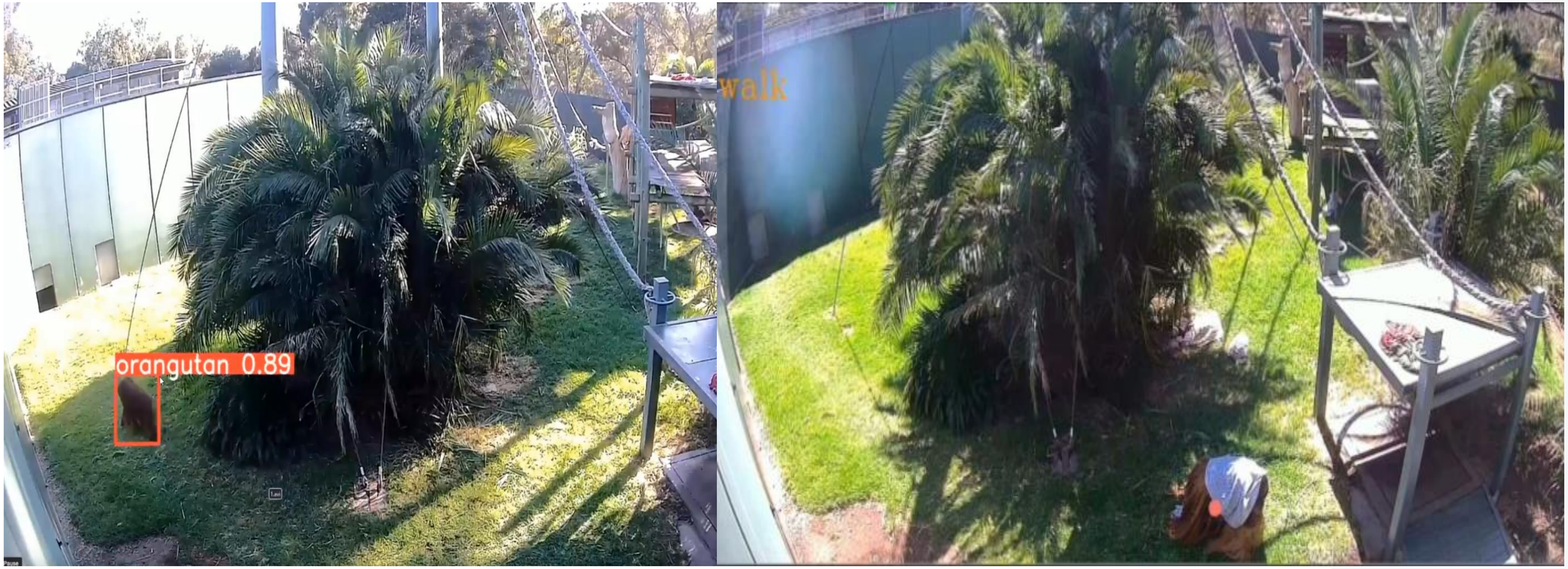
THE UNIVERSITY of ADELAIDE

More experimental demonstrations



Robotic airplane inspection system

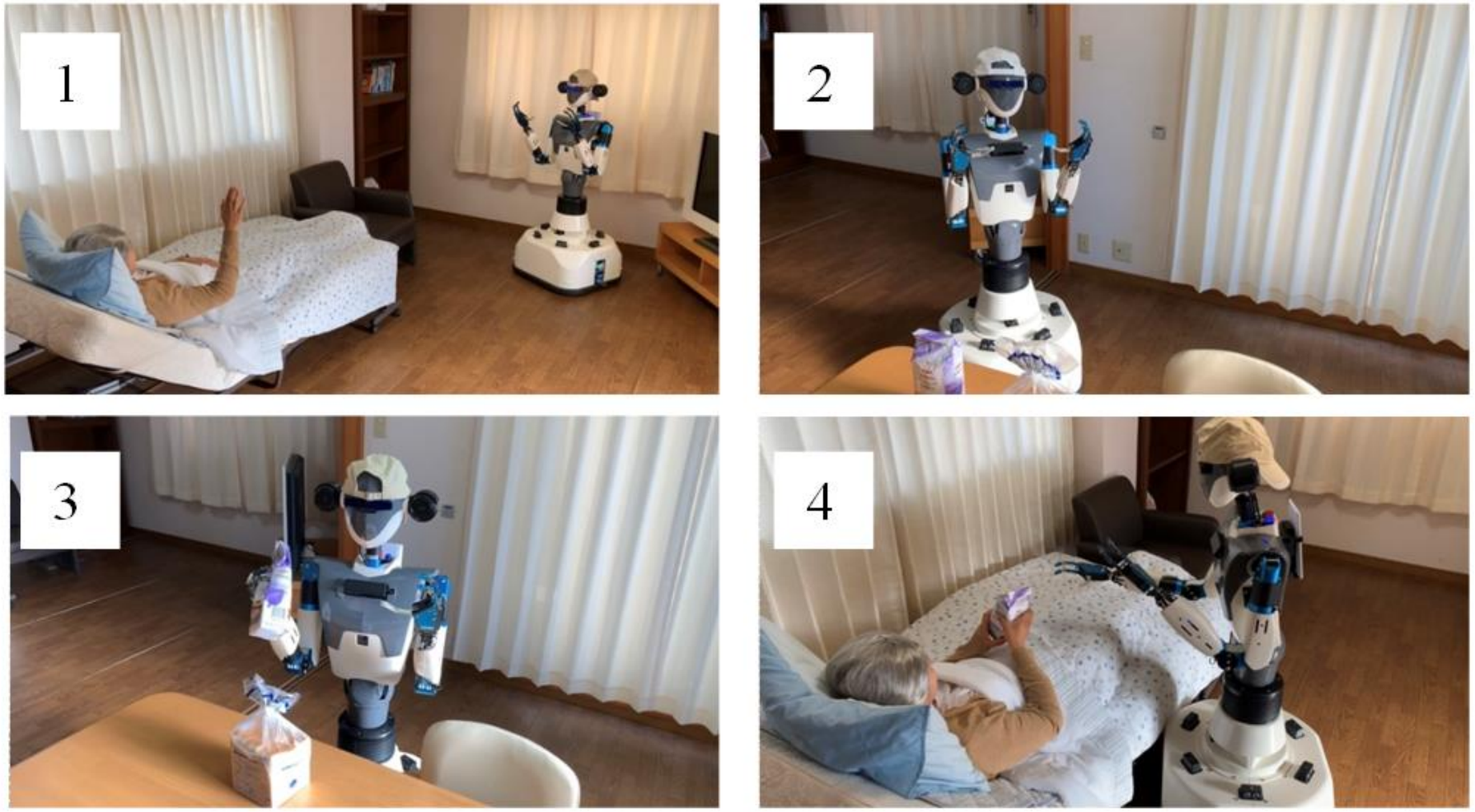
More experimental demonstrations



Animal behaviour detection

THE UNIVERSITY of ADELAIDE

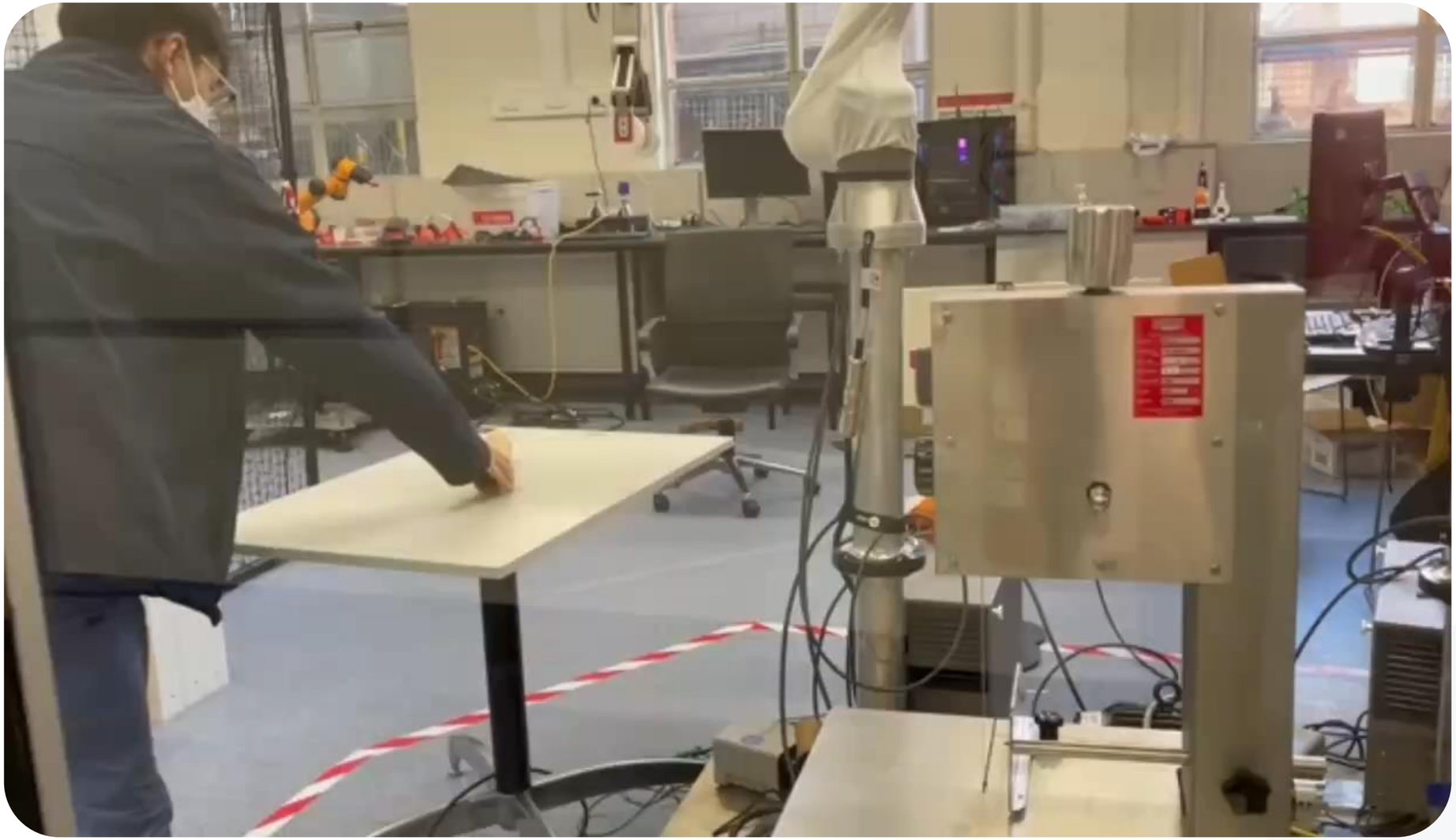
More experimental demonstrations



Life-support robots-Collaborate with Kochi University of Technology

Int. J. Innov. Comput. Inf. Control, 2018, 14(4): 1545-1552

More experimental demonstrations



Collaborative cattle shank cutting

THE UNIVERSITY of ADELAIDE

Outline

1) Introduction and applications of multiagent systems (MAS)

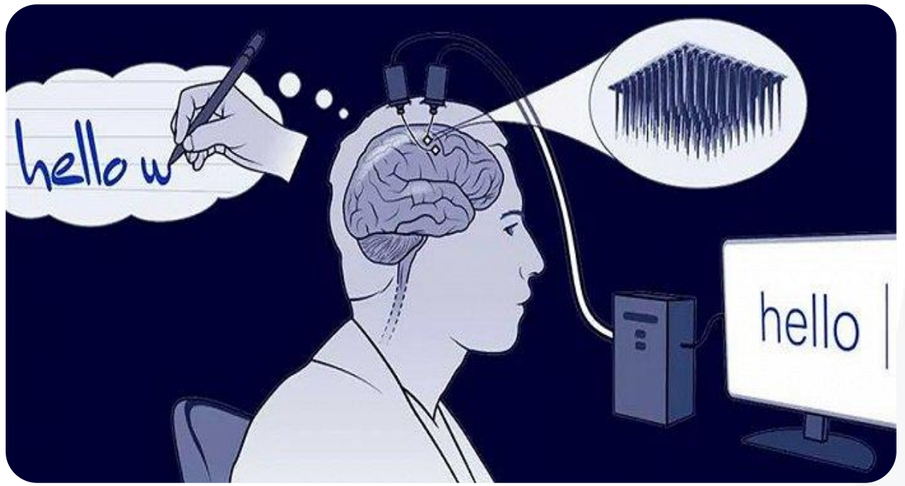
2) Critical problems and challenges of MAS collaboration

3) Key control and AI technologies in MAS

4) Future research directions in MAS

What’s next ?

- **Deep human-agent Interaction and collaboration**

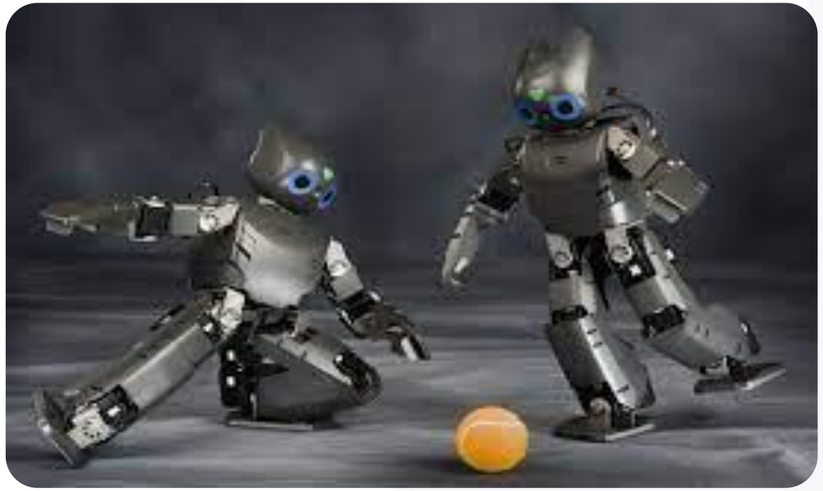


THE UNIVERSITY of ADELAIDE

What’s next ?

- **Deep human-agent Interaction and collaboration**

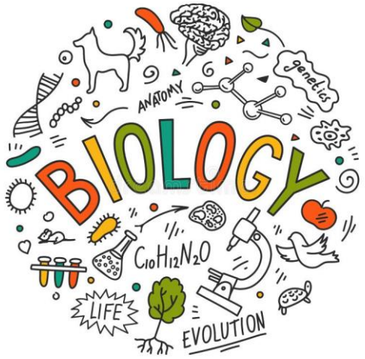
- **Explainable/Understandable AI in MAS**



THE UNIVERSITY of ADELAIDE

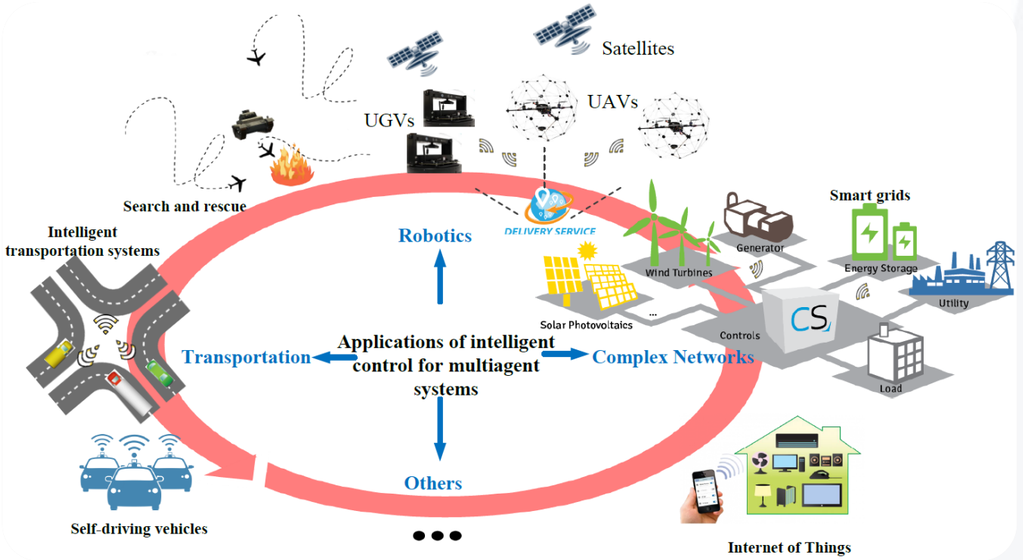
What’s next ?

- **Deep human-agent Interaction and collaboration**



- **Explainable/Understandable AI in MAS**

- **Cross-field applications**



Acknowledgement

Bing Yan

Xin Yuan

Md Tagor Hossain

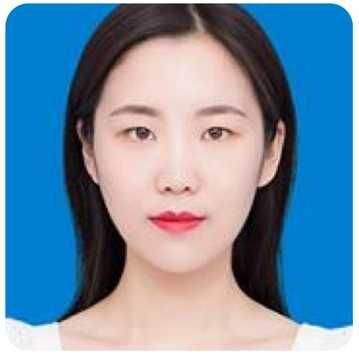
Kamal Mammadov

Yize Yang

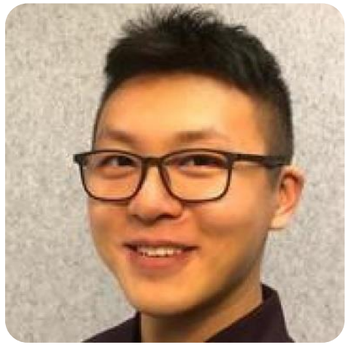
Daotong Zhang

THE UNIVERSITY OF ADELAIDE

Acknowledgement



Zhi Lian



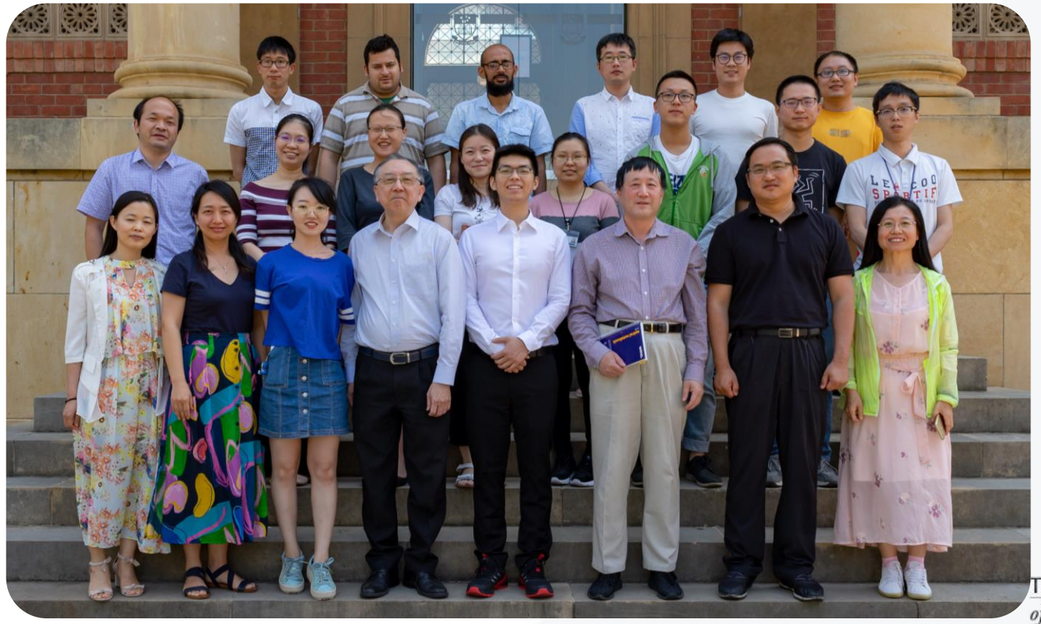
Yang Fei

Saeed Aslam

Yuan Sun

Syed Imranul Islam

Renjie Ma



THE UNIVERSITY of ADELAIDE

Thank you for your attentions!

Any Questions?

THE UNIVERSITY of ADELAIDE