Multi-Robot Collaboration

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AIRS
SHENZHEN INSTITUTE
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深圳市人工智能与机器人研究院

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Why are multi-robot systems essential?

Efficiency ⬆

(Parallel processing)

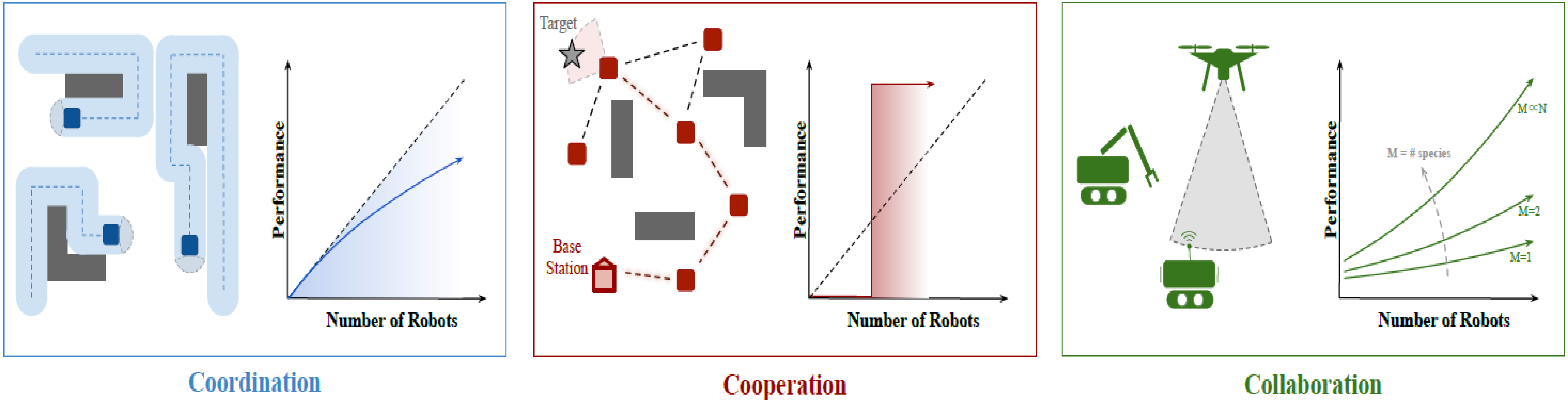
Flexibility ⬆

(On demand deployment)

Resilience ⬆

(Role substitution)

3Cs of Multi-robot Systems



Amanda Prorok, Matthew Malencia, Luca Carlone, Gaurav S. Sukhatme, Brian M. Sadler, Vijay Kumar, "Beyond Robustness: A Taxonomy of Approaches towards Resilient Multi-Robot Systems," arxiv 2021

Freeform Robotics - Research Focus

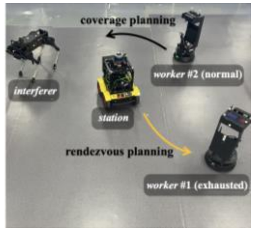
Types of Multi-robot Collaboration

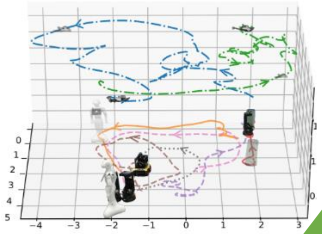

Self-reconfigure

- **Feature:** Physical connection among robots
- **Applications:** Inspection, exploration, general-purpose robot, etc.


Collaborative Manipulation

- **Feature:** Manipulate a same object
- **Applications:** Production, construction, surgery, etc.





Mobile Collaboration

- **Feature:** No physical interaction
- **Applications:** Searching, scanning, etc.

Relative Localization | Environment Perception | Decision Making and Planning

Fundamental Technologies

Background

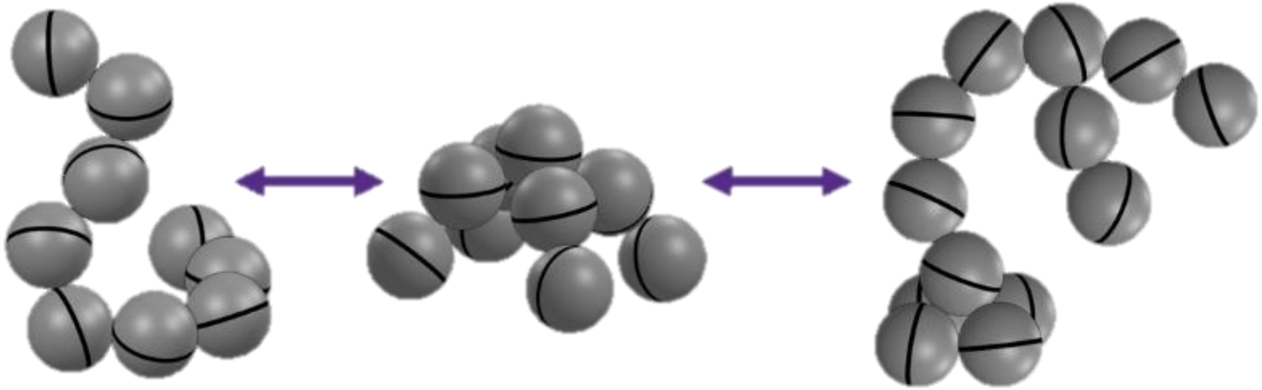
- One type of robot is difficult to cope with all uncertain tasks in dynamic environment
- Deploying redundant teams of heterogeneous robots results in high transportation and maintenance costs



Special-purpose robots

Motivation

Transformable General-purpose Robot



Special-purpose robots

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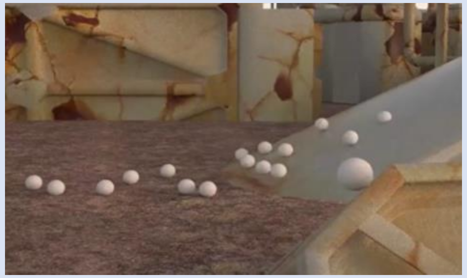
Challenges

1. **How do robots achieve physical collaboration?**
   - Efficient and robust connectors and actuators

2. **How do robots identify the position of each other?**
   - Multi-robot self-contained relative localization



3. **How do robots achieve environment perception?**
   - Source-inconsistent data fusion (hardware, time, viewpoint)

4. **How do robots collaborate to perform tasks?**
   - Multi-robot collaborative planning in dynamic environment

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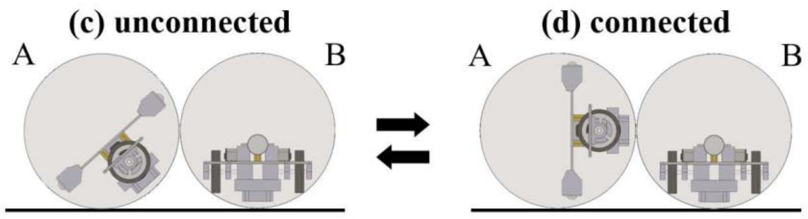
FreeBOT – A Rolling Sphere

Components: Ferromagnetic spherical shell + built-in mobile cart with magnets;

Features: Achieve arbitrary connection and movement of the entire spherical surface;




IROS Best Paper Award on Robot Mechanisms and Design sponsored by ROBOTIS

FreeBOT: A Freeform Modular Self-reconfigurable Robot with Arbitrary Connection Point - Design and Implementation

Guanqi Liang, Haobo Luo, Ming Li, Huihuan Qian, and Tin Lun Lam

The Chinese University of Hong Kong, Shenzhen and The Shenzhen Institute of Artificial Intelligence and Robotics for Society

Paul Oh
IROS 2020 General Chair

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2020 IEEE/RSJ
International Conference on Intelligent Robots and Systems(IROS)
October 25-29, 2020 Las Vegas, NV, USA

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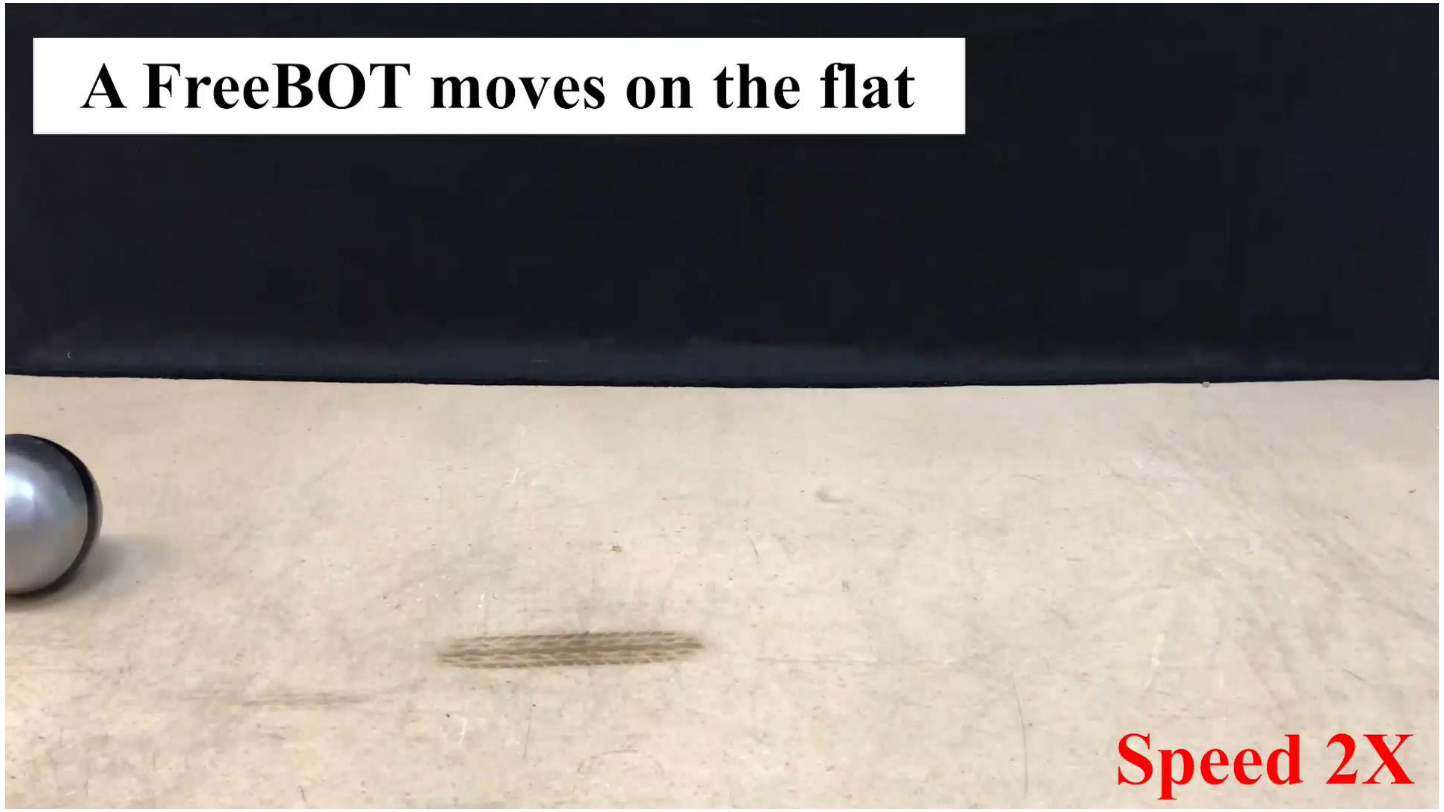


Guanqi Liang, Haobo Luo, Ming Li, Huihuan Qian and Tin Lun Lam, "FreeBOT: A Freeform Modular Self-reconfigurable Robot with Arbitrary Connection Point - Design and Implementation," IEEE/RSJ IROS 2020 ***[IROS Best Paper Award on Robot Mechanisms and Design]***

SnailBot – In the Wild

Components: Ferromagnetic spherical shell + magnet track drive; **Features:** Provides a larger connection area, more stable.

Da Zhao, Haobo Luo, Yuxiao Tu, Chongxi Meng, and Tin Lun Lam, "Snail-Inspired Robotic Swarms: A Hybrid Connector Drives Collective Adaptation in Unstructured Outdoor Environments," Nature Communications, April 2024.

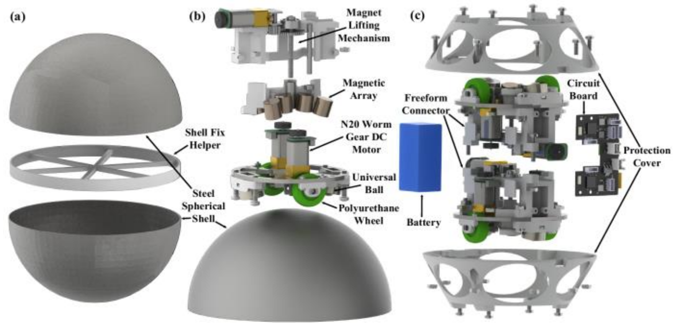
FreeSN – Strut-node MSRR

Components:

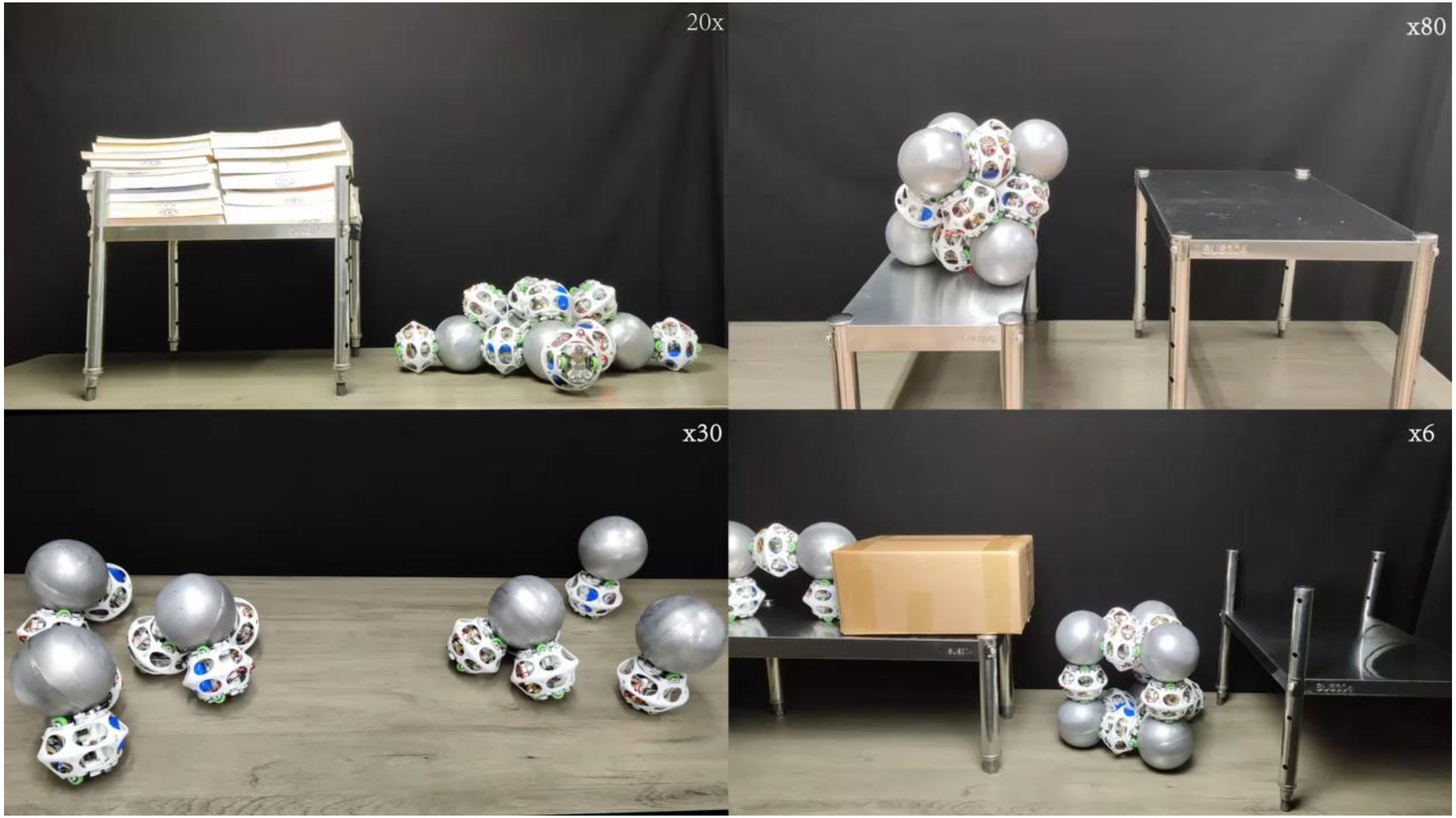
- **Strut module**: Contains two magnetic connectors with lifting mechanisms
- **Node module**: A spherical ferromagnetic shell

Features:

1. Strut-node structure brings good structural stability
2. Enable parallel motion to increase the output force



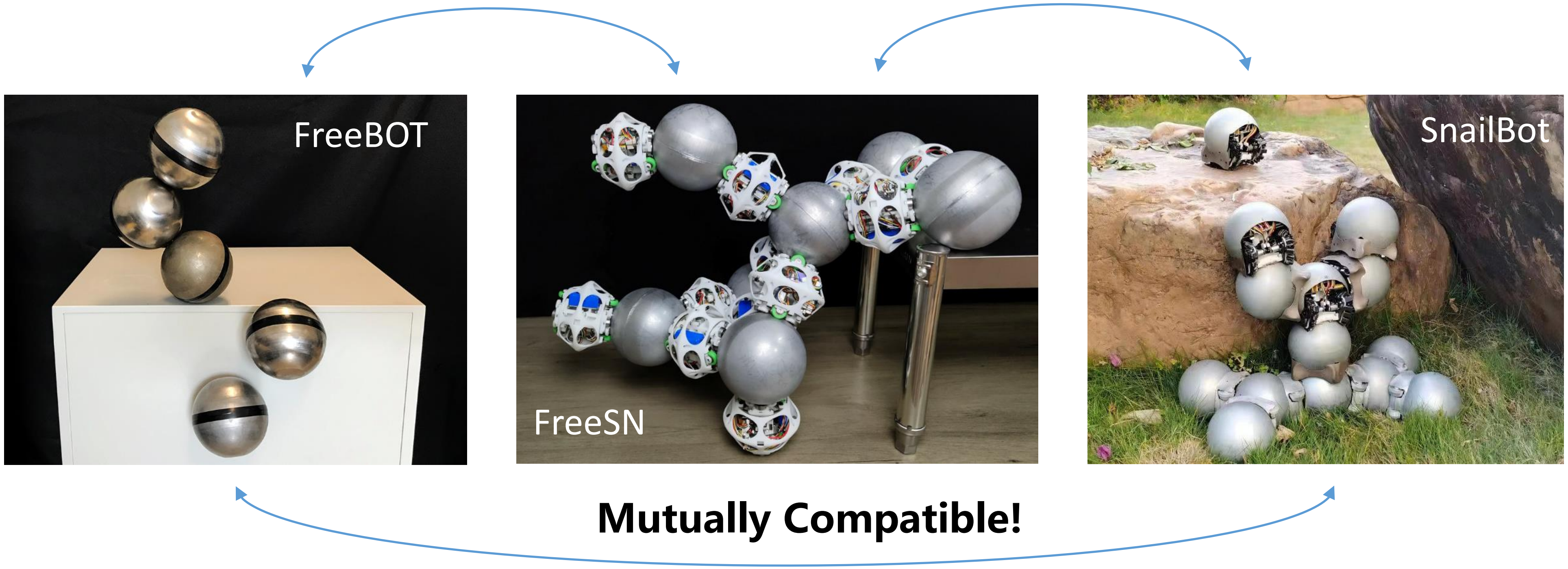
Node Module Strut Module



Yuxiao Tu, Guanqi Liang, Tin Lun Lam, "FreeSN: A Freeform Strut-node Structured Modular Self-reconfigurable Robot, " IEEE ICRA 2022

Compatibility among Freeform Robots

- Freeform Robots: FreeBOT, SnailBot, and FreeSN
- Share the same connecting principle – Magnetic force
- Share the same connecting terrain – Ferromagnetic sphere



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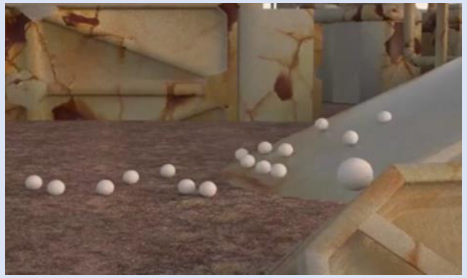

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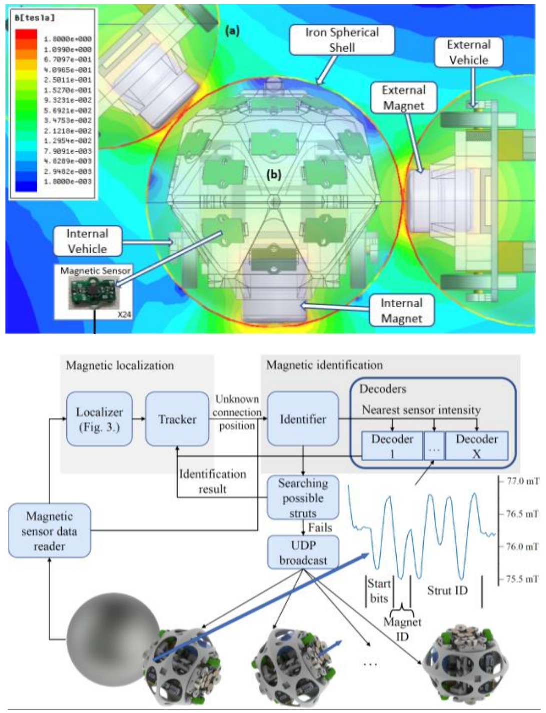
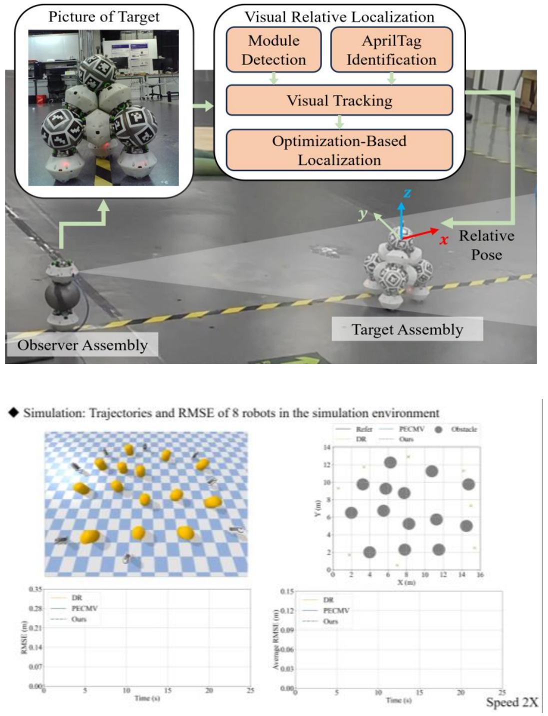
2. Multi-robot Self-contained Relative Localization

Contact-range (0m)
Accuracy ~1mm
Magnetic Array



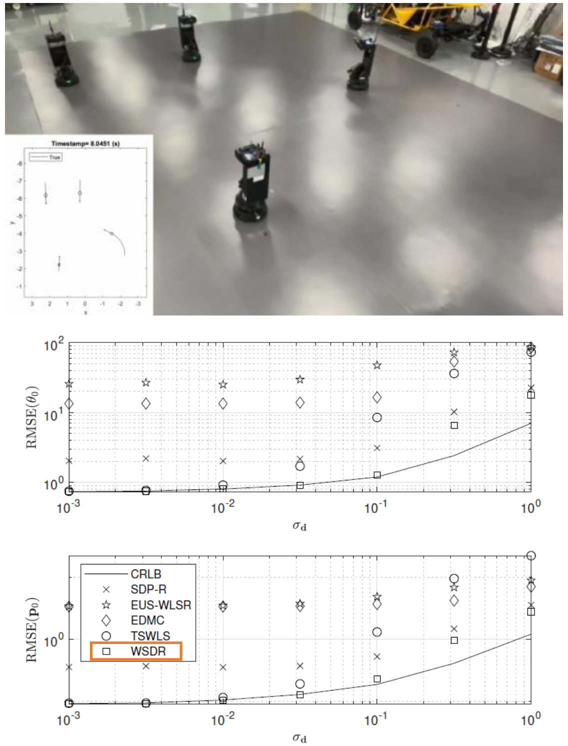
(ICRA 2021, TRO 2023)

Short-range (<5m)
Accuracy ~1cm
Vision-Based



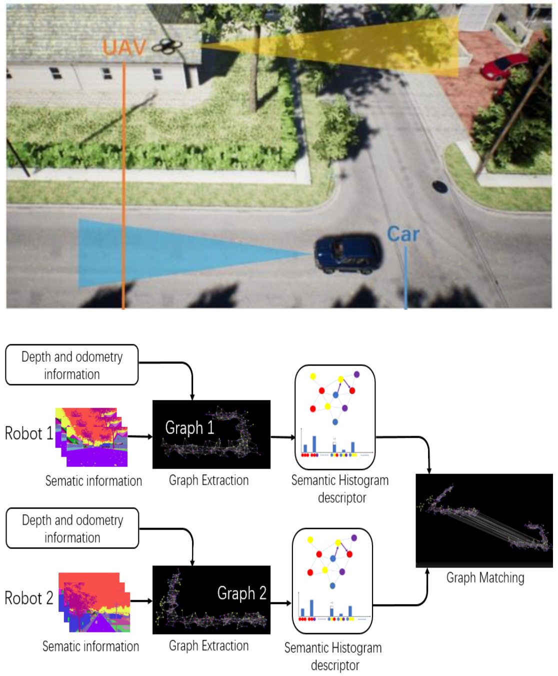
(IROS 2023)

Middle-range (<50m)
Accuracy ~10cm
UWB + Odometry



(RAL 2022, TMECH 2023)

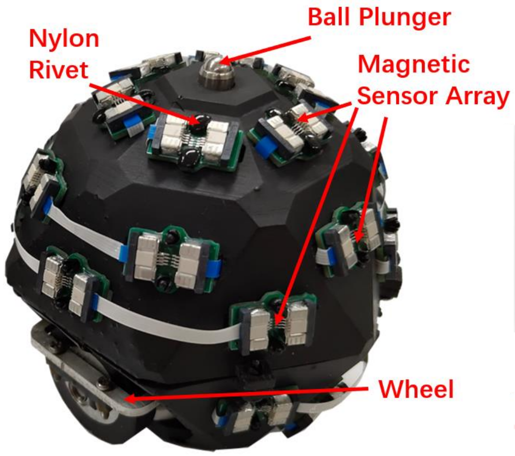
Long-range (>50m)
Accuracy ~1m
Visual Semantic Landmark

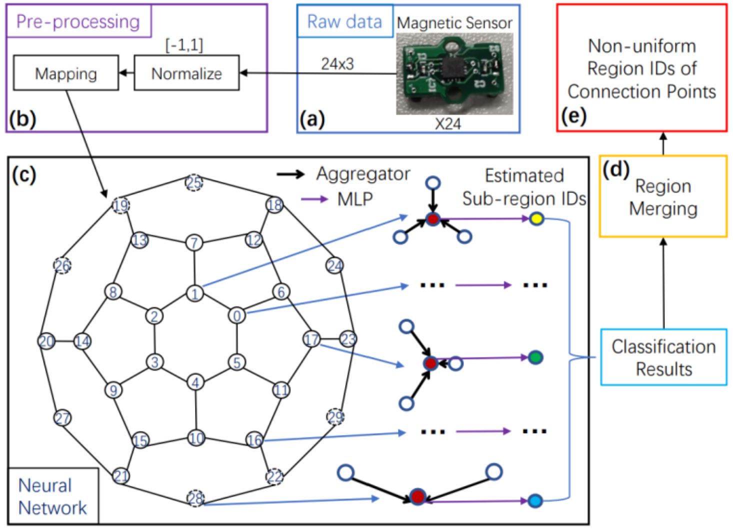


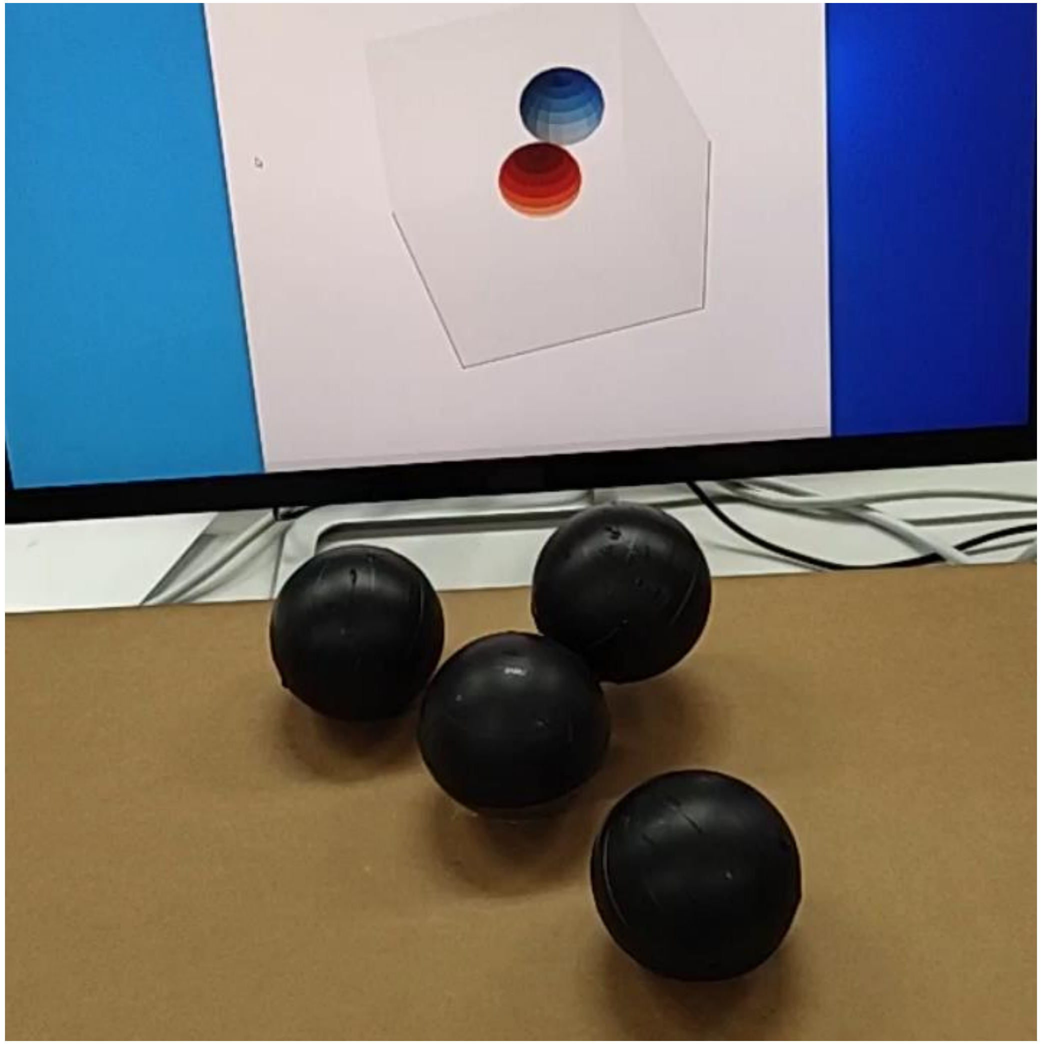
(RAL 2021)

Contact-range (0m) Relative Localization

- **Challenge**: No fixed point connector to identify the location of the connection
- **Approach**: Magnetic sensor array + GNN-based localization algorithm
- **Result**: Real-time configuration detection



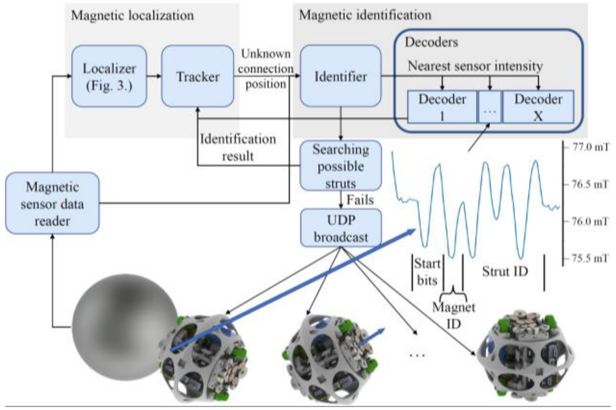


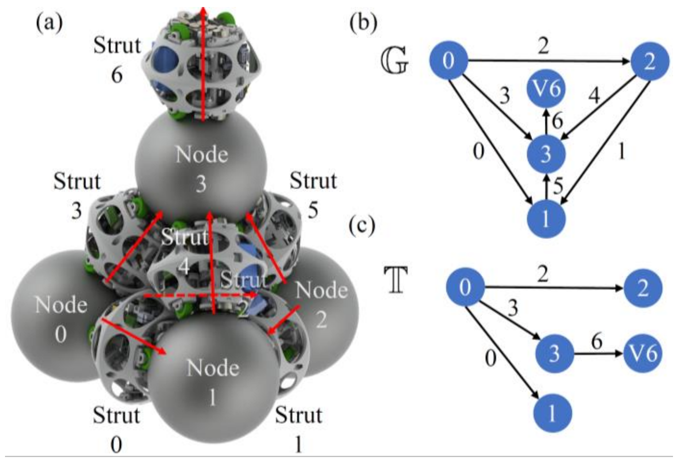


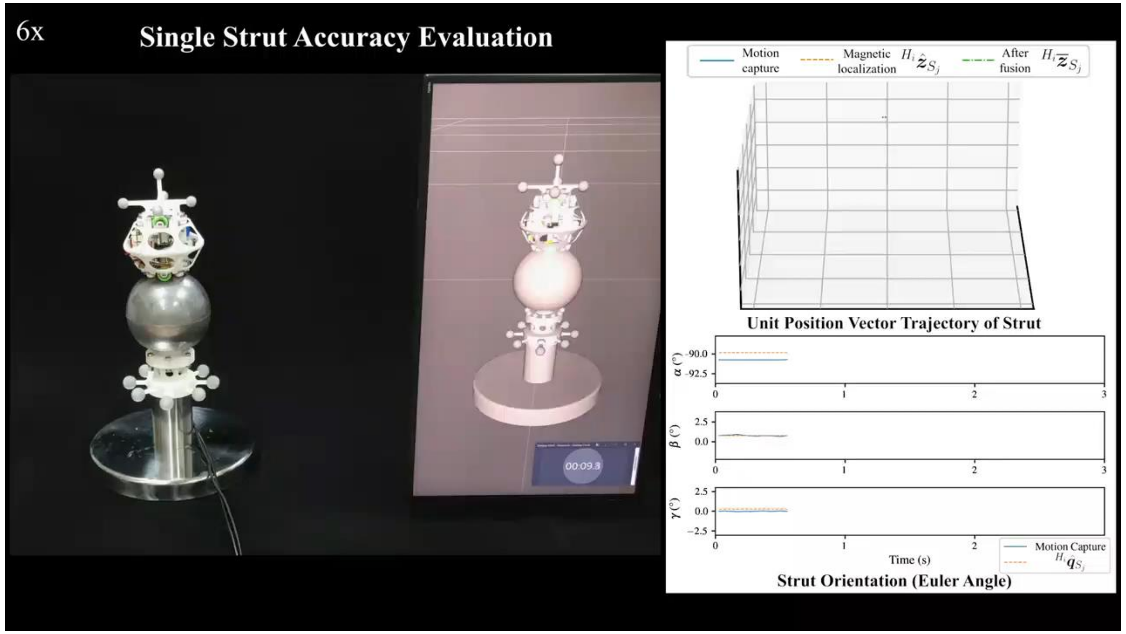
Yuxiao Tu, Guanqi Liang, Tin Lun Lam, "Graph Convolutional Network based Configuration Detection for Freeform Modular Robot Using Magnetic Sensor Array," IEEE ICRA 2021

FreeSN – Configuration Identification

- Estimates the connection topology and the relative pose of each module by:
  1) Magnetic Relative Localization;
  2) Magnetic Module Identification;
  3) Module Orientation Fusion;
  4) System Configuration Fusion.



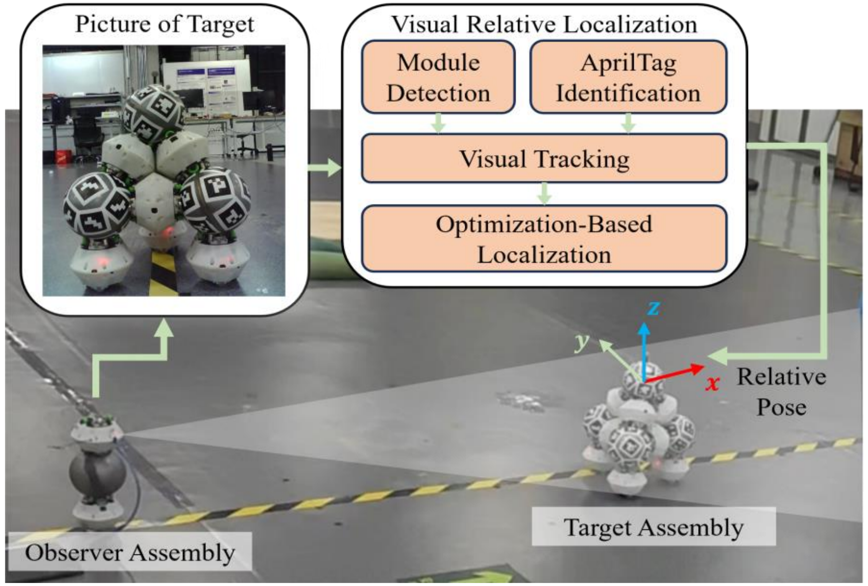




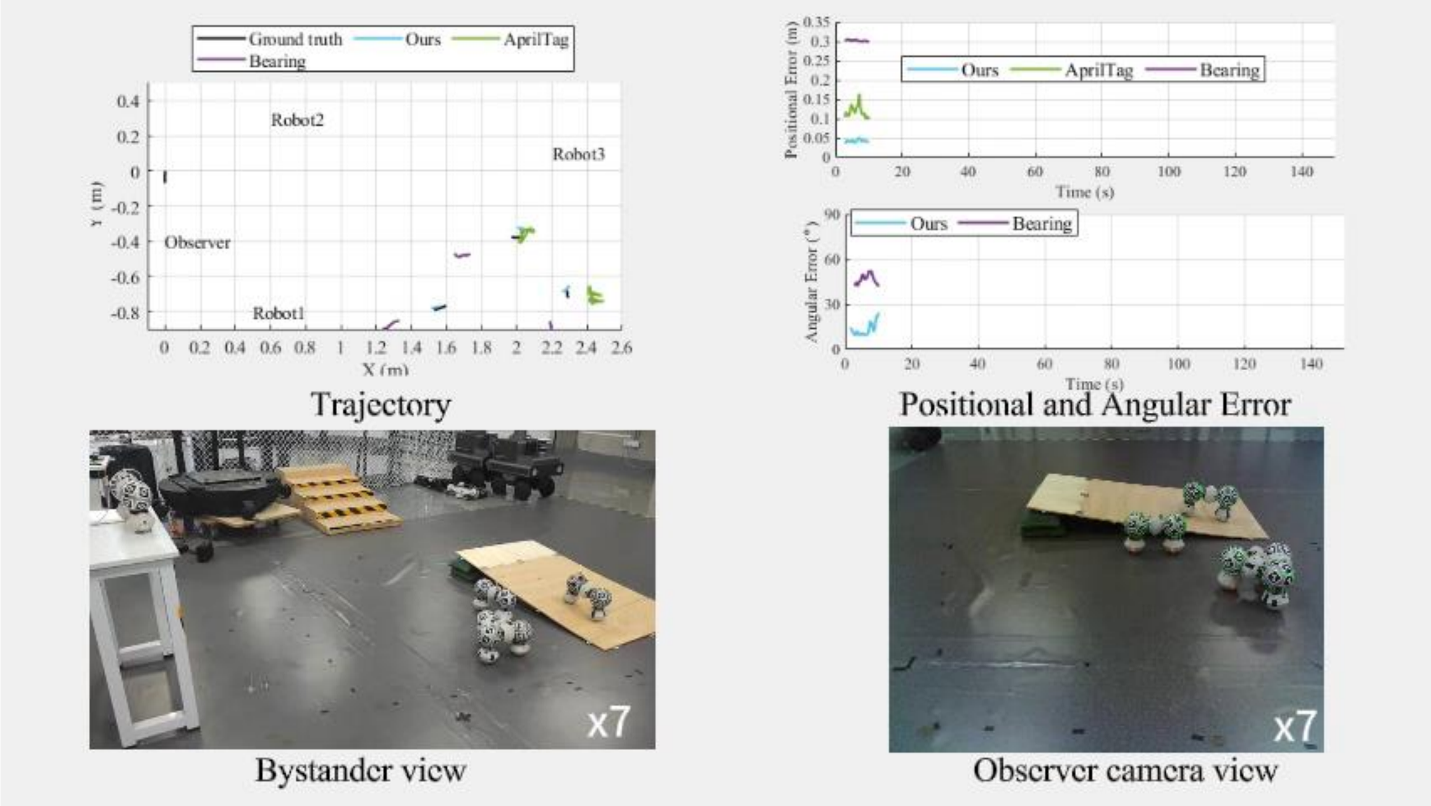
Yuxiao Tu, Tin Lun Lam, "Configuration Identification for a Freeform Modular Self-reconfigurable Robot - FreeSN," IEEE T-RO 2023.

Short-range (<5m) Relative Localization

- **Challenge**: Variable configuration brings unstructured features for visual detection and localization.
- **Approach**: Robust module detection and optimization-based localization that fuses visual measurement and odometry.



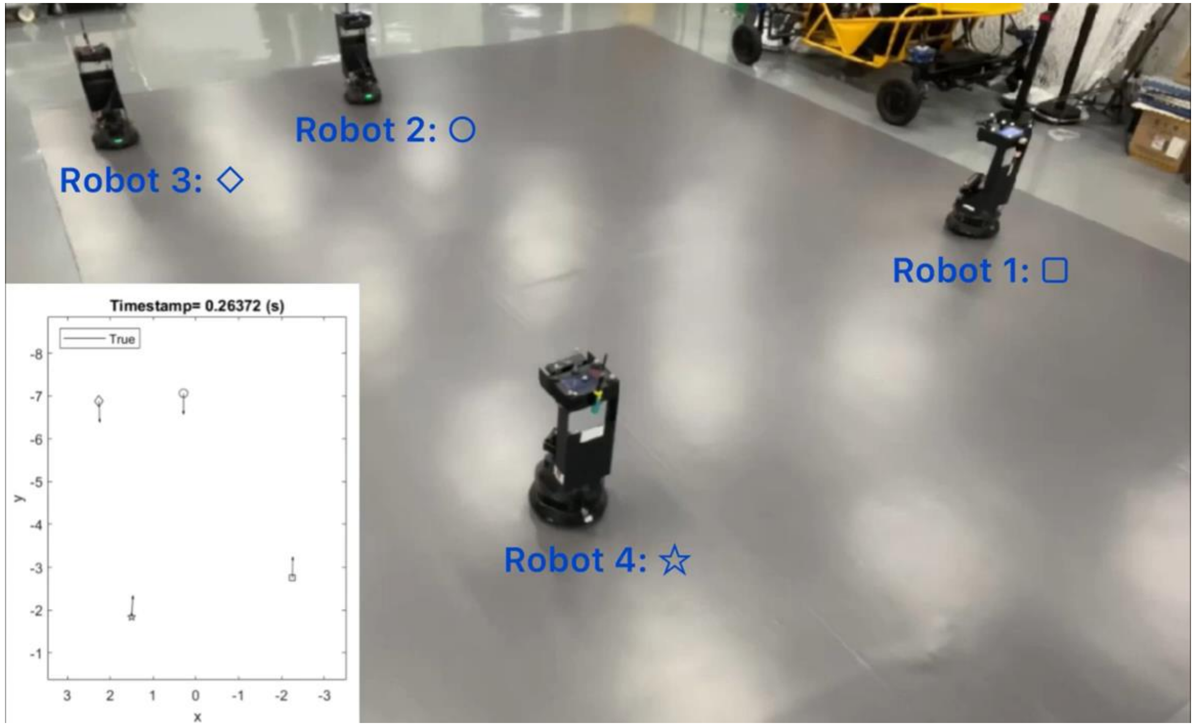
- **Result**: Position accuracy < 0.06m; Orientation accuracy < 2.23°

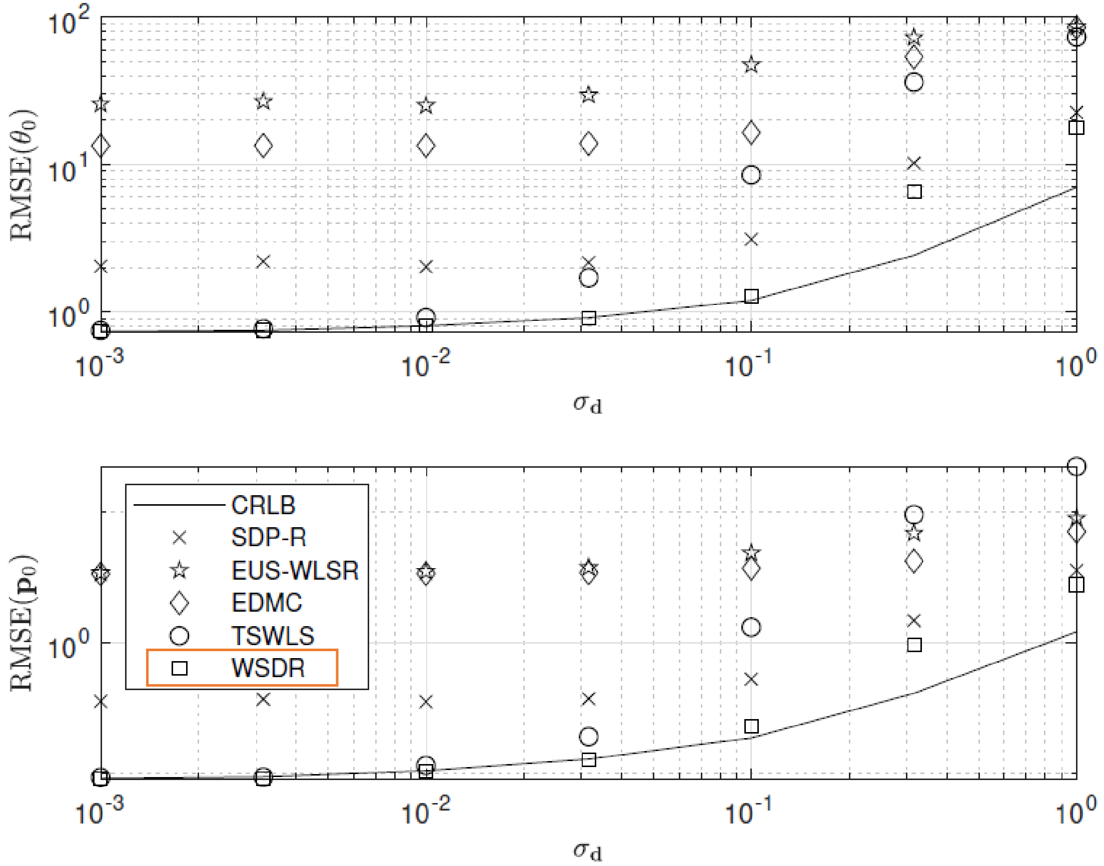


Yuming Liu, Qiu Zheng, Yuxiao Tu, Yuan Gao, Tin Lun Lam, "Visual Relative Localization for Spherical Modular Self-Reconfigurable Robots with the Ability to Adapt to Different Configurations" (Under Review)

Middle-range (<50m) Relative Localization

- **Challenge**: Lack of theoretical analysis of the variance and bias of the estimators.
- **Approach**: Dead reckoning + self-carried UWB +weighted semidefinite relaxation solution
- **Result**: RMSE of the orientation and position are 3.97° and 0.22 meters with affordable hardware.

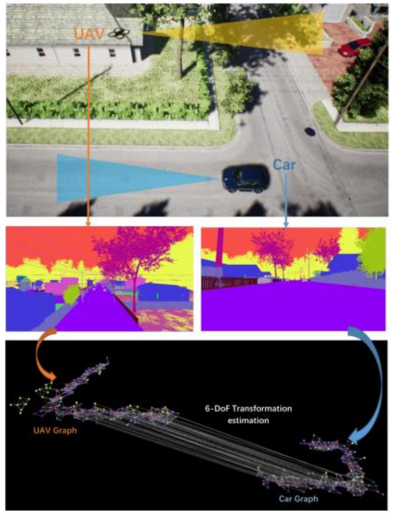


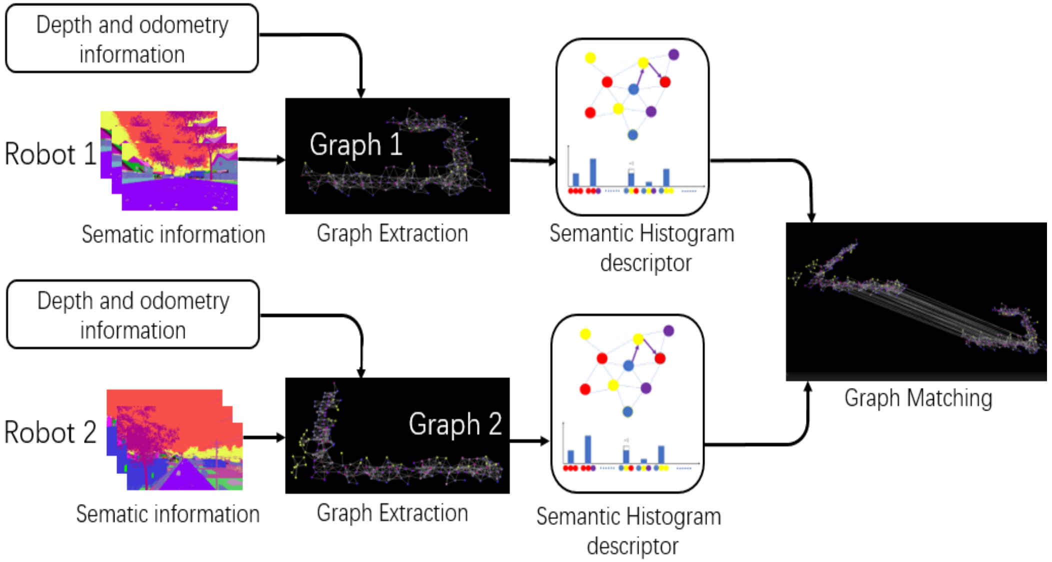


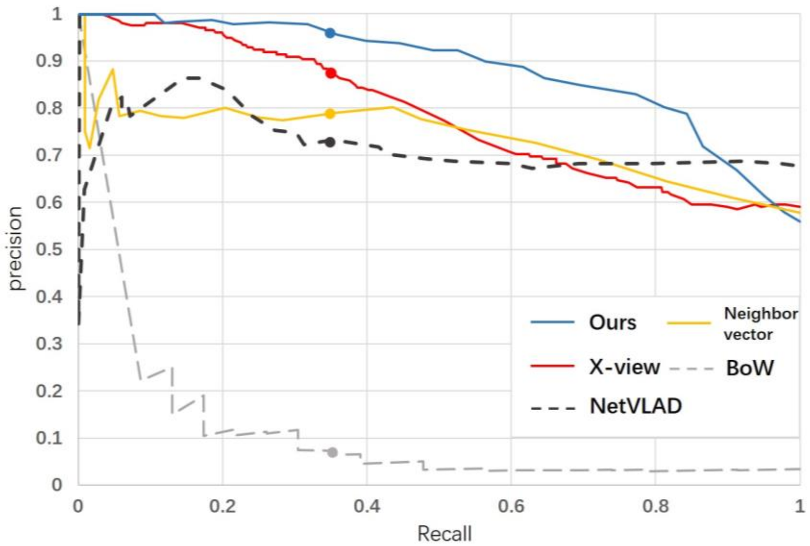
Yue Wang, Muhan Lin, Xinyi Xie, Yuan Gao, Fuqin Deng, Tin Lun Lam, " Asymptotically efficient estimator for range-based robot relative localization," IEEE/ASME TMECH 2023

Long-range (>50m) Relative Localization

- **Challenges**: 1) Large viewpoint difference; 2) High demand on computational resources.
- **Approach**: Semantic Histogram Descriptor + Graph Matching
- **Result:** Matching speed > 30x; Matching accuracy > 10%







Xiyue Guo, Junjie Hu, Junfeng Chen, Fuqin Deng, Tin Lun Lam, "Semantic Histogram Based Graph Matching for Real-Time Multi-Robot Global Localization in Large Scale Environment," IEEE RA-L 2021

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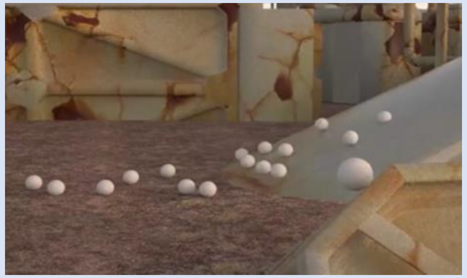

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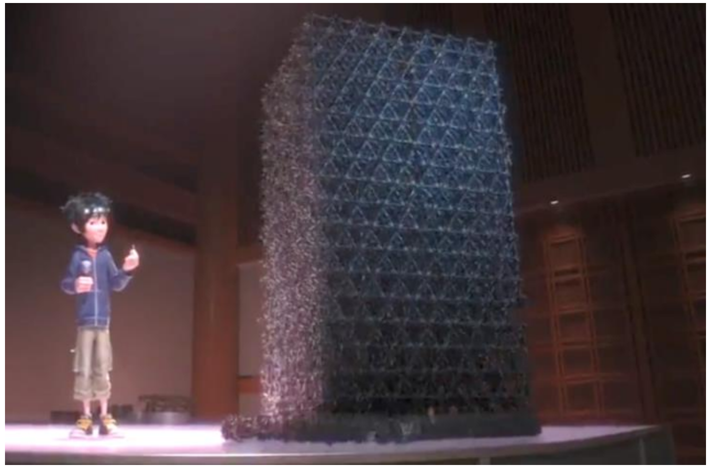
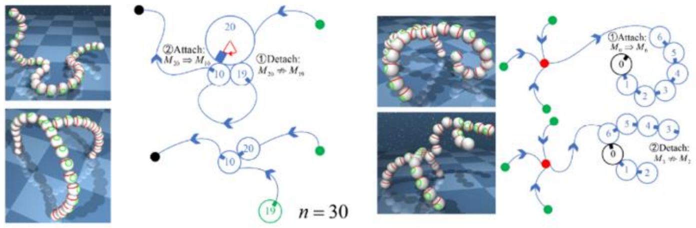
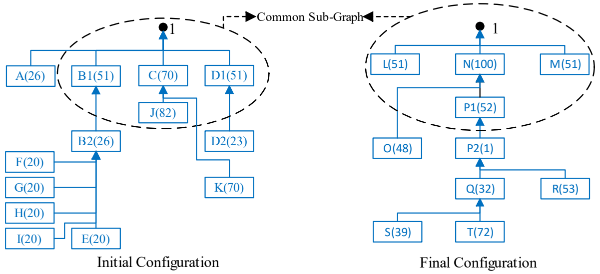
4. Collaborative Planning for MSRR



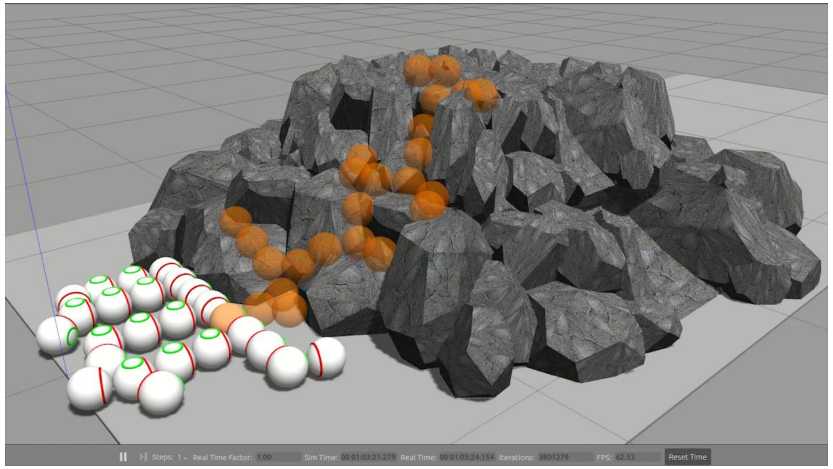
Transformation



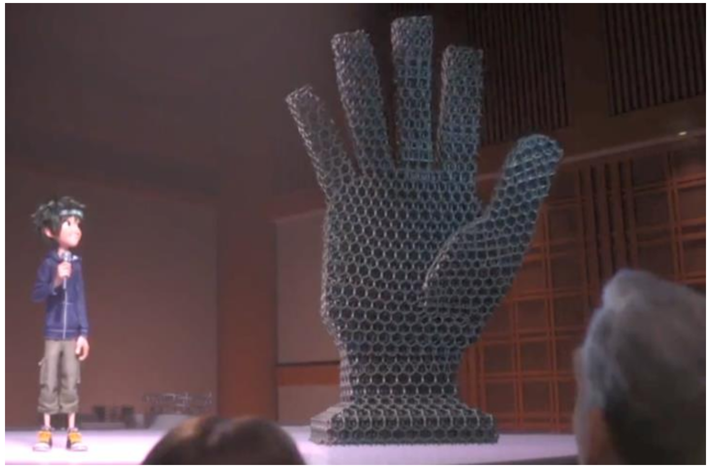


(T-RO 2022)

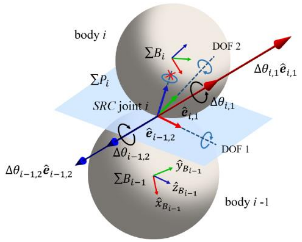
Locomotion

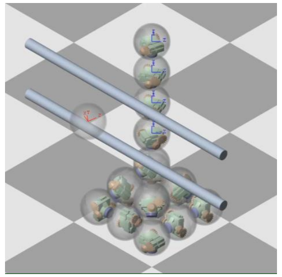


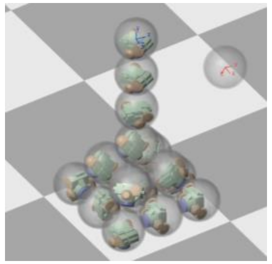
(IROS 2020, RA-L 2022)



Manipulation





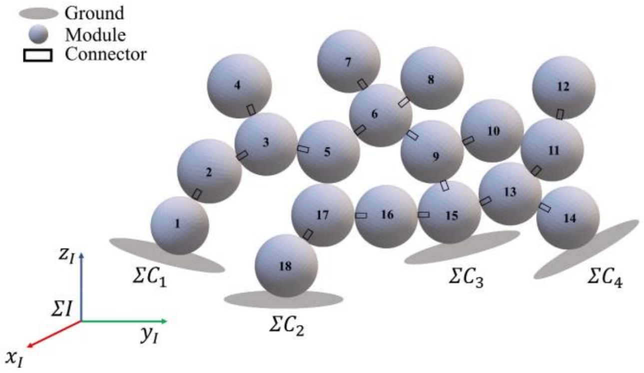


(T-RO 2022)

Linear-Time Quasi-Static Stability Detection

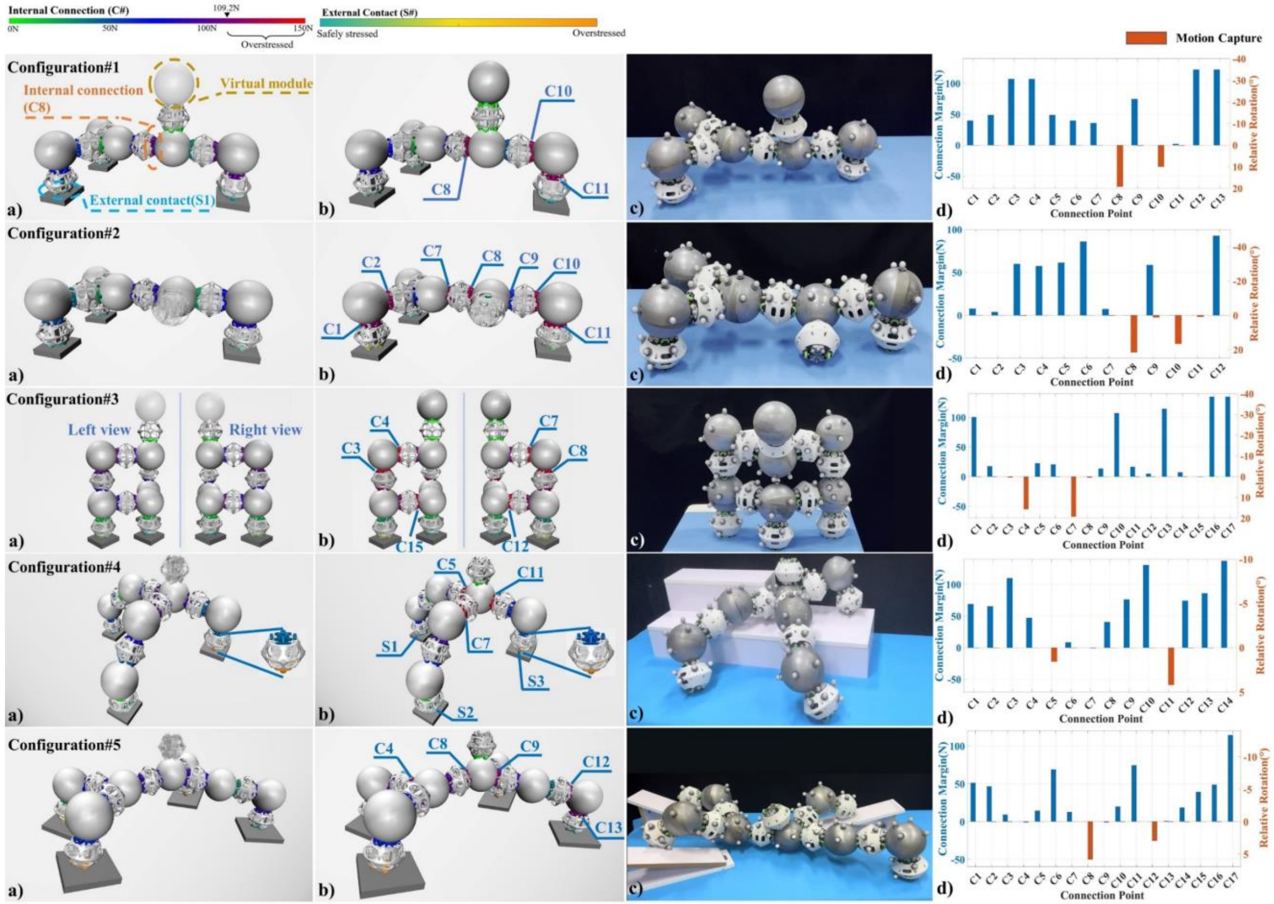
✓ Main idea: By estimating the critical stable state of the configuration instead of using finite element methods for stability analysis, the computational complexity is significantly reduced.

- Considering the connections between modules, contact, and environmental contact.



- Second-order cone program

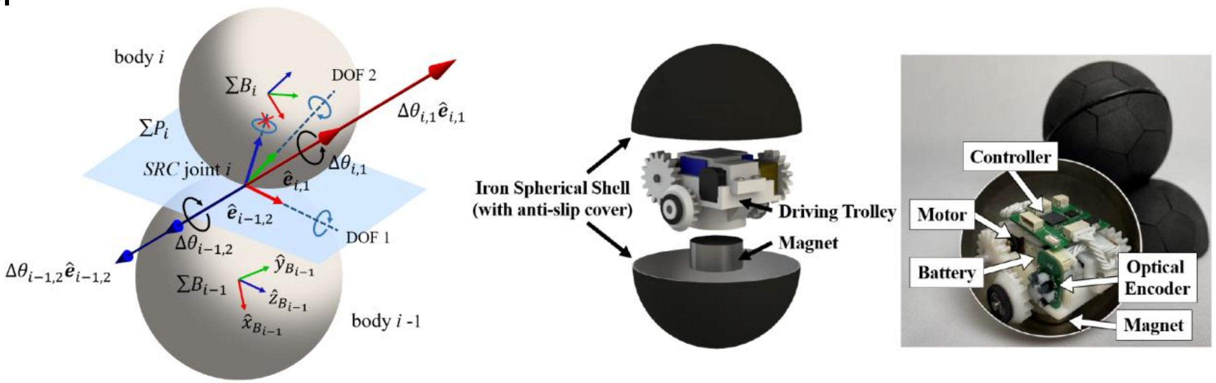
$$
\begin{aligned}
\min \quad & W_A^{max} \\
s.t. \quad & ZX = B \\
& f_{C_{ij}^z} \in K_{C_{ij}}, \\
& f_{\hat{C}_{iu}^z} \in K_{\hat{C}_{iu}}, \\
& \left\|\omega K \mathcal{F}_{A_{ik}}\right\|_2 \leq W_A^{max}, \\
& \mathcal{F}_{A_{ik}} - \mathcal{F}_{max_{ik}}(X) < \mathbf{0} \\
& \forall i \in [1, N], j \in [1, \gamma_i], u \in [1, \beta_i], k \in [1, \alpha_i]
\end{aligned}
$$



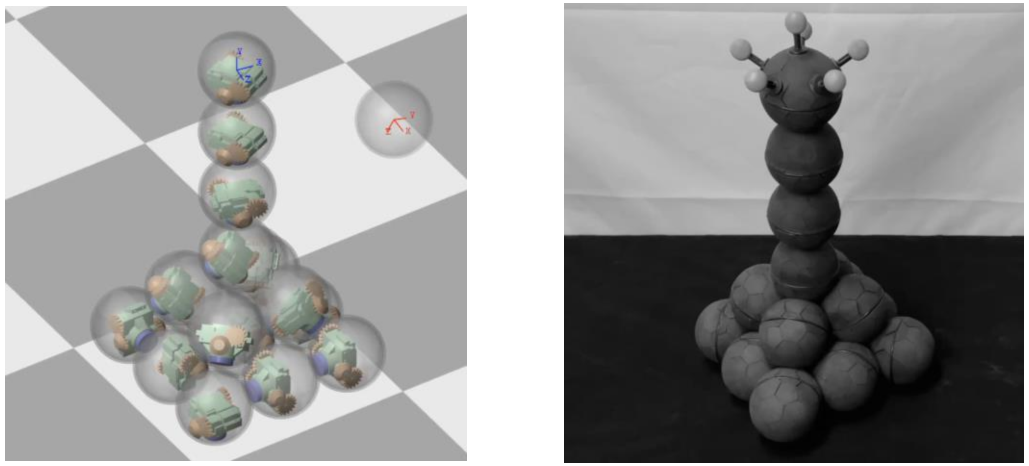
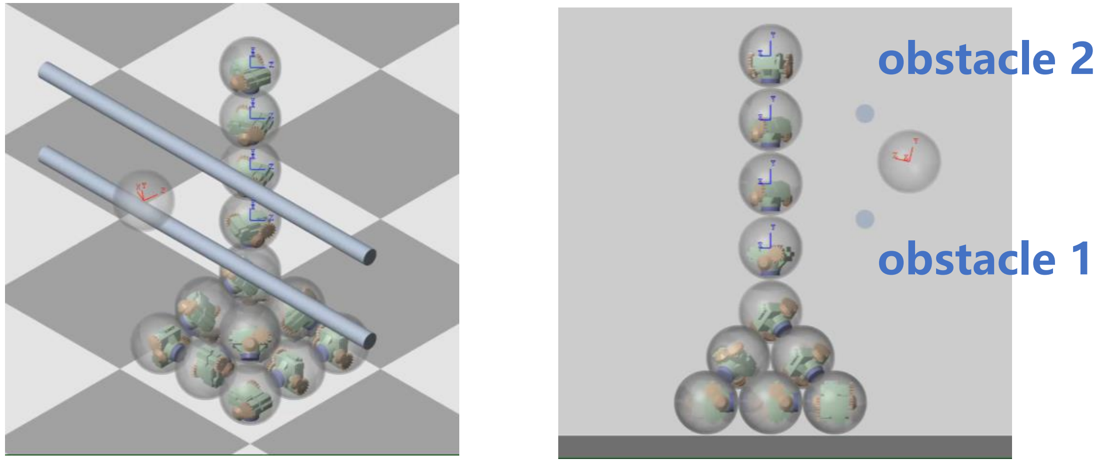
Di Wu, Yuxiao Tu, Guanqi Liang, Lijun Zong, Tin Lun Lam, "Linear-Time Quasi-Static Stability Detection for Modular Reconfigurable Robots" IJRR2024

FreeBOT – Kinematic Modeling and Motion Planning

- **Challenge**: Unique motion modalities and collaborative control methods between modules.
- **Approach**: Establish a kinematic model, planning, and control methods for high-DoF manipulators formed by connecting multiple modules in series.
- **Result**: A novel Spherical Rolling Contact Joint (SRC joint) and its kinematic model, motion planning, and control methods.



- Spherical rolling contact joint (left) that is realized by FreeBOT (right)

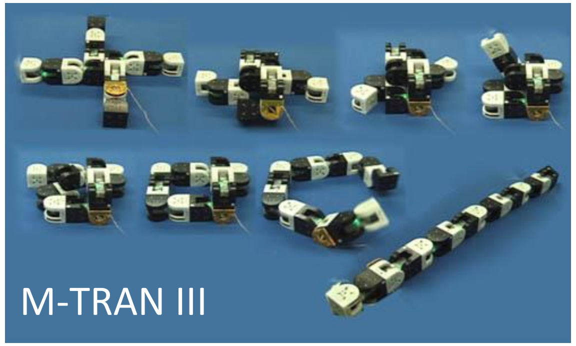



- Point to point reaching desired position in free space
- Reaching target pose while avoiding obstacles

Lijun Zong, Guanqi Liang, Tin Lun Lam, "Kinematics Modeling and Control of Spherical Rolling Contact Joint and Manipulator," IEEE T-RO 2022.

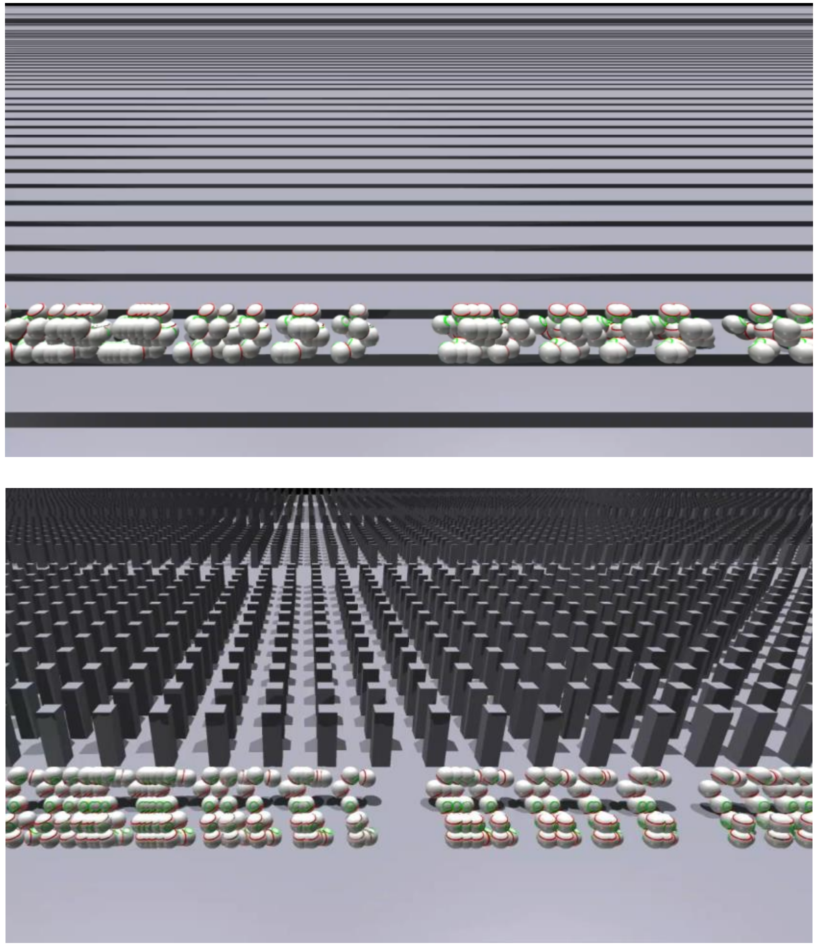
Locomotion of MSRR

- Typical approach – Gait Locomotion
  - Step 1: Form a fixed connection relationship to mimics the shape of an animal (Snake, Quadruped, Hexapod, etc.)
  - Step 2: Generate the gait patterns of the whole body by joints relative motion.

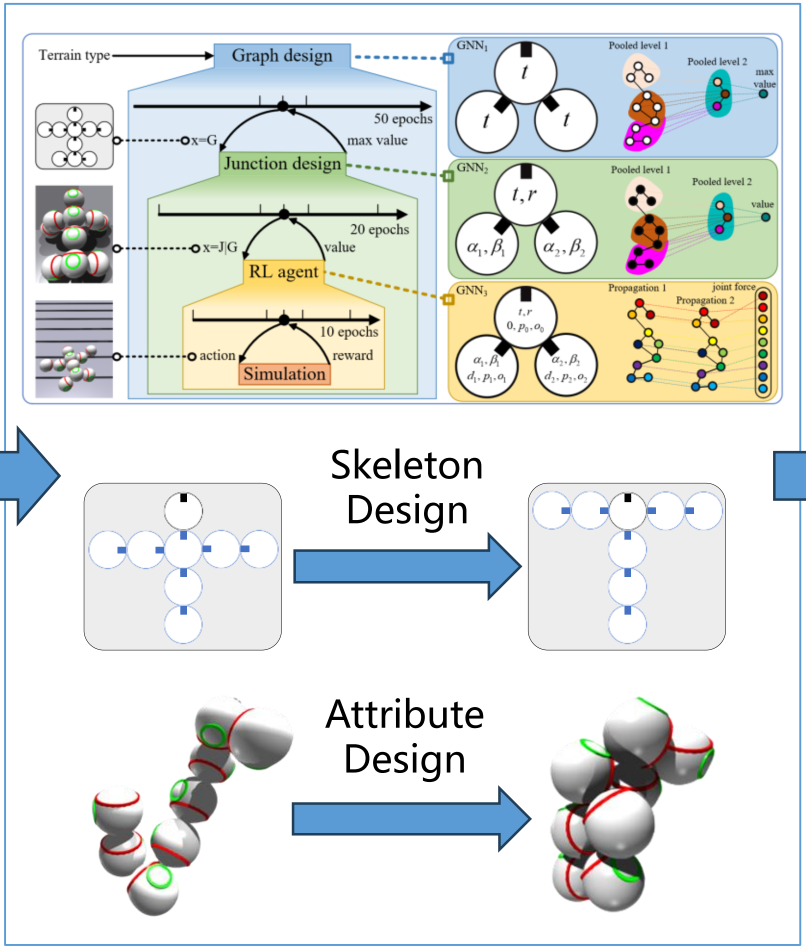


➢ ***Motivation***: Design a configuration suitable for the task terrain.

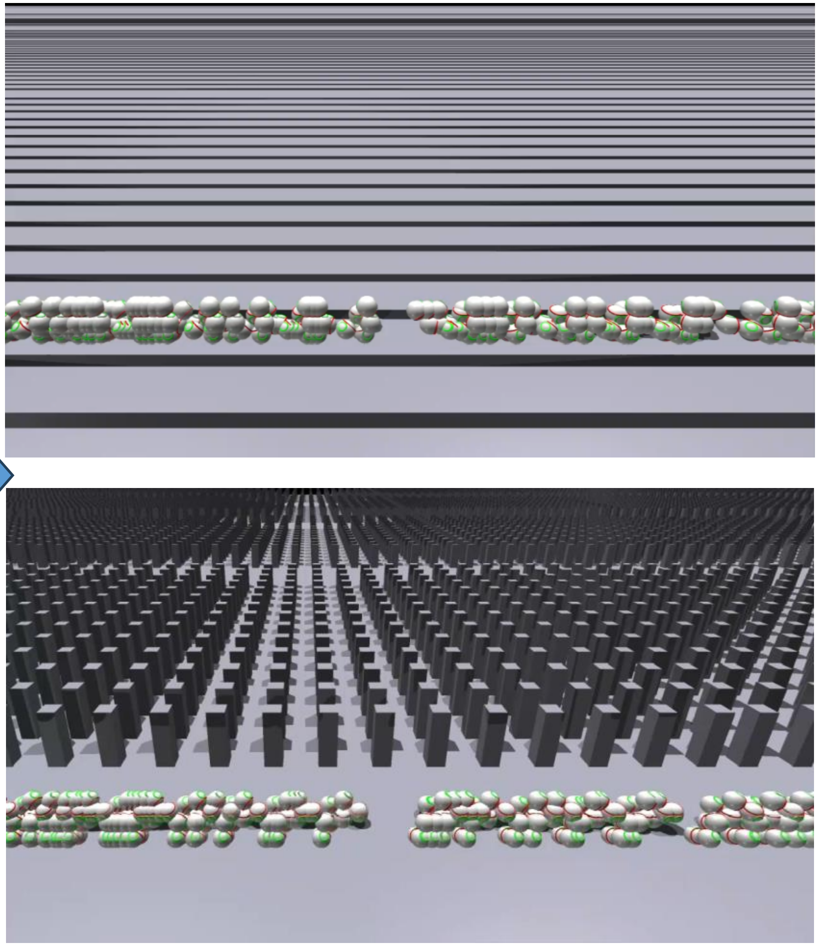
➢ ***Methods***: Gradient ascent for continuous parameters and modified Bayesian optimization for discrete parameters.



Initial



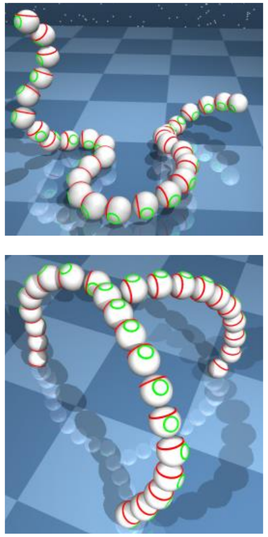
Configuration Design

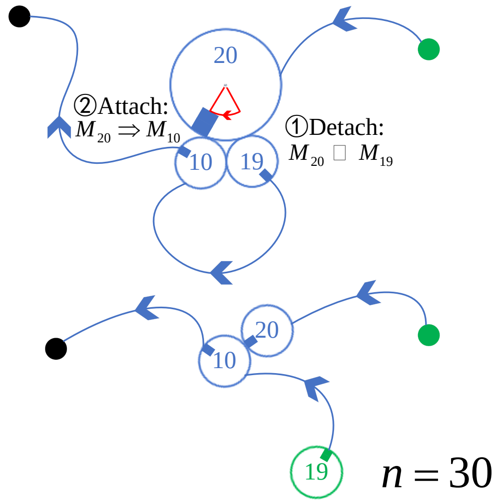


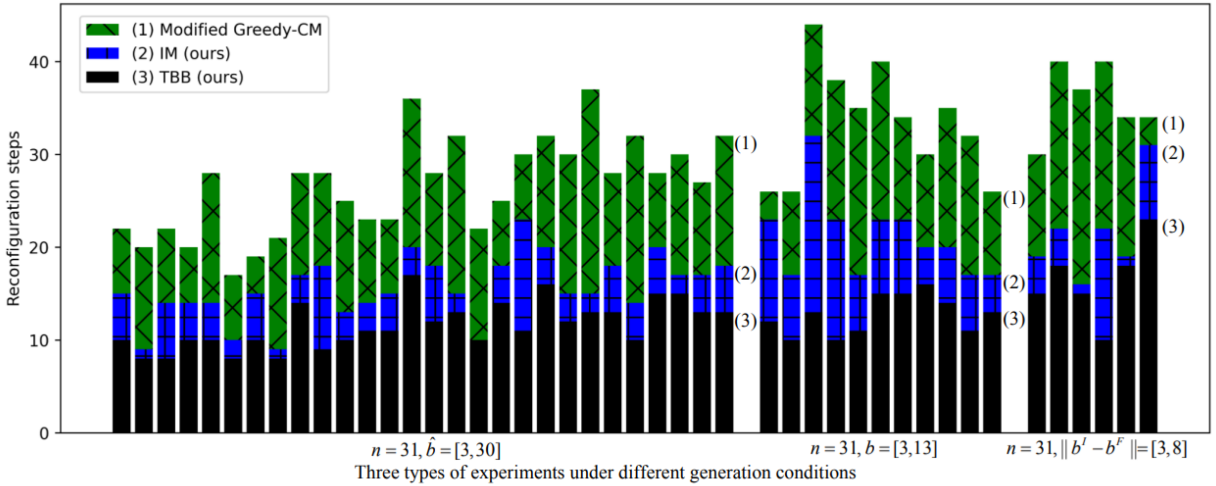
Final

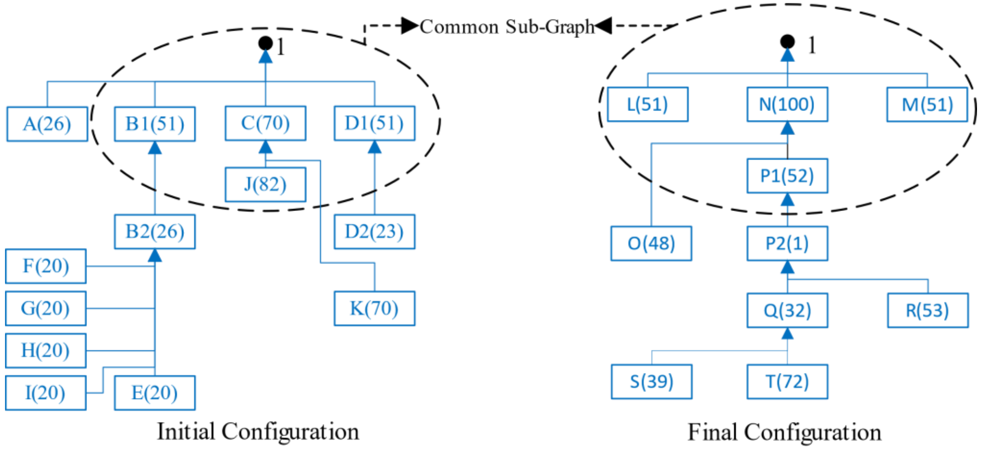
Connection Planning for Transformation

- **Challenge:** Finding the optimal solution involving a huge search space.
- **Approach:** A polynomial-time IM algorithm computes near-optimal solutions by interchanging connection points; 2) an exponential-time TBB algorithm further optimizes the solution of IM by a new branch and bound strategy with stage cost.
- **Result:** IM and TBB verify their near-optimality and optimality on experimental data.





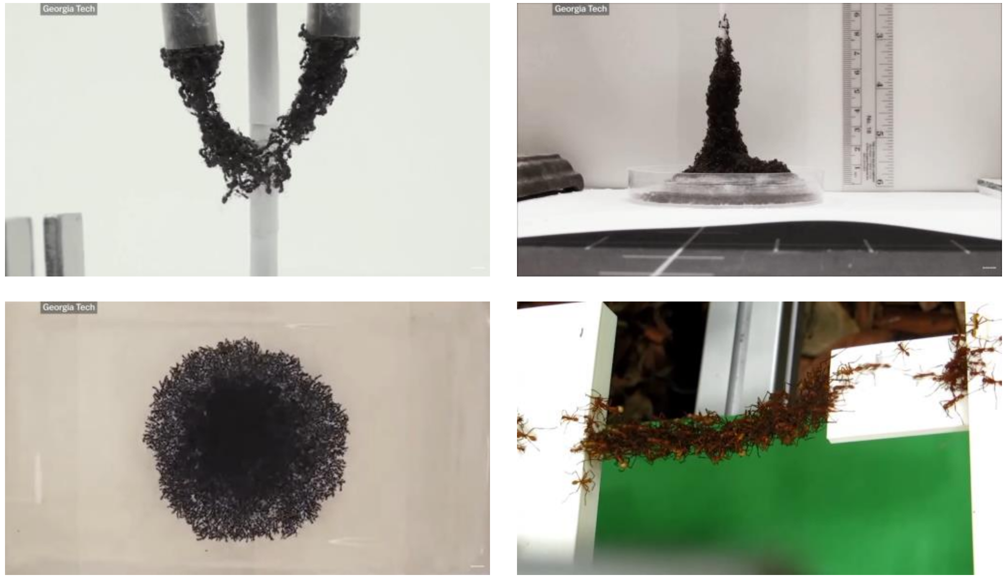




Haobo Luo, Tin Lun Lam, "Auto-Optimizing Connection Planning Method for Chain-Type Modular Self-Reconfiguration Robots," IEEE T-RO 2022

Flow Locomotion

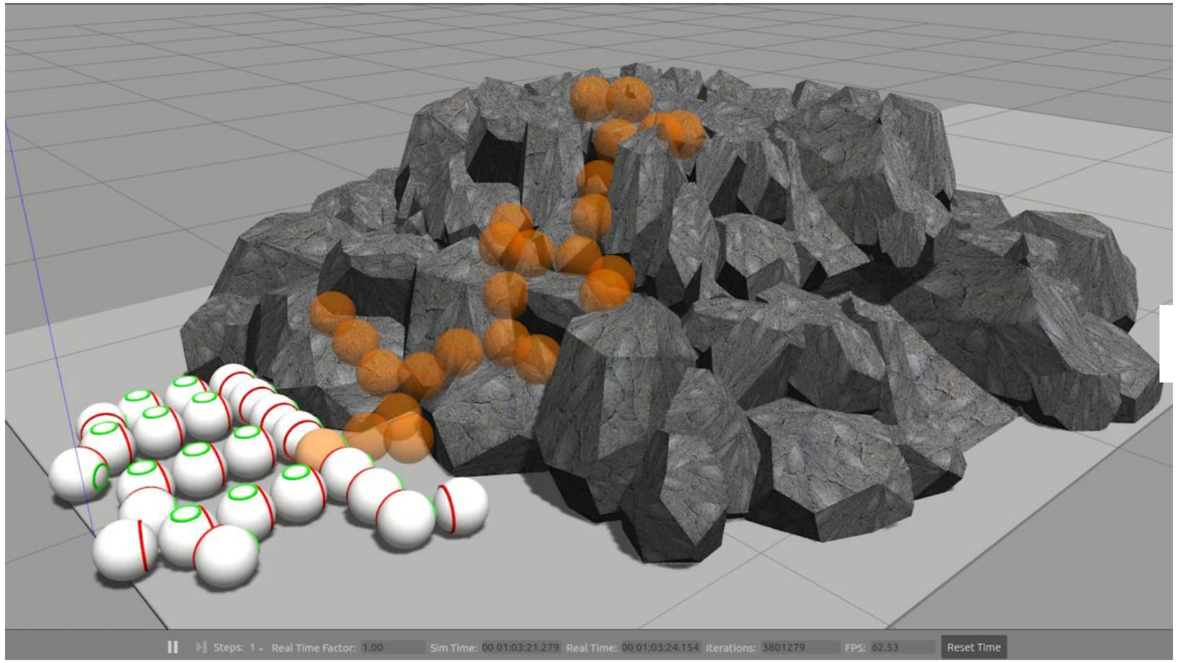
- The locomotion achieved by a series of reconfiguration
- The connection relationship is changing all the time

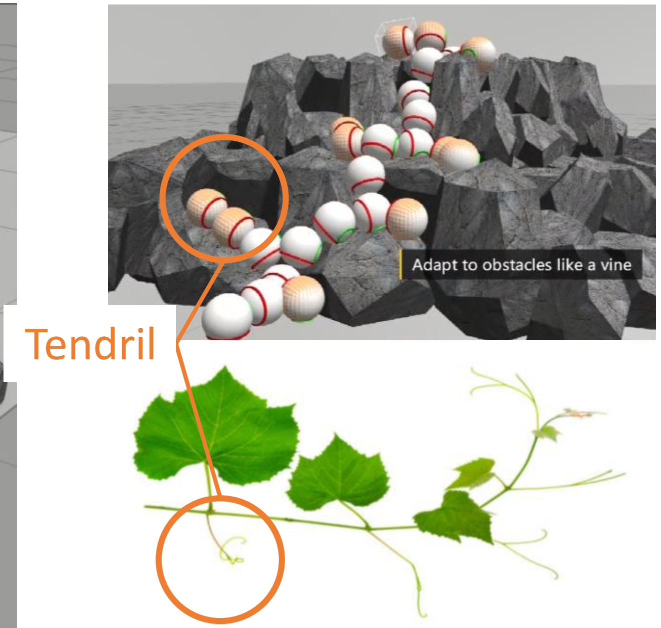


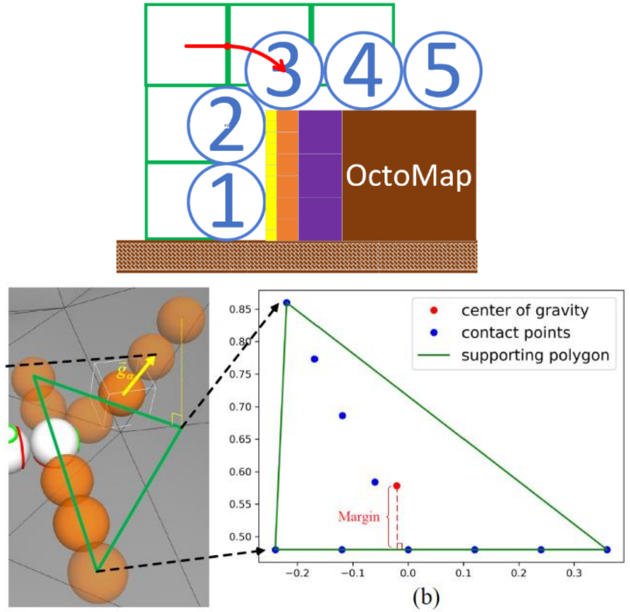
(Source: Georgia Tech, National Geographic)

Flow Locomotion

- **Challenge:** Flow through continuous rugged obstacles and maintain gravity stability
- **Approach**: 1) Configurations are designed to grasp the surface of obstacles like vines;
  2) Motion planning keeps each module moving within the supporting polygon.
- **Result**: The vine-like configuration conforms to the rugged surface of various obstacles.



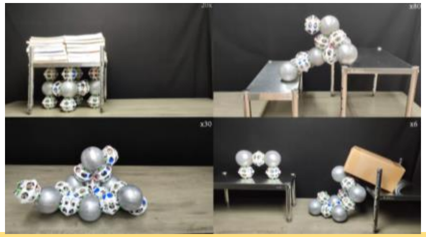




Haobo Luo and Tin Lun Lam, "Adaptive Flow Planning of Modular Spherical Robot Considering Static Gravity Stability, " IEEE RA-L 2022

Freeform Robotics - Research Focus

Types of Multi-robot Collaboration

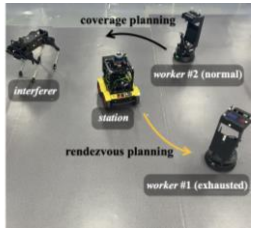


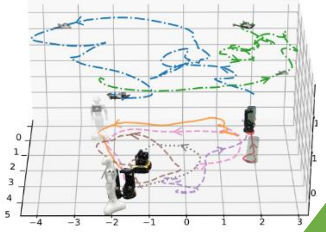

Self-reconfigure

- **Feature:** Physical connection among robots
- **Applications:** Inspection, exploration, general-purpose robot, etc.


Collaborative Manipulation

- **Feature:** Manipulate a same object
- **Applications:** Production, construction, surgery, etc.





Mobile Collaboration

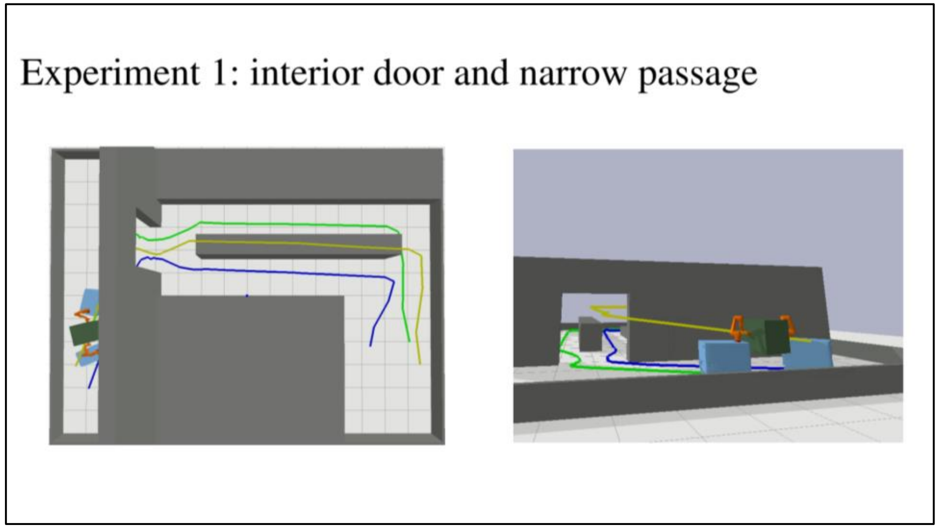
- **Feature:** No physical interaction
- **Applications:** Searching, scanning, etc.

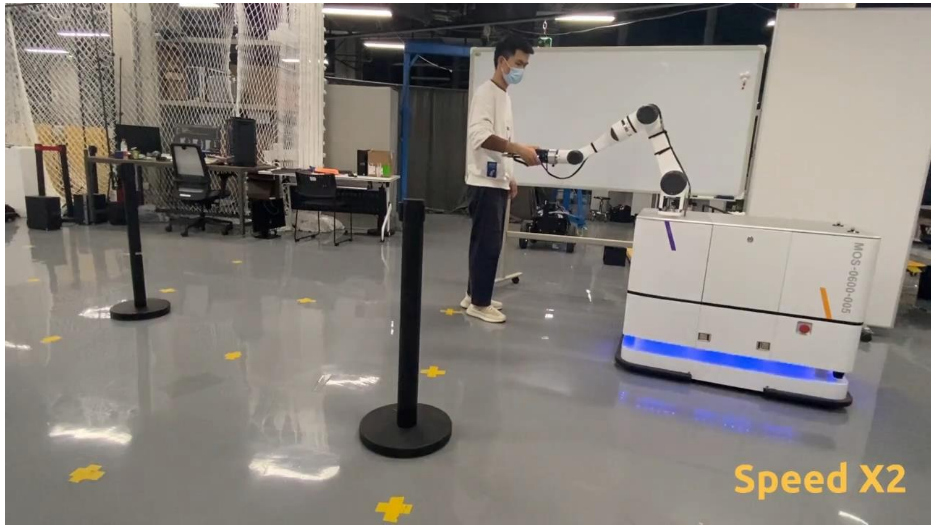
Relative Localization | Environment Perception | Decision Making and Planning

Fundamental Technologies

Multi-robot Collaborative Manipulation

Planning for Multi-robot collaborative mobile transportation (ICRA 2021)



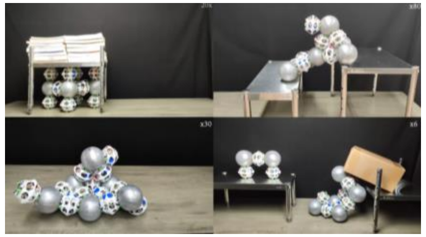


Whole-Body Control (Humanoids 2022)

Robot-to-human Object Handover (CBS 2024, IROS 2022)

Freeform Robotics - Research Focus

Types of Multi-robot Collaboration

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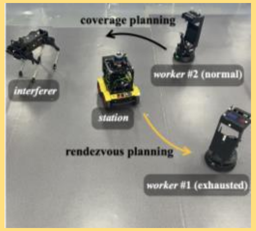

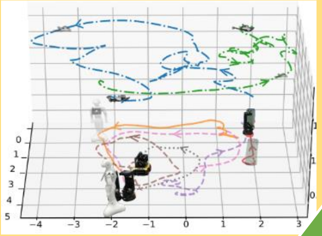

Mobile Collaboration

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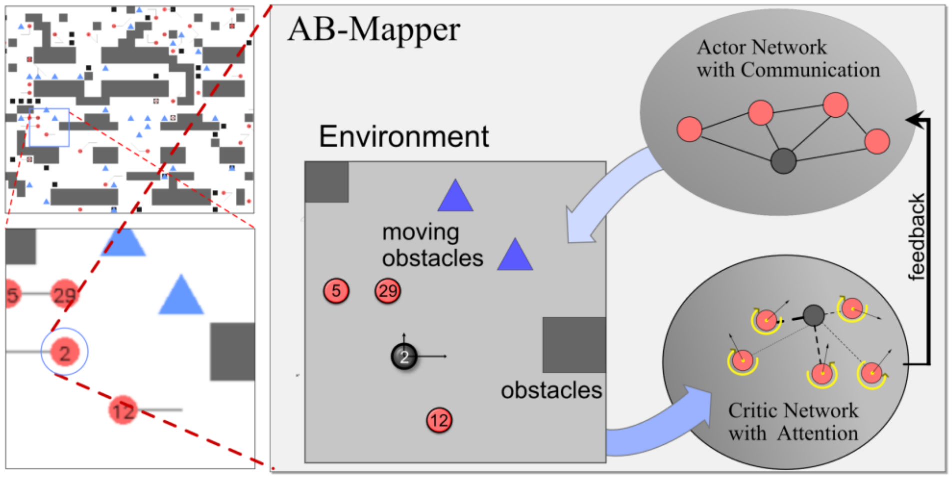
Relative Localization | Environment Perception | Decision Making and Planning

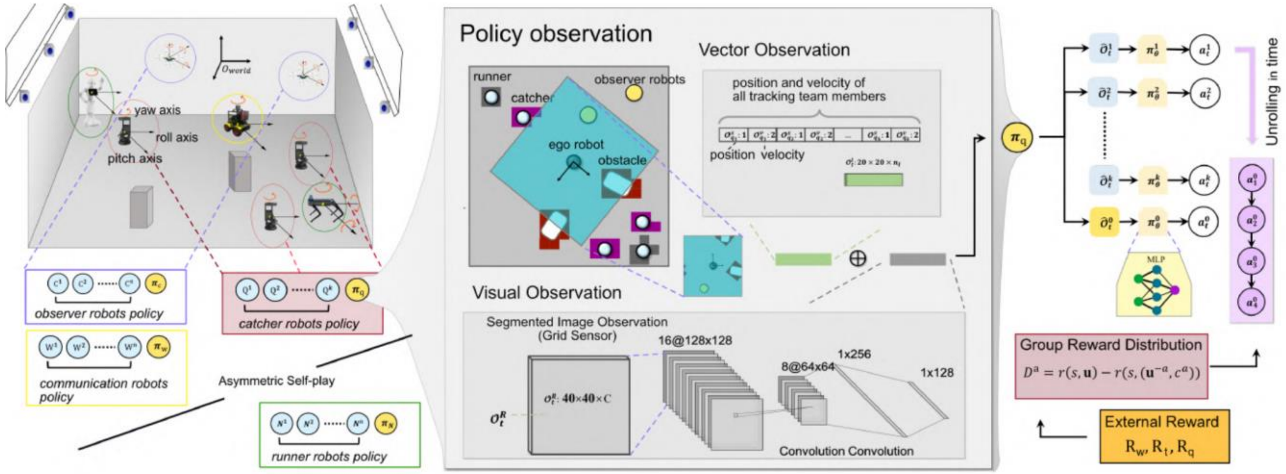
Fundamental Technologies

Multi-robot Mobile Collaboration

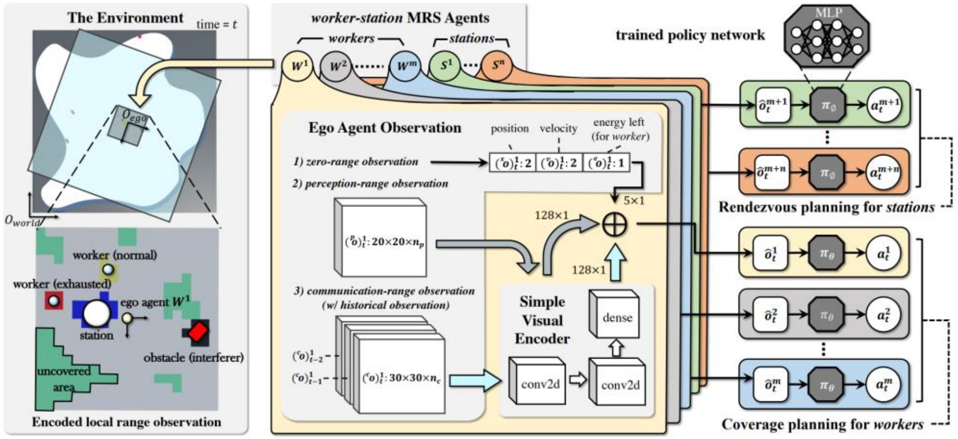
Path planning in dynamic environment (IROS 2022)



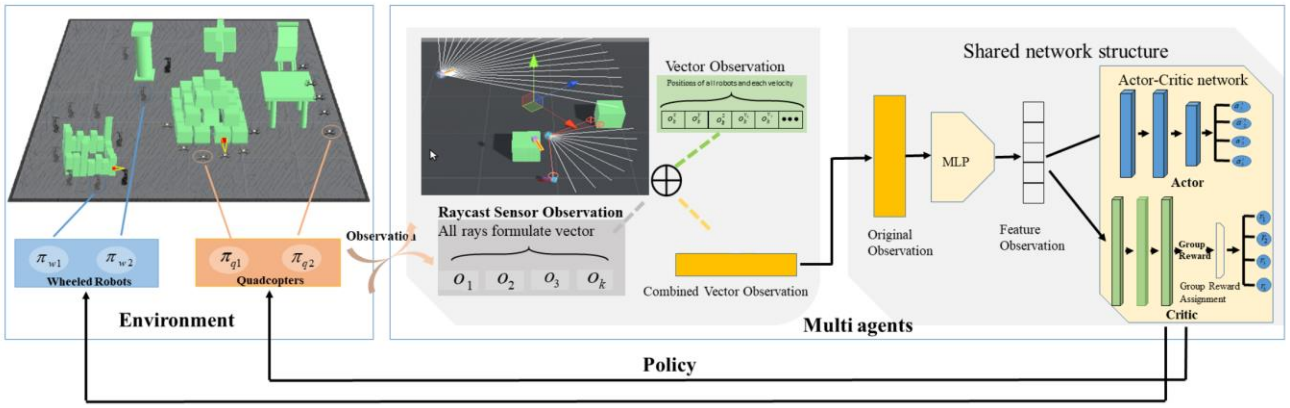
Heterogeneous Team for Catching (TRO 2023)



Heterogeneous Team for Coverage Task (RAL 2022)



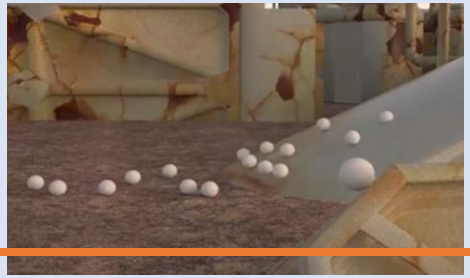
Heterogeneous Team for 3D Surface Inspection (ICRA 2024)



Challenges

1. **How do robots achieve physical collaboration?**
   - Efficient and robust connectors and actuators

2. **How do robots identify the position of each other?**
   - Multi-robot self-contained relative localization



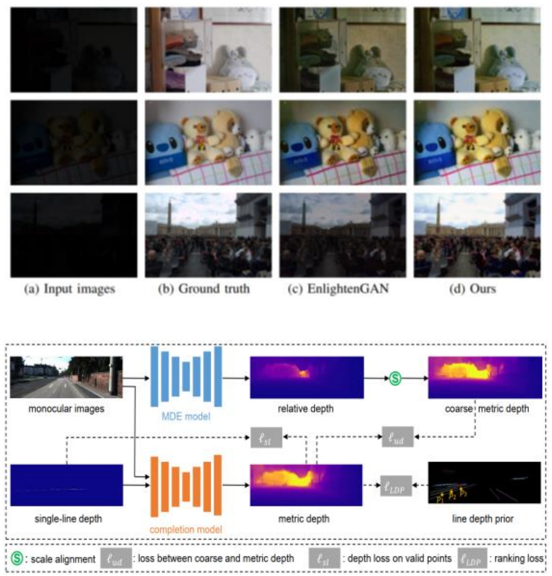
3. **How do robots achieve environment perception?**
   - Source-inconsistent data fusion (hardware, time, viewpoint)

4. **How do robots collaborate to perform tasks?**
   - Multi-robot collaborative planning in dynamic environment

3. Multi-robot Environment Perception

Sensing Enhancement

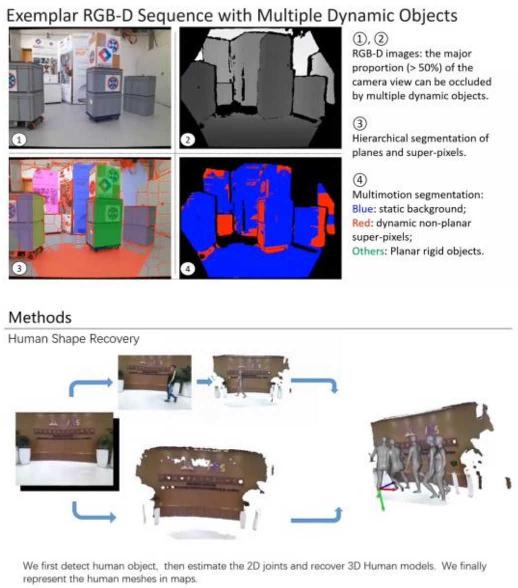
Sensing quality inconsistent (hardware, time)



(RAL 2021, TPAMI 2022, ICASSP 2023, RAL 2023, TNNLS 2023, KBS 2023)

Interference Cancellation

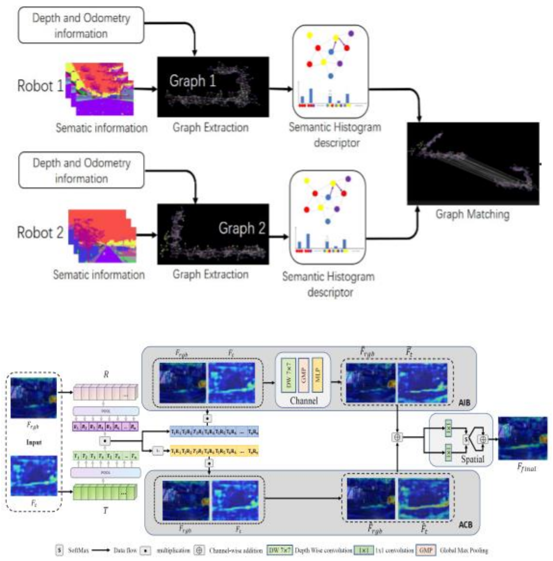
Interference of dynamic objects (robots, human)



(IROS 2021, RAL 2022, TCVST 2023)

Data Fusion

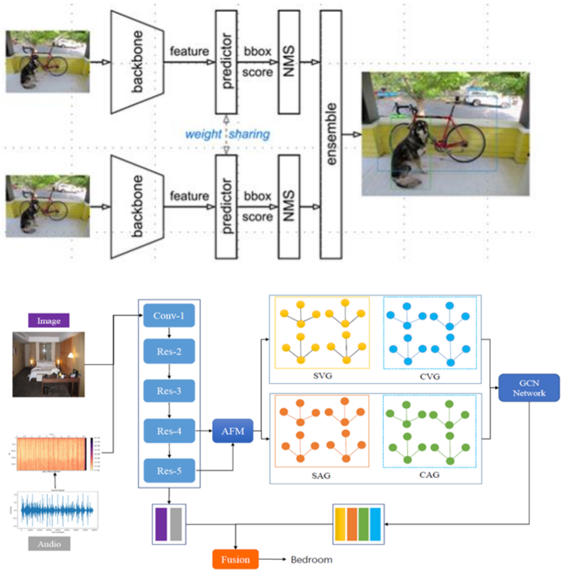
Multimodal, viewpoint inconsistent



(RAL 2021, RAL 2023)

Cognition

Inter-class and inner-class diversity



(IROS 2021, TIP 2022, TIM 2023, CAAI TIT 2024)

Thank You!

Freeform Robotics

freeformrobotics.org