香港中文大學（深圳）
The Chinese University of Hong Kong, Shenzhen

AIRS
SHENZHEN INSTITUTE of ARTIFICIAL INTELLIGENCE AND ROBOTICS for SOCIETY
深圳市人工智能与机器人研究院

Freeform Cellular Robots:
Design, Modeling, Sensing and Control

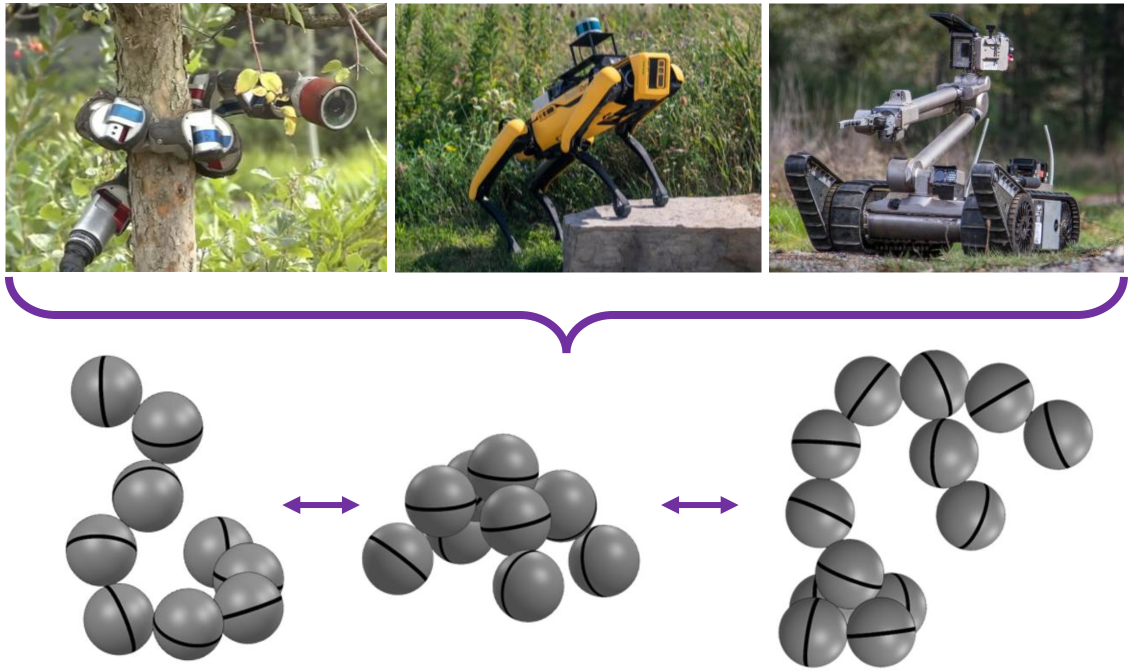
Guanqi LIANG
2024/10/22

Outline

- I Background
- II Design
- III Modeling
- IV Sensing
- V Control
- VI Conclusion

Outline

Background

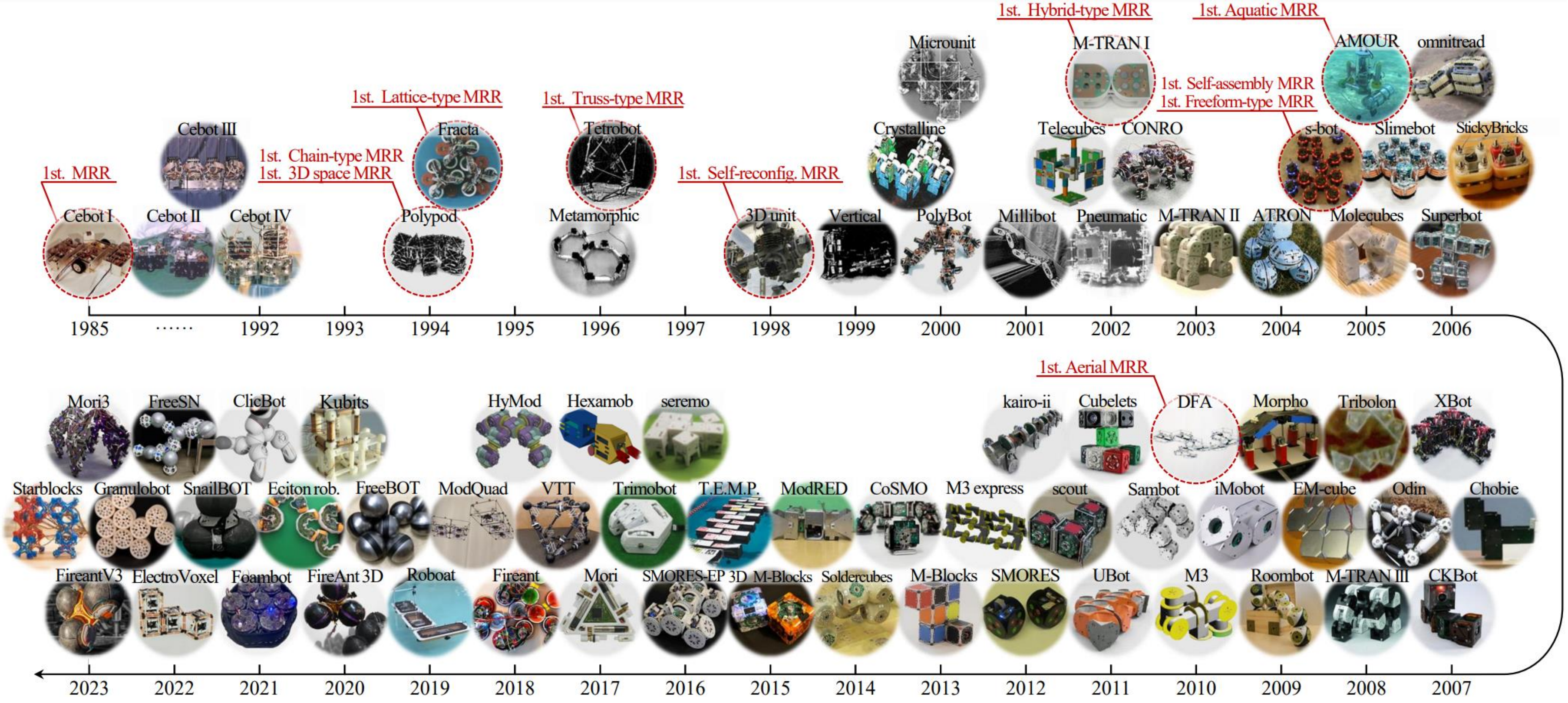


- Fixed-configuration robots have set functions and lack flexibility.
- Reconfigurable robots can change shape to adapt to different tasks.
- Science fiction explores imaginative uses for these reconfigurable robots.

Background

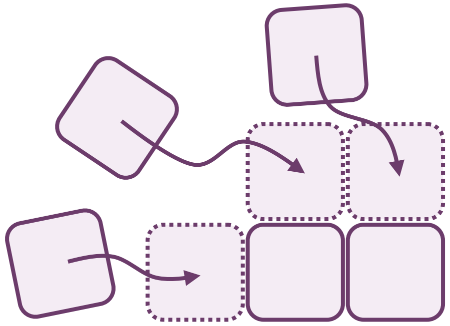
Modularity + Reconfigurability:

By reconfiguring the allocation of modules, the robotic system can attain varied morphologies.

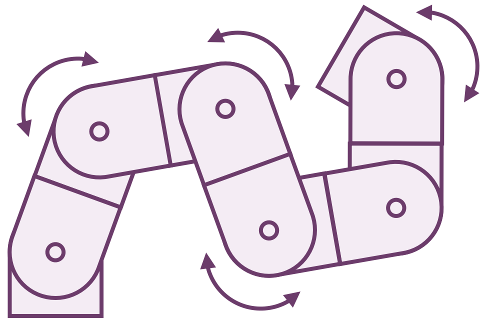


Limitations

- Requires precise face-to-face docking



- Configuration/Motion restricted by constraints



G. Liang, D. Wu, Y. Tu, T. L. Lam, "Decoding Modular Reconfigurable Robots: A Survey on Mechanisms and Design," ***International Journal of Robotics Research* (IJRR),** 2024

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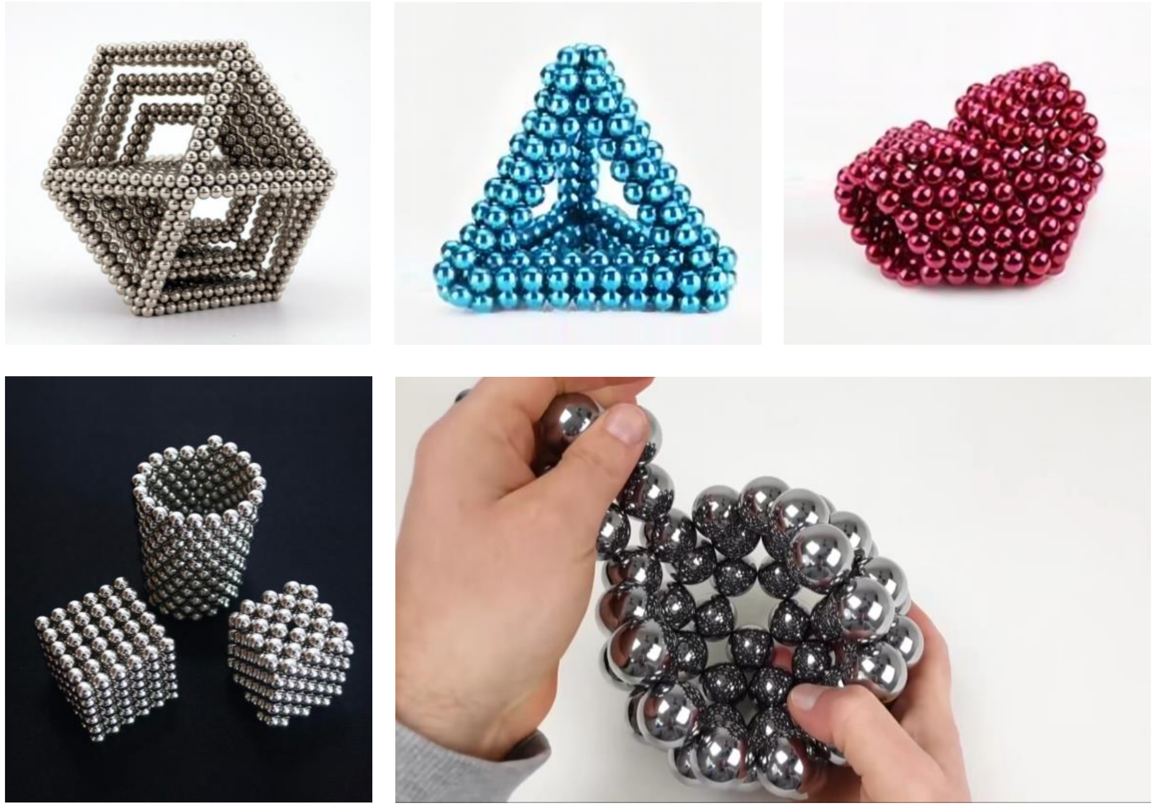
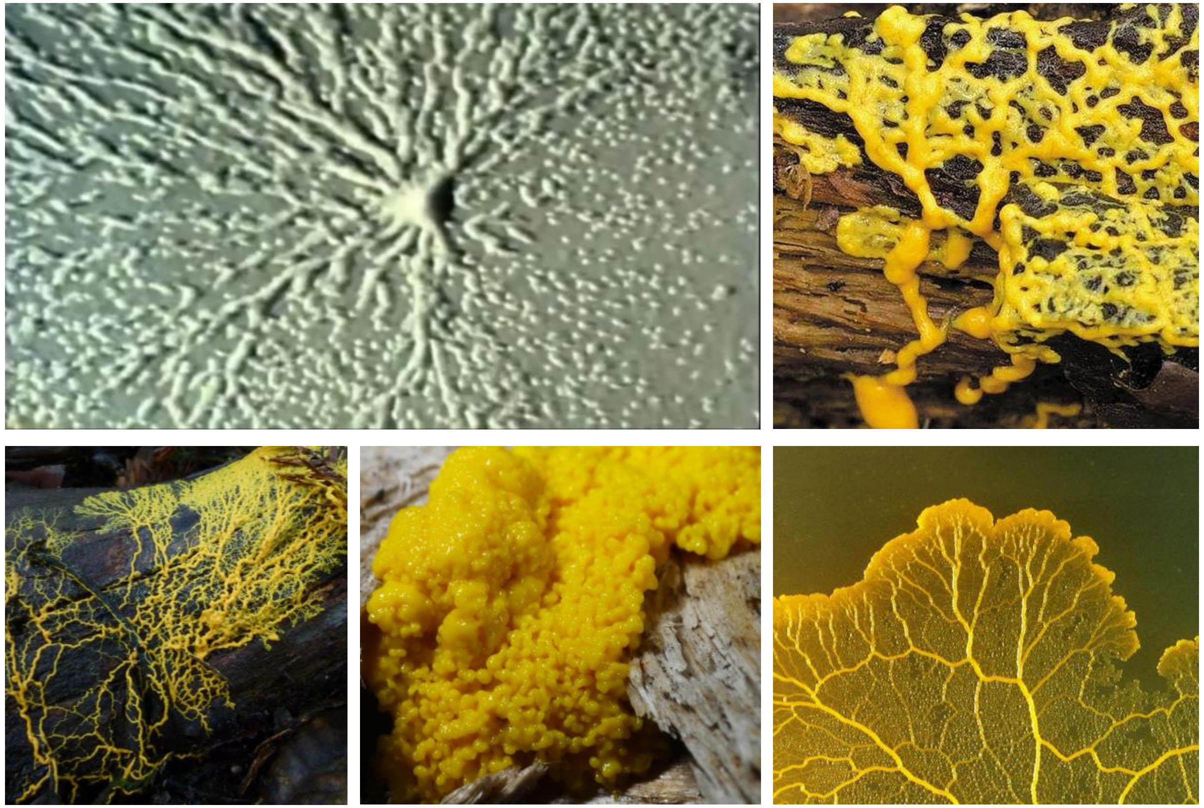
Inspiration

- Buckyball can freely combined and changed into different forms

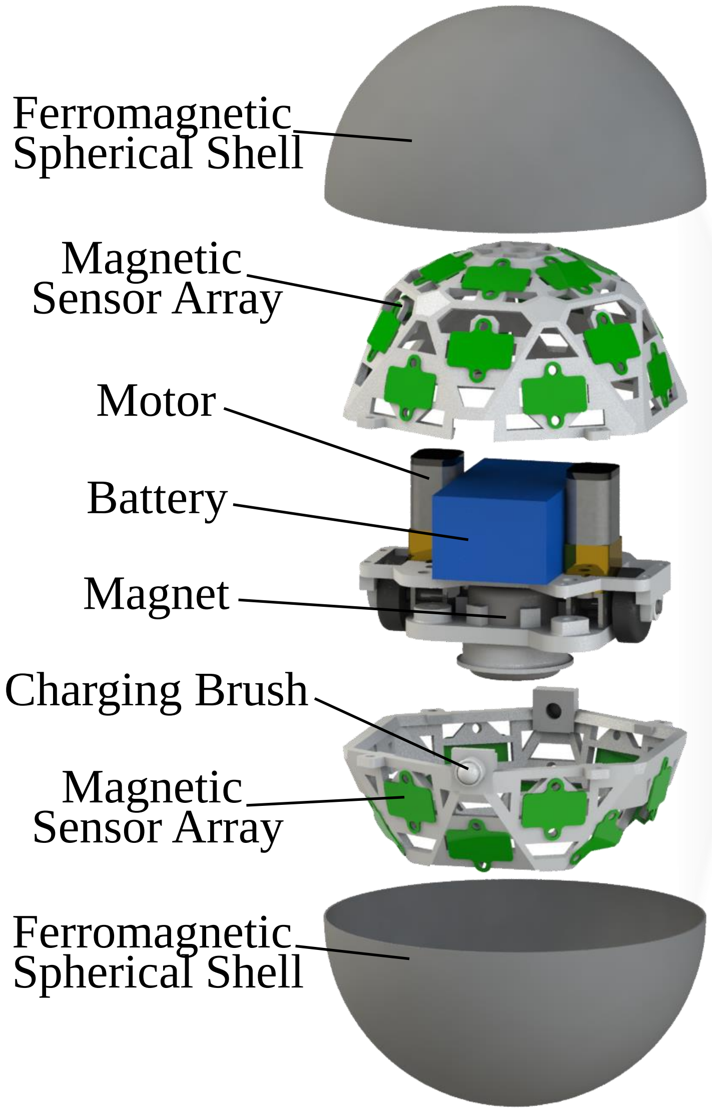


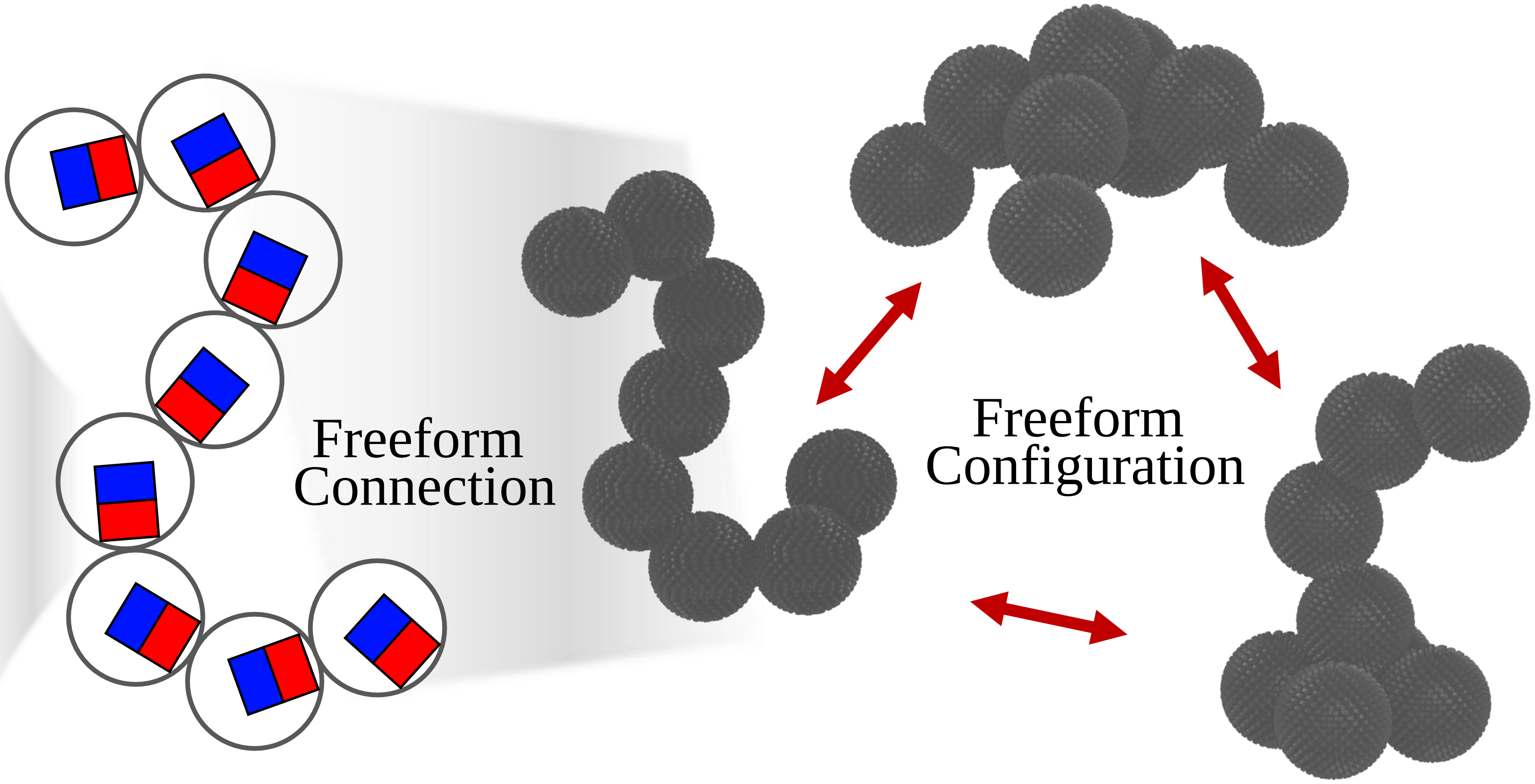
- Groups of slime mold cells can morph into different shapes



We hope to give such characteristics to modular reconfigurable robots

Design of FreeBOT





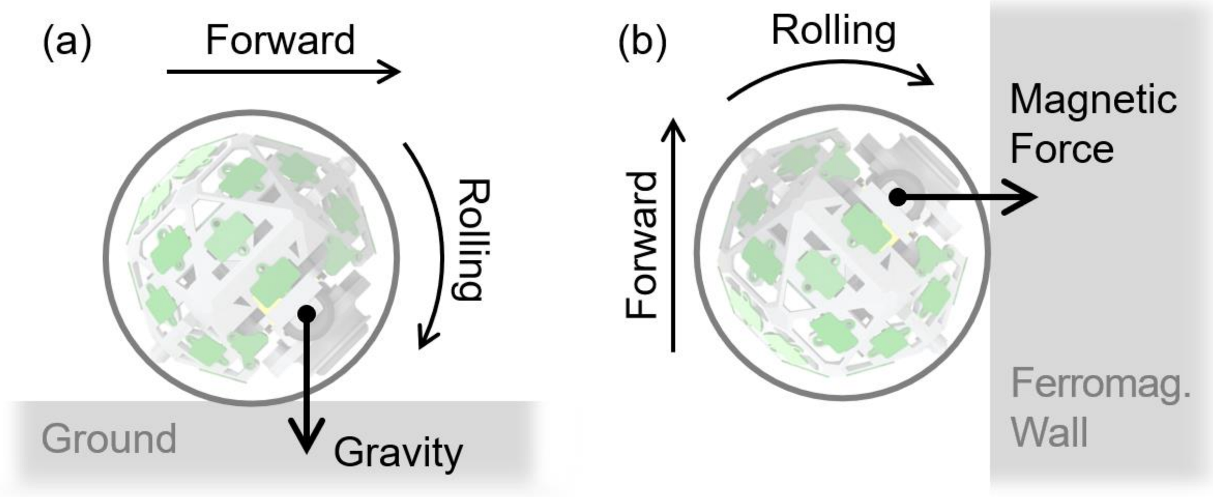
Ferromagnetic Sphere + Trolley with Magnet

= Spheres to connect and move freely at any point

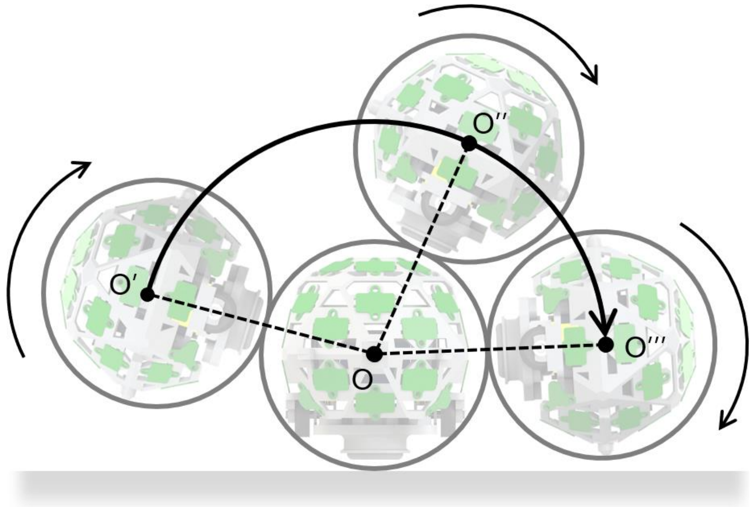
G. Liang, H. Luo, M. Li, H. Qian and T. L. Lam, "FreeBOT: A Freeform Modular Self-reconfigurable Robot with Arbitrary Connection Point – Design and Implementation," **IROS 2020**

Movements of FreeBOT

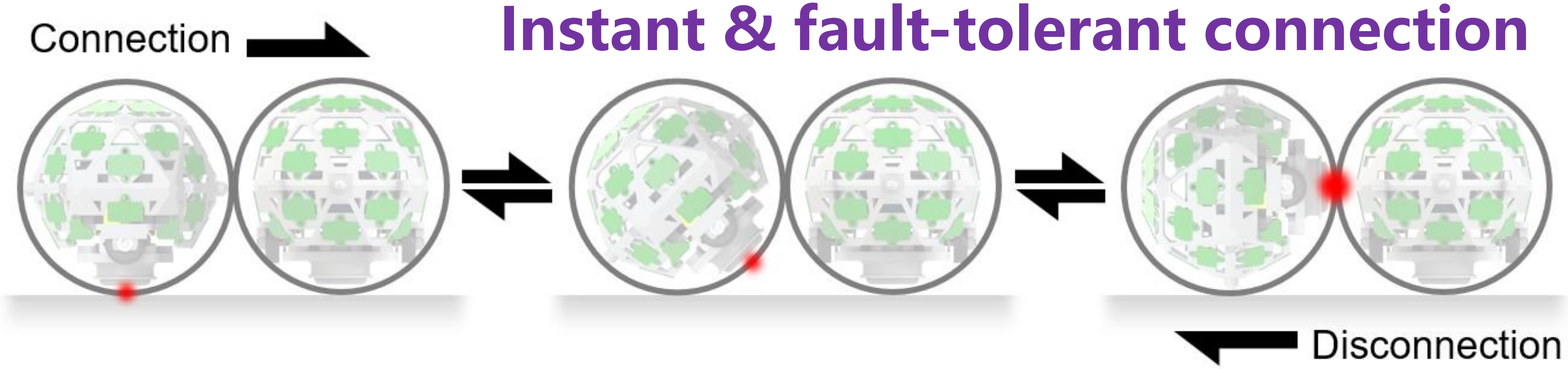
Locomotion across diverse terrains



Dexterous Joint Motion



Instant & fault-tolerant connection



Two motors enable all movements

G. Liang, H. Luo, M. Li, H. Qian and T. L. Lam, "FreeBOT: A Freeform Modular Self-reconfigurable Robot with Arbitrary Connection Point – Design and Implementation," **IROS 2020**

FreeBOT Prototype

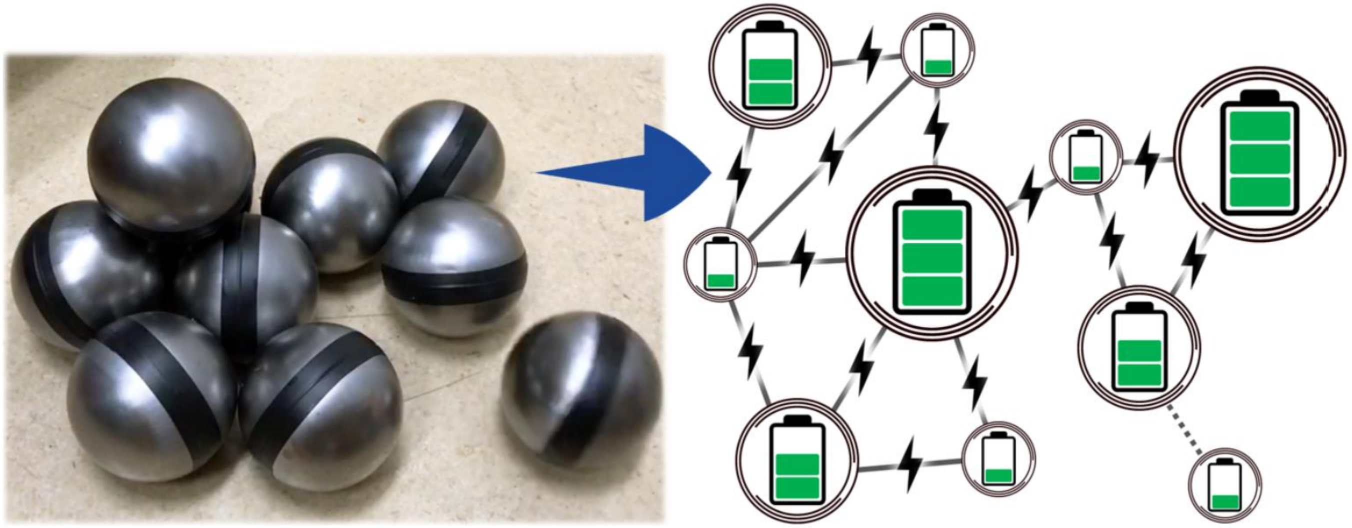
- Instant and fault-tolerant connection
- Move and connect freely among spheres

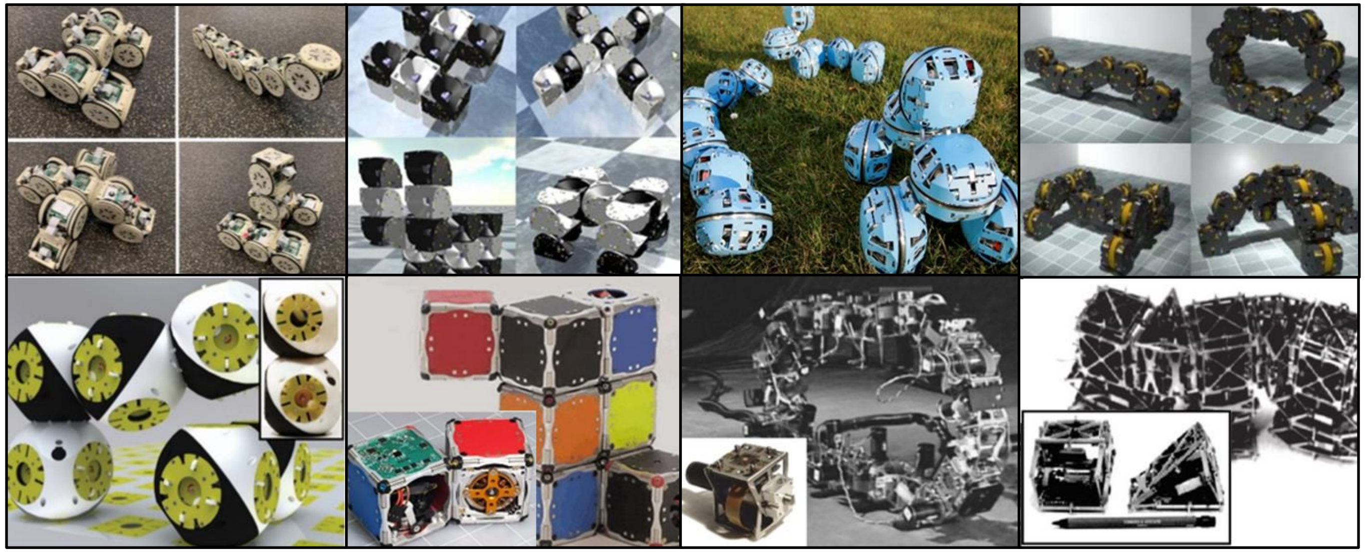
🏆 IROS Best Paper Award on Robot Mechanisms and Design (1/2996)

G. Liang, H. Luo, M. Li, H. Qian and T. L. Lam, "FreeBOT: A Freeform Modular Self-reconfigurable Robot with Arbitrary Connection Point – Design and Implementation," **IROS 2020**

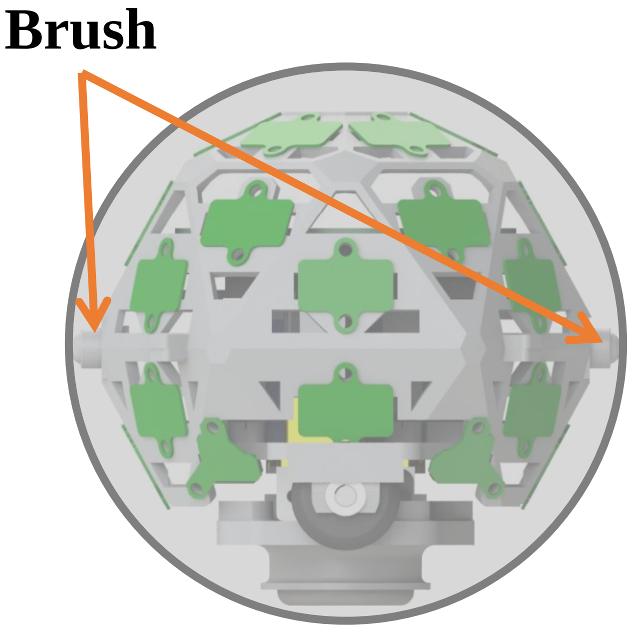
Challenges in Energy sharing

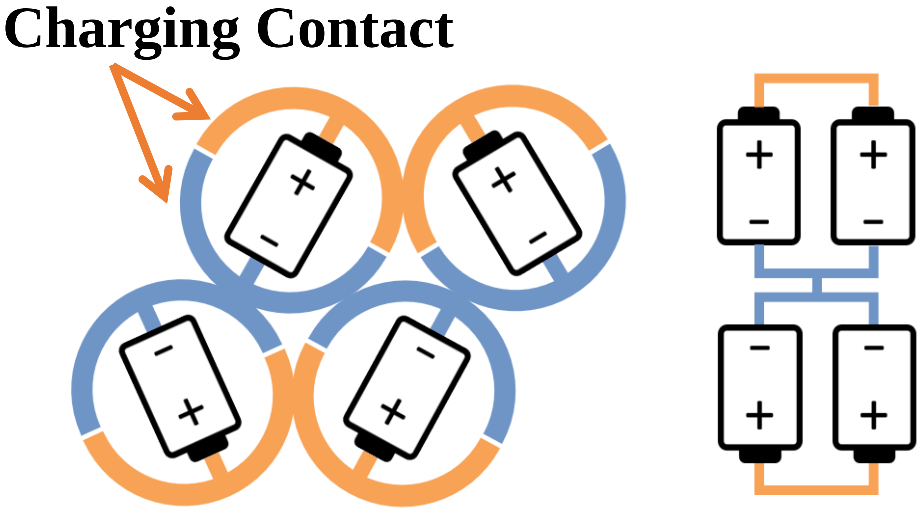
- MRR systems depend on each module energy levels and require energy sharing
- Most MRR systems use fixed-position connectors for real-time energy channels
- FreeBOT's spherical cover complicates battery and energy management.

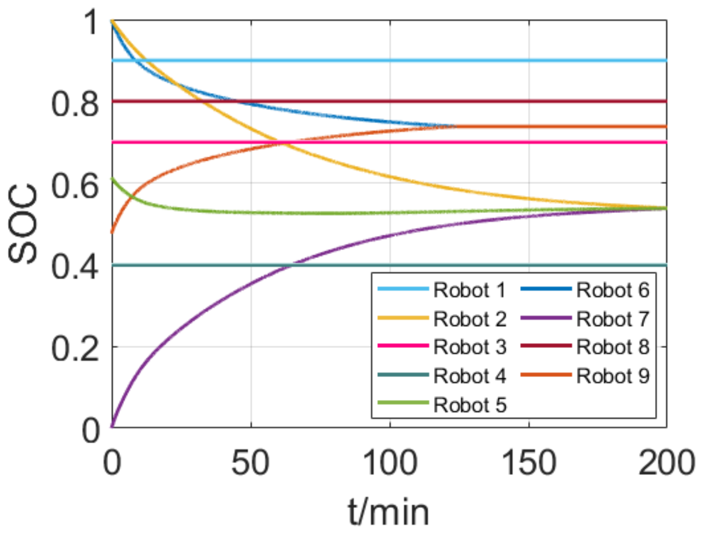




Energy sharing Mechanisms



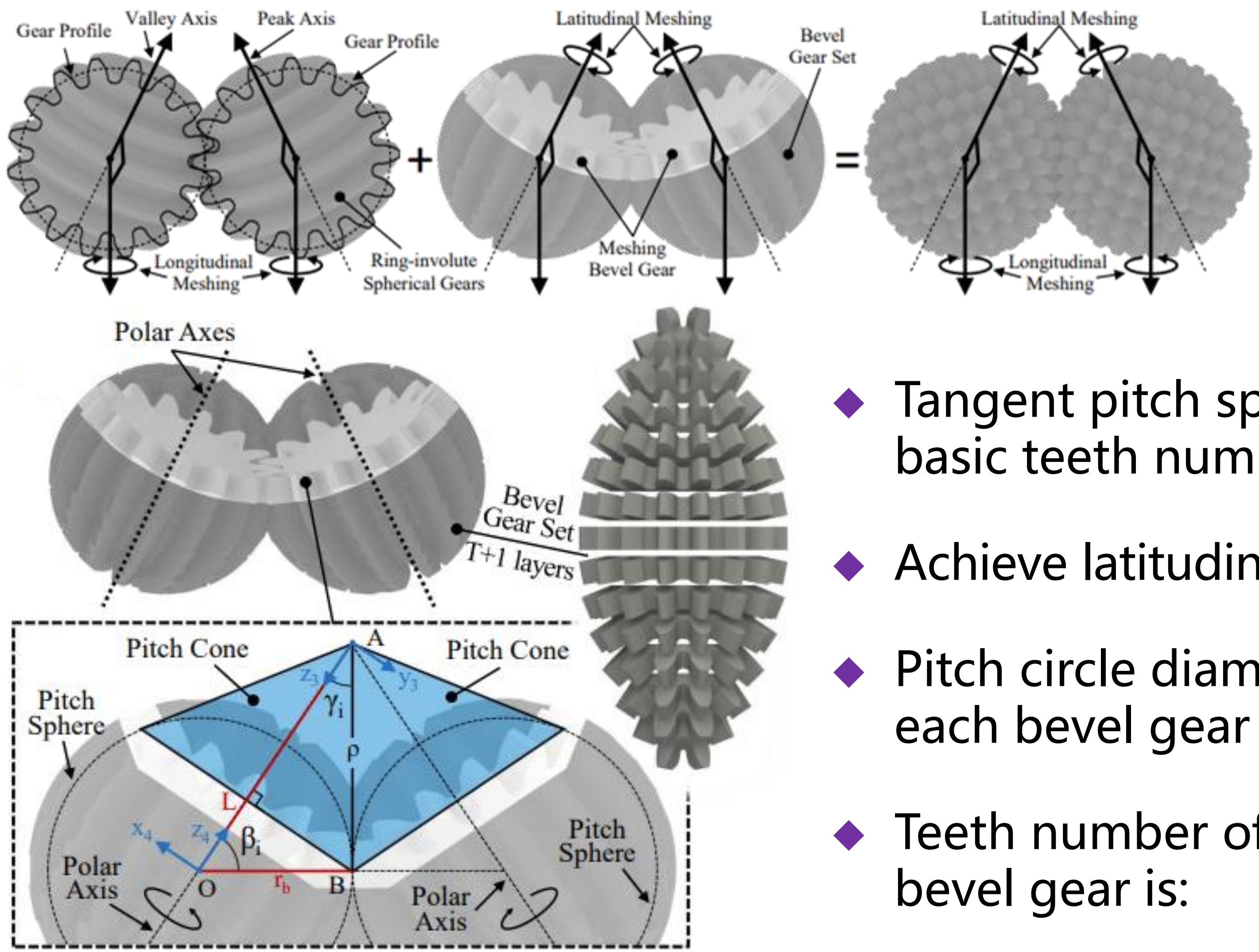




- The switchable brush mechanism extends the battery port outward
- The polarity conversion circuit matches the battery's polarity to the external one

G. Liang, Y. Tu, L. Zong, J. Chen, T. L. Lam, "Energy Sharing Mechanism for a Freeform Robotic System - FreeBOT," **ICRA 2022**

Spherical Gear

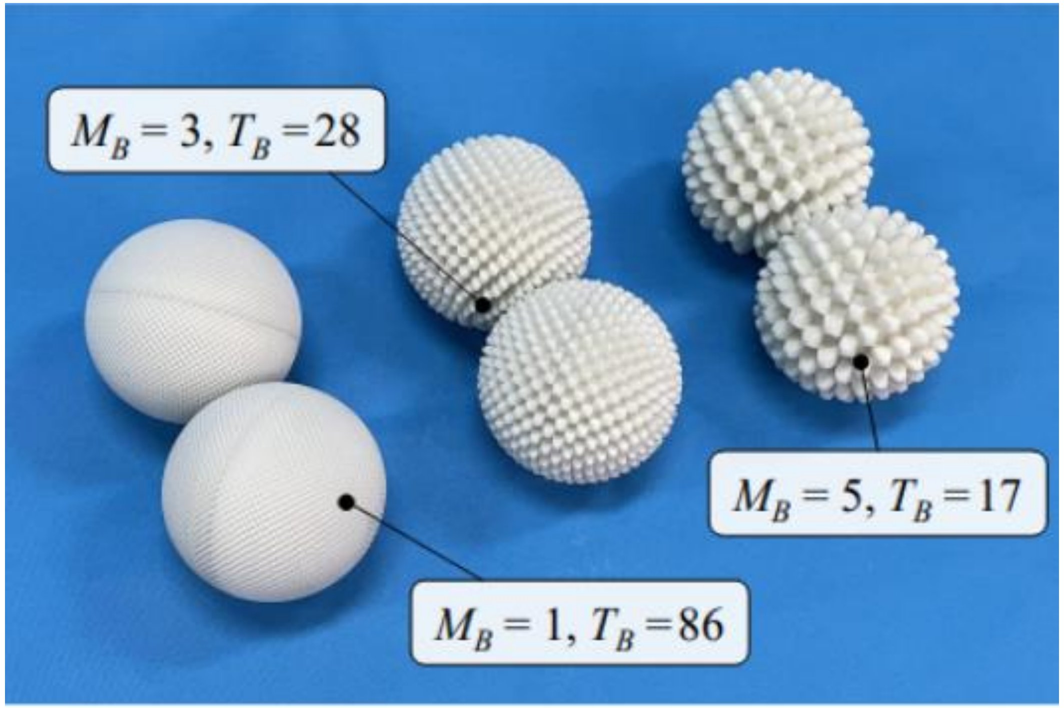


Slippage between spheres impacts the relative motion of modules

- Extend planar gear concepts into 3D
- Globally meshed Spherical Gear combining lat. & long. engagements
- Tangent pitch spheres defined by the basic teeth number & basic module: $D_B = T_B \times M_B$
- Achieve latitudinal meshing by combining T_B+1 bevel gear
- Pitch circle diameter of each bevel gear is: $D_i = D_B \times \sin(\beta_i), i \in Z, i \in [1, T_B + 1]$
- Teeth number of each bevel gear is: $T_i = \left[\frac{D_i}{M_B}\right], i \in Z, i \in [1, T_B + 1]$

G. Liang, L. Zong, T. L. Lam, "DISG: Driving-Integrated Spherical Gear Enables Singularity-Free Full-Range Joint Motion," ***IEEE Transactions on Robotics*** **(T-RO),** 2023.

Spherical Gear



- Prototypes of various parameters
- No-slip rolling between spheres
- Extensive motion range & dexterous joint applications.

G. Liang, L. Zong, T. L. Lam, "DISG: Driving-Integrated Spherical Gear Enables Singularity-Free Full-Range Joint Motion," ***IEEE Transactions on Robotics*** **(T-RO),** 2023.

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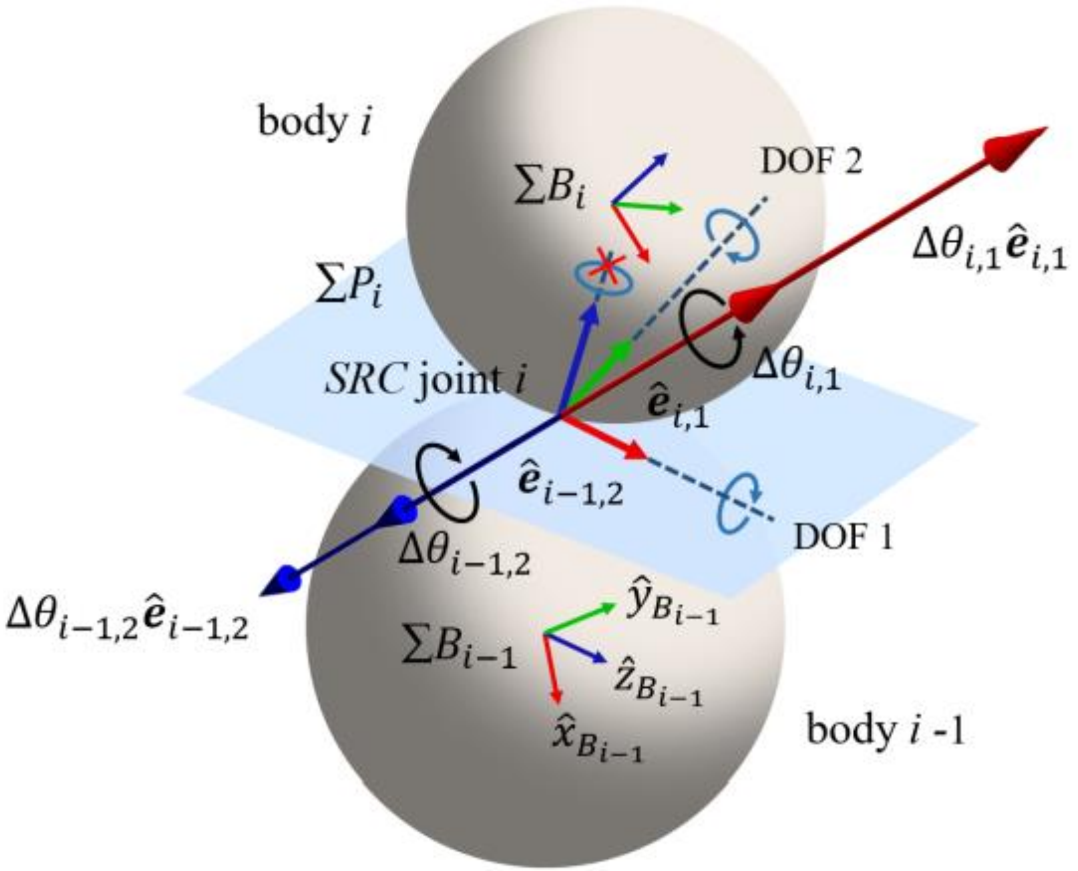
Spherical Rolling Contact Modeling

FreeBOT's unique motion mode surpasses existing model descriptions



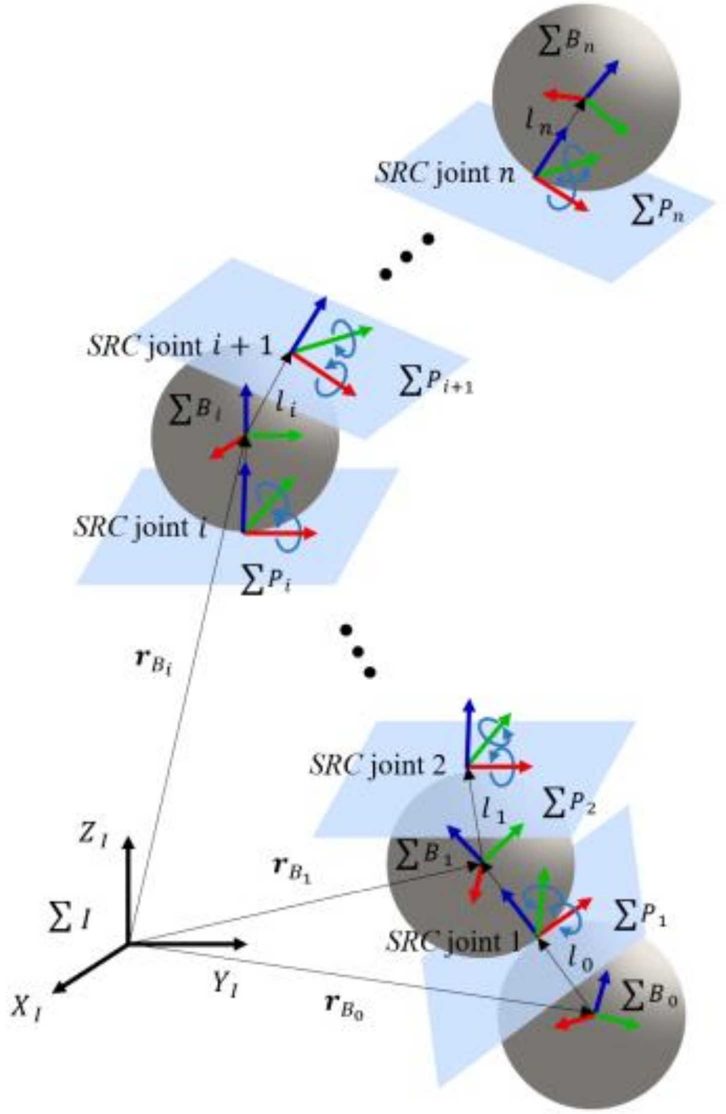
Rotation matrix, ${}^{B_{i-1}}\boldsymbol{R}_{B_i}$	$\boldsymbol{q}_i = \widetilde{\boldsymbol{q}}_{i-1,2}\boldsymbol{q}_{i,1}$
Position vector, ${}^{B_{i-1}}_{P_i}\boldsymbol{r}_{B_i}$	$\begin{bmatrix} 0 \\ 0 \\ l_i + l_{i-1} \end{bmatrix}$
Free modes, $\boldsymbol{\Phi}_i$	$\begin{bmatrix} \boldsymbol{f}_1(\boldsymbol{q}_{i-1,2}) & \boldsymbol{f}_2(\boldsymbol{q}_{i-1,2}) \\ -l_{i-1}\boldsymbol{f}_3^{\times}\boldsymbol{f}_1(\boldsymbol{q}_{i-1,2}) & -l_{i-1}\boldsymbol{f}_3^{\times}\boldsymbol{f}_2(\boldsymbol{q}_{i-1,2}) \end{bmatrix}$
Pose variables	$\boldsymbol{q}_i$
Velocity variables	$\begin{bmatrix} {}^{B_{i-1}}_{P_i}\omega_{B_{ix}} \\ {}^{B_{i-1}}_{P_i}\omega_{B_{iy}} \end{bmatrix}$

- FreeBOT adheres to the constraint of rolling without sliding
- Virtual tangent plane briefly describes.
- The first spatial rolling contact motion

Circular Rolling Contact

L. Zong, **G. Liang**, T. L. Lam, "Kinematics Modeling and Control of Spherical Rolling Contact Joint and Manipulator," ***IEEE Transactions on Robotics*** **(T-RO)**, 2023.

Chain Modeling



Rotation matrix $^{I}\boldsymbol{R}_{B_n} = {}^{I}\boldsymbol{R}_{B_0} \prod_{i=1}^{n} \left({}^{B_{i-1}}\boldsymbol{R}_{B_i} \right)$

Position $^{I}_{I}\boldsymbol{r}_{B_i} = {}^{I}_{I}\boldsymbol{r}_{B_0} + \sum_{j=1}^{i} \left({}^{I}\boldsymbol{R}_{B_{j-1}} {}^{B_{j-1}}_{B_{j-1}}\boldsymbol{r}_{B_j} \right)$

Angular velocity $^{I}_{I}\boldsymbol{\omega}_{B_i} = \sum_{j=1}^{i} \left({}^{I}\boldsymbol{R}_{B_{j-1}} \boldsymbol{\Phi}_{j\omega} \begin{bmatrix} {}^{B_{j-1}}_{P_j}\omega_{B_{jx}} \\ {}^{B_{j-1}}_{P_j}\omega_{B_{jy}} \end{bmatrix} \right) + {}^{I}_{I}\boldsymbol{\omega}_{B_0}$

Linear velocity $^{I}_{I}\boldsymbol{v}_{B_i} = {}^{I}_{I}\boldsymbol{v}_{B_0} + {}^{I}_{I}\boldsymbol{r}^{\times}_{0i} {}^{I}_{I}\boldsymbol{\omega}_{B_0} + \boldsymbol{J}_{B_i v}\boldsymbol{\omega}$

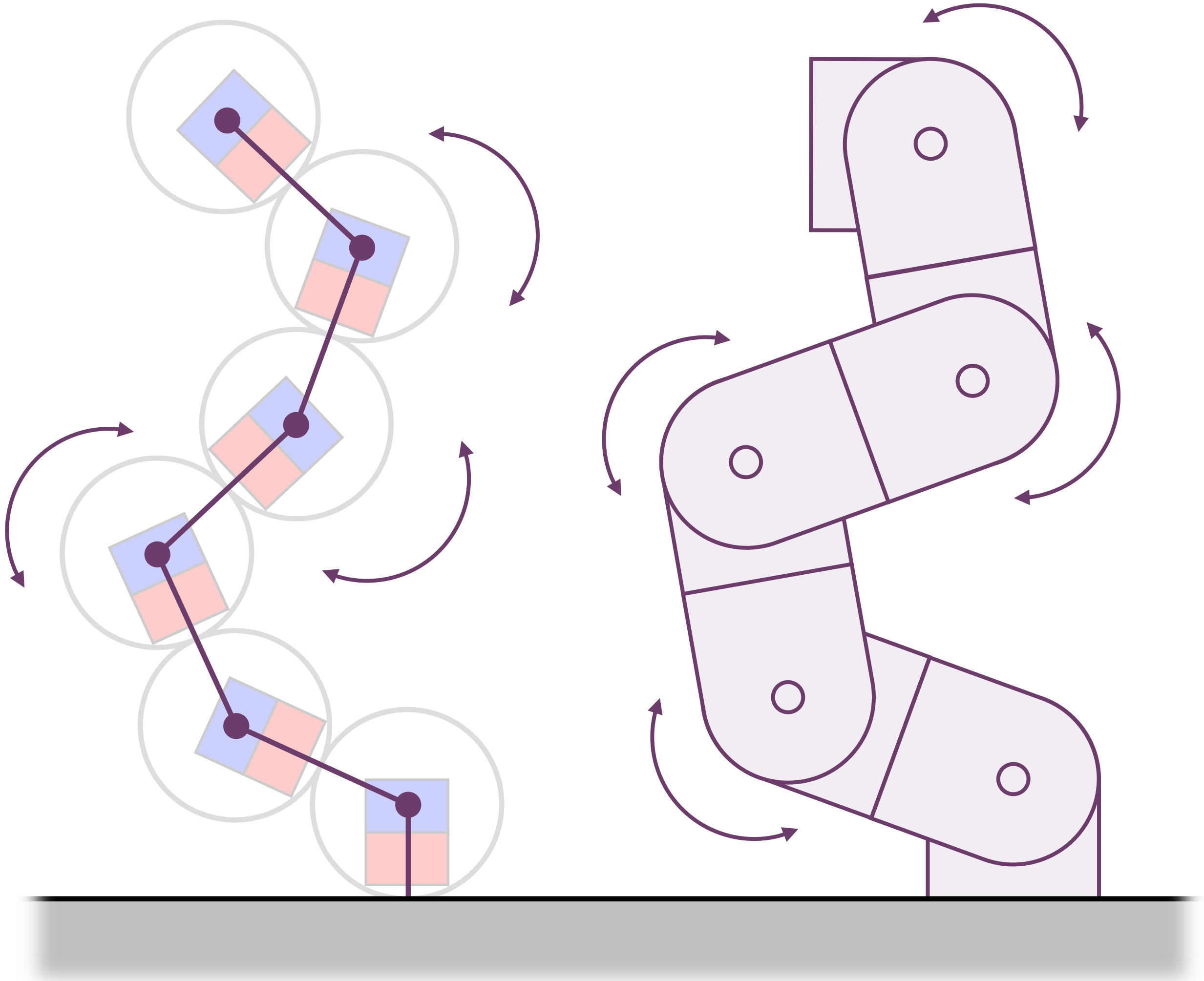
- Modeling FreeBOT Chain Configuration
- Enhanced Dexterity & Extensive Motion Range
- Dexterous Manipulation with High DoF

L. Zong, **G. Liang**, T. L. Lam, "Kinematics Modeling and Control of Spherical Rolling Contact Joint and Manipulator," ***IEEE Transactions on Robotics*** **(T-RO),** 2023.

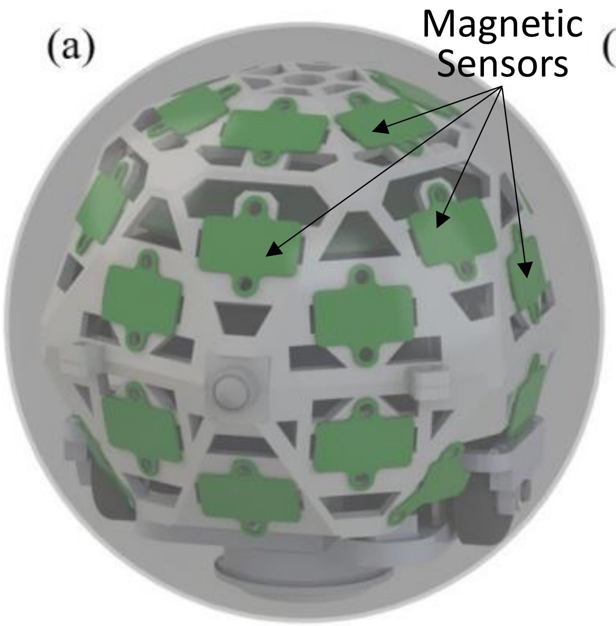
Outline

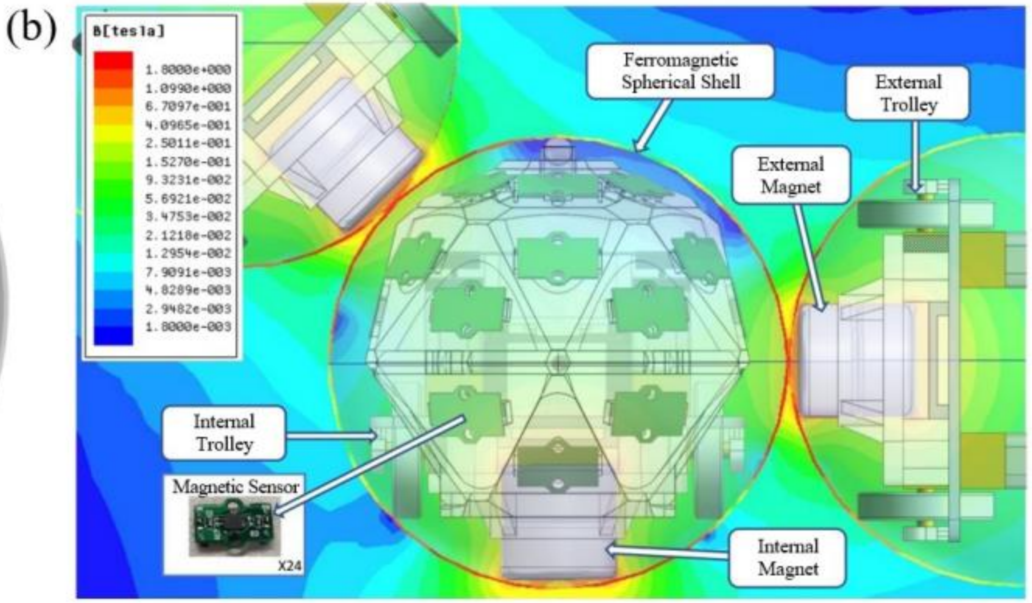
Challenges in Sensing

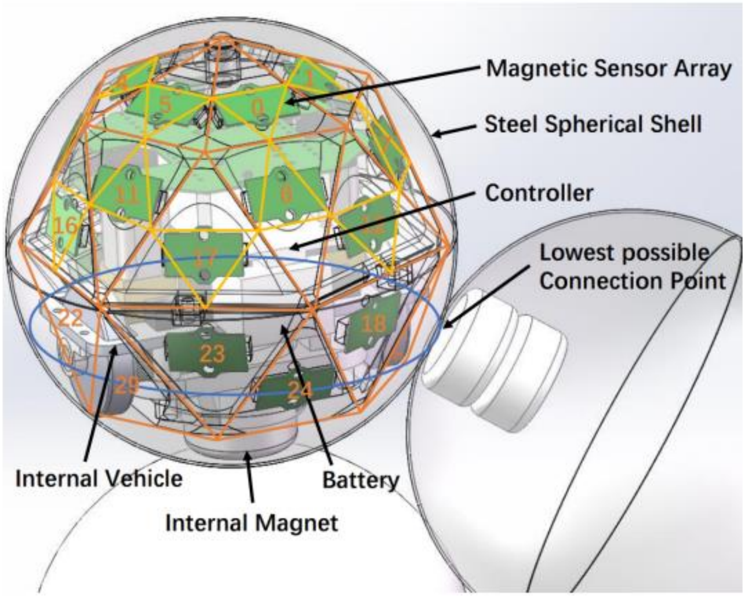
- MRR systems reconfigure module placements for task mobility
- Traditional MRR systems use specialized joint driver, enabling measurement via encoders
- FreeBOT's novel motion mode & spherical coverage present challenges in sensing



Magnetic Sensor Array







- FreeBOT features magnetic sensor array
- Detect the magnetic field on the sphere
- Pinpoint the magnetic connection points

- Magnet position determines the magnetic field

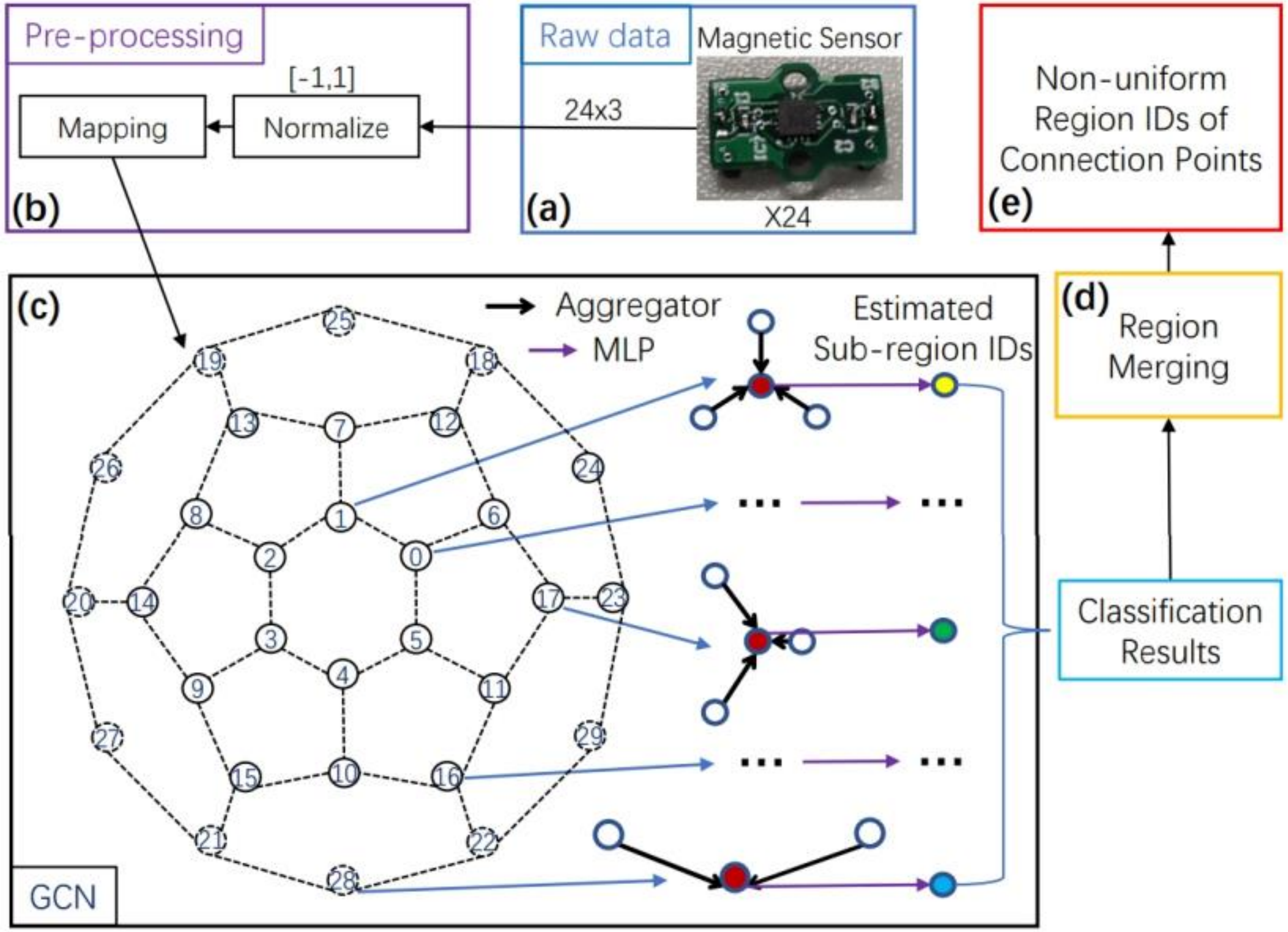
$$B_{\text{sens}} = f(\phi_1, \theta_1, \ldots, \phi_N, \theta_N)$$

- Calculate magnet position based on sensed field

$$(\phi_1, \theta_1, \ldots, \phi_N, \theta_N) = f^{-1}(B_{\text{sens}})$$

Y. Tu, **G. Liang,** T. L. Lam, "Graph Convolutional Network based Configuration Detection for Freeform Modular Robot Using Magnetic Sensor Array," **ICRA 2021.**

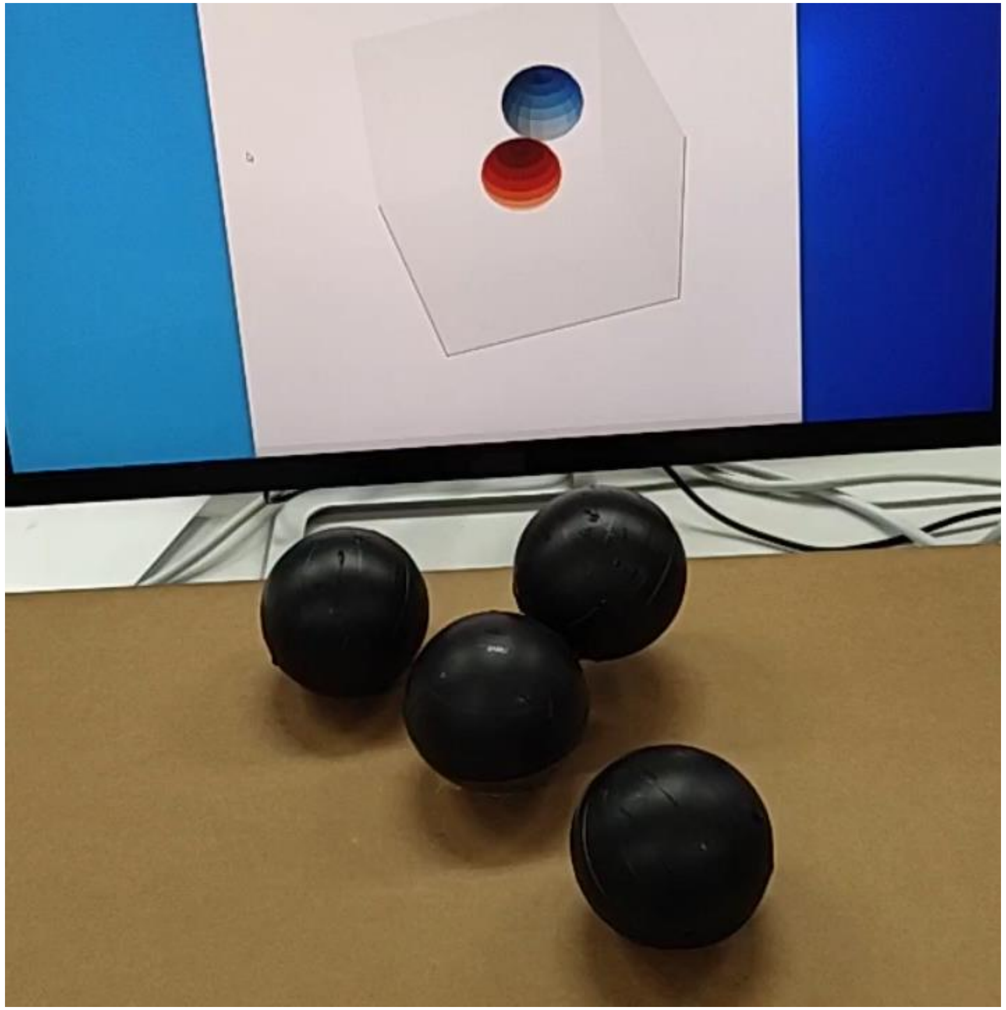
Magnetic Localization



- 3D magnetic sensors densely cover the sphere
- Connection alters sensor readings
- Sampling characteristics across the full sphere
- GCN to classify & merge
- Real-time Localization

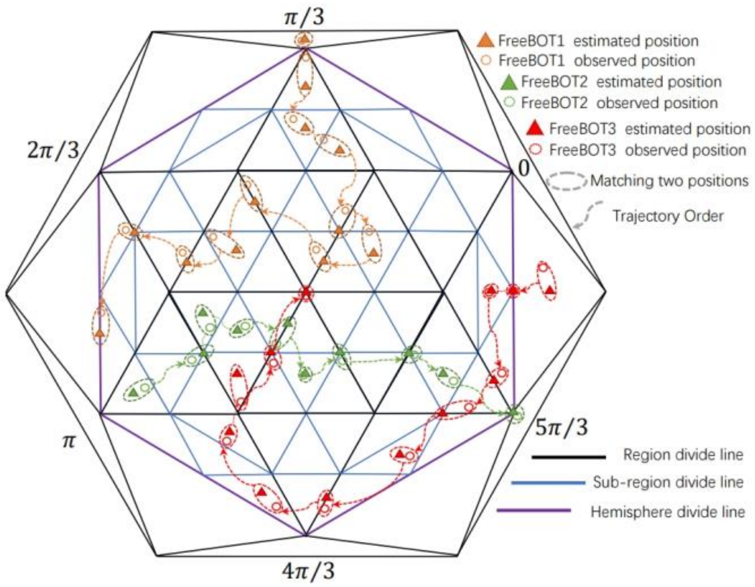
Y. Tu, **G. Liang,** T. L. Lam, "Graph Convolutional Network based Configuration Detection for Freeform Modular Robot Using Magnetic Sensor Array," **ICRA 2021.**

Sensing Results



- Real-time, good-performance FreeBOT connection point determination.
- Multiple FreeBOTs connect simultaneously
- Lightweight onboard computing resources

	Training Accuracy	Validation Accuracy
Group 1	92.2	91.8
Group 2	96.8	94.4
Group 3	96.1	95.3
Group 4	98.1	97.4
Group 5	97.4	94.6
Group 6	98.6	96.2
Group 7	99.2	97.1
Group 8	98.1	97.0
Group 9	98.5	97.5



Y. Tu, **G. Liang,** T. L. Lam, "Graph Convolutional Network based Configuration Detection for Freeform Modular Robot Using Magnetic Sensor Array," **ICRA 2021.**

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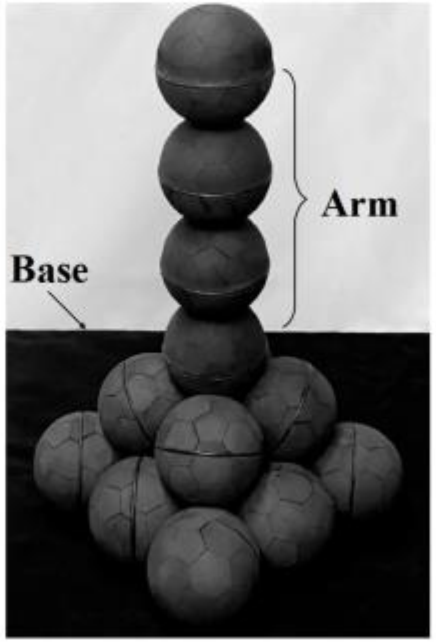
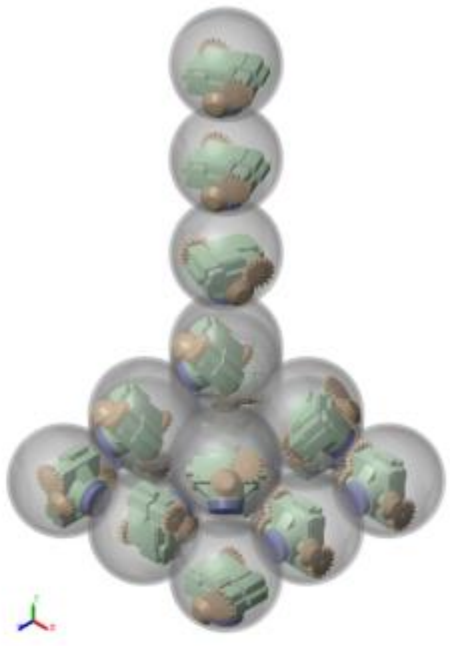
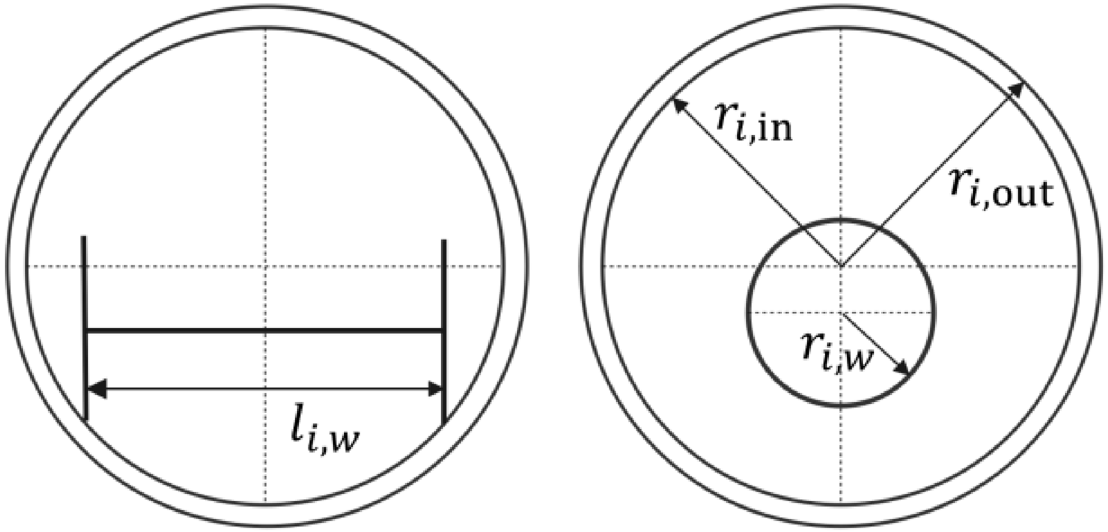
Control for FreeBOT







(a) Front view (b) Side view

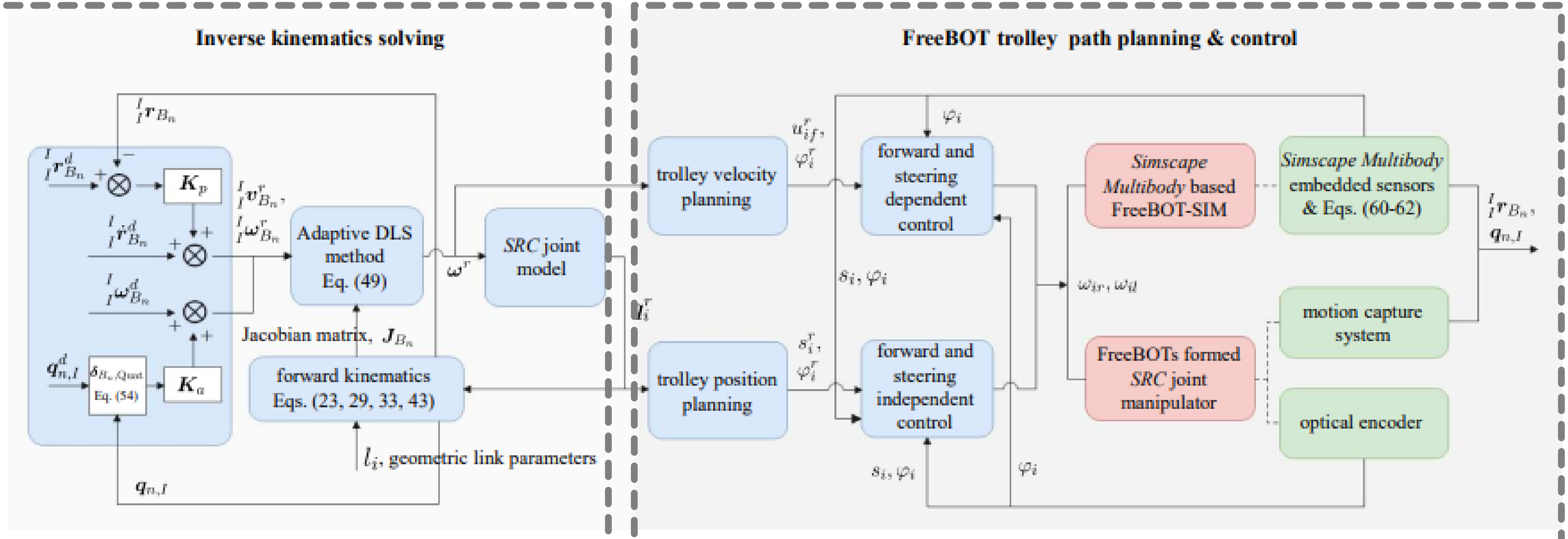
- Multiple FreeBOTs form manipulator
- Controlling multi-DOF rolling motion
- Conceptualized as spheres rolling

Controlling sphere: forward and steering

$$\begin{cases} u_{if} = \dfrac{r_{i,\text{out}}\, r_{i,w}}{\sqrt{4\, r_{i,\text{in}}^2 - l_{i,w}^2}} (\omega_{ir} + \omega_{il}) \\ u_{is} = \dfrac{r_{i,w}}{l_{i,w}} (\omega_{ir} - \omega_{il}), \end{cases} \quad \begin{cases} u_{if} = u_{if}^r \cos \varphi_{ie}, \\ u_{is} = u_{is}^r + k_{\varphi_{i,2}} u_{if}^r \sin \varphi_{ie}, \end{cases}$$

L. Zong, **G. Liang**, T. L. Lam, "Kinematics Modeling and Control of Spherical Rolling Contact Joint and Manipulator," ***IEEE Transactions on Robotics*** **(T-RO),** 2023.

Control for FreeBOT



Plan sphere positions as per task requirements

Drive the trolley to position the sphere

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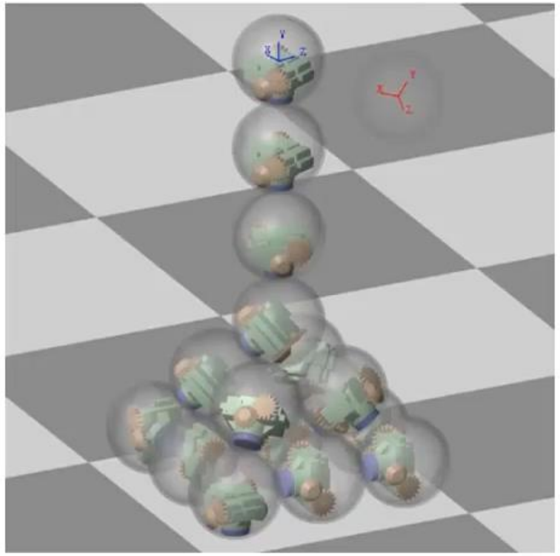
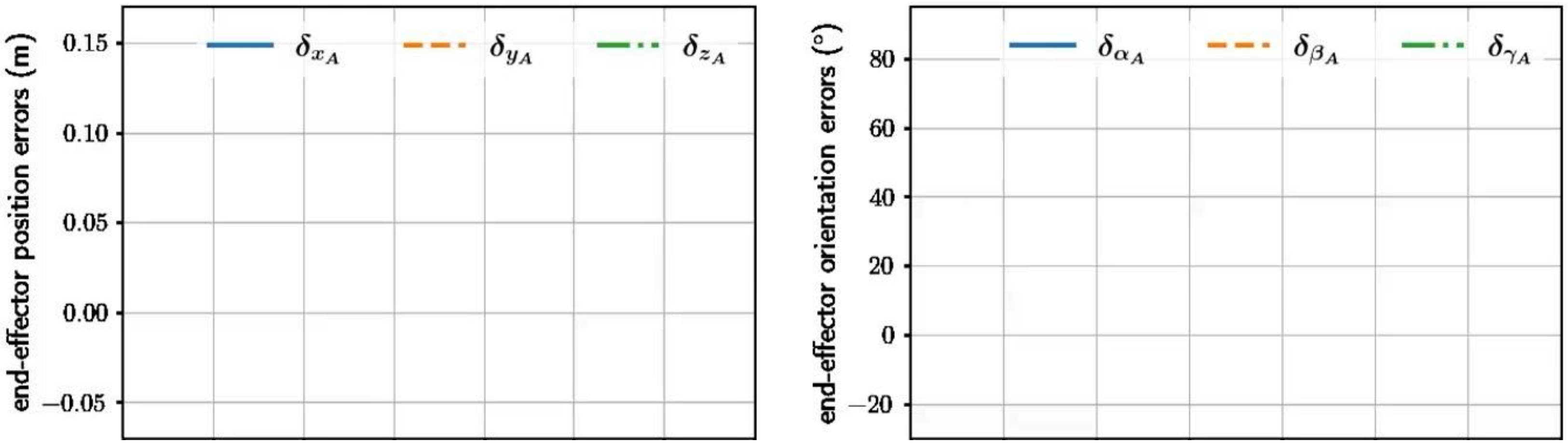
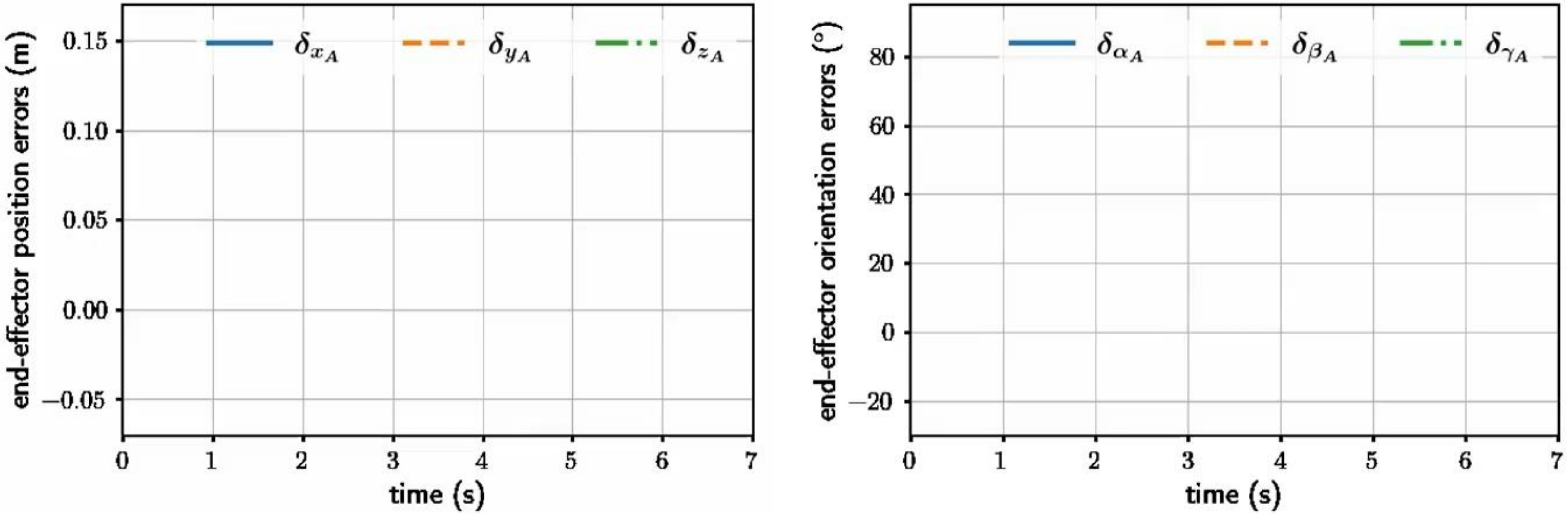
Model-based Chain Control





Position error: < 4mm，Attitude error: < 1.5°



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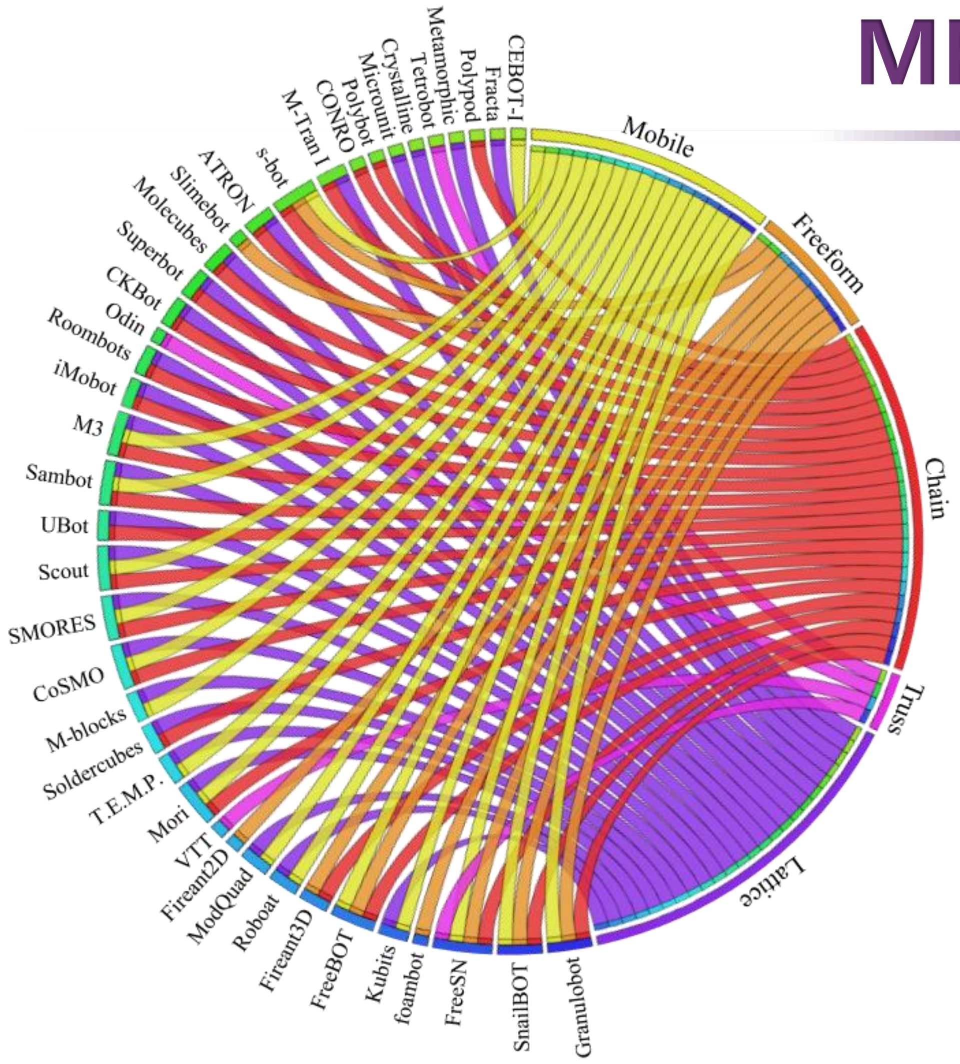
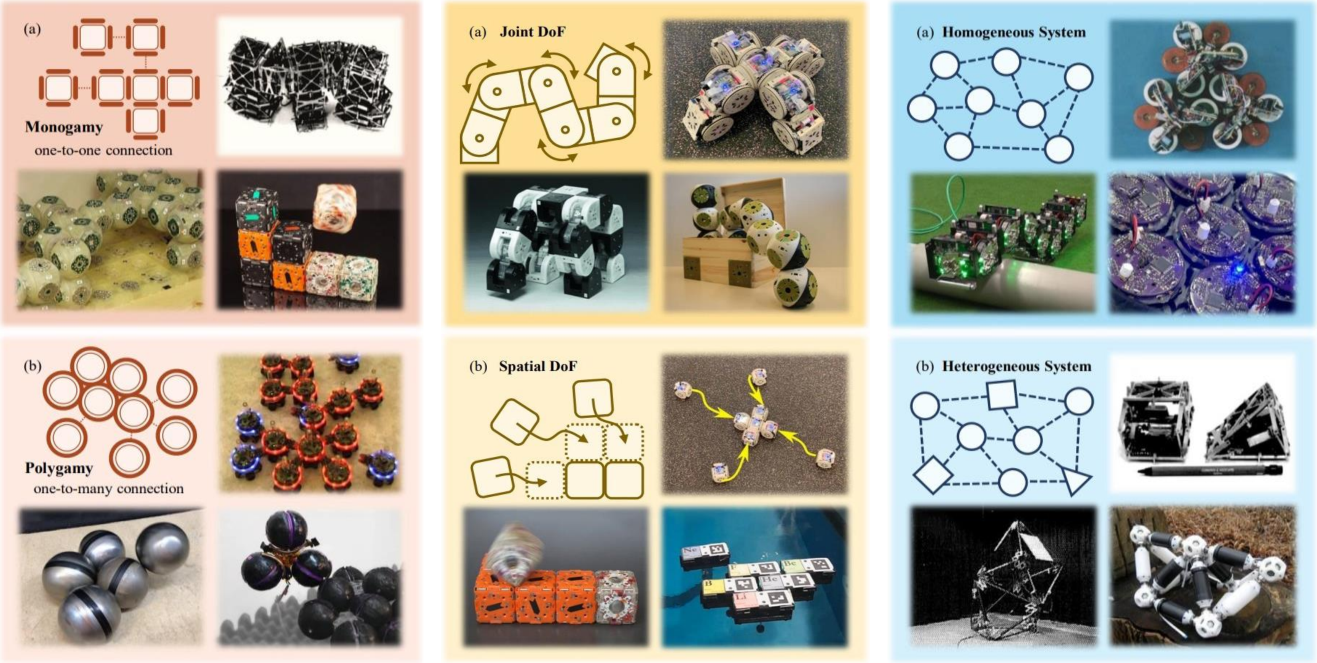
MRR Taxonomy



MRR Type	Lattice	Chain	Mobile	Hybrid: Lattice + Chain	Hybrid: Mobile + Chain	Hybrid: Lattice + Mobile	Hybrid: Lattice + Mobile + Chain	Truss	Freeform
Definition by	Morphology	Morphology	Moving Capability	Multiple Characteristics				Morphology	Connecting Capability
Examples	Fracta	Polypod	CEBOT-I	M-TRAN	JL-2	M-Blocks	SMORES	VTT	FreeBOT
Elements: Connector	Mono.			Mono.		Mono.	Mono.		Poly.
Elements: Actuator		Joint DoF	Spatial DoF	Joint DoF	Spatial DoF Joint DoF	Spatial DoF	Spatial DoF Joint DoF	Joint DoF	
Elements: Homogeneity								Heterog.	



Confusion in previous MRR taxonomy

Systems fitting into multiple categories

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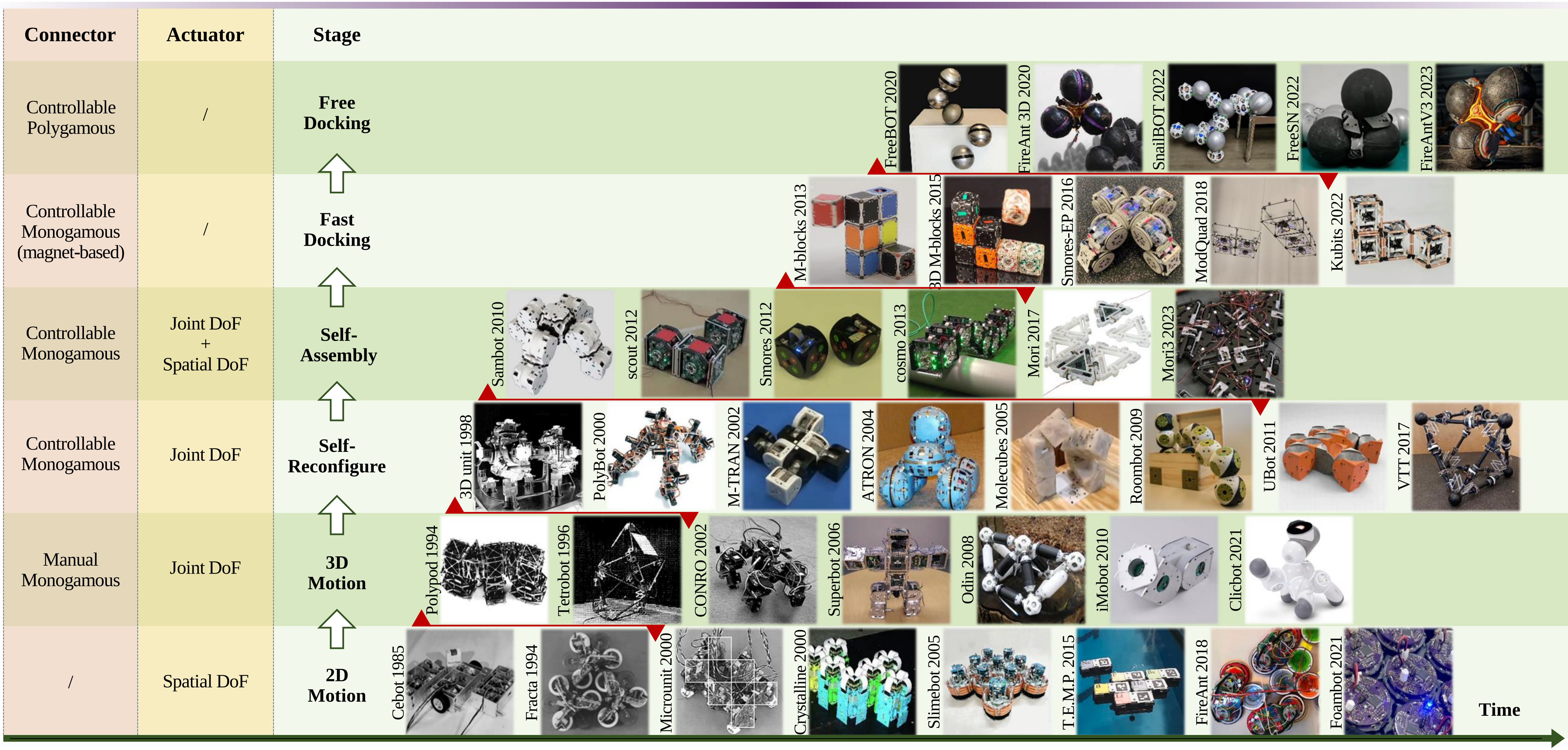
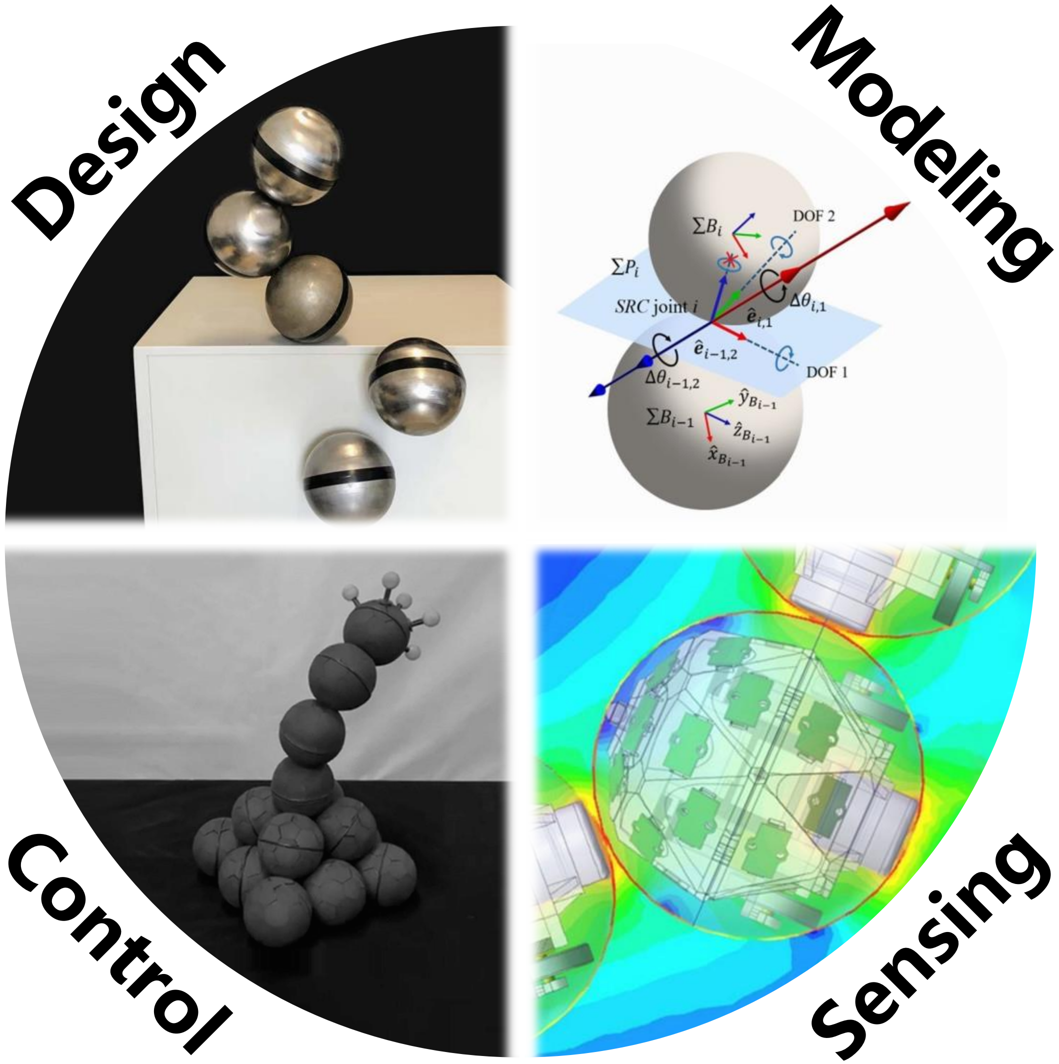
MRR Evolution



G. Liang, D. Wu, Y. Tu, T. L. Lam, "Decoding Modular Reconfigurable Robots: A Survey on Mechanisms and Design," ***International Journal of Robotics Research*** **(IJRR),** 2024

Conclusion

- A new paradigm in freeform robots featuring rapid, free module connections for enhanced efficiency and diversity.
- 3D spherical gears that globally mesh, enabling rolling motion without sliding between spheres.
- Control methods for freeform robots aimed at precise and dexterous manipulation.



- Motion modes for freeform robots, consolidated into a new spatial rolling contact model.
- Magnetic technology integrating driving and sensing for module position determination.
- A trilateral taxonomy categorizing modular reconfigurable robots over the past 40 years, resolving classification ambiguities.

Acknowledgments

中华人民共和国科学技术部
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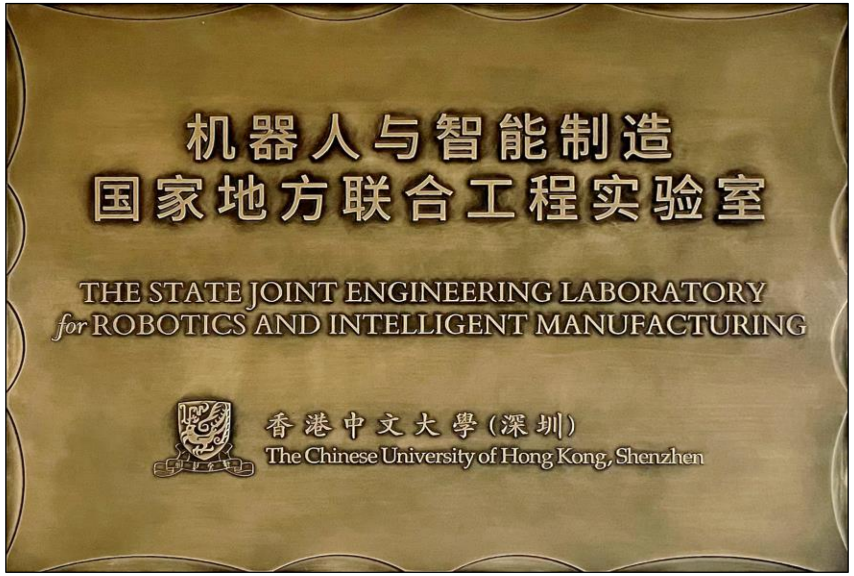
深圳市科技创新委员会



香港中文大學(深圳)
The Chinese University of Hong Kong, Shenzhen

AIRS SHENZHEN INSTITUTE
of ARTIFICIAL INTELLIGENCE AND ROBOTICS for SOCIETY
深圳市人工智能与机器人研究院

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