Aggregating Single-wheeled Mobile Robots for Omnidirectional Movements

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***Abstract*— This paper presents a novel modular robot system capable of self-reconfiguration and achieving omnidirectional movements through magnetic docking for collaborative object transportation. Each robotic module is equipped with a steerable omni wheel for navigation and is shaped to a regular icositetragon with a permanent magnet installed on each corner for stable docking. After aggregating multiple modules by docking and forming a structure that can cage a target object, we have developed an optimization-based method to compute the distribution of all wheels' heading direction, which enables the structure's efficient omnidirectional movements. By implementing a hierarchical controller on our prototyped system in both simulation and experiment, we validated the trajectory tracking performance of an individual module and the team consisting of multiple modules in multiple navigation and collaborative object transportation setting. We demonstrated that the proposed system can maintain caging formation stably and achieve smooth transportation, indicating the efficacy of our hardware and locomotion designs.**

I. INTRODUCTION

Collaborative object transportation is a signature task that indicates how efficiently a team of robots can work together to accomplish what is beyond an individual's capability [1–3]. Indeed, being able to collaborate is not only a critical function in many animal societies and even in human's, but it is also an intriguing approach to extent robots' capability in more challenging environments, such as in space [4] and deep sea [5]. Together with well-designed structures, communication mechanisms, and motion control algorithms, a number of swarm or modular robotic platforms have been developed [6–11].

The strategies for collaboratively transporting objects along with the reference trajectory can be roughly categorized into three types. In the first type, the *pushing strategy*, several robots would actuate the object by generating contact force in certain directions [12–14]. Due to the lack of stable connections, the robots may lose control of the object during transportation, which leads to inefficient movements. To tackle this issue, the *grasping strategy* is developed as the second type. By installing connectors or manipulation mechanisms on each robot, they can build rigid connections with the object to ensure stable transportation and to better reject disturbance [15–17]. However, the extra mechanisms

Fig. 1: **The robots are collaboratively transporting an object with complex shape through caging.** By magnetic docking with each other, robots can better maintain the team formation to exert enough caging force while achieving omnidirectional movements for smooth transportation.

would dramatically increase the size and complexity of each module, reducing it adaptability in different transportation tasks. On the other hand, the *caging strategy* for object transportation avoids the drawbacks and combines the benefits of the above two approaches. The team of robots would encircle the object through a structure formation to passively constrain or control the movement of the object [18–21]. It does not require extra mechanisms to establish connection with the object, but it can stably push the caged object to a destination by navigating in a coordinated manner.

However, implementing the caging strategy for a robot team is challenging. Firstly, the caging formation must be properly maintained throughout the transportation. Without rigid connections with each other or with the object, the caging forces exerted by the formation can easily deviate due to disturbance or possible collisions [22], especially when the caged object has a complex shape. In addition, maintaining structure formation when tracking trajectories with large curvature is very difficult, because each robot has to change its heading direction swiftly, and the team's movements must be well coordinated.

In this paper, we develop a novel modular robot system for efficient collaborative object transportation through caging. Each robot module in the team utilizes an omni wheel with a steering mechanism for navigation. To strengthen the formation of the team, the contour of the robot is shaped to a regular icositetragon (twenty-four-sided polygon) with a permanent magnet installed on each corner for docking.

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Compared with a circular contour that commonly appeared in many other platforms, the polygon-based contour design provides extra shear strength to maintain structure formation while being flexible to establish many docking configurations. Therefore, the proposed robot system can encircle target object with complex shape and cage it robustly; see Fig. 1. Furthermore, by taking advantage of the steerable omni wheel equipped by the robot, the structure can acquire an omnidirectional moving capability to transport the caged object more smoothly. An optimization framework is proposed to compute the heading direction of each robot's wheel such that the structure's controllability and energy efficiency are maximized for omnidirectional movements.

Combining with a hierarchical controller, we verified the proposed robot system for collaborative object transportation in both simulation and real-world experiment. In simulation, we first tested the locomotion of a single robot and of a structure consisting of six robots. Then, we demonstrated the efficacy of the proposed optimization framework which decides the best heading direction of each robot's wheel to achieve the most efficient omnidirectional movements in collaborative object transportation. Finally, in experiment, the team of robots successfully transported object with different weight along with challenging trajectories, indicating the necessity of enabling omnidirectional movements in robot collaborative object transportation.

A. Related Work

In modular reconfigurable robots, various **docking mechanisms** were designed to strengthen the formed structure. Classical discrete docking designs [23–27] greatly constrained the number of possible assemble configurations. Therefore, continuous docking designs were further proposed with advanced scalability to meet more functional requirements, and it could be divided into 2D [28–30] and 3D [31–33] branches depending on the type of connection. In particular, Li *et al*. proposed a passive-adhesion mechanism in [28], the genderless Velcro strap and the Electromagnets ring were proposed in [29, 30], the permanent magnet approach were utilized in [32, 33], and Swissler *et al*. presented the self-soldering strategy [31]. In this work, we utilize paired permanent magnets to approximately build a continuous connector for our robot, which significantly enriches the caging configurations to adapt the geometry of different objects.

Changing route and stabilizing carried object through omnidirectional movements are more efficient during collaborative object transportation. Although equipping different types of wheels, such as orthogonal wheel, spherical/ball wheel, and mecanum wheel [34, 35], can all achieve omnidirectional movements, they could be too bulky to build in small-scale mobile robots. Typical Omnidirectional Wheeled Mobile Robot (OWMR) are designed with specific **transportation capacity** with four fixed omnidirectional wheels, resulting in poor scalability. To solve this issue, Almasri *et al*. proposed a novel OWMR design with multi symmetrically distributed omnidirectional wheels [36] while 6-wheeled and 8-wheeled variants are presented in [37, 38]. In this work, we propose a novel modular design to effectively build 2D connected structure serving an OWMR system where each module is utilized as a steerable onmi-directional wheel. Consequently, the transportation capacity of this system can be increased with more number of modules, the **dynamic property** can also be modified with different topology structure or wheel heading angles.

B. Overview

We organize the remainder of the paper as follows. Sec. II presents the hardware design of our single-wheeled mobile robot. Sec. III and Sec. IV describe the dynamics and control of each module and docked structure, respectively. Sec. V and Sec. VI show the simulation and experiment results of our proposed system with comprehensive evaluations. Finally, we conclude the paper in Sec. VII.

II. Hardware Design

This section describes the hardware design of the proposed modular modular robot system. Each robot module in the system equips with one omni wheel that can change its heading direction by a decoupled steering mechanism for self navigation. A passive and continuous docking mechanism is developed to support flexible structure forming while maintaining a stable connection between robots.

A. Integrated 2-DoF Driving Unit

We propose an integrated 2-Degree of Freedom (DoF) robot unit design (see Fig. 2) to facilitate flexible self-organization, self-formation and self-reconfiguration. The robot consists of two parts: a docking base and a driving hat. Magnets are installed in the base, and spring loaded ball rollers are placed at the bottom of the base serving as suspension supports. All electronic components are integrated in the hat, including a battery, a PCB, a DC motor driving an omni-wheel, and a DC motor with encoder for steering. The hat connects to the base through a set of planet/ring gears, such that the hat can drive the planet gear to steer without changing the docking position. The omni-wheel in the center can drive the robot forward along the steering direction. The bottom of the hat is manufactured with a slice of iron, which automatically attaches to the magnetic top of the base, and increases the friction of driving wheel for better transportation performance.

The PCB contains a wireless integrated MCU (ESP32), by which the robots connect to a WiFi network, receive commands from host computer, and control the motors. By the 2DoF steering and driving mechanism, a single robot can navigate to target position, dock to/undock from current formation, and change docking position continuously. Meanwhile, steering direction of each robot can be modified without breaking current formation, and the swarm can move exactly like a single omnidirectional robot. The important physical and software parameters are summarized in Tab. I.

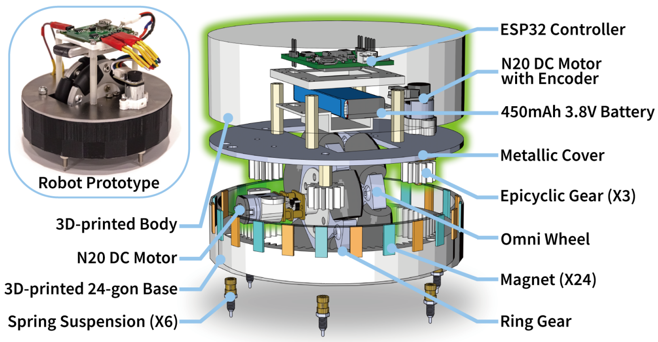


Fig. 2: **The hardware design of the robot.** The driving hat (green) integrates the capability of steering and advancing through two DC motors. The omni wheel supports omnidirectional movements after aggregated to a formation. The spring suspension can be adjusted to provide appropriate friction and keep the balance of the robot.

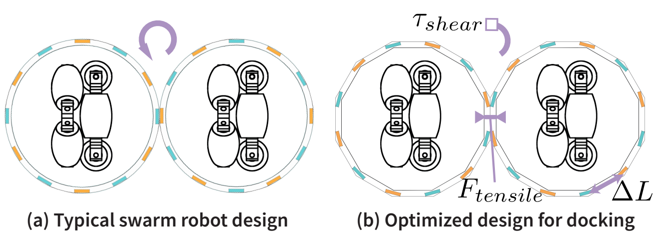


Fig. 3: **Docking mechanism design.** (a) Magnetic docking mechanism applied to a round robot contour could easily slip and break the formed structure. (b) Our polygon-like contour design provides extra shear strength for robots to better maintain formation.

B. Docking Mechanism

We develop an efficient and flexible docking mechanism by utilizing permanent magnets array, as is shown in Fig. 3. Magnets are arranged around the contour of the robot, and adjacent magnets are always in an opposite direction. When robots get close to each other, the magnets array can passively align and attract, making robots docked together.

Fig. 3a illustrates the basic setup of the magnets array with a round robot contour. The robots can easily transfer to a nearby docking position by moving itself. However, the transfer requires very slight shear torque, making the formation sensitive to disturbance. As a result, we optimize the robot contour as is shown in Fig. 3b. Comparing to the round contour, the polygon-like contour can provides more shear strength when transferring between docking positions. And the polygon-like contour can also provide more contact area and generate better stability when transferring objects. Under the same placement of magnets, extra shear torque $\tau = F_{tensile} \cdot \Delta L/2$ is required, in which ΔL differs according to polygon used. In this way, we can adjust the balance between consistency and shear strength of docking.

Considering the friction provided by the wheel, we utilize $10mm \times 5mm \times 1mm$ NdFeB magnets for the array. 24 magnets are equally placed around a regular 24-gon contour of radius $5mm$. The magnets are installed $1mm$ inside the contour presenting a tensile strength of $1.29N$ between robots, and the shear strength is approximately calculated by $\tau = F_{tensile} \cdot \Delta L/2 = 1.29N \cdot 6.5mm = 8.39 \times 10^{-3} N \cdot m$.

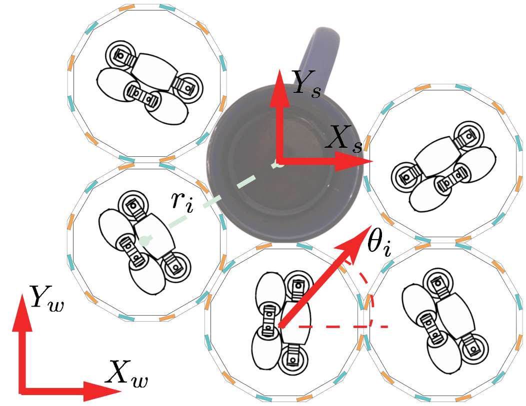


Fig. 4: **The coordinate system of the structure.** The origin of the structure coordinate locates at its geometric center, the heading direction of each module θ_i refers to angle between the direction of the omni wheel and the structure coordinate's X positive direction.

III. System Model & Definitions

Definition 1 (Module) *refers to as the WMR can dock with other modules in the horizontal plane.*

Definition 2 (Structure) *refers to as the omnidirectional WMR composed by n docked modules ($n \geqslant 3$).*

A. Module Kinematics

The kinematics of a single module can be describe as [39]:

$$\begin{aligned} v_{ix} &= v_i \cos\theta_i = \omega_i R \cos\theta_i, \\ v_{iy} &= v_i \sin\theta_i = \omega_i R \sin\theta_i, \end{aligned} \tag{1}$$

where θ_i is the direction of the Wheeled Mobile Robot (WMR), v_{ix} and v_{iy} are the x and y components of its velocity v_i, R is the radius of the omni wheel. Of note, with our customized design, each module is dynamically similar to the differential drive WMR, and it receives two inputs θ_i for heading direction control and ω_i for omni wheel velocity control.

B. Structure Kinematics

With n rigidly connected WMR modules, the connected structure can be treated as one omnidirectional WMR. As shown in Fig. 4, choosing the geometric center of the

TABLE I: Physical and Software Parameters of the Platform

Group	Parameter	Value
Wheeled Vehicle	Contour Diameter $/m$	0.100
	Height $/m$	0.100
	Weight $/kg$	0.253
	Omni Wheel Radius$/m$	0.028
	Maximum Velocity$/m \cdot s^{-1}$	0.073
	Maximum Payload $/kg$	0.330
Docking Mechanism	$F_{tensile}/N$	1.29
	$\tau_{Shear}/N \cdot mm$	8.39
	Align range$/mm$	10
Swarm	Communication delay$/ms$	20
	Motor control rate$/Hz$	500

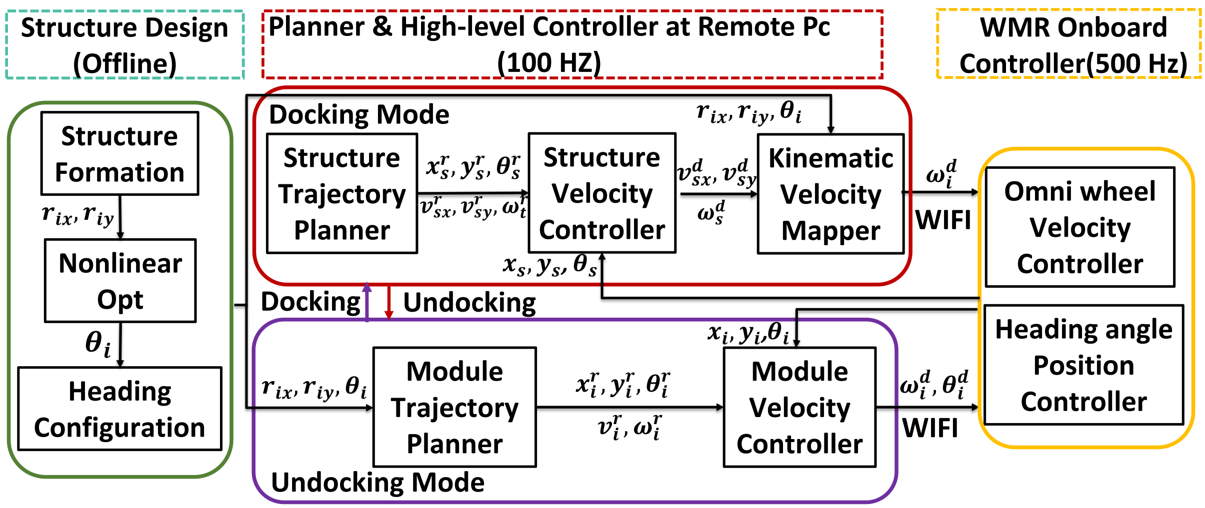


Fig. 5: **Hierarchical Control architecture.** (i) With pre-designed docking formation, the optimal heading configuration in the structure is decided through nonlinear optimization. (ii) In undocking mode, the each module picks its target position and heading from the structure, and tracks the generated trajectory with module controller. (iii) In docking mode, the connected structure is treated as an omnidirectional WMR. The structure controller first calculates desired velocity command for trajectory tracking, and maps it to desired angular velocity of each wheel.

structure as origin (structure frame $\{X_s, Y_s\}$), the velocity of i-th WMR module v_i can be written as:

$$v_i = (v_{sx} - \omega_s r_{i,y})\cos\theta_i + (v_{sy} + \omega_s r_{i,x})\sin\theta_i, \quad (2)$$

where v_{sx} and v_{sy} represent the structure's linear velocities along the x and y axis in world frame, ω_s is the angular velocity, $r_{i,x}$ and $r_{i,y}$ are the position vector's x and y components from the structure origin to i-th WMR's center. Combining with the kinematics equations analyzed of each module and turn the results into matrix form we can get [36]:

$$\boldsymbol{\Omega} = \boldsymbol{M}\boldsymbol{V} \quad (3)$$

where

$$\boldsymbol{\Omega} = \begin{bmatrix} \omega_1 \\ \vdots \\ \omega_n \end{bmatrix}, \boldsymbol{V} = \begin{bmatrix} v_{sx} \\ v_{sy} \\ \omega_s \end{bmatrix}, \quad (4)$$

and

$$\boldsymbol{M} = \frac{1}{R}\begin{bmatrix} \cos\theta_1 & \sin\theta_1 & r_{1,x}\sin\theta_1 - r_{1,y}\cos\theta_1 \\ \vdots & \vdots & \vdots \\ \cos\theta_n & \sin\theta_n & r_{n,x}\sin\theta_n - r_{n,y}\cos\theta_n \end{bmatrix}. \quad (5)$$

Definition 3 (Heading Configuration) *refers to as the heading angle θ_i of each module w.r.t the structure frame.*

Definition 4 (Formation) *refers to as the position vector $r_{i,x}$, $r_{i,y}$ of each module and the topology matrix $\boldsymbol{A}$, where $\boldsymbol{A}(i,j) = 1$ means the ith and jth modules are connected.*

IV. Control

A. Module Control

The desired linear v_i^d and angular velocity ω_i^d of the single module is designed as:

$$\begin{bmatrix} v_i^d \\ \omega_i^d \end{bmatrix} = \begin{bmatrix} v_i^r \cos e_{s\theta} + k_{s1} e_{ix} \\ \omega_i^r + k_{s2} v_i^r e_{iy} + k_{s3} v_i^r \sin e_{s\theta} \end{bmatrix}, \quad (6)$$

where v_i^r and ω_i^r are reference linear and angular velocity, k_{s1}, k_{s3}, and k_{s3} are positive parameters, and e_{ix}, e_{iy}, and $e_{s\theta}$ are errors between the reference trajectory and the real trajectory in x, y, and θ directions respectively,

$$e_{ix} = x_i^r - x_i, e_{iy} = y_i^r - y_i, e_{s\theta} = \theta_i^r - \theta_i. \quad (7)$$

The desired heading direction is calculated with discrete integration:

$$\theta_i^d = \theta_i + \omega_i^d\, dt. \quad (8)$$

B. Heading Configuration Optimization

Assuming the formation of the structure is given, we formulate a nonlinear optimization problem to find the optimal heading configuration for the structure. According to the kinematics relationship Eq. (3), we can calculate the energy consumption of the whole structure as:

$$\sum_{i=1}^{n} \omega_i^2 = \boldsymbol{\Omega}^T\boldsymbol{\Omega} = \boldsymbol{V}^T\boldsymbol{M}^T\boldsymbol{M}\boldsymbol{V} \leqslant \sigma_{max}(\boldsymbol{M}^T\boldsymbol{M})\|\boldsymbol{V}\|^2, \quad (9)$$

where $\sigma_{max}(\cdot)$ is he maximum singular value of a matrix. In the other hand, the omni-direction goal requires $\boldsymbol{M}$ in full row rank. Therefore, the objective function is designed as [40]:

$$\underset{\theta_1,\cdots,\theta_n}{\operatorname{argmin}} \quad cond(\boldsymbol{M}^T\boldsymbol{M}) + \sigma_{max}(\boldsymbol{M}^T\boldsymbol{M}), \quad (10)$$

where $cond(\cdot)$ is the condition number of a matrix, respectively. The left half $cond(\boldsymbol{M}^T\boldsymbol{M})$ considers the controllability of the system and ensures the connected structure is omnidirectional ($cond(\boldsymbol{M}^T\boldsymbol{M}) = Inf$ if $rank(\boldsymbol{M}) < 3$); while the right half $\sigma_{max}(\boldsymbol{M}^T\boldsymbol{M})$ characterize energy consumption minimization Eq. (9). The inequality constraints are design as:

$$0 \leqslant \theta_i \leqslant 2\pi, \qquad \forall i = 1, \cdots, n \quad (11)$$

To build the target structure with modules, the optimized heading configuration and the structure formation will be utilized by the trajectory planner of each module as final configuration to plan the docking motion. After this docking process, the heading angle θ_i of each module is fixed and the structure is controlled as an omnidirectional WMR with constant velocity mapper ($\boldsymbol{M}$ in Eq. (3)) .

C. Structure Control

With the optimal heading angles, the tracking controller of the omnidirectional WMR structure is designed as [41]:

$$\begin{bmatrix} v_{sx}^d \\ v_{sy}^d \\ \omega_s^d \end{bmatrix} = \begin{bmatrix} v_{sx}^r + K_{x1}\boldsymbol{e}_x + k_{x2}\int \boldsymbol{e}_x\, dt \\ v_{sy}^r + k_{y1}\boldsymbol{e}_y + k_{y2}\int \boldsymbol{e}_y\, dt \\ \omega_s^r + k_{\theta 1}\boldsymbol{e}_\theta + k_{\theta 2}\int \boldsymbol{e}_\theta\, dt \end{bmatrix}, \tag{12}$$

where v_{sx}^r, v_{sy}^r, ω_s^r are reference velocities in three DoF, k_{xi}, k_{yi}, and $k_{\theta i}$ are positive control gains, e_x, e_y, and e_θ are the tracking errors. Then the desired velocities $\boldsymbol{\Omega}$ of the omni-wheels can be calculated with Eq. (3).

V. Simulation

A. Simulation Setup

We use WeBots [42] as the physical simulator to test the locomotion of our modular robot and the structure they form. A PROTO is designed to describe the structure and properties of the robot with parameters listed in Tab. I. All robots utilize the same on-board controllerfor motor position and velocity control which takes commands from a high-level controller introduced in Sec. IV.

Four cases are designed to evaluate the capability of proposed WMR in different aspects. we first test the trajectory tracking performance of a single module (*Sim Case 1*) and an omnidirectional structure with six modules (*Sim Case 2*). Then, in *Sim Case 3*, we present a collaborative object transport process conducted by six modules. Finally, we demonstrate the caging capability of the system by transporting multiple objects (*Sim Case 4*).

B. Simulation Results

Sim Case 1: Single Module. A circular trajectory with $R = 1\ m$ is utilized as the reference to test moving capability of the single module. Fig. 6 shows the robot's executed trajectory in the left and the detailed tracking performance in the right. With our navel single steerable omni wheel design, the robot is dynamically similar to a differential drive WMR where the three DoF cannot be independently controlled and only the trajectories that satisfy the nonholonomic constraint can be accurately tracked.

Sim Case 2: Connected Structure. A rectangular structure composed of six modules is built, where the heading angle of each module is optimized with the formulation introduced in Sec. IV-B. As shown in Fig. 7, treating the structure as an omnidirectional WMR, it can maintain the formation stably with magnetic force and track a 3-DoF reference trajectory accurately. Moreover, we implement a baseline that choose each wheel's heading direction by XXXXXXXXXXXXX for comparison.

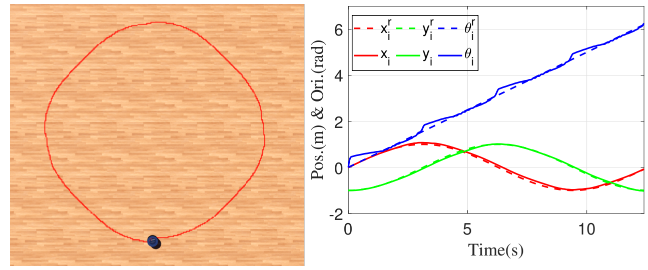


Fig. 6: **Sim Case 1: Circular trajectory tracking performance of Single module.** The single module with 2 controllable DoF can only track trajectories that satisfy the nonholonomic constraint.

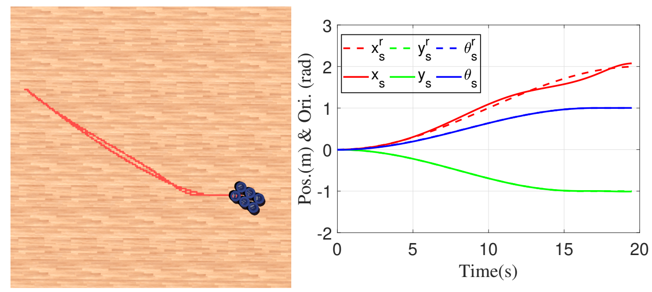


Fig. 7: **Sim Case 2: 3-DoF trajectory tracking performance of a structure.** The connected structure with six modules is over-actuated and can be controlled as an omnidirectional WMR to track x, y, θ trajectories independently.

Sim Case 3: Object Transportation. To demonstrate the system's capability, we design a hexagon-shaped structure for six robots to cage a cylindrical object and collaboratively transport it to a target position (see Fig. 8a). The task can divided into two stages: in stage ①, each module are required to move to the target docking position from the initial position and form the structure around the object; in stage ②, each module first reorients its wheel's heading direction to the optimized one and then drives along the trajectory to transport the object passively. The position and direction of each member is plotted in Fig. 8b in detail.

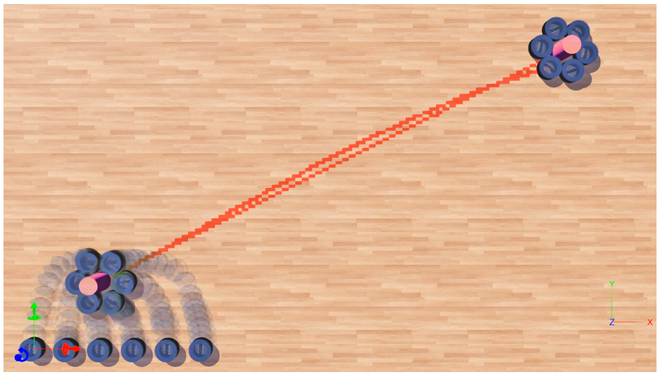
We present the whole process in a collaborative object transportation task. As shown in Fig. 8a, with a pre-designed hexagon-shaped docking structure around the object, the task can divided into two stages: in stage ①, each module are required to move to the target docking position from the initial position and build the structure around the object; in stage ②, each module first reorients its heading direction to the optimized direction, then the structure drives along the trajectory to transport the object passively. The position and direction of each member is plotted in Fig. 8b in detail.

Further more, we demonstrate a multi-object transportation task in *Case 4*. In this case, the 12 modules team is initialized as a docking structure around 3 target objects. As shown in Fig. 9, the objects are encircled by the structure, and transported along the trajectory successfully.

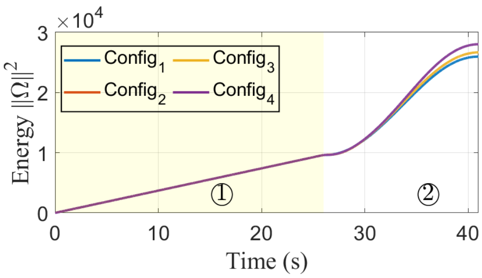
VI. Experiment

A. Experiment Setup

To further demonstrate the capability introduced by our platform, we experiment the proposed mobile robot team in the physical world. Specifically, we use the Vicon mo-



(a) **Simulation visualization.**



(b) **Position and direction of each module.**

Fig. 8: **Sim Case 3: Whole object transportation process with a robot team.** The transportation process can be divided into 2 stages: ① build the target structure around the object, ② transport the object along the trajectory as an omnidirectional WMR

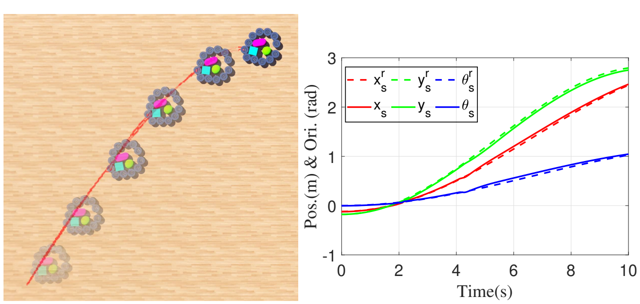


Fig. 9: **Sim Case 4: Multi objects transportation with 12 members robot team.**

tion capture system (MoCap) to measure the position and heading of each module. The trajectory planner and high-level controller of the system runs on a remote PC (AMD Ryzen9 5950X CPU, 64.00 GB RAM), which communicates with the MoCap through Ethernet with 100 Hz. The high-level controller calculates the desired angular velocity ω_i^d and heading angle θ_i^d for each modules and sends them through WiFi. Each module is embedded with onboard omni-wheel velocity controller and heading angle position controller. It regulates them to the desired values with 500 Hz PID loops for a fast low-level response.

Similar to the simulation, four cases of experiments are conducted to demonstrate the capability of proposed WMR swarm. In *Case 1* and *Case 2*, we evaluate the trajectory tracking performance of a single module, and an omnidirectional structure with six modules. In case *Case 3*, we study the object transportation performance of a connected structure with different payloads. Finally in *Case 4*, we present the whole collaborative object transportation process with docking and undocking phases of six modules.

B. Experiment Results

a) Single Module: In *Case 1*, a circular trajectory with $R = 0.25\ m$ is utilized as the reference to test moving capability of the single module. Both reference trajectory and tracking trajectory are plotted in the left of Fig. 10, while the detailed tracking performance of each DoF are plotted in the right.

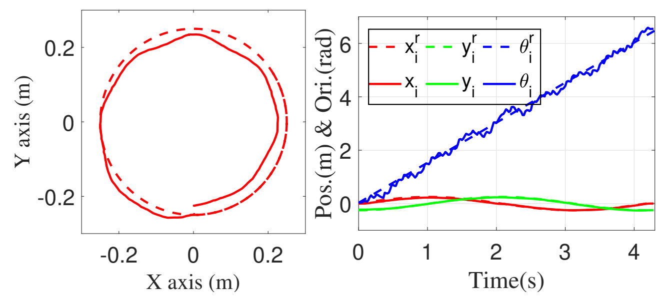


Fig. 10: **Exp Case 1: Circular trajectory tracking performance of Single module.**

b) Multiple Connected Modules: In *Case 2*, a rectangular shape structure composed of six modules is built as an omnidirectional WMR. As shown in Fig. 11, it can maintain the formation stably with magnetic force and track a 3-DoF reference trajectory accurately.

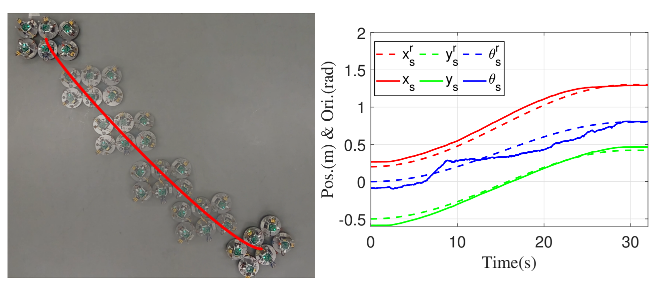
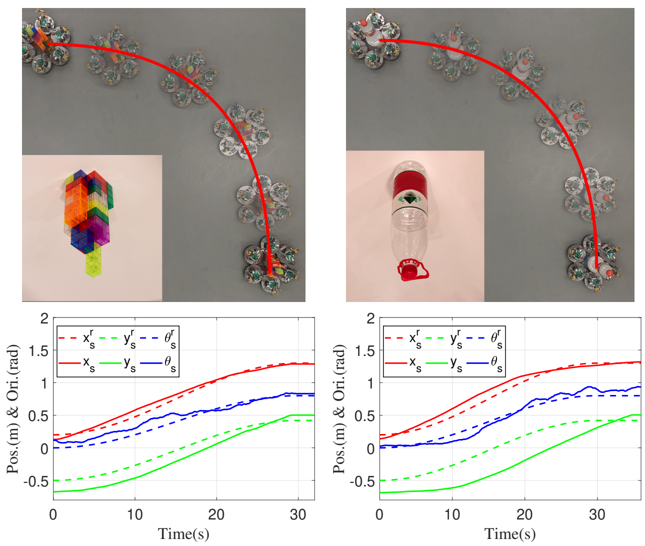


Fig. 11: **Exp Case 2: 3-DoF trajectory tracking performance of a structure.**

c) Object Transportation: In *Case 3*, a hexagon-shaped docking structure composed of six modules is built to transport the objects. As shown in Fig. 12, two objects with different weights (left: $0.3kg$, right $0.3kg$) are successfully transported by the structure along the reference trajectory. Caging the objects tightly, the orientation of the objects can also be accurately controlled by the WMR structure.

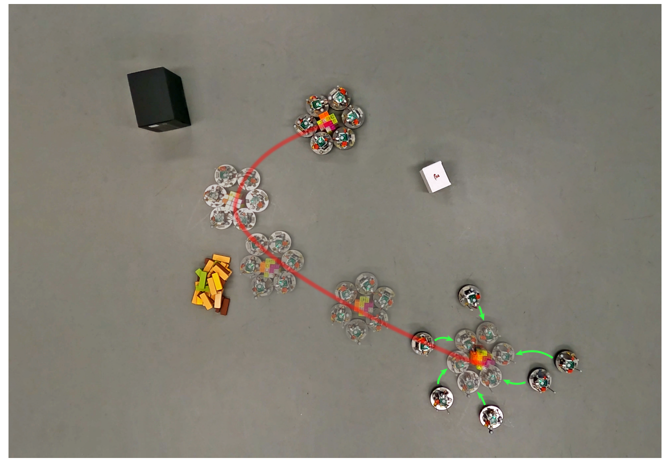
Compared with two cases, the tracking performance becomes worse with more payloads caged which is due to the larger friction forces introduced. This issue can be fixed by utilizing model-reference adaptive controller [43] to replace the structure tracking controller introduced in Sec. IV-C

In *Case 4*, we demonstrate the whole object transportation process. As shown in Fig. 13a, with a pre-designed docking structure around the object, the six modules first move to the target docking position and build the structure around the object in stage ①, then in stage ②, each module first adjust its heading to the optimized direction, then the structure drives along the trajectory as an OWMR with the object caged. The position and direction of each member is plotted in Fig. 13b in detail.

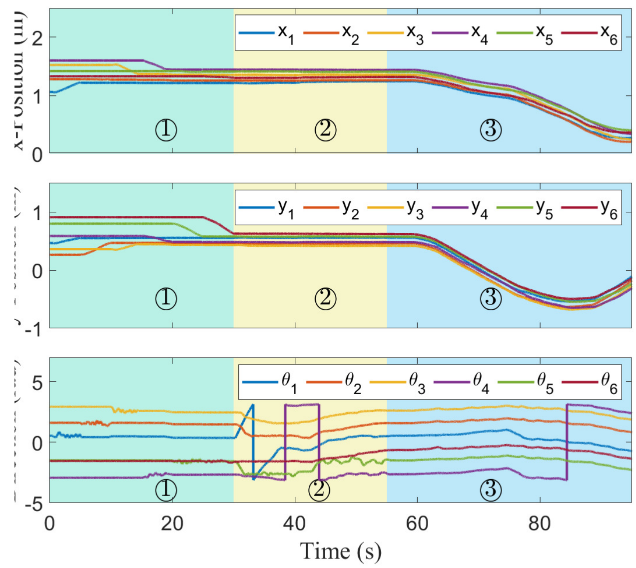


(a) 0.3 kg payload (b) 1.2 kg payload

Fig. 12: **Exp Case 3: 3-DoF trajectory tracking performance of a structure with different payloads.**



(a) **Aggregating and tracking process.**



(b) **Position and direction of each module.**

Fig. 13: **Exp Case 4: Whole object transportation process with 6 members robot team.**

VII. Conclusion

In this paper, we presented a neoteric solution to the collaborative object transportation problem using a self-reconfigurable robot team with the capability of omnidirectional movements. We designed and built a WMR with an omni-wheel, an optimized contour, and a dockable magnet array. A decoupled planning and control framework was also propounded to enable our robot team to perform the entire pipeline of collaborative transportation, including heading configuration optimization, self-navigation, docking, and collaborative motion. We also demonstrated the effectiveness of our solution in both a simulation and a real-world experiment.

The proposed robot system offers a promising approach to solve complex transportation task. By utilizing magnetic docking and self-reconfiguration capabilities, the proposed system can efficiently move objects in any direction while maintaining their relative positions. This feature makes it ideal for scenarios where precise object positioning is crucial, such as in manufacturing, warehousing, and logistics operations. Additionally, the modular design of the proposed robot allows for scalability and flexibility, making it suitable for a wide range of tasks, from small-scale object transportation to large-scale material handling. Furthermore, the use of optimization-based methods and hierarchical controllers ensures that the system can adapt to changes in the environment and operate in a stable and efficient manner.

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