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Multi-Robot Systems and Cooperative Object Transport: Communications, Platforms, and Challenges

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ABSTRACT Multi-robot systems gain considerable attention due to lower cost, better robustness, and higher scalability as compared with single-robot systems. Cooperative object transport, as a well-known use case of multi-robot systems, shows great potential in real-world applications. The design and implementation of a multi-robot system involve many technologies, specifically, communication, coordination, task allocation methods, experimental platforms, and simulators. However, most of recent multi-robot system studies focus on coordination and task allocation problems, with little focus on communications among multiple robots. In this review, we focus on the communication, validation platform, and simulator of multi-robot systems, and discuss one of the important applications, cooperative object transport. First, we study the multi-robot system fundamentals and comprehensively review the multi-robot system communication technologies. Then, the multi-robot system validating platform, testbed, simulator, and middleware used in academia and industry are investigated. Finally, we discuss recent advances in cooperative object transport, and challenges and possible future research directions for multi-robot systems.

INDEX TERMS Communication technology, cooperative object transport, multi-robot system, platform, survey.

I. INTRODUCTION

Multi-robot system (MRS) is an essential area of robotics research with features of better overall system performance, robustness, reliability, scalability, and low cost than a single robot systems. Agriculture, mining, disaster aid, space exploration, logistics, and warehouse application scenarios benefit greatly from multi-robot systems [1].

Cooperative object transport (COT) is a significant MRS application that studies how to handle heavy objects by groups of robots that cannot be transported by a single robot [2]. However, there are many considerations to designing and implementing a cooperative object transport system, such as selecting multi-robot communication mechanism, coordination algorithm, control architecture, task allocation mechanism, and experimental platform that are tightly coupled. Recent cooperative object transport systems are designed for specific real-world applications with different requirements.

The earlier similar research topic is the multi-robot box pushing problem, which requires multiple robots to work together to push a box from source to destination [3], [4]. Then, cooperative object transport is used in a structured environment with obstacles like a warehouse or factory environment [5], [6]. Recent research focus on cooperative object transport system in unstructured and unknown environments like space [7], terrain [8], and underwater [9] environments are proposed.

There is a rare survey that focuses on cooperative object transport. The two most relevant papers are [10] and [11].

TABLE 1. Abbreviations

Abbreviations	Full Name
AEC	Adaptive Erasure Coding
AP	Access Point
COT	Cooperative Object Transport
CRP	Crash Risk Prioritization
DDS	Data Distribution Service
FANETs	Flying Ad hoc Networks
HQP	Hierarchical Quadratic Programming
LoRA	Long Range Radio
MANETs	Mobile Ad hoc Networks
MORSE	Modular OpenRobots Simulation Engine
MRS	Multi-Robot System
OCBC	Optimizing Communication under Bandwidth Constraints
RANETs	Robot ad hoc Networks
ROS	Robot Operating System
UAVs	Unmanned Aerial Vehicles
VANETs	Vehicular Ad hoc Networks

Tuci et al. summarize the related cooperative object transport articles by categorizing them according to the transport strategy: pushing-only strategy, grasping-based strategy, and caging-based strategy [10]. Farivarnejad et al. focus on a review of the control strategies for cooperative object transport. They classify the algorithms based on whether the control architecture is centralized or not: centralized, semi-centralized, or decentralized [11].

In this paper, we focus on three critical topics of MRS: 1) the MRS communication system, 2) MRS validating platform and simulator, and 3) cooperative object transport. Specifically, the main contributions of this paper are as follows:

- This survey provides an extensive analysis of current MRS communication mechanisms, which play an essential role in MRS coordination.
- A comprehensive review of widely used MRS platforms, testbed, simulator, and middleware are compared.
- A summary of recent research works on cooperative object transport systems and their challenges are discussed.

We want to supplement that, in a generalized multi-robot system, the robots can be manipulators, autonomous mobile robots, or unmanned aerial vehicles (UAVs). In this paper, we mainly focus on the situation in which MRS robots are autonomous mobile robots.

The remaining section of the paper is organized as follows: Section II provides the multi-robot system's main concepts, classifications, and representative applications. Section III introduces the multi-robot system's communication systems, and the insufficient issues are analyzed. Section IV reviews the commonly used multi-robot platform, testbed, simulator, and middleware in research and education to provide researchers with helpful guidance to start their research experiments. Section V focuses on the cooperative object transport basic concepts and their state-of-the-art. Section VI provides the challenges of cooperative object transport in real-world applications. Finally, Section VII concludes the paper. The abbreviations used in the paper are in Table 1.

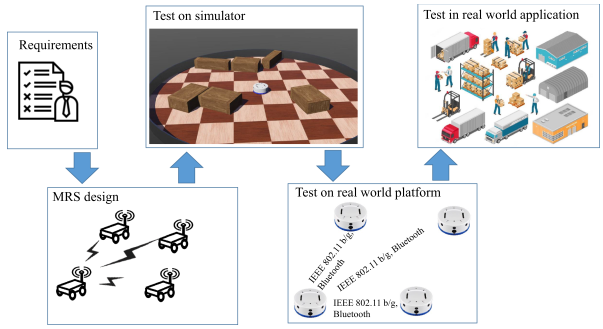

FIGURE 1. MRS concepts.

II. MULTI-ROBOT SYSTEM FUNDAMENTAL

A. MAIN CONCEPT

MRS is a group of robots that work in the same environment for a well-defined goal [12]. In MRS, the real power lies in robot cooperation in the system [13]. The main advantages of MRS over a single robot system are that:

- *Low cost:* Each robot in MRS has lower power consumption. The robots cooperate to complete tasks with less time and low energy consumption than a single robot.
- *Redundancy:* MRS is usually decentralized, and they have fault tolerance mechanisms that endow them with high redundancy and robustness.

Although MRS benefits from cooperation, some unique issues have arisen.

- *Low communication quality:* communication bandwidth limitation, high communication delay, and action conflict of coordination algorithms may cause higher inter-robot crash probability.
- *Low scalability:* Because of the collision detection mechanism of explicit wireless communication, as the number of robots in the system increase, the communication delay will increase exponentially, resulting in low scalability.

The process of researching and developing a multi-robot system is shown in Fig. 1. In general, MRS is designed according to application scenarios and different requirements. Then, the algorithm or system is tested on eligible simulators and platforms. Finally, MRS will be applied practically.

B. MRS CLASSIFICATION

MRS has been studied for many years, and the field of research is growing fast. From the general level, Parker et al. classify the MRS into the collective swarm system and intentionally cooperative systems [14]. From the scope of its characteristics, many researchers attempt to categorize it based on technological aspects used to achieve cooperation. However, there is no universal agreement yet. These aspects include communication methods, coordination mechanisms, control architecture, and decision-making strategy. The researches [12], [15], [16], [17], give the part of classification of aspects mentioned above. A particular note here is that in

Technical point of view

Communication	Coordination	Control architecture	Decision-making
• Explicit communication • Implicit communication	• Strong coordination • Weak coordination Static coordination Dynamic coordination	• Reactive • Deliberative • Hybrid	• Centralized Strong centralized Weakly centralized • Decentralized Distributed Hierarchical

Characteristic point of view

Cooperation type	Awareness of other or not agents	Agent type	Team size
• Cooperative • Competitive	• Aware other agent's actions • Unaware other agent's actions	• Homogeneous • Heterogeneous	• Single • Pair • Limited size • Infinite size

FIGURE 2. MRS classification.

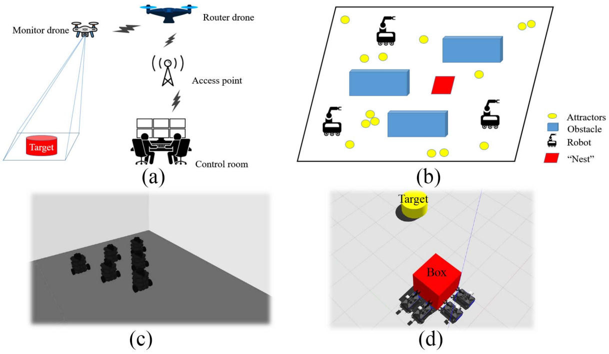

FIGURE 3. MRS applications.

many MRS applications, communication, coordination, and control are tightly coupled to achieve the application goal. As shown in Fig. 2, We categorize the MRS into two categories according to different points of view: one is the technological point of view that includes communication, coordination, control architecture, and decision-making strategy, and the other is the characteristic point of view that is considered when designing an MRS, such as coordination type, agent type, awareness of other agents or not, team size.

The detailed demonstrations are as follows:

- *Communication:* MRS communication methods are categorized by information exchanging mode into explicit communication and implicit communication. Explicit communication directly exchanges information among robots, whereas implicit communication gets other robots' information from environments.
- *Coordination:* Coordination means when the robot in MRS acts, it considers other robots' actions to improve the whole system's performance. The coordination is categorized into strong (or weak) coordination depending on whether coordination protocols or rules are required (or not) when interacting. It's further categorized into static (or dynamic) coordination, whether the coordination protocols are predefined (or generated dynamically according to the analysis of real-time gathered information) or not.
- *Control architecture:* When the environment changes, deliberative MRS can generate a strategy to reorganize all team members. Reactive MRS generated the action to the environment changes just by considering single robot task. Hybrid control architecture combines reactive and deliberative control for better system performance.
- *Decision-making:* Decision-making is a mechanism that chooses a series of actions from several choices. According to the MRS group architecture, it is distinguished into two types: centralized and decentralized. A centralized decision-making mechanism has a leader who collects data and makes decisions. The other robots receive control commands and perform the given actions. The centralized decision-making strategy can be further distinguished into strong centralized and weakly centralized. In strong centralized decision-making, the whole system has just one predefined leader, while in weakly centralized decision-making, more than one agent can be the leader. In distributed decision-making, all robots have equal autonomy and are entirely independent. One or more local central control agents arrange robots into clusters in hierarchical decision-making to build a hierarchical architecture.
- *Cooperation type:* MRS is categorized as cooperative or competitive according to the robots cooperating to achieve global tasks or compete with each other to fulfill their interests.
- *Awareness of other agents or not:* If the robots in the system are aware of the other robots' information or knowledge, it is helpful to perform better coordination. According to this characteristic, MRS can be categorized as aware of other robots or unaware of other robots.
- *Agent type:* According to whether the agents or robots in MRS are identical, it can be categorized into homogeneous and heterogeneous multi-robot system. If all robots' physical structures and capabilities are identical, it is homogeneous. If the MRS is composed of different kinds of robots, it is a heterogeneous system.
- *Team size:* In many multi-robot systems, as the team size increases, the cost of coordination and communication increases exponentially. It is the factor that must be considered when designing a multi -robot system. We categorize them into single, pair, limited and infinite which also proposed by Dudek et al. [18].

C. MRS REPRESENTATIVE APPLICATION

MRS has greatly promoted many applications, such as search and rescue [19], [20], foraging and coverage [21], [22], flocking and formation [23], [24], and cooperative object transport [10]. Darmanin et al. [1] give a brief MRS survey focusing on the MRS application domain. In this part, we aim to summarize and briefly introduce the main applications of MRS. The MRS applications are illustrated in Fig. 3.

1) SEARCH AND RESCUE

Robot systems are essential in searching and rescuing in dangerous or disaster-stricken areas. Multi-robot systems can carry out quicker searches for victims, map the disaster-stricken area, monitor search and rescue activities, or establish emergency communication networks [20]. As shown in Fig. 3(a), a monitor robot monitors the target and transmits real-time information to the router. The router sends it to the control room through the communication network to give a reference for search and rescue.

2) FORAGING AND COVERAGE

Foraging and coverage are fundamental tasks of MRS. The foraging asks the MRS to pick up things strewn around the area. The use of foraging includes toxic waste cleanup, mine cleaning, and service robots. The coverage of MRS is quite similar to foraging in that it demands the robots to analyze all of the points in the environment's free space. The use of coverage includes demining, snow removal, grass mowing, and vehicle body painting. In Fig. 3(b), multiple robots pick up the attractors to the "nest" to achieve foraging.

3) FLOCKING AND FORMATION

Flocking, also known as coordinated motion, means the robot agents move together like schools of fish or flocks of birds. Formation means robots travel collectively along a path in the aggregate. Fig. 3(c) shows six Turtlebot3[1] robots to forming a triangle shape in Gazebo simulator [25]. The formation is the basis of high-level applications, like object transport in logistics and warehouses and searches and rescue.

4) COOPERATIVE OBJECT TRANSPORT

Multi-robot cooperative object transport allows a group of robots move an object to a specific destination [14]. The advantage of cooperative object transport is that separate robots may cooperate to move objects too heavy for a single robot to move independently. Cooperative object transport offers a variety of real-world applications, including logistic handling, truck loading, and carrying goods in a warehouse or factory. Fig. 3(d) illustrate four MANI robots[2] cooperatively push the box to the target location.

III. MULTI-ROBOT SYSTEM COMMUNICATION

Earlier work on MRS used wired cable as the communication medium, which limits the performance on mobility. Recent work has shifted to the use of wireless communication technologies. However, the characteristics of wireless communication (collision avoidance strategies, signal fading) bring many issues for multi-robot communication. Multi-robot coordination based on wireless communication has strict requirements such as low communication latency, high quality of service, and high bandwidth consumption [26]. At the same time, the multi-robot system's characteristics, like high mobility, high dynamic topology, and dynamic routing, make communication-based multi-robot coordination more challenging. To better understand MRS communication, in this section, MRS communication classification is proposed, and recent advance in MRS communication is analyzed.

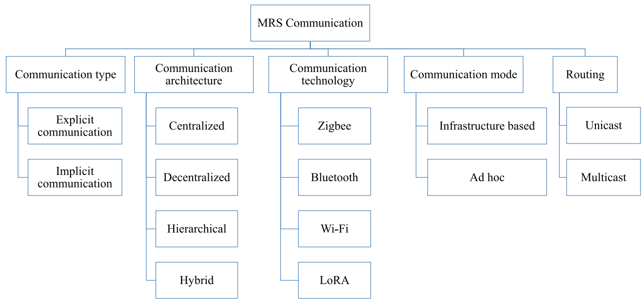

FIGURE 4. Classification of MRS communication.

A. OVERVIEW

There have been several literature reviews survey about the taxonomy of multi-robot system communication. Cao et al. categorize MRS communication according to the mode of interaction: interaction via environments, interaction via sensing, and interaction via communication [15]. Farinelli et al. categorize MRS communication into direct and indirect communication, depending on how robots exchange information [12]. Yan et al. classify MRS communication into explicit and implicit communication according to the information transfer modes [17]. As is shown in Fig. 4, we organize MRS communication from a different scope of view, which is categorized by five prospects: communication type, communication architecture, communication technology, communication mode, and routing.

1) COMMUNICATION TYPE

According to the communication type, we classify MRS communication into explicit and implicit communication.

Explicit communication denotes exchanging data messages with other network entities via onboard communication devices, including robots, system controllers, and so forth. Explicit communication is appealing for ensuring the accuracy of exchanging information (team members' actions, goals) between robots. However, explicit communication necessitates using an additional control framework to effectively send messages, ensure network connectivity and select a more appropriate network protocol for multi-mobile robots. These limits fault tolerance and reliability due to the noisy and limited bandwidth communication channel. The whole system's performance will decrease as the number of robots grows, which may even cause the entire system's breakdown. In detail, Fig. 5(a) and (b) are the explicit communication that needs to communicate with robots; In Fig. 5(a), robots communicate with the central controlling computer; In Fig. 5(b), robots communicate with each other by establishing connections among them.

Implicit communication refers to the robots getting information about other robots via environments inspired by social animals. Fig. 5(c) illustrates the ant foraging process. When

[1] https://www.turtlebot.com/turtlebot3/
[2] www.6-robot.com

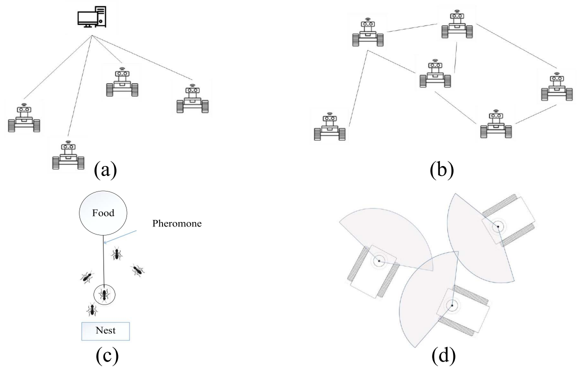

FIGURE 5. Explicit communication vs implicit communication.

the ant (marked by a black circle) finds food, it secretes the pheromone from food to the nest. The ants can get information about the food and move the food to the nest. Fig. 5(d) shows the robots with limited sensing capability to achieve coordination by implicit communication like ants.

2) COMMUNICATION ARCHITECTURE

we classify MRS communication into centralized, hierarchical, decentralized, and hybrid architecture, which also proposed by Jawhar et al. [27].

- *Centralized:* In such an architecture, a single control robot node monitors and manages the other nodes. It receives many other robots' state data and sends the control command to them. So it is easy to suffer from a single-point failure problem, which can reduce the reliability of the whole system. Also, scalability is diminished because of the limited bandwidth and computational capacity.
- *Decentralized:* The decentralized architecture is the most commonly used MRS architecture. There is no centralized monitoring robot node nor hierarchically monitor nodes; each robot can send and receive messages from the others. It is more robust because some robots' failures will not affect the whole system. However, keeping the synchronization and coherency among the robots in a dynamic environment is quite challenging.
- *Hierarchical:* In such an architecture, the control command will transmit hierarchy like in the military organization. The robots are organized like a tree so that high-level robots control a group of low-level robots. This architecture can achieve high scalability and is used in some applications with large-scale robots. However, it appears low reliability due to the failure of the high-level robots may cause the out-of-control problem of large-scale low-level robots.
- *Hybrid:* In such an architecture, local decentralized and hierarchical architecture are combined. It could achieve global synchronization and significant scalability at the same time. This hybrid architecture is used in many MRS.

3) COMMUNICATION TECHNOLOGY

Although wired communication provides high security, bandwidth, reliability, and low delay communication, its limited mobility is unsuitable for multiple robots' communication.

In Table 2, we list some wireless communication schema's main characteristics that need to be considered when designing an MRS communication system [28], [29].

Bluetooth and ZigBee, the instances implemented according to IEEE 802.15.1 and IEEE 802.15.4 respectively, are short-range radios with lower power consumption and higher scalability [30]. Bluetooth is based on a radio transceiver microchip built into digital devices to achieve short-distance communication, like a cell phone to a laptop. ZigBee targets devices like smart tags, meters, lights, and thermostats, as well as those used for sensing and automation, because it uses less power than Bluetooth and is built for scenarios like radio operation for months or years without recharging.

Wi-Fi has greater data rate and bandwidth than other wireless communication technologies listed in Table 2 that is based on well-known IEEE 802.11 family of standards. It can seamlessly connect with the Internet, widely used in MRS communication. However, when the robot count or communication range increases, the communication quality significantly decreases, causing a low data rate. It also has disadvantages, such as low scalability and high energy consumption.

Long Range Radio (LoRA) is a wireless communication technology that based on LoRAWAN standard which is managed by the LoRa Alliance,[3] a non-profit technology alliance. LoRA's longest communication distance can reach several kilometers, which is greatly longer than Wi-Fi. However, it's resilient to the Doppler errors which is an infrastructure-based communication with a higher cost.

4) COMMUNICATION MODE

As for communication modes, we classify into ad hoc modes and infrastructure-based communication.

In the ad hoc mode, all devices in the wireless network communicate directly in the peer-to-peer method. It's suitable for robots within the communication range, which do not need expensive communication infrastructure. However, ad hoc networks can only communicate with each other and cannot connect to the Internet without a specific gateway [31].

Infrastructure-based communication needs an access point (AP) for communication. It provides more security and is easy to manage the network. However, most infrastructures cannot move, so they have low mobility and high cost.

Recent researches on MANETs [32], VANETs [33], [34], and FANETs [35] try to mix the two modes mentioned above. Silva et al. [32] propose a decision algorithm to choose ad hoc mode or infrastructure based mode in MANETs where some nodes have the Internet access. The combined method may reduce hop count by using node with the Internet access,

[3] https://lora-alliance.org/

TABLE 2. Wireless Network Comparison

Schema	Standard	Range	Frequancy band	Max data rate	Channel bandwidth
Bluetooth	IEEE 802.15.1	10 m	2.4 GHz	0.72 Mb/s	1 MHz
ZigBee	IEEE 802.15.4	10 - 1000 m	868/915 MHz; 2.4 GHz	0.25 Mb/s	0.3/0.6 MHz; 2 MHz
Wi-Fi	IEEE 802.11	10-100 m	2.4; 5 GHz	54 Mb/s	25-20 MHz
LoRA	LoRAWAN	2000 m	0.433 GHz	0.11Mb/s	0.125 MHz / 0.5 MHz (up); 0.5 MHz (down)

TABLE 3. MRS Communication Recent Advance

Research focus	Publication	Research summary
MRS coordination in unreliable network	Zhivkov *et al.*, 2019 [40]	Investigate network perturbations impact on multi-robot system's mission performance
	Marcotte *et al.*, 2019 [41]	Propose Adaptive Erasure Coding (AEC) to enable recovery from packet loss using redundancy
	Marcotte *et al.*, 2020 [42]	Propose Optimizing Communication under Bandwidth Constraints (OCBC) algorithm to optimize the transport message
	Alsayegh *et al.*, 2020 [43]	Propose a lightweight communication protocol for data synchronization with less data
	kepler *et al.*, 2020 [44]	Propose a strategy that reduce the communication with novelty metrics determine which data to be reported
	Barcis *et al.*, 2020 [45]	Propose an information distribution framework for MRS
MRS connectivity maintenance	Michael *et al.*, 2009 [46]	Propose a distributed consensus and auction based connectivity maintenance method
	Zavlanos *et al.*, 2011 [47]	Summarize the theoretical framework of graph connectivity of multi-mobile robots
	Khateri *et al.*, 2019 [48]	Compare the two kind of, local and global, connectivity maintenance methods
	Siligardi *et al.*, 2019 [49]	Propose a tri-objective control law to maintain network connectivity
	Malli *et al.*, 2021 [50]	Propose a multi-robot network graph connectivity estimation algorithm that can be regarded as metrics for connectivity condition
	Singhal *et al.*, 2022 [51]	Implement several connectivity maintenance algorithms and test performance on different tasks
	Li *et al.*, 2022 [52]	Propose a reinforcement learning method aiming to navigate while connected maintenance
RANETs routing and protocols	Wang *et al.*, 2003 [53]	Give a brief introduction and review on ad hoc wireless robot network
	Das *et al.*, 2007 [54]	Propose the concept robot ad hoc networks (RANETs)
	Vandenberghe *et al.*, 2012 [26]	Compare the difference between RANETs and VANETs
	Tolstaya *et al.*, 2021 [55]	Propose a graph neural network based method for data distribution in robot ad hoc network
	Tolstaya *et al.*, 2022 [56]	Propose a machine-learning based optimal topology prediction method

and then reduce the communication delay. In VANETs applications, they use roadside unit infrastructure to connect to the moving vehicles and backbone network and use ad hoc mode among vehicles [33], [34]. FANETs also use the base station to communicate with gateway UAVs, and the UAVs communicate in ad hoc mode [36]. Combining these two modes can better play the advantages of the two modes and better tap the potential of the system.

5) ROUTING

As the communication distance increases, the communication signal power will fade in wireless communication. When transmitting messages among multi-robots, especially the robots connected with ad hoc mode, can send a message in one hop, or multi-hops.

Unicast sends messages from one robot to another, and multi-cast sends messages from one robot to many robots [37]. Unicast is essential for coordination-oriented communication between robots communicating information for coordination and control. Multicast is an effective and frequently used group communication primitive for tasks requiring close coordination. Multicast offers a productive way to send the same data to numerous recipients. Reduce latency and bandwidth consumption with multicast [38].

B. RECENT ADVANCES

There are many challenges and research topics on MRS communication. Gielis et al. propose a survey of MRS communication [39]. They focus on the MRS applications that need communication and network technologies for more powerful MRS. The recent findings are data-driven methods and co-design of the robot and communication system.

In this part, we focus on three other important research issues: MRS coordination in unreliable networks, MRS connectivity maintenance, and RANETs routing and protocols, which may affect the performance of cooperative object transport systems that detailed in Section V and listed in Table 3.

1) MRS COORDINATION IN UNRELIABLE NETWORKS

The performance of the MRS tasks is significantly impacted by the unreliable nature of wireless communication, unpredictable latency, and constrained bandwidth. To experimentally check the effect of network disturbance on MRS coordination tasks, Zhivkov et al. propose an MRS communication testbed [40] and investigate two kinds of network perturbations that impact multi-robot systems' mission performance.

As for the unreliable communication condition of the MRS wireless network, in Marcotte's Ph.D. thesis, a technique called Adaptive Erasure Coding (AEC) is proposed that enables recovery from packet loss using redundancy and can exchange latency tolerance for improved packet delivery [41].

As for the limited bandwidth problem, Marcotte et al. propose an Optimizing Communication under Bandwidth Constraints (OCBC) algorithm that evaluates the effect of communication message to the team to optimize the transport message [41], [42]. Alsayegh et al. propose a lightweight communication protocol for data synchronization without exchanging the original required data [43]. Two robots frequently trade a large amount of data in limited communication bandwidth due to the map merging problem. The protocols are computationally fast, allowing the robots to synchronize data (near) correctly with sharing substantially less data (in the order of log n bits). Kepler et al. propose a strategy that reduces communication; the fundamental idea is to give novelty metrics to each data as it is gathered, and only sufficiently novel measurements are reported [44]. Barcis et al. propose an information distribution framework for MRS that can evaluate every message's utility to improve bandwidth usage [45].

2) MRS CONNECTIVITY MAINTENANCE

Multi-robots connected with wireless network have risks of failure caused by communication out of radio range, fading, and affecting the quality of communication and cooperation.

Michael et al. propose a distributed consensus and auction-based connectivity maintenance method that guarantee the local connectivity of robots in the team [46].

Zavlanos et al. summarize the theoretical framework of graph connectivity of multi-mobile robots. Graph theory is a popular theory that can well model multi-robot system communication. They outline many methods, from optimization to potential field and hybrid systems. They all aim for connectivity maintenance during running [47].

Khateri et al. compare the two connectivity maintenance methods: local and global. They summarize that although global connectivity maintenance has common intuition of better flexibility, the experimental result shows local connectivity maintenance method performs better in limited bandwidth networks [48]. Global connectivity methods could provide a large workspace and maximize instantaneous area coverage.

Siligardi et al. propose a tri-objective control law to maintain network connectivity while performing coverage tasks based on Voronoi tessellation of an area of interest [49].

Malli et al. propose a multi-robot networks' graph connectivity estimation algorithm that can be regarded as metrics for connectivity conditions. The algorithm can fast convergence when robots move and increase over time [50].

Singhal et al. implement several connectivity maintenance algorithms, test performance on tasks such as trajectory tracking and multi-agent search, and finally report the result [51].

Li et al. propose a reinforcement learning-based method where the inputs are: distance sensor data and the position of other robots, and the output is robot control commands, aiming to navigate while maintaining the connection [52].

3) RANETS ROUTING AND PROTOCOLS

As for MRS ad hoc wireless communication, Wang et al. give a brief introduction and review [53]. Specifically, communication technologies from infrared to radio frequency, communication network layered models, and applications. Das et al. propose the concept of Robot ad hoc Networks (RANETs) [54] which is a subset of Mobile ad hoc Networks (MANETs). In the field of MANETs, vehicular ad hoc networks (VANETs) and flying ad hoc networks (FANETs) are well researched, and some county or organization's standards (EU, US, JP) are proposed. Unfortunately, to the best of our knowledge, RANETs has no standard.

Although the RANETs and VANETs belong to the field of MANETs, the focuses are different [26]. They both focus on self-organization, quality of service, and security. RANETs usually use infrastructure-less communication, considering energy consumption, high throughput, and low latency used in different application scenarios, from indoor warehouses to outdoor search and rescue, even underwater or space exploration. VANETs are used in an urban environment where roadside units can aid communication conditions, and there is no need to worry about energy storage.

As for RANETs, Tolstaya et al. propose a graph neural network based method for data distribution in a robot ad hoc network [55]. The robots extract network topology information from packets transmitting on the network and feed it to a graph neural network, that output when and where to communicate the most recent state information. RANETs topology affects many network performances, such as delay, reliability, and connections. Macktoobian et al. [56] propose a machine-learning-based optimal topology prediction method to find the optimal network topology of the multi-robot system. They first conduct a ground-truth topology generation algorithm based on the different network configurations. Then, a stacked ensemble model is learned by predicting the optimal topology according to the dataset.

IV. MULTI-ROBOT SYSTEM PLATFORM, SIMULATOR AND MIDDLEWARE

A. PLATFORM AND TESTBED

During the past two decades, many multi-robot platforms and testbeds have been proposed, such as, Khepera [57], [58], e-puck [59], Kilobot [60], [61], Jasmine [62], R-one [63]. In this part, we summarize the representative proposed platform and testbed, shown in Table 4.

K-team and École Polytechnique Fédérale de Lausanne (EPFL) cooperate to produce Khepera, e-puck, and Kilobot. Khepera I is the first edition Khepera robot, a well-known robot platform that first developed by Prof. Mondada in 1999. The latest version is Khepera IV, which has high-precision sensors and a more robust software system: libkhepera and Khepera IV Toolbox. Mondada et al. also propose an education and engineering mobile robot platform: e-puck, which targets university-level engineering education. E-puck support Webots [68] simulator, an open-source multi-robot simulator widely used in academic or commercial settings. Kilobit [60], [61] is a low-cost, small-sized, open-source robot platform that tests collective algorithms on hundreds or thousands of robots, like formation control, foraging, and synchronization.

Mona is a low-cost, open-source, open-hardware mobile robot developed at the University of Manchester and has been designed to be inter-operable with various conventional

TABLE 4. MRS Platform and Testbed

Name	Publication	Size	Protocol	Cost
Khepera I	Mondada *et al.*, 1999 [57]	diameter=55mm	Infrared	N.A.
Khepera IV	Soares *et al.*, 2016 [58]	diameter=140mm	Bluetooth, IEEE 802.11b/g	CHF 2700
Epuck	Mondada *et al.*, 2009 [59]	diameter=75mm	Bluetooth	€ 550
Kilobot	Rubenstein *et al.*, 2014 [61]	diameter=33mm	Infrared	$14.50
Mona	Arvin *et al.*, 2019 [64]	diameter=80mm	Infrared	£ 100
Robotarium	Pickem *et al.*, 2017 [65]	diameter=30mm	IEEE802.11b/g/n	$60
UMBRALLA	Farnham *et al.*, 2021 [66]	diameter=250mm	Bluetooth, IEEE 802.11ac, 5G	$1,000
DOTS	Jones *et al.* 2022 [67]	diameter=250mm	Bluetooth low energy, IEEE802.11, 5G	£ 1000

TABLE 5. MRS Simulator and Middleware

Category	Name	Publication	License	Language
MRS simulator	Stage	Vaughan *et al.*, 2008 [69]	GPL License	C++
	Webots	Michel *et al.*, 2004 [68]	Apache 2.0	C++, Java, Python, Matlab
	Gazebo	Koenig *et al.*, 2004 [25]	Apache License	C++
	Emulab	White *et al.*, 2002 [73]	GPL License	C++
	USARSim	Carpin *et al.*, 2007 [76]	GPL License	Java
	Morse	Echeverria *et al.*, 2001 [74]	BSD-licensed	Python
	MRPT	Claraco *et al.*, 2008 [75]	BSD-licensed	C++
	ARGoS	Pinciroli *et al.*, 2012 [72]	MIT License	C++
MRS middleware	Player	Gerkey *et al.* 2021 [77]	GNU	C, C++, Python, and Ruby
	ROS1	Quigley *et al.*, 2009 [78]	BSD-licensed	C++,Python
	ROS2	Macenski *et al.*, 2022 [79]	Apache 2.0 License	C++, Python
	Robo-NetSim	Kudelski *et al.*, 2013 [80]	N.A.	C++, Python
	ROS-NetSim	Calvo *et al.*, 2021 [81]	N.A.	C++, Python
	CORNET	Acharya *et al.*, 2021 [82]	MIT License	Python

programming environments [64]. Mona has been utilized in teaching and research, particularly in multi-robot systems, because of its compact size, low cost, and multiple add-on modules. Mona can also simulate it in Stage simulator [69].

Robotarium is a remotely accessible swarm robotics research testbed motivated by providing remotely accessible service to avoid the high cost of developing and maintaining a testbed [65], [70]. The users upload their code to the server, and robot and video data are returned to users. The hardware is GRITSBots [71], a cylinder with a diameter of 30 mm that can charge automatically. Wi-Fi establishes the communication between GRITSBots on the ESP8266 chip.

Farnham et al. propose a collaborative robot testbed that is a part of the UMBRELLA project that use different count of robots to move different sizes and shapes objects [66]. It supports many communication technologies (Bluetooth, Wi-Fi, and 5G) and custom radio protocol stacks and uses Docker container and ROS2 data distribution service (DDS) based software architecture.

DOTS is an open-access testbed for multi-robot like Robotarium, which is also the product of the UMBRELLA project. It has newly designed robot platform, the well-established experimental arena that equipped with many communication infrastructures, motion-capturing systems, and cameras [67].

B. SIMULATOR AND MIDDLEWARE

Simulations are safer and cheap experimental tools than the real-world platform. It's usually used before building the system or testing the new algorithms.In this part, we review the recent popular MRS simulator and middleware, which are listed in Table 5.

Physical simulators can accelerate robot prototyping by designing with standard 3D modeling tools or third-party tools and employing physical engines for realistic movement. With the growing attention on robotics research, there are a lot of open-source simulators, for example, Webots [68], Stage [69], Gazebo [25], ARGoS [72], Emulab [73], Morse [74], MRPT [75], USARSim [76].

Webots is a 3D simulator developed and continuously maintained by Cyberbotics, a spin-off company from the Swiss [68]. It allows users to write their control algorithms using C/C++, Java, Python, and MATLAB. It also allows users to design custom robot models and choose their favorite sensors, actuators, and other components. Webots is a cross-platform robot simulator that supports Linux, Mac OSX, and Windows. The source code and binary packages are fully open source, but for private user support or consultation, an annual payment of 2500 CHF is needed.

Stage is a simulator that can simulate multi-mobile robots, sensors, and objects in two-dimensional bitmapped environments [69]. Stage can cooperate with the Player platform [77]. They can run on Linux, Solaris, BSD, and Max OSX.

Gazebo is one of the most popular ROS-integrated simulator. As increasing popularity of ROS, Gazebo is also known as the common choice for most robotics simulations [25].

Unlike physical engines, multi-robot middleware focuses on hardware and software abstraction, interoperability, dynamic source discovery and configuration, software reuse, and real-time service [83]. Usually, middleware and physical simulators work together to complete the interaction and simulation.

Player is a multi-thread TCP socket server that can effectively distribute sensing and control data flow among sensors, processors, and actuators. It provides a transparent access network interface to robot devices to provide a device-independent and language-independent multi-device interaction framework.

ROS is one of the most popular robot middleware nowadays. It abstracts the communication between devices using the publisher-subscriber mode and client-server mode. The processes that perform computation is abstracted as node [78]. Although in ROS, the communication is a peer-to-peer mode between nodes, it needs a particular node: the master node, to provide naming and registration services that may cause a single point of failure problem.

ROS2, a newly designed version of ROS, changes the communication transport mechanism into a data distribution service (DDS) [79]. The features of the DDS, like the dynamic discovery of nodes, quality of service, and scalable architecture, benefit it in meeting some product-grade applications.

Some researchers try to integrate physical simulators with network simulators. RoboNetSim incorporates NS2 [84], NS3 [85] as network simulators, and ARGoS, Stage as physical simulators [80]. ROS-NetSim is an open-source ROS package that interfaces between physical and network simulators in multi-robot systems [81]. They integrate the interface with WINTERSim[4] and the Gazebo simulator. A recent emerging system like CORNET uses mininet-WiFi as a network simulator and Gazebo as a physical simulator [82].

V. COOPERATIVE OBJECT TRANSPORT

A. OVERVIEW

Cooperative object transport is one of the hot-researched applications of MRS. Cooperative object transport requires a set of autonomous robots to coordinate and synchronize pushing/pulling forces to transfer things that cannot be transported by a single robot [86]. As research increases, a variety of approaches have emerged.

The earlier work aims to transport the object from source to destination without obstacle. However, many issues need to be solved when it is used in practical applications. As for structured environments like logistics and warehouses, formation control during transport, cooperative obstacle avoidance, cooperative navigation, and autonomous charging need to be addressed. In these environments, many assumptions like predefined trajectory and prior knowledge of payload characteristics such as weight and geometry structure exist. Although many commercial and academic logistics robots, such as the Kiva system [87], and Alibaba [88]'s logistics robots, are produced, they are designed for particular structured tasks. Usually, one robot transport one load or shelving unit that have large loading capacities, high prices, and large energy consumption. Using multiple cooperative robots to transport object may achieve equivalent load capacity in efficient, robust way with lower consumption.

It is more challenging to cooperative object transport in an unstructured and unknown environment, for example, mining, underwater, or space environment, as summarized in [11]. In this environment, the assumption is minimal prior information, local sensing capability, and no explicit inter-robot communication or global localization. The way to solve this problem is the nature-inspired method, inspired by ant group retrieval, bees, and a school of fishes.

B. STATE OF THE ART

There are many control methods used for cooperative object transport. For example, Occlusion-based method [89], centralized control architecture based method [90], distributed control architecture based method [91] reinforcement learning based method [92]. The different robot platforms (mobile manipulators [24], [93] and lift-based methods [94]) also affect task performance. The two related surveys: [10] and [11] comprehensively summarize cooperative object transport. This paper presents recent advances in specific cooperative object transport topics like decentralized and reinforcement learning-based control strategies, lifting-based cooperative object transport systems, and real-world applications in logistics and warehouse scenarios (multi-robot network, formation maintenance, transport object localization) are added. Table 6 lists a brief description of the publications.

1) DECENTRALIZED CONTROL

Ebel et al. propose an optimization-based distributed multi-robot cooperative object transport schema in which each robot cooperates as equal to decision-making [91]. Besides that, they also consider the formation synthesis and position negotiation problem that determines which robot act in what role and is configured in which position in the transportation process. Farivarnejad et al. propose a decentralized control strategy for multiple robots to achieve cooperative object transport with limited sensing capability and minimal prior knowledge [95]. Decentralized velocity and a position controller for the transported objects are designed based on non-linear control theory in and without obstacle environments. They also extend the controller into a 3D microgravity environment [7]. A PD decentralized controller is designed for cooperative solar panel transport tasks.

2) REINFORCEMENT LEARNING BASED CONTROL

Zhang et al. propose a deep reinforcement learning algorithm in which each robot use a deep Q-learning controller to transport the oversized object for a single robot [92]. Eoh et al. find that a deep reinforcement learning algorithm takes a long time to train a policy, and random action is challenging to train a satisfactory policy [96]. They use curriculum-based learning methods and propose region-growing and single- to multi-robot curricula that raise the success rate of object transportation tasks. Shibata et al. propose an event-triggered deep-reinforcement learning controller [97]. The event-triggered architecture achieves desired transport performance with little communication information exchanges.

[4] http://winter-group.net/download/

TABLE 6. Recent Advance of Cooperative Object Transport

Category	Publication	Brief description
Decentralized control	Ebel *et al.*, 2020 [91]	Propose optimization based distributed multi-robot cooperative object transport schema
	Farivarnejad *et al.*, 2020 [95]	Propose decentralized control strategy for limited sensing capability and minimal prior knowledge cooperative object transport task
	Farivarnejad *et al.*, 2021 [7]	Propose a PD decentralized controller for cooperative solar panel transport task
Reinforcement learning based Control	Zhang *et al.*, 2020 [92]	Propose a deep reinforcement learning algorithm, that each robot equipped with deep Q-learning controller
	Eoh *et al.*, 2021 [96]	Propose curriculum-based learning method: region-growing and single- to multi-robot curricula for training
	Shibata *et al.*, 2021 [97]	Propose an event-triggered deep reinforcement learning controller
Lifting based method	Koung *et al.*, 2021 [94]	Presents an optimization-based control law for lifting based cooperative logistics transport, which consists subtasks: formation control, group navigation, individual and team obstacle avoidance
Multi-robot Network	Aijaz *et al.*, 2020 [98]	Argue the private 5G has significate potential in industrial environment such as warehouse etc.
	Aijaz *et al.*, 2021 [99]	Evaluate the performance of Bluetooth mesh network in logistics environment
	Gielis *et al.*, 2021 [100]	Propose crash risk prioritization (CRP) index that improve the 802.11p standard to use it in robot to robot network
Communication based formation control	Teh *et al.*, 2020 [101]	Investigate the impact of communication quality to the multi-robot system formation control task.
Transport object localization	Hu *et al.*, 2019 [102]	Propose an onboard transported object localization algorithm in cooperative object transport task

3) LIFTING BASED COOPERATIVE OBJECT TRANSPORT SYSTEM

Using small but powerful cooperation capability robots for cooperative object transport is a promising solution to the logistics and warehouse environment. Koung et al. present an optimization-based control law for lifting-based cooperative logistics transport, which consists of subtasks: formation control, group navigation, and individual and team obstacle avoidance [94]. The hierarchical quadratic programming (HQP) approach determines the priority of the tasks to provide optimal control solutions.

4) MULTI-ROBOT NETWORK

As for high-performance wireless communication requirements in Industry 4.0, Aijaz argues that private 5G has significate potential [98]. Its characteristics: unified communication interface, quality of service, mobility, security, and positioning benefit many application scenarios like warehouse operation, remote industrial operation, mining, and railway networks. However, the challenges of private 5G, like network slicing solutions, resource allocation, and integrate with time-sensitive networking, need to be addressed.

As for multiple small and low-cost out-of-box robots for cooperative object transport in logistics and warehouse environments, Aijaz et al. evaluate the performance of Bluetooth mesh networks that act as communication technology between robots [99], [103]. Bluetooth mesh has excellent characteristics like high flexibility, low latency, and perfect reliability for dealing with communication and cooperation tasks. Gielis et al. propose a crash risk prioritization (CRP) index that improves the IEEE 802.11p standard for robot-to-robot networks [100]. The co-design method that integrate CRP into dynamic bacon rate control insight promising performance in the robot-to-robot communication.

5) COMMUNICATION BASED FORMATION MAINTENANCE

Teh et al. investigate the impact of communication quality on the multi-robot system formation control task [101]. They test cooperative trajectory tracking performance using non-holonomic (differential drive) and holonomic (Omnidirectional) robots with imperfect communication conditions. The result shows that communication imperfect (packet loss and latency) significantly affect trajectory tracking performance.

6) TRANSPORT OBJECT LOCALIZATION

Hu et al. propose an onboard transported object localization algorithm in cooperative object transport tasks [102]. Unlike the previous method that uses an additional localization device for the transported object, this algorithm merges the scan data from robots' LIDAR to provide real-time object position.

VI. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

We have reviewed the multi-robot system fundamentals, communication, platform, and cooperative object transport. In this section, MRS challenges and future research directions are discussed.

- *Communication:* MRS Communication is the bridge to realize the MRS cooperation which categorized into explicit and implicit communication. Explicit and implicit communication has advantages and disadvantages, and the selection of communication type depends on the application's requirement. However, the contradiction between high communication and computation energy consumption, the onboard system's limited resource, the current wireless network's delay, and MRS's real-time communication requirement has not been well resolved for explicit communication. 5G, Bluetooth low energy, and more intelligent communication methods integrated with AI technologies may bring more promising communication performance [39].
- *Robustness:* In explicit communication-based MRS, some robots may be out of communication range and lose communication signals while running. Besides, in a leader-follower or centralized architecture-based

MRS, a single-point-of-failure problem dramatically affects the system. The fault tolerance mechanism is increasingly essential to achieving whole autonomous MRS. For example, when the leader robot fails, the followers can quickly choose a new leader, predicting and restricting the robot movement range to avoid the out-of-communication range problem, the ability of self-awareness, and self-repair.

- *Scheduling system:* Most researches on multi-robot co-operative object transport problems focus on the control strategies, obstacle avoidance algorithms that transports the object from the source to the destination without collision. However, in some application scenarios, for example, in smart factory or warehouse, the object mass and size are different, which needs different number of robots to transport. The system must determine how many robots are allocated to transport the object. Furthermore, it needs an intelligent scheduling system to manage the spare and busy robots.
- *Simulators and real-world robot platform:* As shown in Tables 4 and 5, most of the multi-robot system experimental platform's communication technology is Bluetooth or Infrared, which has a lower communication range and bandwidth. However, logistics and warehouse environments need long-range sensing and communication capability, centralized or decentralized scheduling, and a management system for specific tasks. Apart from communication distance, a series of compatible simulators, and middleware, real-world hardware platform solution is complicated and rare.

VII. CONCLUSION

Multi-robot system can carry out more difficult tasks consistently and effectively than a single robot. Effective and reliable communication among robots is essential for multi-robot system coordination. In this review, we introduce the MRS fundamentals, communication mechanism, experimental platform, and the application of cooperative object transport. Although a large scale of multi-robot system applications has been proposed, we believe that MRS's potential has not been fully realized, especially in a smart factory or logistics environment. Multi-robot cooperative object transport with effective communication, scheduling, management, and high fault tolerance still has great potential.

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