A review of multi-agent mobile robot systems applications

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ABSTRACT

A multi-agent robot system (MARS) is one of the most important topics nowadays. The basic task of this system is based on distributive and cooperative work among agents (robots). It combines two important systems; multi-agent system (MAS) and multi-robots system (MRS). MARS has been used in many applications such as navigation, path planning detection systems, negotiation protocol, and cooperative control. Despite the wide applicability, many challenges still need to be solved in this system such as the communication links among agents, obstacle detection, power consumption, and collision avoidance. In this paper, a survey of the motivations, contributions, and limitations for the researchers in the MARS field is presented and illustrated. Therefore, this paper aims at introducing new study directions in the field of MARS.

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1. INTRODUCTION

A multi-robot system (MRS) consists of multiple collaborating robots that are capable of physical movement and they must physically engage with one another. Multi-agent systems (MAS) contain a group of computers that work to complete a mission, with individual nodes remaining stationary. In the MRS, the agent is a robot, while in the MAS, it is the software [1]. Multi-agent robot systems (MARS) research efforts have increasingly been performed since the late 80 s because they produced higher and more detailed results than those of a single robot. ACTRESS and ALLIANCE robots are the first heterogeneous multi-agent robots. The benefits of information sharing among agents, data fusion, and distribution of tasks, time, and energy consumption have rendered MAS research important up to the present [2].

All the applications involving multiple autonomous robots that belong to the category of MAS can be named MARS. At the same time, MAS is related to the category of distributed artificial intelligence (DAIs) [3]. MARS promises to allow new mission groups of aerial, aquatic, and ground applications at a lower cost than that of monolithic systems. Specifically, MARS has a notable use in the unmanned aerial vehicle (UAV) surveillance aircraft, observation satellites, and multi-layered exploratory spacecraft for planets. Several algorithmic models have been suggested to govern the sharing of information of such systems, extending from low-level position control to high-level motion planning and task allocation [4]. Most of the related papers that were published from 2017 to 2021 have been reviewed. Herein, readers should not confuse MRS with MASs and DAIs. For this purpose, the problem statements are demonstrated as following: i) to reach the purpose of the tasks of MAS, it is hard or impossible to define accurately and correctly the behavior as well as the activities of MAS due to the system design; ii) one of the most difficult challenges for MRS is to develop effective coordination strategies among robots to enable them to execute operations effectively in terms of time and working space; and iii) research has been started to use multiple robots to overcome the problems in a changing workspace and to accomplish a specific task. In MARS, a mobile robot may work as an agent and an MRS as MAS. It has been shown that there are a variety of approaches for designing a mobile robot as an agent, and it seems to be extremely challenging to find a standard representation to explain and evaluate these approaches.

The paper is structured into five sections: section 2 explains the proposed research methodologies for MARS. Section 3 discusses the results of the application of MARS. Section 4 highlights the proposed system and design application. And the conclusions are given in section 5.

2. RESEARCH METHOD

The research method has been structured into three parts; the first part focuses on multi-agent systems definitions, structures, and applications. In the second part, the mobile robot system was studies. Ending with the third part when the challenging issues of the multi-robots system were presents.

2.1. Multi-agent systems

Multi-agent systems (MAS) is a part of distributed artificial intelligence that intersects at two study areas: artificial intelligence and distributed computing [5]. It has a set of intelligent agents that communicate with each other and with the environment [6]. Distributed computation is an area that aims at studying how to solve one computing problem that might occur in most processors. The fundamental goal of these processors is to reach their parallelism and synchronization by using data linked for problem-solving. The area of distributed artificial intelligence results from a fusion of distributed computing and the development of artificial intelligence [7]. The integration of MAS, consensus issues in autonomous MR, and sensor networks were investigated in light of the recent increase in distributed control applications with network mobile robots and sensor networks for mobile agents. Two novel algorithms with swapping topologies were proposed: (back-tracking) as well as (history following) [8]. The difficulties that may arise from dealing with intermittent data transmissions and determining when inter-agent communication needs to be executed to ensure the desired formation performance give rise to schedule inter-agent communications. A new dynamics event-triggered communication mechanism (DECM) was created forming a protocol [9]. Interactions among agents are required in MAS. The collective goal was achieved as a result of these interactions [10]. An agent is a system of the computer that works autonomously and flexibly in any environment to accomplish the goals [11]. Figure 1 shows an agent in the environment [6]. Thus, through the use of a multi-agent system, global goals may be accomplished through sensing, knowledge sharing by communications, computing, and control [12]. The algorithms of MAS help users to manage all the groups of agents without the need to send the command to each one of the search and rescue missions, satellite formation control, surveillance drones, package delivery robots, and military weaponry systems development [13].

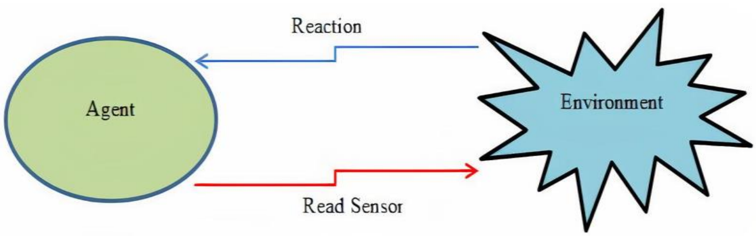

Figure 1. An agent in the environment [6]

The applied MAS is platform-independent, resource-friendly, and thus it is suited for a wide variety of devices and usage cases [14]. Several criteria have been selected to divide the structure of the multi-agent architecture. Table 1 summarizes the categorizations of multi-agent architectures focusing on task division and operation and centralization of data [7].

Table 1. The categorizations of MAS structures [7]

Type	Leader agent	Mediating agents	Parallelism, fault tolerance, and scalability
Centralized MAS	Yes	No	More difficult
Decentralized MAS	No	No	Yes
Federated MAS	No	Yes	Yes

Figure 2 demonstrates the structure of MAS that describes a society of autonomous communicating components devoted to providing solutions for high scale problems, as opposed to a system dependent on either a single entity or agent, which could be a barrier due to insufficient resources or failure at a critical time [15]. The MAS has found multiple applications, including open-source software, communication-computer networks, motion coordination, an E-learning MAS, and an unknown environment. The significant features of MAS, such as efficiency, low cost, flexibility, and reliability were marked as good solutions to resolve difficult goals. MAS has been conducted in many research works using open-source software to create a new multi-agent framework open-source software (MAFOSS). It was used to implement algorithms for multi-agent applications [16]. MAS is one of the most influential and promising 'approaches' to promote the internet of things (IoT) and cyber-physical systems (CPS) technologies. MAS is highly adaptable and this leads to enable the implementation of cooperative/competitive distributed thinking robustness, reconfigurability, reusability, and partial technology independence [17]. The unsolved problem of multi-agent simultaneous localization and mapping (SLAM) is the combining of maps generated by different agents throughout the algorithm. The stable way out is to use more computing agents to discover the environment faster than a single one to reduce the load of each agent [18]. Another field of application is the stochastic aspect of simultaneous perturbation stochastic algorithms (SPSAs) that contributed to the agent motion coordination during the simultaneous perturbation vector operation, where the agent is thought to be able to move arbitrarily depending on the Bernoulli distribution [19]. A multi-agent system for automation of learner's support in a collaborative e-learning platform was studied as well as pre-assess students' prior learning, classify their skills, and make a recommendation for appropriate material suitable to their needs [20], [21]. This research is useful in a situation that involves four agents and four desired target points. For large-scale (MASs), the development of completely decentralized cooperative control (consensus, creation, and containment) is underway for the homogeneous linear time-invariant (LTI) MASs. A modern time-varying formation (TVF) shape format was proposed, as well as a unified framework for designing fully decentralized controllers based on performance measurements [22].

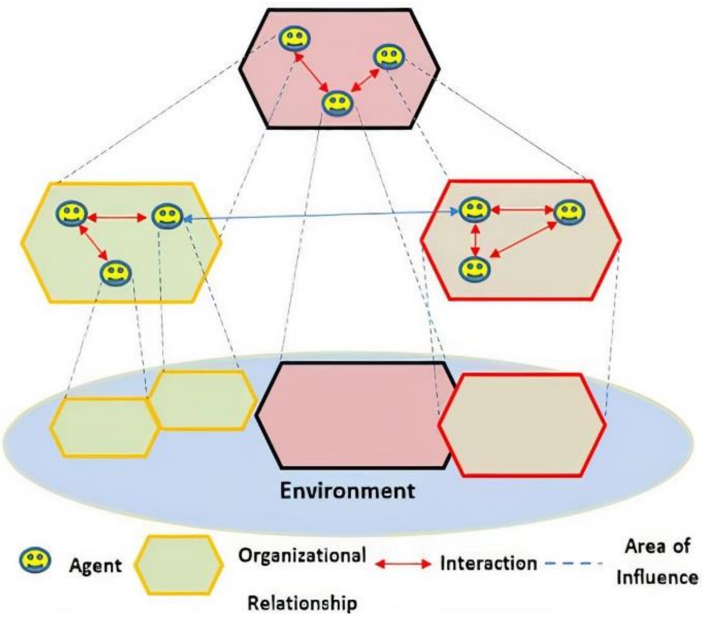

Figure 2. Structure of MAS [15]

2.2. Mobile robots system

Mobile robots can navigate through environments and communicate with each other using sensors and actuators [23]–[25]. Globally, substantial resources have been dedicated to robotics research and development, autonomous mobile robots, physiological reactions, and robot collaboration. Therefore, mobile robots will be widely used in industry and homes in the immediate future [26], [27]. There are two types of mobile robots: autonomous mobile robots (AMR) and autonomous guided vehicles (AGV). The main difference between AMR and AGV is related to the autonomy mechanism. An AGV navigates in a pre-defined area on a pre-defined route using physical directions. Global positioning system (GPS)-aided AGV can navigate its way to a target in an obstacle-free outdoor environment depending on its calculation of the shortest path and use the corresponding GPS data 96. AGVs have long been used in manufacturing, but they have recently been replaced by AMR. AGVs are well-suited to repetitive activities, such as line-follower robots that are often built and manufactured for specialized purposes. AGVs cannot make decisions because of the lack of a decision system based on artificial intelligence. Therefore, the roles that they would execute must be meticulously prepared and all information must be defined to them by the programmer. In this context, AGVs operate according to pre-programmed instructions and protocols that make the quick transition impossible. Therefore, the biggest drawback of AGVs is their inability to rapidly execute shifting functions [24]. Hence, to develop the various task achievement conception of the transport system for AGVs, it is necessary to create an automated warehouse, where packages are delivered by mobile vehicles (agents) [28]. As a result, the importance of route planning in the setting and avoiding collisions among agents in a multi-agent structure is considered the biggest challenging issue.

Recently, the movement of autonomous mobile robots (AMRs) can occur safely in cluttered environments, comprehending natural voices, identifying actual things, locating and navigating themselves, designing routes, and performing self-thinking. AMRs were designed using intelligent, cognitive, and behavior-based management methodologies and technologies for maximizing output variability by keeping input dictionaries and technical sophistication to a minimum. As a result, AMRs fall into the general category of intelligent robots. A computer that can extract information from its environment and use knowledge about its function to transfer safely in a meaningful and purposeful manner is described as an intelligent robot. In general, a robot is described as a computer that makes an intelligent link between perception and behavior [29]. Future factories and warehouses would use a fleet of autonomous robots that will operate together to achieve a shared target established by the enterprise system with minimal human involvement using cloud robotics platforms that can support this type of collaboration. The design of a fleet management system for a community of autonomous mobile robots (AMR) is utilized in three configurations: single-master, multi-master, and cloud robotics platforms [30].

In a community of mobile robots, each robot will have its route planning approach. For a multi-robot mission, the strategy designed for a single robot may be integrated. This can be accomplished by multi-robot system coordination (MRSC). To obtain optimal synchronization in all stages of MRSC, all robots in the group will maintain a particular geometric pattern of movement. A system for controlling and coordinating a community of non-holonomic mobile robots equipped with range sensors was demonstrated with an emphasis on trajectory generation and data sharing [31]. To achieve synchronization among multiple robots in a group, various control approaches have been developed such as the leader-follower method (LFA), in which one robot serves as a leader, whose motion sets the direction for the whole group [32].

In addition, MRS is used in a wide range of applications that are conducted to simplify the life of humans such as in health care [33], where the MRS is handling the coronavirus disease 2019 (COVID-19). This task was accomplished by disinfecting both the human body and the outer environment [34]. The contribution of MRS in education was by using the eduMorse as an open-source tool to create a novel framework for education in the scope of mobile robots. The goal of eduMorse is to help students bridge the difference between theoretical principles and functional application by exposing them to problems such as route planning and triangulation without having to focus on a real hardware network, but also in a concrete setting [35]. The applicability of mobile robots to support the elderly for the future is made by visual interaction, in which robots can follow human movements and avoid undesired actions. Therefore, mobile robots must be able to detect human movements in a residential environment and use cloud-based intelligent robot platforms with multiple control methods. Various modes for controlling the robot were presented based on the robot's vision system, and then to complete that movement, the mobile robot recognizes human control orders on one side [36]. In an emergency relief scenario, the multi-agent (MA) architecture was used to intelligently control aerial robots. It was used to develop and create a multi-agent framework for intelligent management of cooperative flight drones and quadcopters so that they can conduct a fast, yet efficient survey of the disaster site following an earthquake for which detection systems are still ineffective [37]. The majority of autonomous robots come with an intelligent control system that greatly expands their capabilities. Even though the population is entirely heterogeneous, the intelligent control scheme offers possibilities for autonomous robotics group management, where any of the robots can operate in the miscellaneous robot's environment without disrupting others [38]. The big goal is to use cloud computing to enable a mobile robot vision system to reliably meet real-time constraints. Thus, the human cloud mobile robot (HCMR) architecture with a data flow process was suggested in [39] by simplifying computing activities, distributing workloads, parallelizing work among cloud computation nodes to reduce the capacity of data transmitted and retrieved between the mobile robot and the cloud server.

When several processing units are used, a distributed system is created inside a single robot. As a result, the system architecture is much more critical in multi-computer robots than it is in single-computer robots. For robotic systems, the concept of a modular and distributed device architecture was developed in [40]. Since most works are centralized, there are currently few studies relevant to a decentralized MRS. As a result, a proposal for the development of a decentralized MRS for tracking and surrounding a stationary goal was suggested in [41]. While the usage of autonomous mobile robots in warehouse systems has yielded notable benefits such as increased efficiency, better room utilization, and lower operating costs, the high complexity and versatility of mobile vehicles have created a resource-competitiveness challenge [42], [43]. The use of blockchain in conjunction with other distributed platforms, such as robotic swarm systems, will provide the capabilities needed to render robotic swarm operations more protected, autonomous, scalable, and even productive, by utilizing the robots as nodes within the network and enveloping their transactions in chains. The mixture of blockchain technologies and swarm robotic systems will provide creative solutions [44]. The mobile robots are fitted with sensors that determine the robot's distance from the space in which the items they pass are located. Therefore, measurements are still associated with noise signals, and hence filters are used to get an approximation of the direction and inclination of the mobile robot trajectory through space and planning [45]. On the other hand, a position sensor based on computer vision was established to offer information about the real-time position of the robots on the platform when the Khepera IV robot was used as platform. It was used due to its flexibility and because it builts-in sensors [46].

2.3. The challenges of multi-robot systems

Autonomous mobile robots faces many challenges. These challenges have been studied by many researchers to solve the tasks in this field. The major challenges are related to free navigation, localization, path planning, and static and dynamic obstacle avoidance. These challenges are summarized in Figure 3 [47].

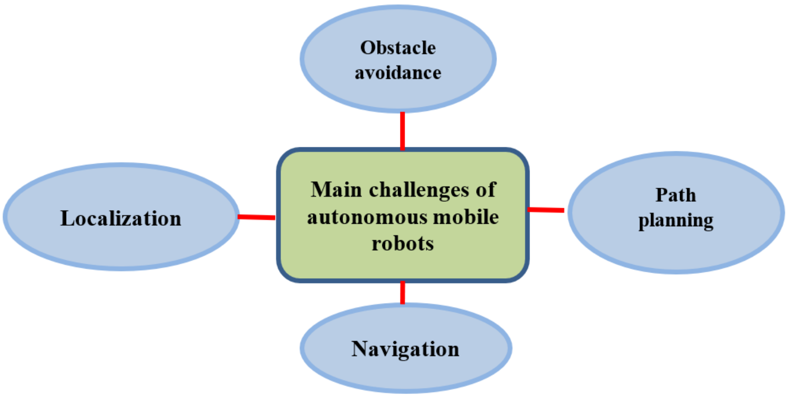

Figure 3. Challenges of autonomous mobile robots [47]

Obstacle avoidance between the mobile robot and obstacles is an important issue for mobile robot systems [48]–[51]. In complex environments, the mobile robot cannot achieve precise locations such as on slippery surfaces [52]. The navigation of mobile robots is considered the most difficult problem in robotics systems. Model-based methods and behavioral-based methods are the two types of navigation methods. Robots being stuck in front of obstacles are a common problem in robot navigation. Recently, researchers used soft computing methods for navigating mobile robots since they are more effective than other current methods [53]–[57]. Moreover, a single mobile robot used as a leader can be employed for navigation while the rest of the mobile robots are instructed to follow it. The arrival of a new survey site enforces a new restriction to the navigation plan. As a result, the mobile robot that serves as the leader must consider this latest site [58]. The main condition to successful navigation is the ability to localization and building maps of unknown environments used for a mobile robot, which is also called simultaneous localization and mapping (SLAM) [59]. The locomotion system is an essential part of mobile robot design that takes into account not only the medium where the robot moves but also other elements including maneuverability, controllability, topographical conditions, efficiency, and stability [60]–[62]. The navigation framework with both a local path planner and global path planner is shown in Figure 4 [63].

The autonomous mobile robot path planning is an essential task in real life for the last few decades [64]–[67]. There are some path planning strategies, likes combinatorial method, sampling-based method, and bio-inspired method [68]. The optimal path planning for multiple goals finding tasks is achieved by a genetic algorithm [69], [70]. To be safe during navigation from the start configuration to the target configuration, it is necessary to find a collision-free motion in an obstacle-prone environment [71]–[74]. Path planning is extremely important in motion planning and cooperative navigation of several robots. The problem of multi-robot path planning is still extremely difficult due to its high difficulty and the existence of hard non-deterministic polynomial-time problems [75]. Figure 5 shows the path planning categories [76].

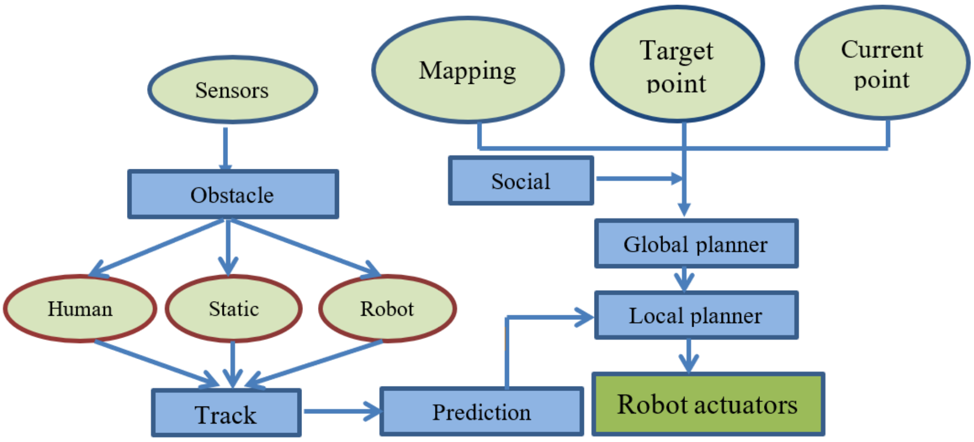

Figure 4. The navigation framework with both a local path planner and global path planner [63]

The path planning problem in a multi-robot system is challenging, because finding the best collision-free paths are affected by dynamically changing environments due to the robots' movement [77]. The main constraints in robot navigation, and thus path planning in various mediums, can be summarized by dynamic environments, movement restriction, inland robots, energy efficiency, situational awareness, atmospheric conditions in ground robots, surface robots, under actuation and environmental effects in aerial robots, winds, and water depth [78], [79]. An optimized path planning approach capable of adapting to a changing setting was developed by integrating the advantages of online and offline methods [80]. At large system scales, finding decentralized path planning and coordination solutions is key to efficient system performance [81]. According to the planning scope, path planning in the navigation system of mobile robots can be divided into global and local planning [62], [82] Another kind of multi-agent path finding is known as multi-agent observation planning when the multi-agent path-finding problem is reformulated to provide protection requirements in a way that the routes of the mobiles are arranged simultaneously with an observation plan [83].

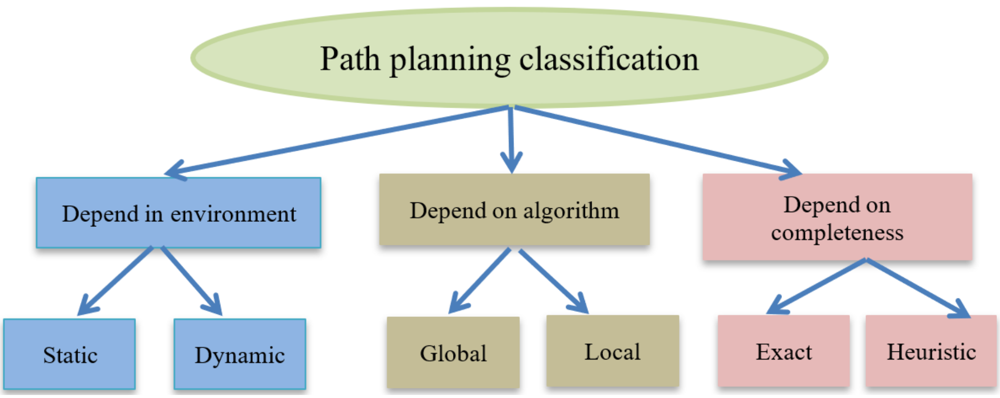

Figure 5. Path planning categories [76]

3. RESULTS AND DISCUSSION

In this section, many papers related to application of MARS were presented. For each paper, the most important points such as: (motivations, contributions, and limitations) were listed and summarized in Table 2. In addition, solving the limitation point for each paper was suggested. At the end, a discussion was provided.

Table 2. The most important points that are related to MARS

Ref.	Motivation	Contribution	Limitation points	Solving the limitation point
[84]	Developing a systematic approach that implements a modular decision method for generic robot collaboration systems.	Creation of complete middleware to allow autonomous mobile robot decision-making in harsh and dynamic environments.	1-Dynamic changes of negotiation factors. 2-Integration of additional theorem solvers. 3-Semantic matching of suggestion values.	Negotiation factors were improved by [3].
[85]	Cooperation and integration (ROS) between the UAV and the Unmanned ground vehicle (UGV) autonomous robots.	Improvement of the multi-agent system using many different scenarios.	The system is particularly in the simulation stage of development.	Not addressed in any of the 105 references listed in this review.
[86]	Achieving robust plan execution of autonomous robots in dynamic environments.	1-The hybrid robot software architecture. 2-The Auto Robot multi-agent improvement framework.	1- Safety conditions of robot behaviors. 2- The problem of task allocation. 3- Unified interfaces for sensor data.	Not addressed in any of the 105 references listed in this review.
[87]	Developing a heterogeneous multi-agent system (MAS) of the group (UAV) and (UGV).	Studying of mobile agents in a simulation environment integrating robot operating system (ROS), virtual robot experimentation platform (V-REP) simulation environment, and Java agent development framework (JADE) multi-agent system.	It is still in the stage of simulations.	Not addressed in any of the 105 references listed in this review.
[88]	The problem of the collective mapping of an undefined indoor environment from a homogeneous MR team.	Using a homogeneous mobile robot team to describe a distributed multi-agent collaborative approach for indoor environment mapping.	Reducing the accuracy of the final maps, as well as creating fictitious obstacles.	This limitation was fixed in [89].
[89]	Distributed SLAM is a major challenge in multi-robot systems.	Suggesting a novel multi-agent system for the SLAM.	The system lacks proof of stability and convergence.	Not addressed in any of the 105 references listed in this review.
[90]	Exploring unknown environments.	Using extended particle swarm optimization (PSO) for controlling multi-cooperative robot exploration in an unknown environment.	Used just one optimized algorithm (PSO), Unstable network communication.	This limitation was enhanced in [75].
[91]	Using multi-master systems for controlling wireless networking communication with multiple robots.	Implementation of a decentralized control architecture based on multi-master systems.	It does not take the wireless security among robots and base stations.	Not addressed in any of the 105 references listed in this review.
[92]	Employing a multi-robot system as an agent-based system for distributed systems for simulation purposes.	Using common ontology and reinforcement learning as an agent adaptability feature to provide a multi-robot system agent-based model.	It is still in the stage of simulations, not application in real-time.	A multi-robot system agent-based model was applied in a real environment in [93].
[93]	Decentralized collaboration in multi-agent robots.	Suggesting spatial intentions maps as a modern way of communicating intent for enhanced multi-agency reinforcement learning collaboration.	The system works in the presence of static obstacles, not in the presence of dynamic ones.	Not addressed in any of the 105 references listed in this review.
[94]	Controlling distributed autonomous engineering artifacts (agents).	The implementation of a decentralized system of high-level control for a set of mobile robots (MR).	Used an old SLAM algorithm.	Filatov and Krinkin [18] used a modern algorithm.
[95]	A multi-agent path finding (MAPF) problem.	Presenting (ros-dmapf), a distributed (MAPF).	It is not an easy way for navigating dense maps and it is not fit on maps with obstacles.	A deep learning model was used to solve the limitation in [96]
[97]	The need for robots that can comfortably communicate with humans in daily environments.	Presenting extensions to the simple pre-existing DALI implementation, which adds a lot of useful new functionality, including the ability for a DALI MAS to communicate with robots.	Sensors, actuators, vision, and other physical elements are not discussed in this article.	Not addressed in any of the 105 references listed in this review.
[98]	Distributed control of multi-agent systems (DC-MAS).	1- Asymptotic exponential functions and graph theory are used. 2-For multi-agent nonholonomic wheeled robot systems, in which the issue of distributed formation control is solved.	The system is based on the nonlinear kinematics model and the controller is suggested to be of the fixed-gains control parameters.	This limitation was solved by [55], [99]
[100]	Automated cruise control for safety in robot swarms.	Presenting a class of Non-smooth barrier functions (NBFs) and allowing formulation of Boolean compositional NBFs via max. and min. operators.	The system doesn't include temporal logic specifications for NBFs.	This limitation was solved by the Martinez *et al.* in [101]
[102]	A problem within the standard broadcast control framework.	The proposed modified broadcast controller was confirmed to reach the convergence w.p.1.	The method does not incorporate collision avoidance into the broadcast controller to protect the robots from damage,	Not addressed in any of the 105 references listed in this review.
[103]	Cooperative of mobile robots.	Proposed a nearest zero-point algorithm	The algorithm is in the stage of simulations.	Not addressed in any of the 105 references listed in this review.
[104]	Coordination of mobile robots.	Propose an approach used for motion planning of a swarm of MAMR depend on simple rules.	1-The algorithm is in the stage of simulations. 2-Used just one optimized algorithm.	A petri-net architecture combined with the navigational strategy was used to solve the limitation in [105].

This review focused and discussed MARS in various real-world applications. Particularly, from Table 2, we can discuss the results of the application that were divided into three parts. The first part was related to MAS, the second one was related to MAR, and finally, the third part was related to MARS. Many challenges and limitations have been demonstrated and they prevent high efficiency of the performance of MARS in the real world. The most crucial challenges are related to path planning, controller design, obstacle avoidance, real-time computing, and reduction of energy consumption. Another essential problem is communication among robots, which greatly affects the system's performance. The researchers provided several solutions to overcome the challenges and limitations such as those in [2]; including broadcasting the information to the robots by sending information directly to them and avoiding losses and time delay during the transmission process.

4. THE PROPSED SYSTEM AND DESIGN APPLICATION

The proposed system for the real-time applications of the multi-agent robot system is shown in Figure 6, which consists of five mobile robots that are distributed in a building that has five floors. Each mobile robot has a specific function in each floor with a different map environment. The process of management and control of each mobile robot is controlled by the main server (management robot systems). Figure 7 shows the proposed architecture with the layers of management of the robot system presenting the function of each part. Most of the limitations that were found in other research works will be overcome in this proposed system, such as designing path planning with static and dynamic obstacles avoidance; communication network and the real-time computer control using the proposed hybrid meta-heuristic algorithms, secure network communication, and an adaptive intelligent controller for each robot, respectively.

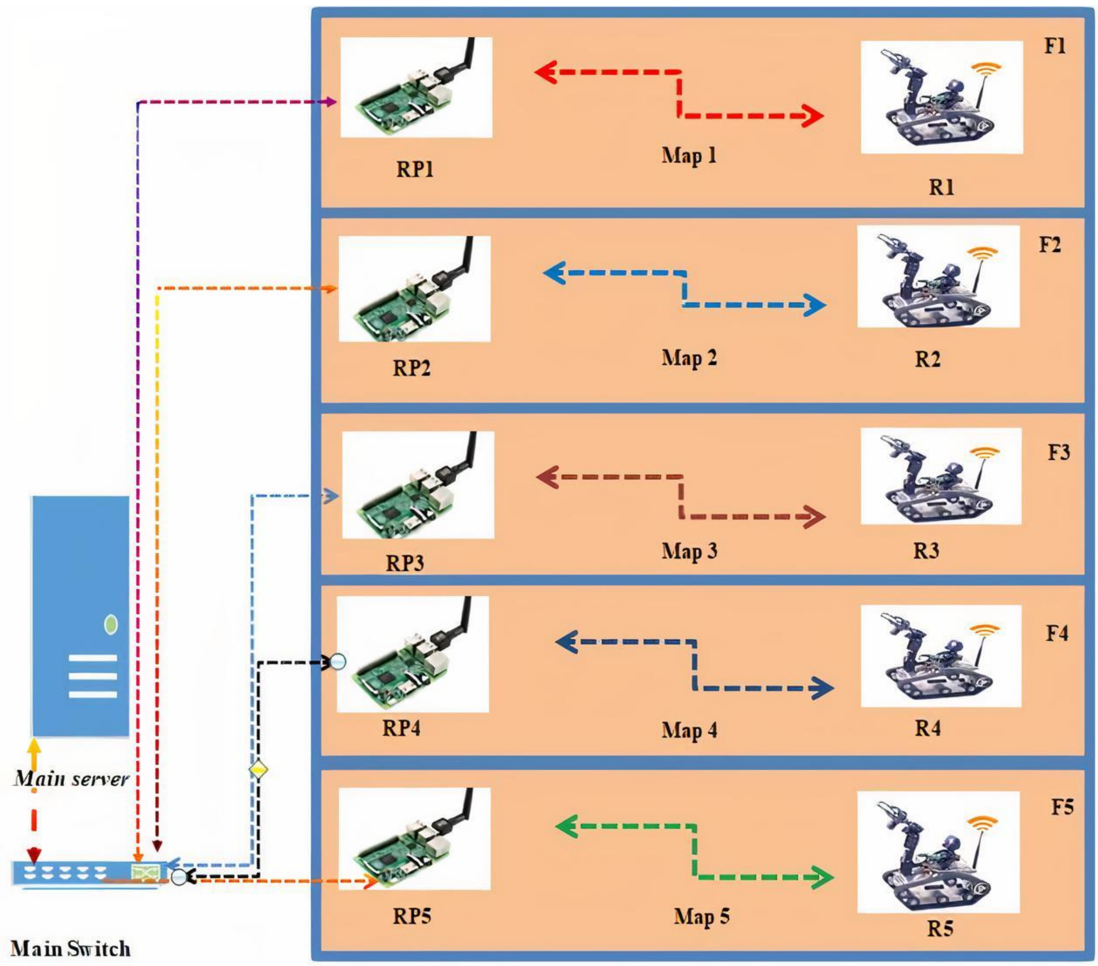

Figure 6. The proposed system

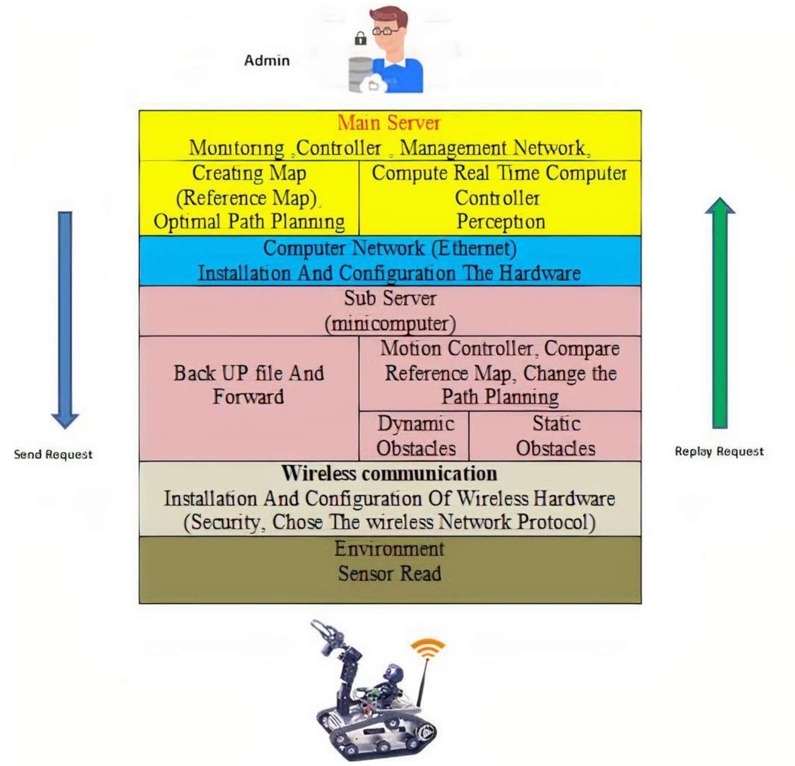

Figure 7. Architecture layers of the proposed system

5. CONCLUSION

A multi-agent robot system (MARS) is a system in which robots work together to achieve a given task by moving around in the environment. Generally, a fully autonomous mobile robot is considered as an agent. The present paper attempted to provide a global overview of a large number of publications in the area. In this article, studies of existing applications in multiple disciplines, the challenges in developing MARS, and the methods to study MARS performance were presented. Moreover, the existing works in each sub-field were surveyed and discussed. MARSs are still facing many limitations and challenges in different areas, such as the algorithm in the stage of simulations, the real-time processing, the unstable communication among the mobile robots and the base station, and the safety issue. In addition, complex obstacles are still to be investigated, where task connectivity preservation and collision avoidance issues are important. Many applications associated with MARS were presented including finding the best path planning, exploring unknown environments, and rescuing missions after a disaster in an urban area. As an application of this review, our research proposed a system for an environment that includes many robots distributed in a building having five floors to do a variety of tasks.

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