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Dual-Swarm Features and Its Challenges for System of Sensor Networks and Mobile Multi-Robots

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***Abstract*¡** A swarm is a decentralized and self-organized collective with lots of simple but autonomous and homogeneous individuals. Swarm intelligence is defined to describe its emergent behaviors. Both Sensor networks and mobile multi-robots can have swarm features. The combination and cooperation of these two systems is a tendency recently. From the view of swarm organisms, the challenges of combination of sensor networks and mobile multi-robots are discussed and a layered dual-swarm framework is presented, which has a 3D communication structure, and which is possible to organically inherit traditional swarm technology while building an efficient interaction channel for both swarms to cooperatively work together. Finally, a control strategy based on virtual entities is introduced to induce and control the behaviors of the robot swarm through wireless sensor networks.

***Keywords*¡ sensor networks, mobile multi-robots, dual swarms, controllability**

I. INTRODUCTION

It is a current trend to combine wireless sensor networks (WSN) and multi mobile robots (MMR) as there are great application potentials, such as disaster emergency response, military, communication and industry, etc. For example, in road communication, autonomous vehicles can be induced to choose suitable pathways and behaviors with the support of intelligent road information networks based on sensor networks. At port, sensor networks can cooperatively work with the smart equipments (mobile robots) to configure distributed resource formation and optimally schedule their tasks in time.

There are mainly three kinds of combinations: (1) WSN-MMR. In this system, mobile robots can be used to spread and maintain the nodes of WSN[1]. With the support of WSN, robots can more effectively navigate in an unknown environment. And PEG(Pursuit Evasion Game) problem could be solved with global search [2]. (2) Mobile sensor networks. The nodes have mobility as robots and the network is self-organized as WSN. The system can work more actively than WSN with static nodes [3]. (3) Wireless sensor and actuator networks (WSAN). In this kind of networks, sensor nodes and actuator nodes communicate at the same network level. They cooperate with each other to sense and response to events of surroundings [4].

This paper concerns a new combination of WSN-MMR and discusses about the cooperation and constraints between WSN and MMR. Swarm is introduced into the system here and the challenges on organization and control of the system are discussed. The concept of dual-swarm is put forward. A kind of layered framework and the communication structure are designed.

In this paper, part 2 summaries the recent works related to this research. Part 3 compares the swarm features of WSN and MMR. And the system of dual-swarm is defined here. Part 4 is dedicated to the discussion of challenges for organizing and controlling the dual-swarm system composed of WSN and MMR. Part 5 presents the new structure and control strategy design for WSN-MMR. Finally, the conclusion is given.

II. RECENT RELATED WORKS

Ant colonies, fish schools, and bird flocks are biological collectives. Their collective intelligence caused great interests of researchers and was abstracted as swarm intelligence. Italian scientist Dorigo firstly researched on swarm intelligence and developed an ant system and an algorithm of ant colony optimization[5-6]. Then many other swarm systems were developed, such as particle swarm[7], boids[8], etc. Successful applications have been made in engineering optimization, production management, robotics, and pattern recognition, etc. Swarm intelligence is an important method for modeling and analysis of complex systems[9].

Both WSN and MMR are collective systems with distributed and autonomous individuals. Many researchers have tried much to introduce the algorithms of ant colony and particle swarm into WSN and MMR[10-12]. Interesting intelligent emergencies have been generated and several typical platforms of mobile swarm robots have been put forward: Swarm-bots[13], I-Swarm[14], and GroundScouts[15], etc.

Framework design is the base of application of swarm theory on robots and WSN. [16] presented a general framework for swarm systems to integrate decision making and AI with swarm intelligence. In this framework, an individual is divided into a dynamic agent and a particle. The particle is designed for storing physical states of the individual in the system. The dynamic agent is used for observation, decision making and reaction of the individual, and is the basis to integrate modern artificial intelligence. [17] designed a layered architecture for swarm robots grouped for multi-tasks. A two-layer architecture was built for mobile sensor networks: the upper layer is a dynamic self-organizing union for task allocation based on ant colony. The lower is SOM-based[18]. For a system with both WSN and swarm robots, its framework is designed into 5 layers: sensor/actuator, communication, execution, knowledge processing and decision making[19].

Control of swarm behavior and intelligence is another important problem for swarm application. There are two aspects: (1) Given a desired swarm behavior of the entire system, how to design the local rules of each individual? For formation control, there are mainly virtual structure, artificial potentials [20], leader-follower[21], and double PSO (Particle Swarm Optimization) swarm based on constraints[22], etc. PSO is also used for target exploring[23]. Virtual Pheromone is proved to be a useful way for path planning and navigation. Virtual pheromones can be made with infra-red[13] and RFID[24]. (2) Given local rules and behaviors of individuals, how to control the collective behavior of a swarm? Soft control could be a way. One or several controllable shill agents were added into a multi-agent system (e.g. Boids), the collective behavior of the system was changed as expected in simulation and the control was effective analytically and numerically [25,26].

III. SWARM FEATURES OF WSN AND MMR

A swarm means a family with a mass of movable individuals. Each individual can have simple intelligence and can locally communicate with its neighbor members. Swarm intelligence is the behavior emergence of the system. There are many kinds of swarms (flocks, schools) in nature. Ant, bee, fish, etc., are typical swarms.

A. Swarm features of WSN

Wireless sensor network is data-centered network with sensing ability. There are lots of autonomous nodes which are scattered in an area and self-organized into a system. Therefore, it can be treated as a swarm system.

1) Normally the nodes are immobile. But data and information can move over the network and from one node to another. So it is a numerical swarm.

2) Nodes are separately scattered in space. So the system can be treated as a discrete swarm.

3) Each node can communicate with other nodes. They can directly talk with their neighbors and communicate with remote nodes by ad hoc. The communication capability is much stronger than that of a traditional swarm.

4) Each node can sense its surrounding and makes its own decision according to its sensing.

5) If needed, special signals such as infrared can be designed on nodes for indirect interaction besides its wireless network.

6) There is a way for a node to remotely communicate with clients. That means that it is possible to remotely control a swarm through WSN.

B. Swarm features of MMR

System of multi mobile robots (MMR) is a swarm with very important physical features.

1) Each robot is autonomous and can be treated as a swarm individual.

2) Each robot is a physical object with shape, size, etc. But a traditional swarm individual is an ideal point.

3) Each robot has weight and inertia. It can not sharply change the direction and speed of its motion as numerical swarm does.

4) Each robot can locate itself or be located by the system, but the preciseness will be rather low with present technique. There are some other uncertaintiesly too, such as network delay, damage of an robot, etc.

C. Dual-swarm system

How do they work or act when two swarms meet with each other?

Researches show that they might fight with each other or melt into one society when two ant families meet. So do bee families. The results depend on information exchange. When the individuals from one ant part can send the similar/same odor as that of the other part, they can be accepted as their own part. Otherwise, they will be fought and killed. In human sociality, there are also many collectives, such as villages, towns, cities, etc. With good architecture, clear communication and suitable constraints, the society can boost peacefully.

Successfully developed artificial swarms are ant colony, boids, particle swarm, and so on. Typical and basic algorithms of swarm intelligence optimization are ACO (Ant Colony Optimization) and PSO. They are population based stochastic optimization techniques and have been successfully applied in TSP, quadratic assignment, scheduling, graph coloring, network routine, etc.

However, basic ACO and PSO have some disadvantages. They easily converge to local optima. The parameters of ACO are not easy to configure and its computation is heavy and time consuming. The exploring of PSO is with tendency of premature convergence. Therefore, researchers are trying to improve ACO and PSO. One way is to mix ACO and PSO. ACO can be used to improve the decision making process of each particle in PSO for selecting the best guide, and the new algorithm is called PSO-ACO, which is successfully used for clustering [27]. Other possible combinations are ACO-ACO, PSO-PSO and ACO-PSO.

Learnt from the researches on natural biology and artificial collectives, a dual swarm system is defined in this paper as a system with two or more swarms. Each swarm can work independently when there is no interruption from another. To make them cooperative, special communication and interaction should be built up.

IV. CHALLENGES OF THE CONTROLLABILITY OF THE DUAL SWARM SYSTEM OF WSN-MMR

The combination of WSN and MMR extremely increase the complexity and dynamics of the system, while it improves the capability of adaptation, expansion, and interaction. It is not simply putting them together, but complements their advantages to make it more adaptable, extendable, and smart. This combination brings great opportunity and technology difficulties in front of the design and control of the system.

A. *Mechanism of interaction between WSN and MMR*

Normally we hope WSN and MMR can help each other to produce emergent intelligence which is cooperative, predictable and controllable. Proper interaction is needed. But WSN and MMR are two different swarms. They have their own local behaviors and interaction rules. Is it possible to build communication channels between them but not to change their own local interaction rules? Can the feedback channel intervene and induce the swarm behavior? Obviously, traditional, peer-to-peer, static, centralized interactions are not solutions in this case.

B. *Framework of the system*

To make the two swarms work orderly and cooperatively, an efficient framework is needed. Traditional formal structure cannot properly organize two different swarms. Biological and social architectures should be referred to build a loose but cooperative organism. In the organism, each swarm can work relatively independently. Through the interaction of messages between them, they can learn from each other, collaboratively develop and converge faster to expected targets.

C. *Resource management and scheduling*

There are resources on different levels. In an individual, a sensor node or a robot, the resource is limited for sensing, storage, computation, and even power. Each unit autonomously manages and schedules its resources.

On the level of entire system, sensor nodes and robots are resources. As a swarm, these resources are rich, but dynamic and distributed. Each unit has its own behavior rules and surrounding condition, and can not be strictly consistent and synchronous. How to coordinate and schedule these resources to meet target requirements and conditional constraints is a hard question.

On application level, users may want to configure and use these resources. Transparent and service-oriented resource management is needed for inquiry and scheduling.

D. *Dynamic and robust control*

Both networks of WSN and MMR are topologically dynamic. Time delay, message lost, asynchronous and inconsistent messages are the features of the networks. On the other hand, the communication channel is strong and with self-maintenance. Therefore, it is a good method to mix swarm evolution with external intervention. With the strategy of swarm evolution, each individual can work autonomously in the case of message deformation and return to cooperative status with the help of its neighbors. With external intervention, lost or missing units can be dragged into normal status and speed the convergence of swarm intelligence. But how to mix these two different strategies, especially when there are two swarms, is a challenge.

E. *Message publication and subscription*

Message publication and subscription is a good way to manage information transmission of loose coupled, distributed system such as data-centered WSN [28]. It can reduce the couples of the system. It can also improve transmission transparency, data integrity, and timing.

In this system, the situation is different. There are data transmissions in wireless sensor networks, in multi mobile robots and between them. MMR should efficiently interact with WSN. At the same time, message flooding should be avoided in the networks to prevent the collapse of the system. Therefore, message publication-subscription should be improved to fit into this multi-layered communication.

F. *Localization and navigation for emergent intelligence*

With the combination of WSN and MMR, there are huge sensing data and swarms can emerge intelligence in a proper case. On one hand, with the support of sensing data, localization and navigation of autonomous units can be improved with swarm theory. On the other hand, swarm intelligence will be influenced by the preciseness of unit¡s localization and navigation.

V. STRUCTURE DESIGN OF DUAL SWARM SYSTEM OF WSN-MMR

There are many kinds of WSN and MMR. In general, suppose the nodes of WSN are immobile, and the robots of MMR are with a certain capabilities of mobility and implementation. Swarms have been introduced into WSN and MMR. For example, discrete ant colony is introduced into WSN as sensor nodes are disparately scattered in an area. Particle swarm is introduced into MMR, with special physical parameters.

A. *Layered swarm framework*

Referred to biological social hierarchical system, a layered framework can be designed to put WSN and MMR on different layers, as figure 1.

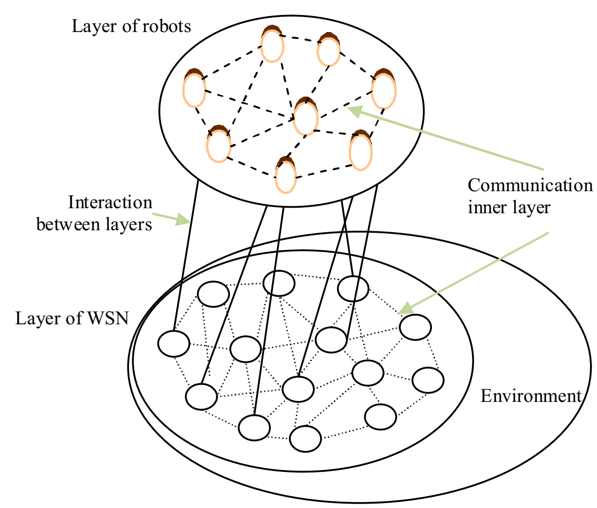

Fig. 1 Layered structure of WSN-MMR

In this structure, the inner communication modes of WSN and MMR are kept and the two swarms of WSN and MMR can work according to their own local behaviors and interaction rules.

To build up message exchange between WSN and MMR, a communication channel between the layers is set up. The principles for the channel are: limited message, local interaction and non multi-hop. Therefore, message exchanged between layers will not be transmitted over the layers.

B. Swarm structures

We have separately used ant colony and particle swarm for WSN and MMR. But the traditional numerical swarms are different with WSN and MMR. Both MSN and MMR have their own physical features and they can have more capabilities to sense, make decision, and control. So referring to [16], we design a structure for WSN and MMR individuals with agent technology, as figure 2.

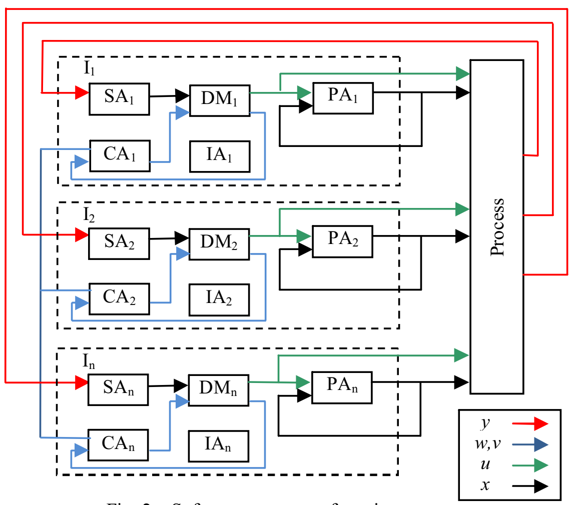

Fig. 2 Software structure of a unit

Here, PA is a particle module, which is defined to contain the physical states of a unit (or an individual I_i). $x_i \in X$. For WSN nodes, it includes the position, sensing data processed, etc. For MMR robots, it includes the position, size, speed, etc.

SA is a sensing module to process sensing data. It can observe and process the vector y_i of the environment. DM is a decision making module, and CA is a communication module to share information and action in a swarm. Incoming message w_i can be received and outgoing message v_i can be sent through CA. Vector u is determined by DM module according to vector y_i and message v_i, and sent to PA and process modules. IA is an interaction module to share information and action between swarms. Process is a module to describe the set of what must be sensed and/or controlled by the units or individuals, for example, an artificial potential field of a swarm.

C. Interaction between WSN and MMR

With the communication channel between layers and the interaction module in each unit, message interaction between layers can be implemented according to the system¡ s requirements. Two possible methods can be designed:

1) Special protocol: WSN and MMR both have wireless network. We can define a special protocol to limit the range of message transmission. When the interaction messages broadcast on the wireless channel, they will not be relayed so that they can only be received and understood by neighbor units on the other layer. The content of messages is limited to the local behavior parameters of the swarm units. This strategy can reduce jamming and make it possible to take part in forming the artificial potential field.

2) Artificial pheromone. As each sensor node is immobile and grid-like scattered, artificial pheromone can be left over the nodes to record the motion path and frequency of mobile robots. The artificial pheromone can be managed by the IA modular on each node. It can simulate natural pheromone of ants, accumulation and volatilization. On the other hand, the artificial pheromone can be remotely and premeditatedly changed in order to intervene and control the artificial potential field.

D. Design of virtual entity

Virtual entity is defined as an entity which has the total features of what it wants to represent but without its real shape. In other word, it is numerical. Here we want to develop a kind of virtual entity on WSN to realize the control and scheduling of the swarm on MMR.

As virtual entities are numerical and produced on WSN nodes, they can be remotely controlled: when to bear, how to move, and when to disappear, etc. they can work as shills or spies to induce the behaviors of the robot swarm.

There are three kinds of virtual entities and the relative control strategies according to the targets of control and schedule.

1) Virtual individuals. A virtual individual is simulated on the WSN nodes, which only has the state of robots but without the shape and size of the robots. The state parameters are managed on IA module. Virtual individuals can jump from one node to another and send messages to the robot swarm. From the swarm, they work as its units and can join the swarm potential field, as figure 3.

2) Virtual targets. Virtual targets are simulated on the WSN nodes to work as temple targets, which only have the state of real targets. As figure 4, the virtual targets jump from nodes to nodes toward the real targets and send messages to the robot swarm and induce them along the expected direction.

3) Virtual pheromones. Virtual pheromones are a kind of artificial pheromones which is made up of on WSN nodes, either by mobile robots or by control algorithms. It means how frequent the robots passed by the nodes. When we remotely or by program change the strength of pheromones, we can change the potential field and then control the moving path and direction of the robot swarm.

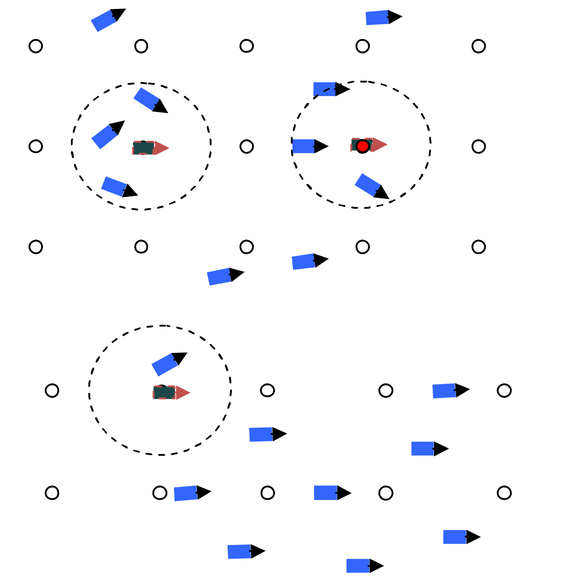

Fig. 3 Virtual individual

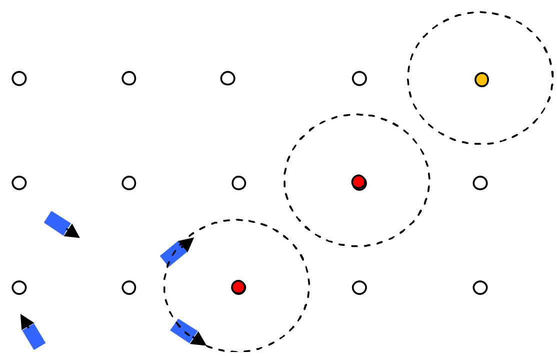

Fig. 4 virtual targets

VI. CONCLUSION

WSN and MMR are two important multi agent systems with bright application future. Their combination, however, makes the system dynamic and complex. From swarm theory, this paper discusses their swarm features and puts forward a concept of dual-swarm and explores the challenges of dual-swarm composed with WSN and MMR. As an example of possible solution, a layered swarm framework is put forward, which is structured with 3D communication channels, two channels for each layer and one channel between the layers. To predictably control the robot swarm through WSN, a concept of virtual entity and its control strategy are presented.

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