Handbook of Research on Design, Control, and Modeling of Swarm Robotics

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A volume in the Advances in Computational Intelligence and Robotics (ACIR) Book Series

Information Science REFERENCE
An Imprint of IGI Global

Published in the United States of America by
Information Science Publishing (an imprint of IGI Global)
701 E. Chocolate Avenue
Hershey PA, USA 17033
Tel: 717-533-8845
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E-mail: cust@igi-global.com
Web site: http://www.igi-global.com

Library of Congress Cataloging-in-Publication Data

Handbook of research on design, control, and modeling of swarm robotics / Ying Tan, editor.
pages cm
Includes bibliographical references and index.
ISBN 978-1-4666-9572-6 (hardcover) -- ISBN 978-1-4666-9573-3 (ebook) 1. Robotics--Research. 2. Swarm intelligence--Research. 3. Robots--Control--Research. I. Tan, Ying., editor.
TJ211. H2645 2016
629.8'9263824--dc23
2015032768

This book is published in the IGI Global book series Advances in Computational Intelligence and Robotics (ACIR) (ISSN: 2327-0411; eISSN: 2327-042X)

British Cataloguing in Publication Data
A Cataloguing in Publication record for this book is available from the British Library.

All work contributed to this book is new, previously-unpublished material. The views expressed in this book are those of the authors, but not necessarily of the publisher.

For electronic access to this publication, please contact: eresources@igi-global.com.

Chapter 1
A Survey on Swarm Robotics

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ABSTRACT

In this chapter, the current work on swarm robotics is briefly reviewed. Swarm robotics, inspired from nature swarm, is a combination of swarm intelligence and robotic, and shows great potential in several aspects. Firstly of all, the cooperation in nature swarm and swarm intelligence is briefly introduced, and the special features of the swarm robotics compared with single robot and other multi-individual systems is also presented. Then we describe the modeling method for swarm robotics and list several widely used swarm robotics entity projects and simulation platforms for interested researchers. Finally, as the main point of this chapter, we summarize the current researches on swarm robotic algorithms, i.e., cooperative control mechanisms for swarm robotics for flocking, navigating and searching applications.

INTRODUCTION

Cooperation in Nature Swarms

Most swarm intelligence researches are inspired from how nature swarms, such as social insects, fishes or mammals, interact with each other in the swarm in real life (Bonabeau, Dorigo, & Theraulaz, 1999). These swarms range in size from a few individuals living in small natural areas to highly organized colonies that may occupy large territories and consist of more than millions of individuals. The group behaviors emerged in the swarms show great flexibility and robustness (Camazine, 2003), such as path planning (Vittori et al., 2006), nest constructing (Theraulaz, Gautrais, Camazine, & Deneubourg, 2003), task allocation (Beshers, & Fewell, 2001) and many other complex collective behaviors in various nature swarm as shown in (Barbaro et al., 2009; Menzel, & Giurfa, 2001; Thorup, Alerstam, Hake, & Kjellén, 2003).

Individuals in the nature swarm shows very poor abilities, yet complex group behaviors can emerge in the whole swarm, such as migrating of bird crowds and fish schools and foraging in ant and bee colonies. It's tough for an individual to complete the task itself, even a human being without certain experiences can find it difficult, but a swarm of animals can handle it easily. Researchers have observed intelligent group behaviors emerging from a group of individuals with poor abilities through local communication and information transmission.

DOI: 10.4018/978-1-4666-9572-6.ch001

- **Bacteria Colonies:** Bacteria often function as multicellular aggregates known as biofilms, exchanging molecular signals for inter-cell communication (Shapiro, 1998). Communal benefits of multicellular cooperation include a cellular division of labor, collectively defending against antagonists, accessing more resources and optimizing population survival by differentiating into distinct cell types. Bacteria in biofilms have shown more than 500 times increased resistance to antibacterial agents than individual bacteria of same kind (Costerton, Lewandowski, Caldwell, Korber, & Lappin-Scott, 1995).
- **Fish Schools:** Fish schools swim in disciplined phalanxes and are able to stream up and down at impressive speeds and making startling changes in the shape of the school without collisions as if their motions were choreographed. Fishes pay close attention to their neighbors when schooling with the help of eyes on the sides of heads and "schooling marks" on their shoulders (Bone, & Moore, 2008). Fishes can benefit from fish schools in foraging (Pitcher, Magurran, & Winfield, 1982) and predator avoidance (Moyle, & Cech, 1988).
- **Ant and Bee Colonies:** Ants communicate with each other using pheromones, sounds, and touch (Jackson, & Ratnieks, 2006). An ant with a successful attempt leaves trail marking the shortest route on its return. Successful trails are followed by more ants, reinforcing better routes and gradually identifying the best path (Goss, Aron, Deneubourg, & Pasteels, 1989). Experiments in (Ravary, Lecoutey, Kaminski, Châline, & Jaisson, 2007) suggest that arts can choose roles based on previous performance. Ants with higher successful rate intensified their foraging attempts while the others ventured out fewer times or even change to other roles.
- **Locusts:** Buhl et al. (Buhl et al., 2007) confirmed the prediction from theoretical physics that as the density of animals in the group increases, the group rapidly transit from disordered movement of individuals to highly aligned collective motion. They also demonstrated a dynamic instability in motion that groups can switch direction without external perturbation, potentially facilitating the rapid transfer of directional information.
- **Bird Crowds:** From long time ago, human makes use of birds' ability to precisely location home more than 5,000 kilometers away. Birds gather into special formations during migration and locate the destinations with the aid of a variety of senses including sun compass, time calculation, magnetic fields, visual landmarks as well as olfactory cues (Wallraff, 2005).
- **Primates:** Cooperation among primates can be complex, such as make tools and use them to acquire food and for social displays, deception (Parr, Winslow, Hopkins, & de Waal, 2000), recognize kin and conspecifics (Parr, & de Waal, 1999) and learn to use symbols and understand aspects of human language. Primates also use vocalizations, gestures, and facial expressions to convey psychological state.
- **Human Beings:** Dyer et al. (Dyer et al., 2008) has shown leadership and consensus decision making can occur without verbal communication or obvious signaling in a group of humans. They found that a small informed minority could guide a group of naïve individuals to a target with improved time and accuracy efficiency to the target. Even when conflicting directional information was given to different members, consensus decision can be made highly efficiently.

From the introduction above, we can see that as the cooperation in the swarm increases, the group behaviors become more complex while the population size is going down and the each individual is playing more important roles in the behavior.

It's difficult to imagine how such sophisticated abilities can emerge from the swarm consisting of such simple individuals with limited cognitive and communicating abilities. Nevertheless, in most cases a whole swarm of individuals do have the ability to solve many complex problems easily while a single individual of the same species cannot. Of course, in such organisms without organizers, there still exist some mechanisms yet undiscovered which promise the whole task is divided into small pieces capable for individuals to handle and aggregates the outputs of agents into collective behaviors (Camazine, 2003). The purpose of our researches in swarm intelligence and swarm robotics is to explore such mechanisms for real-life applications (Garnier, Gautrais, & Theraulaz, 2007).

Swarm Intelligence

As an emerging research area, swarm intelligence has attracted attentions of many researchers from several aspects since the concept was proposed in 1980s. It has now become an interdisciplinary frontier and focus of many disciplinary including artificial intelligence, economics, sociology, biology and etc. It has been observed long time ago that some species survive in the cruel nature taking the advantage of the power of swarms, rather than the wisdom of individuals. Individuals in such swarm are not highly intelligent, yet they complete complex tasks through cooperation and division of labor and show high intelligence as a whole swarm which is highly self-organized and self-adaptive.

Swarm intelligence is a soft bionic of the nature swarms, i.e. it simulates the social structures and interactions of the swarm rather than structure of an individual in traditional artificial intelligence. The individuals can be regarded as agents with simple and single abilities. Some of them have the ability to evolve themselves when dealing with certain problems to make better compatibility (Wang, Zhu, & He, 2005). A swarm intelligence system usually consists of a group of simple individuals autonomously controlled by a plain set of rules and local interactions. These individuals are not necessarily unwise, but are relatively simple comparing to the global intelligence achieved through the system. Some intelligent behaviors never observed in a single individual will soon emerge when several individuals begin cooperate or compete. The swarm can complete the tasks that a complex individual can do while having high robustness and flexibility and low cost. Swarm intelligence takes the full advantage of the swarm without the need of centralized control and global model, and provides a great solution for large-scale sophisticated problems.

BACKGROUND

Characteristics of Nature Swarms

Since swarm robotics is mostly inspired from nature swarms, it's a good reference for analyzing the characteristics of swarm robotics from characteristics of nature swarms, researches of which started more than a century ago.

The first hypothesis is quite personified (Büchner, 1881) and assumes each individual has a unique ID for cooperation and communication. The information exchange in the swarm is regarded as a centralized network. Queens in ant and bee colonies are supposed to be responsible for transmitting and assigning information to each agent (Reeve, & Gamboa, 1987). However, Jha et al. (2006) proved the network in the swarm is decentralized. Thanks to the researches in recent half century, we can now assert that there are no unique IDs or other globally storage information in the network. No single agent can access to all the information in the network and a pacemaker is therefore inexistent.

Biologists now believe social swarms are organized as a decentralized system distributed in the whole environment which can be described through probabilistic model (Deneubourg, Pasteels, & Verhaeghe, 1983). Agents in the swarm follow their own rules according to local information. Group behaviors emerge from these local rules which affect information exchange and topology structure in the swarm. The rules are also the key component to keep the whole structure is flexible and robust even when sophisticated behaviors are emerged.

Definition of Swarm Robotics

Swarm robotics is a new approach to the coordination of multi-robot systems which consist of large numbers of mostly simple physical robots (Tan, Y. 2013). It is supposed that a desired collective behavior emerges from the interactions between the robots and interactions of robots with the environment. This approach emerged on the field of artificial swarm intelligence, as well as, but not limited to, the biological studies of insects, ants and other fields in nature, where swarm behavior occurs.

The research of swarm robotics is to study the design of large amount of relatively simple robots, their physical body and their controlling behaviors. Individuals in the swarm are normally simple, small and low cost so as to take the advantage of building large populations. A key component of the system is the communication between the agents in the group which is normally local, guarantees the system is scalable and robust.

A plain set of rules at individual level can produce a large set of complex behaviors at the swarm level. The rules of controlling individuals are abstracted from the cooperative behavior in nature swarms. The swarm is distributed and decentralized, and the system shows high efficiency, parallelism, scalability and robustness.

Potential applications for swarm robotics include tasks that demand for miniaturization, like distributed sensing tasks in micro machinery or the human body. On the other hand swarm robotics can be suited to tasks that demand cheap designs, for instance, mining tasks or agricultural foraging tasks. Swarm robotics can be also involved in tasks that require large space and time cost and dangerous to human being or the robots themselves, such as post-disaster relief, target searching, military applications and etc.

CHARACTERISTICS AND APPLICATION SCOPES OF SWARM ROBOTICS

Some researchers have summarized the properties of swarm robotics, such as robustness, flexibility and scalability (Şahin, 2005). In this section, advantages and characteristics of the swarm robotics system are presented through comparison with single robot and other similar systems with multiple individuals. It can be seen that these characteristics are quite similar with that of nature swarm.

Comparing with Single Robot

To complete a sophisticated task, the single robot must be designed with complicated structure and control modules resulting in high cost of designing, construction and maintenance. Single robot is vulnerable especially when a small broken part of the robot may affect the whole system and difficult to predict what will happen. Swarm robotics can achieve the same ability through inter-group cooperation and takes the advantage of reusability of the simple agents and low cost of construction and maintenance. Swarm robotics also takes the advantage of high parallelism and is especially suitable for large scale tasks.

If we compare the corresponding nature species, single robot is inspired from human behavior and swarm robotics inspires from social animals. Due to the restriction of current technology, it's hard to simulate human interactions using machines while mechanisms in animal groups are easier to apply. This gives swarm robotics a bright future in dealing with complex and large scale problems. The advantages of swarm robotics are listed below.

- **Parallel:** The population size of swarm robotics is usually quite large and can deal with multiple targets in one task. This indicates the swarm can perform greatly in tasks involving multiple targets distributed in a vast range in the environment and the search of the swarm would save time significantly.
- **Scalable:** All the interaction in the swarm is local and this allows individuals to join or quit the task at any time without interrupting the whole swarm. The swarm can adapt to the changes of population through implicit task re-allocating schemes without the need of any external operations. This also indicates the system is adaptable for different size of population without any modification of the software or hardware which is very useful for real-life applications.
- **Stable:** Similar to scalability, swarm robotics systems will not be affected greatly even when part of the swarm quitted due to majeure factors. The swarm can still work towards the objective of the task although performances may degrade inevitably with fewer robots. This feature is especially useful for tasks under dangerous environments.
- **Economical:** As mentioned before, cost of swarm robotics is significantly low in designing, manufacturing and daily maintaining. The whole system is cheaper than a complex single robot even the robotics in the swarm can be hundreds or thousands. Since the individuals in the swarm can be massively produced while single robot requires precision machining.
- **Energy efficient:** Since individuals in the swarm are much smaller and simpler than a giant robot, the energy cost is far beyond the single robot comparing with the battery size. This means the life time the swarm is enlarged. In environments without fueling facilities or where wired electricity is forbidden, swarm robotics can be much useful than traditional single robot.

As summary of these advantages, swarm robotics can be applied to sophisticated problems involving large amount of time, space or targets, and certain dangerous may exist in the environment. Typical applications of this type includes UAV controlling, post-disaster rescuing, mining, geological survey, military applications and cooperative transportation. Swarm robotics can complete these tasks through cooperative behavior emerged from individuals while single robot can barely adapt to such situation. This is the reason why swarm robotics has become important researching areas in last decade.

Differences with Other Multi-Agent Systems

There exist several research areas inspiring from the nature swarm, which are often confused with swarm robotics, for instance, multi-agent system and sensor networks. These research areas also utilize the cooperative behavior emerged from multiple agents in the group for specialized tasks. However, there are several differences between these systems which can distinguish these systems fundamentally, as shown in Table 1.

From the table, we can see that the main differences among swarm robotics and other systems lay on the aspect of population, control, homogeneity

Table 1. Comparisons among swarm robotics and other systems

	Swarm Robotics	Multi-Robot Systems	Sensor Networks	Multi-Agent Systems
Population Size	Varies in great range	Small	Fixed	In a small range
Control	Decentralized and Autonomous	Centralized or Remote	Centralized or Remote	Centralized or Hierarchical or Network
Homogeneity	Homogeneous	Usually Heterogeneous	Homogeneous	Homogeneous or Heterogeneous
Flexibility	High	Low	Low	Medium
Scalability	High	Low	Medium	Medium
Environment	Unknown	Known or Unknown	Known	Known
Motion	Yes	Yes	No	Rare
Typical Applications	Post-disaster relief Military applications Dangerous applications	Transportation Sensing Robot soccer	Surveillance Medical care Environmental protection	Net resources management Distributed control

and functional extension. Multi-agent and sensor network systems mainly focus on behaviors of multiple static agents in known environments while robots in multi-robot systems are quite small and usually heterogeneous with external controls.

Since homogeneity and scalability is considered at the beginning of design of the system, swarm robotics shows great flexibility and adaptability comparing with other systems. Multi-robot systems usually involve heterogeneous robots and may achieve better performance on specialized tasks at the cost of flexibility, reusability and scalability. Besides scalability, which is introduced in previous section, characteristics of swarm robotics among other three cooperative systems are listed below:

- **Autonomous:** Individuals in swarm robotics systems must be autonomous, i.e. capable of interacting and motioning in the environment. With these key functions, cooperative mechanisms inspired from nature swarms can be conducted into swarm robotics. Although systems like sensor networks are far different with swarm robotics from such point of view, but the researches in the area can indeed throw some lights on swarm robotics researches.
- **Decentralized:** With a good set of cooperative rules, the individuals can complete the task without centralized controls which promises the scalability and flexibility of the swarm. In the same time, the swarm can benefit more in the environments when communication is interrupted or lagged and improves the reaction speed and precision of the swarm.
- **Local Sensing and Communications:** Due to the restriction of hardware and cost, robots in the swarm usually have a limited range of sensing and communicating and thus the whole swarm is distributed in the environment with this constraint. Actually, using global communications will lead to a significant decline in scalability and flexibility, as the communication cost will explode exponentially as population grows. Nevertheless, certain controlling global communications are acceptable, for instance updating controlling strategies or sending terminal signals, so long as it's not used in the interaction between individuals.
- **Homogenous:** In a swarm robotics system, the robots should be divided into as fewer roles as possible and number of robots acting as each role should be as large as pos-

sible. The role here indicates the physical structure of the robot or other statuses that cannot change into one another dynamically during the task. A state in a finite state machine does not count in our definition. This definition indicates a swarm, no matter how large it is, is not considered as swarm robotics if the roles of robots are divided meticulously. For instance, robots football usually is not considered as swarm robotics, since each individual in the team is assigned a special role during the game.

- **Flexibility:** A swarm with high flexibility can deal with different tasks with the same hardware and minor changes in the software, as nature swarms can finish various tasks in the same swarm. Individuals in the swarm show different abilities and cooperation strategy when dealing with different tasks. Swarm robotics should provide such flexibility, especially in similar tasks, such as foraging, flocking or searching. The swarm can switch to different strategies according to the environment. The robots can adapt to the environment through machine learning from the past moves and can change to a better strategy.

Application Scopes of Swarm Robotics

The studies on robotics application in target searching have grown substantially in recent years. It is more preferable when the working area is dangerous or inaccessible to human. Problems involved in swarm robotics researches can be classified into two classes so far. One class of the problems mainly bases on the patterns, for instance aggregation, cartography, migration, self-organizing grids, deployment of distributed agents and area coverage. Another class of problems focuses on the entities in the environment, e.g. searching for targets (Stormont, 2005), detecting odor sources (Marques, Nunes, & de Almeida, 2006), locating ore veins in wild field (Acar, Choset, Zhang, & Schervish, 2003), foraging, rescuing victims in disaster areas (Kantor et al., 2003) and etc. Besides these problems, swarm robotics can also be involved into more sophisticated problems, mostly hybrid of these two classes, including cooperative transportation, demining (Zafar, Qazi, & Baig, 2006), exploring a planet (Landis, 2004) and navigating in large areas.

Deduced from the advantages and characteristics introduced in previous section, several potential application scopes (Şahin, 2005; Xue, & Zeng, 2008) of swarm robotics which are very suitable are listed below.

- **Tasks Cover Large Areas:** Swarm robotics system is distributed and specialized for tasks requiring a large area of spaces, e.g. tasks cover large areas. Robots in the swarm are distributed in the environment and can detect dynamic changes of the entire area, such as chemical leaks or pollutions. Swarm robotics can complete such tasks in a better way than sensor networks, since each robot can patrol in an area rather than stay still. This means the swarm can monitor the area with fewer agents. Besides monitoring, robots in the swarm can locate the source, move towards the area and take quick actions. In urgent cases, robots can aggregate into a patch to block the source as a temporary solution.
- **Tasks Dangerous to Robots:** Thanks to the scalability and stability, the swarm provides redundancy for dealing with dangerous tasks. Swarm can suffer loss of robots to a great extent before the job has to be terminated. The robots are very cheap and are first choices in areas which will probably damage the workers. In some tasks, the robots may be irretrievable after the task and use of complex and expensive robots are thus economically unacceptable while swarm robotics with cheap individuals can

provide reasonable solutions. For example, Murphy et al. (2009) summarized the usage of robotics in mine rescue and recovery. They pointed out that although several applications already in use, the robots are beyond the requirement to show desired performance under the tough environment under the ground. They proposed 33 requirements for the robots so as to achieve an acceptable behavior.

- **Tasks Require Scaling Population:** Workload in some tasks may change over time and the swarm size should scale based upon the current workload for high efficiency in both time and economic. For example, in the task of clearing oil leakage after tank accidents, the swarm should maintain high population when the oil leaks fast at the beginning of the task and gradually reduce the robots when the leak source has been plugged and the leaking area is almost cleared. The swarm also scales among different regions if the progress of these regions becomes unbalanced. Stormont (2005) described the potential for using swarms of autonomous robots to react to the first 24 hours of a disaster site. He summarized the swarm that can search for victims with the highest probability of finding survivors and made some suggestions for future researches in this area.
- **Tasks Require Redundancy:** Robustness in swarm robotics systems mainly benefits from the redundancy of the swarm, i.e. removing some robots does not have a significant impact on the performance. Some tasks focus mainly on the result rather than the process, i.e. the system should make sure the task will complete successfully, mostly in the way of increasing redundancy.

In recent years, researchers from especially American and European institutes have already utilized swarm robotics in several real-life applications including most of the tasks mentioned above.

William M. Spears et al. proposed a framework, called Physicomimetics, for the distributed control of swarms of robots (Spears, Spears, Heil, Kerr, & Hettiarachchi, 2005). They focused on robotic behaviors that are similar to those shown by solids, liquids, and gases. Different formations are adopted for different tasks, including distributed sensing, obstacle avoidance, surveillance and sweeping.

Nikolaus Correll and his colleagues from École Polytechnique Fédérale de Lausanne, Switzerland proposed a swarm-intelligent inspection system to inspect of blades in a jet turbine (Correll, & Martinoli, 2006). The system is based on a swarm of autonomous, miniature robots, using only onboard, local sensors.

MIT's Senseable City Lab developed a fleet of low-cost oil absorbing robots called Seaswarm (Homepage of seaswarm project) for ocean-skimming and oil removal. Its nanomaterial can absorb up to 20 times its weight in oil. The system provides an autonomous and low cost solution for protection ocean environment.

Roombots is a novel self-reconfiguring modular robotic system (Spröwitz, 2010). The autonomous modular robots can assembly into robot that can alter its shape to adapt to a given task and working environment such as self-assembly and reconfiguration of static objects like furniture in the day-to-day environment.

Formica (English, Gough, Johnson, Spanton, & Sun, 2008) is a scalable, biologically-inspired swarm robotics platform. Its novel mechanical design permits production on standard circuit board assembly lines. The system takes the advantage of small cheap, long-life robots, supporting peripherals and can scale to population with several hundred individuals. Scientists believe such swarms are suitable solutions for tasks like Mars reconnaissance, earthquake recovery and etc.

Swarm robotics can be useful in military applications as well. Pettinaro et al (2002) proposed a self-reconfigurable robot system for accomplish tasks including foraging, searching and rescuing with the ability to cope with occasionally failure. Military experts believe bionic aero vehicles inspired from swarm intelligence technology will become reasonable in a few years. We may see machine bees or cockroaches with reconnaissance equipment and bombs show up in future wars.

MODELING SWARM ROBOTICS

General Model of Swarm Robotics

Swarm robotics model is the key component of cooperative algorithm that functions the behaviors and interactions of all individuals. In the model, robots in the swarm should have some basic functions, such as sensing, communicating, motioning and etc.

We divide the model into three modules based on the functions the module utilizes to accomplish certain behaviors: information exchange, basic and advanced behavior. Among three modules, information exchange plays the most important role in the model. Robots in the swarm exchange information with each other and propagate the information to the whole swarm through autonomous behaviors resulting in the swarm-level cooperation.

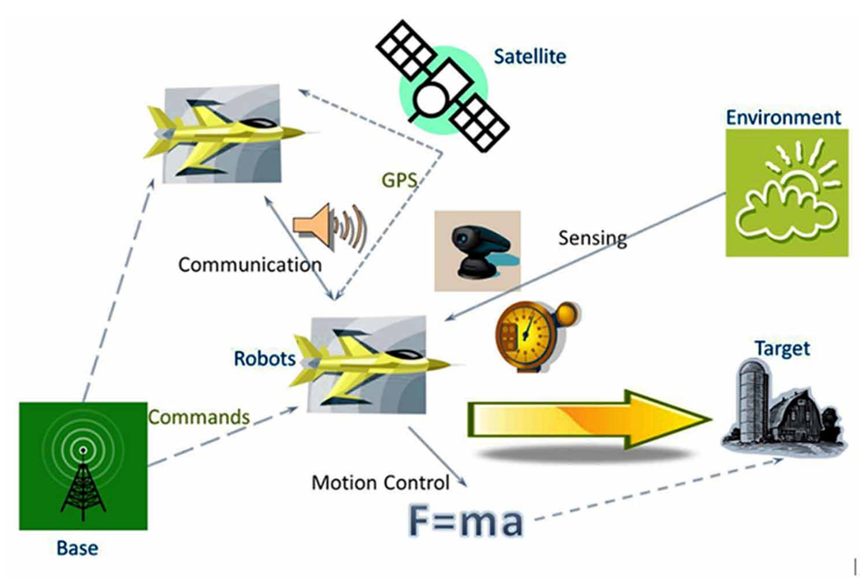
General model of swarm robotics are visualized as Figure 1. Robots communicate with each other and environment on their way to the target.

Information Exchange Module

Information exchange is inevitable when robots cooperate with one another and is the core part for controlling swarm behaviors. The main functions of individuals involved in this module are limited sensing and local communication. Information exchange of a robot falls into two categories: interact with robot or the environment. The strategies can be either same of different for these two categories in the swarm due to different applications.

In nature swarms, individuals can have direct interactions such as tentacles, gestures or voices. However, the indirect interactions are far more subtle. Individuals sense the information in the environment, react and leave messages back to the

Figure 1. General model of swarm robotics



environment. Environment act as the sticky notes and pheromones are the most common pencils in wild (Dorigo, Bonabeau, & Theraulaz, 2000). Such mechanism with positive feedback can optimize the robot-level behaviors and swarm-level behaviors can finally emerge (Xia, & Ruwei, 1999).

There are three ways of information sharing in the swarm (Cao, Fukunaga, & Kahng, 1997): communicate directly, communicate through environment and sensing. More than one types of interaction can be used in one swarm, for instance each robot senses the environment and communicates with their neighbor. Balch (2005) discussed the influences of three types of communications to the swarm performance. He designed three tasks and compared the performance in simulation. Some researchers also discussed the possibility of swarm cooperating without communications; however communication and sensing can indeed improve the efficiency of swarm for most applications.

- **Direct Communication:** Direct communication is similar with wireless networks and also consists of two types: peer-to-peer and broadcast. Thanks to the development in mobile devices, several existing technologies can be adopted immediately. Hawick et al. (2002) proposed a physical architecture for a swarm of tri-wheel robots using both IEEE802.11b wireless Ethernet and Bluetooth. However, the wireless sensors cost almost half of a total robot. Another disadvantage of such scheme is that the bandwidth required will go into exponential explosion as the population grows. In this way, direct communication in the swarm should be limited.

Although several existing wireless technologies are available, the protocols and topologies that are specialized for swarm robotics remain undiscovered. Existing computer networks are designed for data processing and information sharing between the nodes. Communications in swarm robotics should take the full advantage of local sensing and motioning abilities while pay special attention to boost the cooperative behaviors of individuals and dynamic topologies of the swarm (Dorigo et al., 2005).

- **Communicate through Environment:** Environment can act as the intermediary for robots' interactions. Robots left traces in the environment after one action to stimulate other robots that can sense the trace, without direct communication among individuals. In this way, subsequent actions tend to reinforce and build on each other, leading to the spontaneous emergence of swarm-level activities. The swarm imitates as ants or bees and interacts with the help of virtual pheromones. Such interactive scheme is exempted from the exponential explosion of the population but has some limitation on the environment to support the pheromones.

Ranjbar-Sahraei et al. (2012) implemented a coverage approach using markers in the environment without direct communication. Payton et al. (2005) proposed a swarm robotics using the biologically inspired notion of 'virtual pheromone' for distributed computing mesh embedded within the environment. The virtual pheromones are propagated in the swarm other than the environment. Grushin and Reggia (2006) solved the problem of self-assembly of pre-specified 3D structures from blocks of different sizes with a swarm of robotics using stigmergy.

- **Sensing:** Individuals can sense robots and environment nearby using on-board sensors if they can distinguish robots and other objects from the environment. Robots sense objects and targets in the environment and accomplish tasks like obstacle avoidance, target search, flocking and etc. The main issue of this scheme is how to integrate all the sensors in the swarm efficiently for cooperation in the swarm. Cortes et al (2002) explored how to control and coordinate a group of autonomous vehicles, regarded as agents with sensors, in an adaptive, distributed and asynchronous way.

The main difference between communication and sensing is whether individuals send out messages actively or receive messages passively. Although more precise and abundant, communication requires more complex hardware and synchronization and the cost of bandwidth, energy and time will grow extremely fast as population grows. The cooperative model of swarm robotics should try to simplify the communication and use as much sensing as possible. Colors, luminance and relative positions can be used for sensing and can provide rich information without communications. In some tasks, swarm can exchange all the information only with sensors.

Basic Behavior Module

Basic behaviors of individuals include functions like motioning and local planning and are one of most significant differences with multi-agent and sensor network systems. Robots and their behavior controls are homogeneous and form the fundaments of group behaviors. Based on the input from communication or sensing, robots compute their desired movements. With an excellent control module, the swarm can rely less on the communication with the help of prediction and more directed interactions, rather than broadcasts. The swarm can improve the performance with less information exchange and high scalability.

Advanced Behavior Module

Robots in complex swarm robotic systems may have extra functions including but not limited to task decomposition, task allocation, adaptive learning and etc. (Tan, Fan, & Xu, 2001) Robots with these native functions can simplify the design of the algorithms but make the physical design of real robot more complex. Robots can also achieve similar functions with carefully designed cooperative algorithms. Whether implement such functions in hardware or software depends on the physical designs of the robots, controllers and sensors so as to make better use of the components (Li, Chen, Zhang, & Deng, 2006). Details of how robots cooperate with each other are presented in the following section.

Task allocation and learning are emphasized here as they are normally quite important to a swarm of robots. Task decomposition and allocation can greatly improve efficiency for especially complex tasks. Kalra and Martinoli (2006) compared the costs and benefits of different types of task allocation approaches in real world with noises. Learning is also useful since parameters of the control mechanism are hard to tune. With the help of self-adaptive learning and optimizing methods, the swarm will show better adaptability in different environments. Li, Martinoli and Abu-Mostafa (2004) discussed the problem of using different learning methods in swarm robotics and compared performance in simulation. Zhang et al. (2006) applied evolutionary neural network to evolve swarm robotics controllers and demonstrated in structure inspection problems.

Modeling Methods for Swarm Robotics

Modeling is a method used in many research fields to better understand the internals of the system that is investigated. Modeling is helpful in swarm robotics researches since a swarm robotic algorithm is supposed to be scalable to population size of hundreds of thousands. The time and money are the limitation for such scales of experiments, yet with model and simulation, experiments can be done in an easier way.

Considering the characteristics of swarm robotics, modeling methods are divided into four types according to reference (Bayindir, & Sahin, 2007): sensor-based, microscopic, macroscopic and swarm intelligence based. The four methods are described in detail in this section.

- **Sensor-Based Modeling:** In sensor-based modeling method, sensors and actuators of the robots are modeled as the main components of the system along with objects in the environment. Then, the interactions of the robots are modeled as realistic and simple as possible. This modeling method is the mostly used and the oldest method for robotic experiments.

Earlier researches using sensor-based modeling methods, such as (Howard, Matarić, & Sukhatme, 2002) and (Trianni, Groß, Labella, Şahin, Dorigo, 2003), do not consider the real physical limitations while latter researchers introduces physical principles into the model like (Bahgeçi, & Sahin, 2005) and (Min, & Wang, 2010).

- **Microscopic Modeling:** In microscopic modeling, robots and interactions are modeled as a finite state machine. Behaviors of each robot are defined as several states and transfer conditions are based on the input from communication and sensing. Since the model is based on the behaviors of each robot, the simulation should run for several times to obtain the averaged behaviors of the swarm.

In most swarm robotics researches, probabilistic microscopic models are used, since noise can be modeled as probability in the model. In a probabilistic microscopic model such as (Ijspeert, Martinoli, Billard, & Gambardella, 2001), probabilities are valued from experiments of real robots and the model is iterated with these probabilities for state transfer in the simulation to predict the behavior of the swarm.

- **Macroscopic Modeling:** Macroscopic modeling is a modeling method opposite to microscopic modeling. In macroscopic modeling, the system behavior is defined as difference equations and a system state represents the average number of robots in this state at the time step.

The main difference between microscopic and macroscopic models is the granularity of the models. Microscopic models the behavior at individual level to simulate the group behaviors while macroscopic models at the swarm level directly. The microscopic model iterates for the swarm behavior while the macroscopic model can give out the final state of the swarm. In this way, the macroscopic model can have a global glance at the swarm while microscopic can show the details of the swarm behaviors. (Lerman, Martinoli, & Galstyan, 2005)

Probabilistic macroscopic models are also widely used by the researchers. Martinoli et al. (2004) applied macroscopic modeling to stick pulling problem from a basic model which contains only two states up to model with all states. They also compared microscopic, macroscopic and sensor-based models and described the shortages of macroscopic model.

- **Modeling from swarm intelligence algorithms:** Cooperative schemes from swarm intelligence algorithms are introduced into swarm robotics in many researches. Since the robots use the same or similar schemes with these algorithms, the models and other methods used to analyze these algorithms, which are quite mature than that in swarm robotics, can be used directly for robot researches.

The most commonly used algorithm from swarm intelligence is the particle swarm optimization (PSO) which mimics the flocking process of the birds. The particles fly in the fields and search for the best. It can be found obviously that many commons remain between PSO and swarm robotics. A mapping between particle and robot can be presented easily. (Xue, & Zeng, 2008)

Besides PSO, researchers also introduce other swarm intelligence algorithms into swarm robotics. Ant colonies have inspired many successful swarm models. These inspired approaches provide effective heuristics for searching in dynamic environments (Dorigo, & Birattari, 2010) and routing (Arora, & Moses, 2009).

However, there still many problems remaining when introducing cooperative schemes from swarm intelligence. Schemes in these algorithms consider mostly global interactions and introduce large amount of random moves for high diversity. Some schemes also contain operations to reset positions of searching agents. However, these operations are unavailable in swarm robotics. How can the schemes in swarm robotics avoid such operations while taking full advantage of the scalability and flexibility serves as the direction for researchers to explore in future.

As to the methods used in swarm robotics, some researchers have classified the articles according to the methods used to design or to analyze swarm robotics systems. The deigned methods include behavior-based design methods and automatic design methods, and the former consist of probabilistic finite state machine design, virtual physics-based design while the latter involves reinforcement learning and evolutionary robotics. In addition, the microscopic models, macroscopic models and real-robot are served as analysis methods. (Brambilla, Ferrante, Birattari, & Dorigo, 2013).

Cooperation Schemes between Robots

Cooperation belongs to the advanced behavior in the swarm robotics model. In swarm robotics, cooperation occurs at two levels: individual level and swarm level. The former is a must for robot's activities and coordinates the input from environment with the response, learning and adapting behaviors. The latter is an aggregation of former cooperation resulting in typical collective tasks such as gather, disperse or formation. Several sub problems have been proposed for cooperation between robots which are described in detail in this section.

The problems considered in this section are mainly on physical layer of the robot.

- **Architecture of the Swarm:** The architecture of the swarm is the framework for robotic activities and interactions and determines the topology for information exchange among robots. The swarm performance in cooperation depends largely on the architecture. The architectures of the swarm should be selected carefully according to the scale, relations and cooperation of the robots. (Min, & Wang, 2010)
- **Locating:** Global coordinating systems do not exist in the swarm. Therefore, each robot in the swarm has to maintain a local coordinating system of its own and should be able to distinguish, identify and locate nearby robots. Thus, a method for rapid locating other robots using on-board sensors is very important for swarm robotics. (Borenstein, Everett, Feng, & Wehe, 1997)

Absolute positioning technologies from single robots have been applied in some researches like (Feng, Everett, & Borenstein, 1994), yet combinations of sensors with special filters are wildly adopted, for instance (Martinelli, Pont, & Siegwart, 2005) and (WANG, LIU, WAN, & SHAO, 2007).

The sensors can sense different waves including ultrasonic, visible light, infrared ray or sound (Jiang, Zhao, & Li, 2007).

However, relative positioning in swarm robotics are more realistic since the abilities of the robots are limited and no global controls exist. Therefore light weighted relative positioning algorithms need to be found. Pugh and Martinoli (Pugh, & Martinoli, 2006) characterize and improve an existing infrared relative localization module used to find range and bearing between robots in small scale swarm robotics system. Kelly and Martinoli (Kelly, & Martinoli, 2004) developed an on-board localization system using infrared sensors for indoor applications. A three dimensional relative positioning sensor for indoor flying robots was proposed by Roberts et al. (2012), designed to enable inter-robot spatial coordination and goal directed flight.

- **Physical Connections:** Physical connections are used in situations that single robot can overcome, such as overpassing large gaps or cooperative transportation. In these tasks, robots should communicate and dock before continue the jobs. Mondada et al. (2004) introduces several types of physical connections, sensors and actuators for overcoming gaps and stairs. Wang and Liu (2006) developed a localizing and docking method using infrared rays. Zhang et al. (2006) proposed a reconfigurable robot for urban search and rescue with limited structures and fixed number of modules. Nouyan and Dorigo (2004) solved exploration and navigation tasks in an unknown environment using chained robots. The dynamics and qualities of the chain formation process are evaluated in simulation.
- **Self-Organization and Self-Assembly:** Self-organizing is a dynamic scheme for building a global structure through only local interactions of the basic units. The basic units or robots do not share a global control or have an external commander. The swarm level structure emerges from the individual level. The robots interact with the others through the structures already built, i.e. behaviors of robots are guided by process of the building. Such schemes can be easily found in nature, as ants or bees colonies building nests. Self-organization can be conducted by the biological study on these animal behaviors.

During the process of nest building, the ants can interact with the environment in two ways: discrete or continuous. Discrete interaction reacts to the type of stimulation while continuous interaction reacts to the amount of stimulation. A model utilizing discrete interactions has been proposed: the position a unit to be arranged is decided by the structure nearby. Simulation shows the model can result in a structure very similar with bees cave. (Nembrini, Reeves, Poncet, Martinoli, & Winfield, 2005)

Self-assembly systems can be inspired from the bee cave construction model. The behaviors in the swarm are conducted by the existing structures and prior knowledge. Payton et al. (2003) used pheromones to enhance such schemes. The swarm starts with random behaviors and converges to a pattern. The Swarm-bot Project (Dorigo et al., 2005) introduced in section 4.1.3 is a self-organization and self-assembly system. Each robot has multiple connector port, so that the swarm can aggregate into large structure.

ENTITY PROJECTS AND SIMULATIONS

Swarm Robotics Entity Projects

In recent years, swarm robotics has become a research interest for Chinese researchers, yet most of these are quite simple and only simulates in the computer (Chen, & Fang, 2005). The Project SI

(Homepage of project SI) is a relatively complete projects of real robots.

In the early 1980s, researchers from Europe and USA have begun researches in developing a group of mobile robots. Some earlier projects include CEBOT (Fukuda, Nakagawa, Kawauchi, & Buss, 1989), SWARMS (Beni, 1988), ACTRESS (Asama, Matsumoto, & Ishida, 1989) and etc. However, these projects are quite preliminary. As the researches of swarm robotics go deeper in computer simulation, the entity projects have also been boosted. Nowadays, there are several projects that provide the designs of a swarm of robots which will be briefly summarized in this section.

- **Project SI:** Project SI is developed by the Embedded Lab of Shanghai Jiaotong University. The project consists of a swarm of mobile robots named eMouse controlled by swarm inspired algorithms. The robots are designed to be reconfigurable in sensors and communication protocols, cheap in cost and strong in motion control. The eMouse does not contain sensors when designing but leaves interfaces for connecting different sensors for various applications.

The project team has completed the designing of the fifth generation of the robot and implemented several cooperative algorithms on the system. They implemented several primitives (Evans, 2000) including clump, disperse, generalized disperse, attract, swarm, scan and message transmissions. Based on a set of testing tools, for instance monitoring through trace extraction and live update over wireless network, they solved real life applications inspired from swarm intelligence.

- **SamBots:** Sambots is a project for a swarm of self-assembly. Multiple Sambots can form new structures through self-assembly and self-reconfiguration. The team realized the robots by innovative design of the docking mechanism and reasonable distribution of the perception system. (Wei, Chen, Tan, & Wang, 2011) The docking mechanism is installed on an active docking interface, which can rotate around the main body of the robot. With such scheme, the robots can connect with others robots freely into a chained structure. Sambots can compose into several structures through different configurations, including snake, caterpillar, ring, triangle, quadruped orthogons, six-limbed insects and etc.
- **The Swarm-Bots Project:** Swarm-bots (Dorigo et al., 2005), sponsored by the Future and Emerging Technologies program of the European Commission, is a project aimed for exploring design, implementation and simulation of self-organizing and self-assembling artifacts. The project, that lasted 42 months, was successfully completed on March 31, 2005 with several awards for their contributions.

The main scientific objective of the Swarm-bots project is to explore a new approach to the design and implementation of self-organizing and self-assembling artifacts. The aim of the team is to construct a large swarm-bot using a number of simpler, insect-like, robots (s-bots) with relatively cheap components and capable of self-assembling and self-organizing to adapt to its environment. The project developed both simulation and entity robots and presented their results on the two platforms.

S-Bot (http://www.swarm-bots.org/) (Mondada et al., 2005), very versatile, with many actuators, developed in the Swarmbots project.

- **Swarmanoid Project:** Since October 1, 2006, the Swarmanoid project (Dorigo et al., 2011) is extending the work done in the Swarm-bots project to three dimensional environments. The team introduced three types of small insect robots: eye-bots, hand-bots, and foot-bots, contrary to s-bots in previous project. The swarmanoid consists about a total number of 60 robots from the three types. The team has won the AAAI 2011 video competition.

Eye-bots, capable to fly or attach to the ceiling, are designed to sense and analyze the environment from a high position to provide an overview. Foot-bots, previously named as s-bots, are able to move on rough terrain and transporting either objects or other robots. Hand-bots climb vertical surfaces of walls or objects and work in a space zone between those covered by the foot-bots (the ground) and eye-bots (the ceiling). With the combination of three types of robots, the swarm can handle those tasks that require operations in all dimensions. The team also developed distributed controlling algorithms and communications as well as a simulation platform (Pinciroli, 2007) for the project.

- **Pheromone Robotics Project:** The Pheromone Robotics Project (Payton, Daily, Hoff, Howard, & Lee, 2001), started from 2000, is coordinated by Professor David Payton. The project aims to provide a robust, scalable approach for achieving swarm level behaviors using large numbers of small-scale robots in surveillance, reconnaissance, hazard detection, path finding, payload conveyance and small-scale actuation (Payton, Estkowski, & Howard, 2003). The team exploited the notion of a virtual pheromone, implemented using simple beacons and directional sensors mounted on each robot. Virtual pheromones only facilitate simple communication and coordination with little on-board processing.
- **The I-Swarm Project:** The I-swarm project (Seyfried et al., 2005), hosted by Professor Heinz Wtirn from 2004, combines micro-robotics, distributed and adaptive systems as well as self-organizing biological swarm systems. The project facilitates the mass-production of micro-robots, which can then be employed as a real swarm consisting of more than 100 micro-robot clients. These clients are all equipped with limited sensors and intelligence, each with a size of less than 3x3x2 mm and velocity of 1.5mm/s. With such tiny sizes, the swarm can work cooperatively in a small world (such as inside creatures) with very cheap costs.
    - Jasmine robot (http://www.swarm-robot.org/) (Kornienko, Kornienko, & Levi, 2005), developed under the I-swarm project
    - I-Swarm robot (http://www.i-swarm.org/) (Valdastri et al. 2006), very small, also developed by the I-swarm project.
- **iRobot Swarm Project:** iRobot Swarm Project (Şahin, 2005) is a projected by MIT for cooperating over 100 robots. The goal of the project is to develop distributed algorithms for robotic swarms composed of hundreds of individual robots robust to complex real-world environments and tolerant to the addition or failure of any number of individuals. The project team has developed global monitoring devices as well automatic charging stations. The most of work in the project was done by Mclurkin and his colleagues (McLurkin, & Smith, 2007).
- **e-Puck Education Robot:** The main goal of this project is to develop a miniature mobile robot for universities. The robots have several features specialized for such purpose. The robots have a clean mechanical structure simple to understand, operate and maintain. The robots are cheap and flexible and can cover a large spectrum of educational activities thanks to a large potential in its sensors, processing power and extensions (Mondada et al., 2009).

Researches based on e-puck project has already exceeds 60 by the end of 2010. Potential educational fields include mobile robotics, real-time programming, embedded systems, signal processing, image or sound feature extraction, human-machine interaction or collective systems.

- e-puck robot (http://www.e-puck.org/) (Mondada et al., 2009), designed at EPFL for educational purposes.
- Khepera robot (Mondada, Franzi, & Guignard, 1999), for research and educational purposes, is developed by École Polytechnique Fédérale de Lausanne (EPFL, Switzerland), and widely used in the past, nowadays has fallen in disuse. Khepera III robot (http://www.k-team.com/) (Pugh, Raemy, Favre, Falconi, & Martinoli, 2009), is designed by K-Team together with EPFL.
- The miniature Alice robot (Caprari, & Siegwart, 2005) is also developed at EPFL. The robot itself is 2x2x2 cm^3 and is able to move, sense, receive remote commands and locally communicate with neighbor robots.

- **The Kobot Project:** Kobot (Turgut, Çelikkanat, Gökçe, & Şahin, 2008), conducted by Middle East Technical University, is a new mobile robot platform which is specially designed swarm robotics. The robots are equipped with an infrared-based short range sensing system for measuring the distance from obstacles and a novel sensing system for sensing the relative headings of neighboring robots.
- **The Kilobot Project:** Kilobot project (Rubenstein, Ahler, & Nagpal, 2012) aims to design a robot system for testing collective algorithms involving hundreds or thousands of robots. Each robot is made with low-cost parts and takes 5 minutes to assemble. The system also provides overall operation of a large swarm, such as programming, powering on, and charging all robots.

Simulation Platforms

The researches of swarm robotic systems require plenty of physical robots, making it hard to afford for many research institutions (Shi, Tu, Zhang, Liu, & Wei, 2012). Simulations on computers are developed to visually test the structures and algorithms on computer. Although the final aim of the research is real robots, it is often very useful to perform simulations prior to investigations with real robots. Simulations are easier to setup, less expensive, normally faster and more convenient to use than physical swarms (Michel, 2004). In this section, we summarize several widely used simulation platforms.

- **Player/Stage:** The widely-used Player Project (Collett, MacDonald, & Gerkey, 2005) is one of the most famous simulators and aims to produce free software for robot and sensor researches. Player project is a robot server that provides full access and control of robotic platform, sensors and actuators for researchers. Stage (Vaughan, 2008) is a scalable simulator that is interfaced to Player and can simulate a population of 1,000 mobile robots in a 2D bitmapped environment in parallel. Physics is simulated in a purely kinematic fashion and noise is ignored in Stage.
- **Gazebo:** Gazebo (Koenig, & Howard, 2004) is a simulator that extends Stage for 3D outdoor environments. It generates both realistic sensor feedback and applied the ODE physic engine instead of the naive one in Stage. Gazebo presents a standard Player interface in addition to its own native interface. In this way, controllers written for Stage can be used in Gazebo and vice-versa.

- **ÜberSim:** The ÜberSim (Browning, & Tryzelaar, 2003) is a simulator developed at Carnegie Mellon for a rapid validation before upload the program to real robot soccer scenarios. ÜberSim uses ODE physics engine for realistic motions and interactions. Although originally designed for soccer robots, custom robots and sensors can be written in C in the simulator and upload to robots using TCP/IP.
- **USARSim:** USARSim (Carpin, Lewis, Wang, Balakirsky, & Scrapper, 2007), shorted for Urban Search and Rescue Simulation, is a high fidelity multi-robot simulator, originally developed for search and rescue (SAR) research activities of the Robocup contest. It has now become one of the most complete general purpose tools for robotics researches and educations. It is built upon a widely used commercial game engine, the Unreal Engine 2.0. The simulator takes full advantage of high accuracy physics, noise simulation and numerous geometrics and models from the engine. Evaluations have shown that USARSim can simulate the real time robots well enough for researchers thanks to the high fidelity physics engine.
- **ENKI:** Enki (http://gna.org/projects/enki/) is an open source, fast 2D physics based robot simulator written in C++. It is able to simulate cinematics, collisions, sensors and cameras of robots working on a flat surfaceEnki is able to simulate robot swarms hundred times faster on the desktop computer than real-time robots. Enki is built to support several existing real robot systems, including swarm-bots and E-puck, while user can customize their own robots into the platform.
- **WEBOTS:** Webots (Michel, 2004) is a development environment used to model, program and simulate mobile robots available for more than 10 years. With Webots the user can design complex robotic setups, with one or several, similar or different robots with a large choice of pre-defined sensors and actuators. The objects in the environment can be customized by the user. Webots also provide remote controller for testing real robots. Until now, Webots robot simulator has been used in more than 1018 universities and research centers in the worldwide.
- **SwarmBot3D:** SwarmBot3D (Mondada et al., 2005) is a simulator for multi-robotics but designed specifically for the S-Bot robot of the SwarmBot project.
- **Breve:** Breve (Klein, & Spector, 2009) is a simulation package designed for simulating large distributed artificial life systems in continuous 3D worlds. Behaviors and interactions of agents are defined using Python. Breve uses ODE physics engine and OpenGL library that allows observers to view the simulation in the 3D world any position and direction. Users can interact at run time with the simulation using a web interface. Multiple simulations can interact and exchange individuals over the network.
- **V-REP:** V-REP (Homepage of v-rep project) is an open resource 3D robot simulator that allows creating entire robotic systems, simulating and interacting with dedicated hardware. V-REP is based on distributed control architecture: control programs (or scripts) can be directly attached to objects in the scene and run simultaneously in both threaded and non-threaded fashions. This makes it very versatile and ideal for multi-robot applications, and allows users to model robotic systems in a similar fashion as in reality where control is most of the time also distributed. V-REP possesses several calculation modules, for instance sensor simulation (proximity or camera), inverse and forward kinematics, two physics engines (Bullet and ODE), path

planning, minimum distance calculation, graphing, etc.

- **ARGoS:** ARGoS (Pinciroli et al., 2011) is a new pluggable, multi-physics engine for simulating massive heterogeneous swarm robotics in real time. Contrary to other simulators, every entity in ARGoS is described as a plug-in and easy to implement and use. In this way, multiple physics engines can be used in one experiment and robots can migrate from one to another in a transparent way. Results have shown that ARGoS can simulate up to about 10,000 wheeled robots with full dynamics in real-time. ARGoS is also able to be implemented in parallel in the simulation.
- **TeamBots:** TeamBots (Balch, 2000) is a collection of Java simulation for mobile robotics research. Some execution on mobile robots sometimes requires low-level libraries in C. TeamBots supports prototyping, simulation and execution of multirobot control systems and is compatible to the Nomad 150 robot by Nomadic Technologies and Cye robot by Personal Robotics.
- **Microsoft Robotics Studio:** Microsoft Robotics Studio (Jackson, 2007) is a simulator developed by Microsoft Corporation. It allows multi-robotic simulation and requires the Windows platform.

COOPERATIVE ALGORITHMS

Researches in swarm robotics so far are still quite simple. Most of the algorithms are designed for every encountering application and algorithms with high usability are still yet undiscovered. A main reason for such situation is that there is still not a common and standard definition for swarm robotics system and application problems. The problems abstracted in swarm robotics researches are in a wide variety with different settings and it's hard to provide a uniform description for all problems. No benchmark test has yet been proposed by the society. Therefore, different researching works can provide little experience to each other and different algorithms cannot compare to each other easily. Thus the whole progress of swarm robotics researches is still quite slow.

Earlier Progress of Swarm Robotics Algorithms

In the earlier years of swarm intelligence research, scientists simulated the cooperative mechanisms in the nature and explored the possibility of reproducing swam behaviors using artificial agents.

Self-organizing clustering observed in bacteria was one of the first swarm behaviors reproduced by scientists (Floreano, & Mattiussi, 2008). The individuals in the swarm are controlled by a simple rule: the possibility of joining or leaving a colony is conducted by the density nearby. In the experiment, 1500 individuals in the swarm gradually clustered into three colonies without any prior information or external control.

A similar approach simulating ants' behavior of clearing up graves are also proposed (Chatty, Kallel, Gaussier, & Alimi, 2011). The task of the swarm is to collect all the items in the area together. There are no predefined storage spots available. Individual in swarm follows a simple and local rule to transport an item from spot of low density to high density only. Experiment shows the swarm completed the task for collecting 80 items without communication. They also explored the how these rules can impart on the result.

Another famous attempt for simulating co-operating abilities in the early years is the stick pulling experiment (Ijspeert, Martinoli, Billard, & Gambardella, 2001). In this experiment, the stick is long enough for one robot to pull out, i.e. two robots have to pull out the stick together. The aim of this test is to verify the swarm can emerge simple intelligence with simple rules even if no communication is available. The swarm can finish the task by the rule that a robot waits for other robots for a random time before leaving for another stick.

Dispersing uniformly in an indoor environment is one of the early algorithms that focus on the distributed structure of swarm robotics. McLurkin and Smith (McLurkin, & Smith, 2007) proposed an algorithm for a swarm of iRobot. The algorithm in divided into two steps executed alternately: one disperses the robots and the other detects the border. In this way, the swarm can gradually expand in the environment.

Features of Swarm Robotics Algorithms

A swarm robotics algorithm must fit and make full use of the features of swarm robotics. The algorithm should explore the cooperation between robots and share some features with swarm robotics system. For example, Stirling et al. (2010) studied on a swarm of flying robots searching in an indoor environment containing rooms and corridors. They introduced a strategy that saves energy significantly, i.e. robots move one by one while all other robots pin to the roof to save energy. However, their job requires the swarm to transverse the whole environment with very poor time efficiency. Since only one robot is moving in one time, the cooperative advantages of the swarm can hardly appear. In this way, it is hard to be classified as swarm robots algorithm in this case.

We define five features for swarm robotics algorithm in this section: simple, scalable, decentralized, local and parallel.

- **Simple:** Since the capability of each robot is limited, the algorithm should therefore be as easy as possible. A simple algorithm can help reduce the cost of a single robot. Even complex and efficient swarm behaviors can emerge from a well-designed simple cooperative algorithm. In most cases, the robots are considered to be a finite state machine with only a few states.
- **Scalable:** The algorithm designed for swarm robotics must be scalable for any population sizes to guarantee the system is a scalable one. In an algorithm, the designer should consider allowing robots join and especially quit the swarm dynamically. All the operations of the robots that interact with the whole swarm should be designed carefully so as not to affect the performance when population is very large.
- **Decentralized:** The robots in a swarm are autonomous and so will the algorithm be. An algorithm should always avoid any external and centralized controls. Although an individual may be affected by others, it should make the decision on its own rather than be commanded to. A decentralized algorithm is quite possible to be scalable.
- **Local:** Local communication and local interaction is the special feature of swarm robotics. The algorithm should also follow this rule as it is the key for scalability. Since the robots can simulate global communication and interaction using local one with special scheme and some delay for the information to propagate in the swarm, direct use of global operations should be avoided.
- **Parallel:** The swarm usually consists of many robots. Therefore, algorithms should be as parallel as possible so that the robots can deal with multiple targets in the same time which is one of the advantages of the swarm robotics.

According to these features, scientists have proposed many swarm robotics algorithms. However, the research of swarm robotics is still at the start and the main interests of the researchers are some basic tasks for instance formation control, obstacle avoidance and etc. A unified framework has yet not been proposed. We believe as the researches progress, several benchmark applications will be proposed and the algorithms will unleash various characteristics of the swarm robotics, such as scalable, robustness and flexibility. By that time, researchers will focus more on complicated problems consists by these benchmark applications resulting in more applicable algorithms for real life problems.

Fundamental Tasks of Swarm Robotics

In past decades, swarm robotics is deployed in various scopes of applications (Şahin, 2005) including odor localization, mobile sensor networking, medical operations, surveillance and search-and-rescue. The tasks of these applications are very sophisticated and hard to propose a direct solution. To solve these tasks, we propose several basic tasks of swarm robotics, such as flocking, navigating, obstacle avoidance and etc. Among these tasks, flocking is the most important and fundamental. Apparently, coordinating a large number of robots at the swarm level with individual rules is not an easy task. Emerging group behavior from interactions of robots with environment and other robots has been the main interest of the researches since the area has been introduced.

Flocking is widely observed in many nature swarms or even human beings. Creatures in the social groups show a great diversity in their population due to the differences in age, morphology, nutritional state, personality and leadership status of the individuals, thus it is surprising that they can achieve flocking with limited rules and interactions in such a blended group. Inspiring schemes from these groups can aid the development in basic tasks of flocking, directed navigating, searching and obstacle avoidance.

Flocking Strategy and Formation

The "Boids" model, proposed by Reynolds (1987), is a typical individual model for flocking behavior using distance metrics. The model is widely adopted in various applications including spacecraft, UAV, robot and etc. In these applications, group behaviors cannot be explicitly defined at group level and the use of individual rules are adopted (Barnes, Fields, & Valavanis, 2009).

The most common use of the "Boids" model in swarm robotics flocking is in the form of virtual forces. Hettiarachchi and Spears (2009) introduced a "Physicomimetics" framework which controls the robots' behavior using physical forces virtually generated by the interactions. They employed two types of forces from the physic laws: Newtonian Force Law and Lennard-Jones Force Law and the swarms showed quite similar results with the real material following these laws in their simulation.

Moeslinger et al. (2011) proposed a flocking behavior for robots which interprets all the interactions as attraction and repulsion forces only. The forces are decided by whether the distance falls in attraction and repulsion zones. With different setup of two zones, they achieved flocking for a small group in a constrained environment.

Hashimoto et al. (2008) proposed a control algorithm for a swarm of robots based on the gravity center of the local swarms which are overlapped partially to increase the stability of the whole swarm. Local forces such as attraction and repulsion are also applied to each robot to increase the stability of the local swarm and thus the entire swarm.

Lawton et al. (2003) presented a behavior-based approach to formation maneuvers. They decompose complex formation maneuvers into a sequence of maneuvers between formation patterns. They present three formation control strategies to deal with different topologies and purposes.

Although most models in swarm robotics assume the individuals are interacting with all their neighbors within certain distance, some biological researches provide new idea. By reconstructing the three dimensional positions of a few thousand birds during flocking, Ballerini et al. (2008) showed the interaction does not depend on the metric distance, but rather on the topological distance with six to seven neighbors on average. Various simulations in computer also show that a topological interaction grants significantly higher cohesion of the aggregation compared with a standard metric one. Based on such observation, some researchers also proposed selecting strategies before interacting with nearby robots so that only a fixed number of neighbors are used. Lee and Chong (2008) proposed a flocking control inspired by fish schools. They select two neighbors for team maintenance and local interactions. Ercan et al. (2010) introduced a regular tetrahedron formation strategy for selecting three neighbors that forms the best tetrahedron to ensure formation.

Miyagawa (2010) has shown that swarms can flock without distance information. He utilizes a strategy inspired from tau-margin, the assumption that animals especially birds perceive time to contact rather than distance. Robots in the swarm are equipped with light bulbs of 10-watt so as to perceive tau-margin by utilizing optical inverse square law.

Barnes et al. (2009) presented a method for organizing a swarm of unmanned vehicles into a user-defined formation by utilizing artificial potential fields generated from normal and sigmoid functions. The potential functions along with nonlinear limiting functions are used to control the shape of swarm to user desired geometry.

Directed Flocking

Besides the flocking strategy, direction control in flocking are the most concern in flocking researches and are widely adopted in navigation, migration and searching applications. Until now, there already exist a number of studies for directing the swarm with target positions and propagating information in the swarm.

Informed Individual

A common and naïve strategy for direct flocking is the "informed individual". It was first observed in nature swarms by Couzin and his colleagues (Couzin, Krause, Franks, & Levin, 2005), who conducted a study on effective leadership and decision-making in animal groups and published their work in Nature. In their experiment, only a few of the individuals in the group are aware of the target direction. The results demonstrate that these informed individual can lead the whole group towards the destination. Later, Correll et al. (2008) utilized such scheme in cow herd to guild the swarm.

From then on, similar schemes are also introduced to swarm robotics. McLurkin (2004) developed a strategy in his mater thesis for the task of following the leader with a linear formation. Robots line up in the topology, follow the predecessors and guide the successors. The leader is guided by other controls for the final destination of the group. The group forms the line without any external orders and can handle obstacles in the environment and communication failures that may encounter.

Nasseri and Asadpour (2011) investigate the controlling effects of a swarm with only a small fraction of robots having the knowledge of final goal. The informed robots cannot transmit information directly yet the swarm can flock towards the desired target in simulation. They also investigated how the parameters can influence on the performance.

A self-organized flocking behavior for a swarm of robots was presented by Turgut et al. (2008) without using emulated sensors or priori knowledge of the destination. The simulation has shown that with only local interactions, the robots will share a common flocking direction in a self-organized process until the sensing noise exceeds to a certain extent. In their follow-up work (Çelikkanat, & Şahin, 2010), they studied how the swarm can be steered toward a desired direction through guiding some of individuals externally. Their results are qualitatively in accordance with the ones that were predicted in Couzin et al. (2005) model. These two works are evaluated in both physical systems and simulations in an environment with obstacles.

Stranieri (Stranieri, 2011) studied self-organized flocking behaviors of two types of robots: aligning and non-aligning. Aligning robots has the ability to agree on a common heading direction with their neighbors. A heterogeneous swarm of these two kinds of robots can achieve good flocking performance in simulation if the motion control strategy and interact mechanisms are carefully designed.

Potential Field Functions

Another commonly used swarm formation control strategy is the potential field functions. Ge and Fua (2005) presented a scalable and flexible approach that to effectively control the formation of a group of robots. They introduced artificial potential trenches and represented formation structures in terms of queues and vertices, rather than with nodes. Robots are attracted to and move along the bottom of the potential trench and distribute with respect to the density nearby automatically. In their follow up work, Fua et al. (2007) investigated the operation of the queue-formation structure with limited communication. Information interaction classified as two scales: the fast-time and slow-time scale. The former scale involves only local real time communication and in the latter scale, information is less demanding and can be collected over a longer time from the swarm. In this way, the swarm is incrementally guided into the specific formation in a more efficient manner.

Aggregation, foraging, and formation control of robots are investigated by Gazi et al. (2007) using artificial potentials and sliding mode control. They considered a significantly more realistic and more difficult setting with non-holonomic unicycle agent dynamics models compared with other studies.

Balch and Hybinette (2000) presented a new class of potential functions for navigating to a goal location in obstacle environment. The approach is inspired by the way molecules “snap” into place as they form crystals and the swarm can arrange themselves to a geometric formation.

Positioning and Navigation

In flocking and migration, positioning of the goal, nearby robots and various obstacles in the fields is also an important task. In the application taking place in the large outdoor environment, global positioning is expensive and requires more hardware, which is unaffordable for swarm robotics. Thus, local positioning in flocking should be specially focused.

Navigation

Rothermich et al. (2005) developed a distributed localizing and mapping method based on a swarm of iRobots. Since the swarm does not share a global coordinating system, the swarm should gather and move together to maintain a virtual one. In the swarm, some robots will serve as beacons if run into a newly searched area and will turn back to mapping and searching robots if there are already several beacons nearby. With such scheme, the swarm can maintain the coordinating system to draw the map with high accuracy in a distributed way.

Correll and Martinoli (2005) developed an intelligent inspection system using only on-board local sensors. They introduced the strategy of beaconing robot in the swarm and compared with beaconless approaches. They also analyzed the system with probabilistic microscopic and macroscopic models.

Spears et al. (2007) developed a relative localization module for determining positions of nearby robots based on trilateration for searching problems. Robots identify nearby robots with three marking points equipped physically on robots to match the distance and direction of their neighbors. This strategy is fully distributed, scalable, inexpensive and robust. The system provides a framework for both localization and information exchange.

Stirling et al. (2012) presented a new autonomous flight methodology for autonomous navigation and goal directed flight in unknown indoor environments using a swarm of flying robots. The approach is entirely decentralized and relies only on local sensing without global positioning, communication, or prior information about the environment.

Marjovi et al. (2010) proposed a navigation method by guiding the swarm using wireless connections when searching for odor sources. At least three individuals in the swarm will act as beacons which broadcast coordinates to the whole swarm to maintain a global coordinate system while the others searching for the odors. The shortcoming of this research is the beacons are broadcasting the coordination in a large area while other robots should detect the distance with the beacons from a long distance which requires expensive hardware.

Simulating Ant Colonies

Ant colonies in the nature are famous for the navigation and migration behaviors with the help of pheromones. Researchers in the swarm robotics society employed such scheme into swarm robotics by simulating pheromones using part of the robots in the swarm which served as beacons.

An interesting study is proposed by Sperati et al. (2010). In their experiment, a robotic swarm manages to collectively explore the environment, forming a path to navigate between two target areas, which are too distant to be perceived by an agent at the same time. Robots continuously move back and forth between the two locations while interacting with their neighbors. Behaviors of the robots are controlled by neural network and the swarm evolves to optimize the path. They observed that the swarm will finally converge to the shortest path. In their follow up work, one of the schemes simulating ant colonies is proposed (2011). They searched for an efficient exploration and navigation strategy for the same problem. They evaluate one run of a robot through the time and distance spent to find the path and optimize the searching using evolutionary methods. The final results show great flexibility and robustness.

Ducatelle et al. (2011) investigated how simple local interactions between the robots of the different swarms can cooperate to solve complex tasks through using eye-bots and foot-bots from the swarmanoid project. Foot-bots move back and forth between source and target and avoid obstacles without any interaction with other foot-bots; eye-bots simulate the pheromones in the environment and guide passing by foot-bot with local directions. Eye-bots update the weights of the directions and move towards the optimized path to accelerate the searching process. Simulation results show this system is capable of shortest path finding and automatic traffic spreading.

Obstacle Avoidance

Obstacle avoidance is also considered an important basic task in the swarm robotics society. In most researches, some sort of potential functions are applied to robots. The swarm steers around the encountered obstacles according to the potential fields. Khatib (1986) first introduced this concept in real-time obstacle avoidance. He used a time-varying artificial potential field for moving obstacles. This solution successfully converted the traditionally high level planning problem into distributed real-time operations even in complex environment.

Some recent examples also used such scheme. Das et al. (2002) proposed an approach that switches between several controllers depending on the state of the robot for obstacle avoidance. Shao et al. (2005) proposed a similar kinematic controller and modified the desired bearing to steer robots around obstacles. Do (2008) use a potential function for avoiding collisions within the swarm. The function alters robots' trajectory if they are not at their heading direction. In the work of Ercan et al. (2010) obstacles generate a virtual repulsive force similar to the mechanism in atomic nucleus and robots play the roles of electrons to fly around the nucleus.

Kurabayashi and Osagawa (2005) proposed formation transition and obstacle avoidance adapting to geometrical features appear in Delaunay diagram. The robots select their neighbors in the diagram by the proposed strategy and form topology connecting all individuals lead by certain robot. The algorithm shows some flexibility but is vulnerable in robustness.

Min et al. (2005) proposed a new method for avoiding obstacles in dynamic environment based on the second order motion model for robotics. A mathematical model based on the destination of robot, velocity and direction of obstacles is proposed and optimized using PSO. Simulation experiment shows this method is better than tradition artificial potential field methods though requiring large computation overload since each robot with maintain a PSO model separately as the method is designed for single robots.

As to the tasks performed by swarm robotics, they also can be viewed from the angle of swarm behaviors. And the tasks or behaviors in swarm robotics include aggregation, flocking, foraging, object clustering and sorting, navigation, path formation, deployment, collaborative manipulation, task allocation, order source localization, hole avoidance and rendezvous problem, and so on. Some researchers (Brambilla, Ferrante, Birattari, & Dorigo, 2013) have also classified these collective behaviors into four categories: spatially-organizing behaviors, navigation behaviors, collective decision-making, and other collective behaviors, which is comprehensive and reasonable.

SWARM ROBOTICS SEARCHING ALGORITHMS

Currently, swarm robotic searching algorithms are the most concern by the researchers besides those basic tasks mentioned in previous section. In this section, we classify searching strategies in two types: inspired from swarm intelligence algorithms or inspired form other methods. These two types of algorithms vary from many aspects, such as searching schemes, ways to detect targets and information exchanges inside the swarm.

Inspired from Swarm Intelligence Algorithms

From the general point of view, swarm optimization algorithms share several similarities with swarm robotics searching, e.g. searching for the best points using a swarm of individuals. Particle swarm optimization (PSO) is the swarm intelligence approach that adopted most in the swarm robotics due to the great similarity with flocking and searching schemes. Besides PSO, other methods have also inspired many successful approaches, such as ant colony optimization (ACO), glowworm swarm optimization (GSO). The scope of these approaches includes path finding, navigation, odor localization and etc.

Swarm intelligence shows great ability in scalable, flexibility and robustness and is suitable for real life applications with the aid of various existing strategies. However, the shortcomings of these algorithms are also introduced in the same time, e.g. large quantity of random moves, global interactions and especially, tend to get trapped in the local minimal. Couceiro, et al. (2011) proposed a RDPSO for solving the last issue. They divide the swarms into sub-swarms with dynamic topology updated in several iterations based on a reward and punishment mechanism. However, the sub-swarms are divided ignoring the distance metrics and escape the local minimum at the cost of global communication and coordinating system.

We divide the usage of swarm intelligence algorithms into three types.

1. Optimize Parameters

The first type of searching algorithms inspires strategies from other methods with several parameters which are hard to optimize, such as neural network or heuristic schemes. Swarm intelligence algorithms are employed to optimize these parameters.

Meng (2008) proposed a collective construction task consists of searching for randomly distributed building blocks and transporting these blocks to predefined locations. The method employed virtual pheromone trail for information exchange and task allocation for cooperative transportation. A modified PSO is proposed to balance the exploration and exploitation in their work.

Pugh et al. (2005) explored using PSO on noisy problems of unsupervised robotic learning. He adapted a technique of overcoming noise from genetic algorithms (GA) and evaluated it on unsupervised learning of obstacle avoidance using a swarm of robots. In his follow-up work with Martinoli (2005), they presented an adaptive strategy for localization of multiple targets. The search algorithm is inspired by chemotaxis behavior in bacteria, and the algorithmic parameters are updated using PSO.

To overcome the weakness and difficulty of the logical design of behavioral rules, Oh and Suk (2010) proposed an artificial neural network controller that is applied to the mission of searching obstructive areas using a swarm of UAVs. Genetic algorithm is applied to evolve the weights in the neural network which shows superior results to other controllers.

Yang and Li (2011) proposed a path planning algorithm based on improved PSO. The center of the path is described as cubic splines and the path planning is equivalent to parameter optimization of these cubic splines. Results show that obstacle avoiding paths can be optimized using such scheme.

2. Modeling Individual Behaviors

In this type of algorithms, each robot is regarded as a particle or agent correspondingly in the swarm intelligence algorithm. The searching environment is normally interpreted as fitness values. The swarm uses the fitness to search for the targets.

Pugh and Martinoli (2006) explored the possibility of adopting PSO strategies in swarm robotics searching directly. Each robot is regarded as a particle and various neighborhood topologies and PSO update strategies are verified. In their follow-up work (Pugh, & Martinoli, 2007)], they designed an effective algorithm that allow a swarm of robots to work together to find targets. They proposed techniques inspired from PSO modified to mimic the swarm robotics search process. Analysis of parameters and setups in the model are also presented at an abstracted level.

Marques et al. (2006) presented a PSO inspired algorithm for searching odor sources in a large search space. Robots try to repulse on each other when no chemical cue exists nearby to improve the swarm performance. Hereford, Siebold, and Nichols (2007) applied PSO on a swarm of robots searching for the light spots in a room containing obstacles. Each robot is regarded as a particle and broadcast its information to the whole swarm. The shortcoming of the experiment is that it only considers three robots with a large amount of global communication to maintain gbest in the swarm.

Derr and Manic (2009) considered problem of exploring an unknown environment to find targets at unknown locations. They used PSO with a novel adaptive RSS weighting factor to locate targets. Zhu, Liang, and Guan (2011) presented a PSO-inspired search algorithm that coordinates robots to find targets without precise global information. They also introduced a Cartesian geometry based method unifying relative coordinate systems to improve robustness and efficiency.

Zhang et al. (2011) proposed a strategy based on modified glowworm swarm optimization for multiple odor source localization. This strategy includes global random search, local GSO based search. A discovered source is marked as forbidden area to ensure the swarm does not locate this source again.

An interesting resource exploration task on Mars was imagined by Kisdi and Tatnall (2011). They suppose the situation that a lander leads a swarm of workers who cannot interact with each other. The lander is unable to move and serves as a shared memory as well as the coordinator of the swarm. Workers search in the environment at the area ordered by the lander and return the results back to the lander. The scheme of the lander is similar with that of maintaining archives in multi-objective search in swarm intelligence. Human interaction is also available at the lander to mark interesting areas.

Zheng (2013) proposed a group explosion strategy (GES) for searching multiple targets using swarm robots, which inspired from the explosion schemes of fireworks. Compared with RPSO, their algorithm is more efficient and scalable. To overcome some drawbacks discovered in experiments, together with his partners (Zheng, Li, Li, & Tan, 2014), he proposed the improved group explosion strategy (IGES), which is much simpler and more efficient than the comparative algorithms. In addition, some environmental restrictions, such as decoys (Zheng, Li, Li, & Tan, 2014), are considered, and based on the previous work, an idealized model for the basic search problem and three kinds of environmental restrictions is built (Li, & Tan, 2014).

3. Mixing Two Methods Above

Some algorithms try using the swarm intelligence model and optimizing parameters using swarm intelligence in the same time. Doctor, Venayagamoorthy, and Gudise (2004) proposed a method utilizing two layers of PSO for controlling unmanned mobile robots in target tracing applications. The robots are controlled by schemes in inner layer of the PSO and parameters of inner layer are optimized by the outer layer. Signal intensity from targets is defined as the fitness to search for the swarm.

Solutions for real-time uniform coverage tasks in military applications under the harsh and bandwidth limited conditions are proposed by Conner et al. (2008). They encode each robot as a genome and exchange speed and direction with neighbors. A force-based genetic algorithm uses at the swarm level to determine the behavior of each robot under the threats of hostile attacks, obstacles and intermittent stoppage of communication. The swarm always tries to rearrange the positions to compensate for the missing robots.

Inspired from Other Methods

Olfaction is a common ability that animals use in their everyday activities, such as hunting, mating, interacting and evading predators. Such schemes inspired from animals are widely used in swarm robotics applications localizing odor sources, which have attracted a growing interest in areas such as anti-terrorists, locating toxic or harmful gas leakage, checking for contraband, exploring mineral resources in dangerous areas and search-and-rescue in collapsed building. (Li, Yang, Cui, & Geng, 2011)

A common olfaction based algorithms can be decomposed into three or four sub procedures first proposed by Hayes (2002) and Li et al. (2006). The swarm first searches for a plume and follows the plume to the odor source one a plume is located. The sub-procedures are different in various approaches such as the gradient descent method (Russell, 2005), zigzagging method (Li, Farrell, & Card, 2001), and the upwind method (Hayes, Martinoli, & Goodman, 2003).

Cui et al. (2004) proposed a biasing expansion swarm approach to collaboratively search and locate various number of emission sources in an unknown area using a swarm of simple robots. Jatmiko et al. (2007) provided a model of odor-gated rheotaxis combined from chemotaxic and anemotaxic (upstream) methods to solve odor source localization problems. The combined model can achieve high accuracy in real life scenarios containing dynamic sources, random winds and obstacles.

Russell et al. (2003) summarized and compared the implementation and evaluation of four chemotaxis algorithms which provide fast, simple and cost-effective solutions for olfaction based searching applications in obstructive environments. They listed the details of the algorithms together with typical results of these algorithms obtained in both simulated and practical experiments.

Besides olfaction, other searching applications and strategies are also proposed. Varela et al. (2011) developed an algorithm aimed for coordination of a group of UAVs to monitor environment. The UAV swarm can locate the undesired phenomenon. The UAVs compare the average fitness of last five iterations with their neighbors and select the direction of the best neighbor to search in the next iteration. They validated the algorithm in real UAVs monitoring and industrial area.

Wu and Zhang (2012) develop a switching strategy for locating a local minimum in an unknown noisy scalar field. Robots will switch to cooperative exploration only when they are not able to converge to a local minimum at a satisfying rate according to a cooperative filter. The switching strategy can result in faster convergence and is robust to unknown noises and communication delays.

A robust-satisficing approach based on info-gap theory is suggested as a solution for a spatial search-planning problem by Sisso et al. (2010). The swarm is given uncertain prior information data with severe errors. The proposed method shows great superior in robustness to the expected-utility maximizing strategy.

Lee and Ahn (2011) proposed a foraging algorithm specially focused on energy efficiency. Through adding several temporal storage stations in the environment the swarm can improve searching efficiency since robot will move shorter distance to the storage before next forage. The swarm is divided into two part, one part searches for the food and send the food to the nearest station while others transfer from the station to the nest. In this way, both time and energy efficiency are improved.

Besides these common methods, other strategies are also proposed by researchers. Nouyan and Dorigo (2006) proposed a chain based path formation algorithm to generate a chain of robots from nest to a destination unknown to the swarm. In their method, each robot is regarded as a finite state machine with only three states: explore, search and chain. The robot explores in the field for any existing chains, searches for the end and joins. With limited sensing and communication, the swarm can chain up with great robustness and scalability. In their follow up study (Nouyan, Groß, Dorigo, Bonani, & Mondada, 2006), they extend the task by transporting the target back to the nest. The robots have to work together and pull the target along the chain back to the nest while chaining robots will join the transportation after the target has passed them. Their work is one of the most complicated tasks that have ever been considered in self-organizing robot swarms in real life projects.

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

Swarm robotics is a relatively new researching area inspired from swarm intelligence and robotics. Although a number of researches have been proposed, it's still quite far from practical applications. We hereby propose several fundamental problems for researchers to solve in future before the system can really be adopted in daily life. How can the cooperative schemes inspired from nature swarms integrate with the limited sensing and computing abilities for a desired swarm level behavior? How to describe the swarm robotics system in a mathematical model which can predict the system behavior at both individual and swarm levels? How to propose new and general strategies that can take full advantages of the swarm robotics system? And finally, how to design a swarm of robots with low cost and limited abilities yet still have the potential to show great swarm level intelligence through carefully designed cooperation?

Besides cooperative algorithms to provide control for the swarm, manufacturing is a fundamental need for developing swarm robotics systems. With the help of advances in Micro Electro Mechanical technology in the aspects of mechanical transmission, sensors, actuators and electronic components, size and cost of robots have been significantly reduced these days. We believe the progress of hardware technologies and cooperative schemes in both biology and swarm intelligence in future will boost the development of swarm robotics systems.

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KEY TERMS AND DEFINITIONS

Communicate through Environment: Robots left traces in the environment after one action to stimulate other robots that can sense the trace, without direct communication among individuals.

Flexibility: A swarm with high flexibility can deal with different tasks with the same hardware and minor changes in the software, as nature swarms can finish various tasks in the same swarm.

Robustness: Swarm robotics systems will not be affected greatly even when part of the swarm quitted due to majeure factors.

Scalability: The system is adaptable for different size of population without any modification of the software or hardware which is very useful for real-life applications.

Sensing: Individuals can sense robots and environment nearby using on-board sensors if they can distinguish robots and other objects from the environment.

Swarm Intelligence: A soft bionic of the nature swarms, i.e. it simulates the social structures and interactions of the swarm rather than structure of an individual in traditional artificial intelligence.

Swarm Robotics: A new approach to the coordination of multi-robot systems which consist of large numbers of mostly simple physical robots. It is supposed that a desired collective behavior emerges from the interactions between the robots and interactions of robots with the environment.