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Swarm Robotics: An Overview

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ABSTRACT

A robot swarm is essentially a decentralized multi-robotics system that can collectively accomplish missions that a single robot could not achieve by itself. It has some unique characteristics that differentiate it from centralized multi-robot systems. Swarm robotics is inspired by the swarming nature of insects and birds. It employs a large number of simple robots which can perform complex tasks in a more efficient way than a single robot. It consists of multi-robotics in which large numbers of robots are coordinated in a distributed and decentralized way. The goal is to control a large number of simple robots to solve complex tasks. This paper presents an overview of swarm robotics and its applications, benefits, and challenges.

KEYWORDS: *robots, robotics, swarm robotics, multi-robot systems*

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INTRODUCTION

Robots are already disrupting several industries. The use of robots in dangerous environments eliminates or reduces risks for humans. There are several excellent examples of miniature robots that have been previously constructed. Robots are increasingly being deployed across personal, commercial, and industrial sectors. We are moving towards a society where humans are actually outnumbered by autonomous and semi-autonomous agents in their home as well as work lives. More recent robot designs leverage key desirable features such as modularity, processing power, and energy consumption against cost and size [1].

Swarm robotics is an approach which makes use of several robots to solve a complex problem that a single robot cannot solve. A swarm of robots can accomplish more than the sum of its parts. A robot swarm is a self-organizing multi-robot system characterized by high redundancy and flexibility. It promotes the development of systems that are able to cope well with the failure of one or more of the robots. The loss of individual robots does not imply the failure of the whole swarm.

Inspired by the swarm behaviors of social insects, swarm robotics has attracted the attention of the robotic community. Swarm robotics collectively solve complex problems that individual robots cannot handle. Each robot can move autonomously and connect with the other. The swarm enabling algorithms allow individual robots plan, share, and coordinate their trajectories and tasks to achieve a common goal. Like any other robot, a swarm robot has two main components; hardware and software. In essence, software is the brain of the system. It gives a simulation environment to the functioning of the robot. The hardware brings into action, directions simulated by the software [2].

WHAT IS A ROBOT?

The word "robot" was coined by Czech writer Karel Čapek in his play in 1920. Isaac Asimov coined the term "robotics" in 1942 and came up with three rules to guide the behavior of robots [3]:

1. Robots must never harm human beings,
2. Robots must follow instructions from humans without violating rule 1,

3. Robots must protect themselves without violating the other rules.

Robotics has advanced and taken many forms including fixed robots, collaborative robots, mobile robots, industrial robots, medical robots, police robots, military robots, officer robots, service robots, space robots, social robots, personal robots, and rehabilitation robots [4,5]. Robots are becoming increasingly prevalent in almost every industry, from healthcare to manufacturing.

Although there are many types of robots designed for different environments and for different purposes/applications, they all share four basic similarities [6]: (1) All robots have some form of mechanical construction designed to achieve a particular task; (2) They have electrical components which power and control the machinery; (3) All robots must be able to sense its surroundings; a robot may have light sensors (eyes), touch and pressure sensors (hands), chemical sensors (nose), hearing and sonar sensors (ears), etc. (4) All robots contain some level of computer programming code. An autonomous robot must have a basic body structure (the chassis), sensors, a central control system (microprocessor), actuators (motors), a power supply and an overall program for its behavior. Programs are the core essence of a robot since they provide intelligence. There are three different types of robotic programs: remote control, artificial intelligence, and hybrid. Some robots are programmed to faithfully carry out specific actions over and over again (repetitive actions) without variation and with a high degree of accuracy.

The advantages of robotics include heavy-duty jobs with precision and repeatability. Despite these advantages, there are certain skills to which humans will be better suited than machines for some time to come. Humans have the advantages of creativity, decision-making, flexibility, and adaptability.

BACKGROUND ON SWARM ROBOTICS

Swarm robotics is the study of how to design multi-robots that operate without any form of centralized control. A swarm consists of a large number of simple entities that interact with each other and with the environment with no central control. A large number of simple robots can perform complex tasks in a more efficient way than a single robot. The goal is to keep the cost of individual robots low to allow scalability, making each member of the swarm less demanding of resources. Another goal is for swarm robots to perform tasks to cover a wide region.

Swarm robotics is a field of multi-robotics in which large number of robots are coordinated in a distributed and decentralized way. Inspired by social insects, swarm robotics is an approach for coordinating multiple robots for a desired collective behavior. This approach emerged on the field of artificial swarm intelligence. Swarm intelligence is the emergent collective intelligence of groups of simple agents. It is the collective behavior of decentralized, self-organized systems, natural or artificial. It belongs to the emerging field of bio-inspired soft computing and optimization. It is inspired from the biological entities such as birds, fish, ants, wasps, termites, and bees [7,8]. The design of robot swarms is guided by swarm intelligence principles, which are illustrated in Figure 1 [9]. Figure 2 depicts the general model of swarm robotics [10].

A robot swarm is a decentralized system characterized by locality of sensing and communication, self-organization, and redundancy. Although a swarm robotics usually consists of homogenous agents, in recent years, heterogeneous swarm (i.e., a swarm composed of different types of robots) has found its way to swarm robotics. Robot swarms coordinate the collaborative behaviors of a large number of relatively simple robots in a decentralized manner. A collective decision is the result of a process distributed among a collective of agents that leads the collective to make a choice that, once made, can no longer be traced back to any of its individual agents. Collective decisions are widespread in group-living animals such as social insects, birds, fishes, and many other living collectives, rely on simple interaction mechanisms to do so. Collective decision-making behaviors focus on how robots influence each other in making decisions [11]. As shown in Figure 3, collective behaviors include spatially organizing behaviors, navigation behaviors, decision-making behaviors, human interaction behaviors, and other behaviors [12].

Swarm robotics focuses on the study of distributed robotics systems composed of a large number of independent and autonomous robots. Nature provides us with abundant examples of how large numbers of individuals can make decisions without the coordination of a central authority [13]. Robots in the swarms need a mechanism to explore the environment. The ability to make decisions collectively is a fundamental pillar for the development of autonomous robot swarms. An example of swarm robotics is shown in Figure 4 [2].

The three main inherent, desirable properties of swarm robotics [14]:

1. **Robustness:** This is the ability of the system to continue to operate despite failures in the

individuals. The swarm robotic system should be able to operate despite disturbances from the environment or the malfunction of its individuals.

2. **Flexibility:** The ability of the system to offer solutions to a variety of tasks by utilizing different coordination strategies. Swarm robotics aim to attain a variety of tasks. Swarm robotics enables flexibility because of the distributed and self-organized nature of the swarm.
3. **Scalability:** Scalability means that the systems must be able to work with different sizes of groups. The swarm should be able to operate under a wide range of group sizes and support large number of individuals without impacting performance considerably.

In addition to these properties, the following main distinguishing characteristics of swarm robotics are important [15,16]:

1. Robots must be autonomous, able to sense, and actuate in a real environment.
2. The number of robots in the swarm must be large or at least the control rules allow it.
3. Robots in a swarm only interact with close peers and the neighboring environment. They do not need global knowledge nor supervision to operate.
4. As swarms are decentralized and self-organized, individual robots can dynamically allocate themselves to different tasks and hence meet the requirements of specific environments.
5. A robot swarm is characterized by high redundancy due to the large number of robots composing it. Such redundancy prevents robot swarms from having a single point of failure.
6. A robot smarm is also characterized by its ability to act in a coordinated way without the presence of a coordinator or an external controller.
7. The interactions among the individuals are based on simple behavioral rules that exploit only local information that the individuals exchange directly or via the environment,
8. The overall behavior of the system results from the interactions of individuals with each other and with their environment.
9. Swarm robotics promotes the development of systems that are able to deal with a broad spectrum of environments and operating conditions.
10. Coordination is distributed, so that scalability becomes one of the properties of the system.

Some of these characteristics are illustrated in Figure 5 [17]. Based on the above properties, it is possible to design swarm robotic system that are scalable, parallel, and fault tolerant.

APPLICATIONS OF SWARM ROBOTS

Potential applications for swarm robotics are many. Typical applications of swarm robotics are demining, tracking, cleaning, planetary or underwater exploration, search and rescue missions, manufacturing, construction efforts, environmental remediation, medical applications, precision agriculture, supply chain management, military reconnaissance, and surveillance. Swarms can be useful natural disasters or accidents. Other applications include the following [18]:

- They are used in tasks that demand miniaturization such as nanorobotics and microbotics. Flying microrobots could be instructed to pollinate a field.
- They are used in search and rescue missions. Swarms of robots could be sent to places that rescue-workers cannot reach safely and explore the unknown environment. Drone swarms are used in target search, drone displays, and delivery.
- They are used in micro aerial vehicles which have been tested in tasks of autonomous surveillance.
- Autonomous swarms are used in manufacturing and known as swarm 3D printing. This is particularly useful in cases where traditional 3D printing is not able to be utilized due to hardware size constraints.
- Swarm robotics has been used to investigate the conditions under which some complex social behaviors might result out of an evolutionary process.
- Swarm robotics can be used to detect chemical leaks or pollution.
- Swarm robotics is promising in solving the problem object transportation.
- In the military, by leveraging unmanned aerial vehicles (UAVs) acting together as a swarm, better battlefield awareness can be reached. The US Army is already using swarm robotics detecting and destroying any type of unmanned vehicles. Swarms of military robots can form an autonomous army.
- In civil engineering, particularly in disaster relief situations, swarms of micro-robots could self-assemble to build temporary structures such as bridges

- In agriculture, swarm of robotics can be used to support local navigation and discerning weeds from cultivated plants. Robot swarms will enable precise farming.
- Swarming aerial robots autonomously operate in a complex 3-D world such as an airspace that is getting increasingly crowded with drones and commercial airplanes.

Some of these application of swarm robotics are displayed in Figure 6 [17].

BENEFITS

Swarm robots have the characteristics of being simple, robust, and low cost, so that they could be manufactured and deployed in mass. Swarm robotics is getting increasing attention in the robotics community due to its many benefits. Perhaps the major advantage of swarm robotics is that it can provide good solutions where other traditional search techniques fall short. The inherent characteristics of swarm robots allow then to achieve scalable, flexible and fault-tolerant exploration and mapping. The possible real commercial applications of swarm robotics will take place when robots get to be mass produced and the costs of building swarms of robots decrease [17].

Some other advantages of swarm robotic systems include the following [1]:

- Robots are autonomous that can cope with their environmental changes.
- Robots can combine their powers and abilities to form complex structures and offer unlimited features.
- A robot swarm could autonomously perform simultaneous localization and mapping (SLAM) by using self-organized exploration schemes to navigate in hazardous environments.
- A robot swarm is suitable for performing missions in unknown environments in which the risk of failure of individual robots is high.
- A robot swarm is most useful in situations where the main constraint is time or cost rather than high precision.
- With a swarm, one can implement tasks that would be difficult if not impossible for larger robots to do in cost effective manner.
- The inherent characteristics of swarm robots allow then to achieve scalable, flexible, and fault-tolerant exploration and mapping.
- The systems are flexible. That means they can be applied in different fields and for a verity of tasks.
- The systems are scalable. That means all robots can manage to obtain its goals no matter how big or small the swarm is.
- Parallelism makes the systems work more faster. Parallelism means tasks can be divided into sub tasks that can be allocated to different robots.
- Robots are designed very simply, that means they are also cost effective.

CHALLENGES

In spite of its potential to promote robustness, scalability and flexibility, swarm robotics has yet to be adopted for solving real-world problems. Several challenges are preventing the real-world uptake of swarm robotics systems. Scalable applications are still far away.

Swarm robotics is far from being considered a mature technology due to the following challenges [11,21]:

- Miniaturization and cost are key constraints in building large multi-robot systems.
- Integrating all the sensors in the swarm efficiently for cooperation is challenging.
- Fault tolerance is an open issue in swarm robotics since the most common way to produce a map in a multi-robot system implies some sort of centralization and hence a single point of failure.
- Reaching a consensus in a decentralized system requires additional delays and data sharing, which cannot be neglected for cost- or time-constrained applications.
- Swarm-robotic systems are usually stochastic, nonlinear, so building mathematical models for validation and optimization is hard.
- There is a need to precisely figure out how to describe a swarm robotics system in a mathematical model that predicts the system behaviors.
- Lack of standard definition for swarm robotics system and application problems.

CONCLUSION

Swarm robotics is the use of numerous, autonomous robotics to accomplish a given complex task which an individual robots cannot perform. Swarm robotics is an area of research that is inspired by swarm intelligence and robotics. It has its origins in swarm intelligence. It is an attractive field of research that applies swarm intelligence to groups of simple homogeneous robots. More information about swarm robotics can be found in the books in [22-28] and the following journals devoted to robot-related issues:

- Robotica

- Robitics and Autonomous Systems
- Advanced Robotics
- Autonomous Robots
- Journal of Robotics
- Journal of Robotic Systems
- Journal of Robotic Surgery
- Journal of Robotics and Mechatronics
- Journal of Intelligent & Robotic Systems
- Journal of Mechanisms and Robotics-Transactions of the ASME
- Journal of Automation, Mobile Robotics and Intelligent Systems
- Intelligent Service Robotics
- IEEE Journal on Robotics and Automation
- IEEE Robotics & Automation Magazine
- IEEE Robotics and Automation Letters
- IEEE Transactions on Robotics
- International Journal of Medical Robotics and Computer Assisted Surgery
- International Journal of Robotics Research
- International Journal of Social Robotics
- International Journal of Humanoid Robotics
- International Journal of Advanced Robotic Systems
- ISRN Robotics
- Recent Trends in Mobile Robots
- Science Robotics
- Swarm Intelligence

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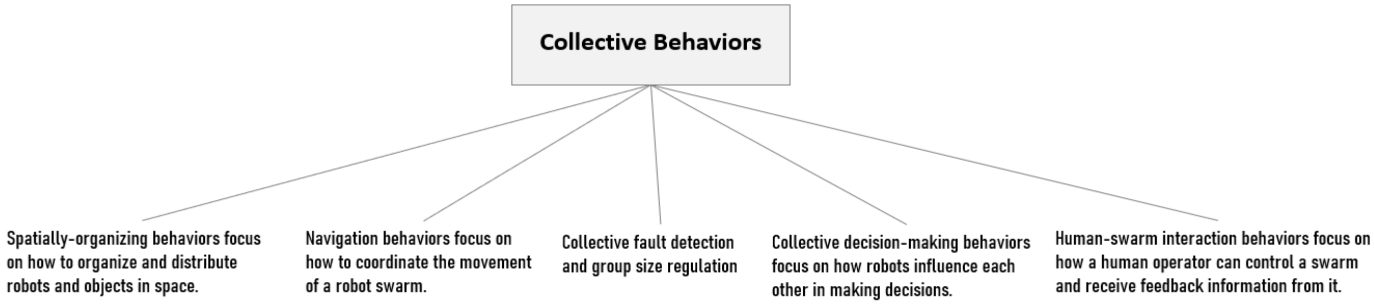

Figure 1 Collective behaviors [9].

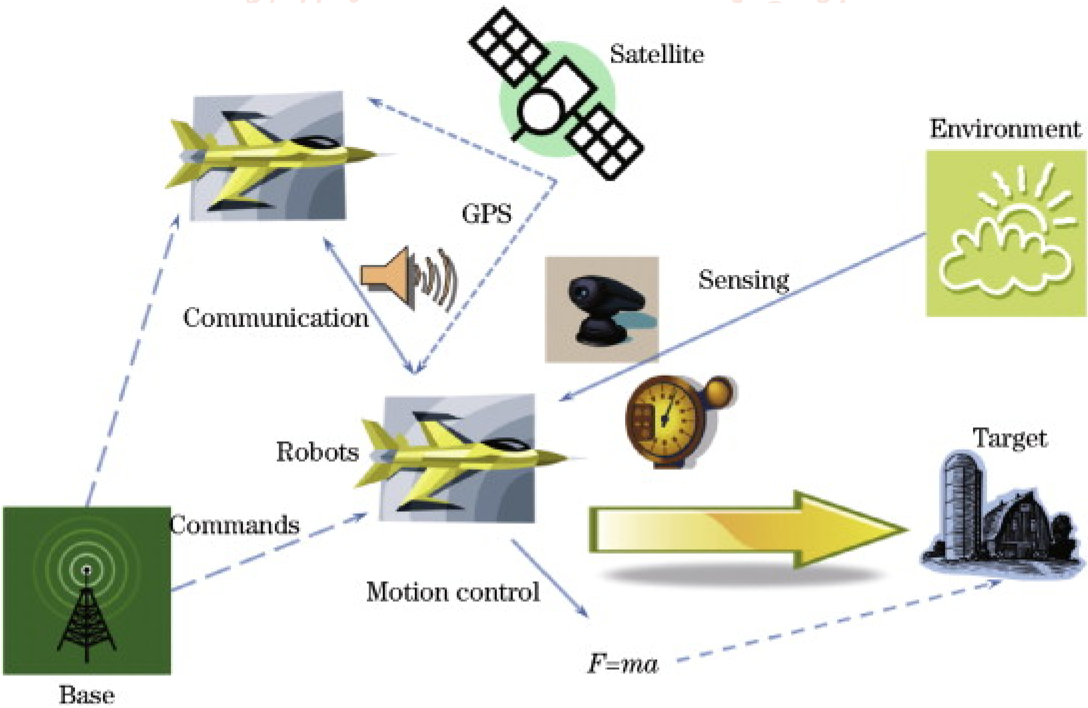

Figure 2 The general model of smart robotics. [10].

Figure 3 The five principles of swarm intelligence [12].

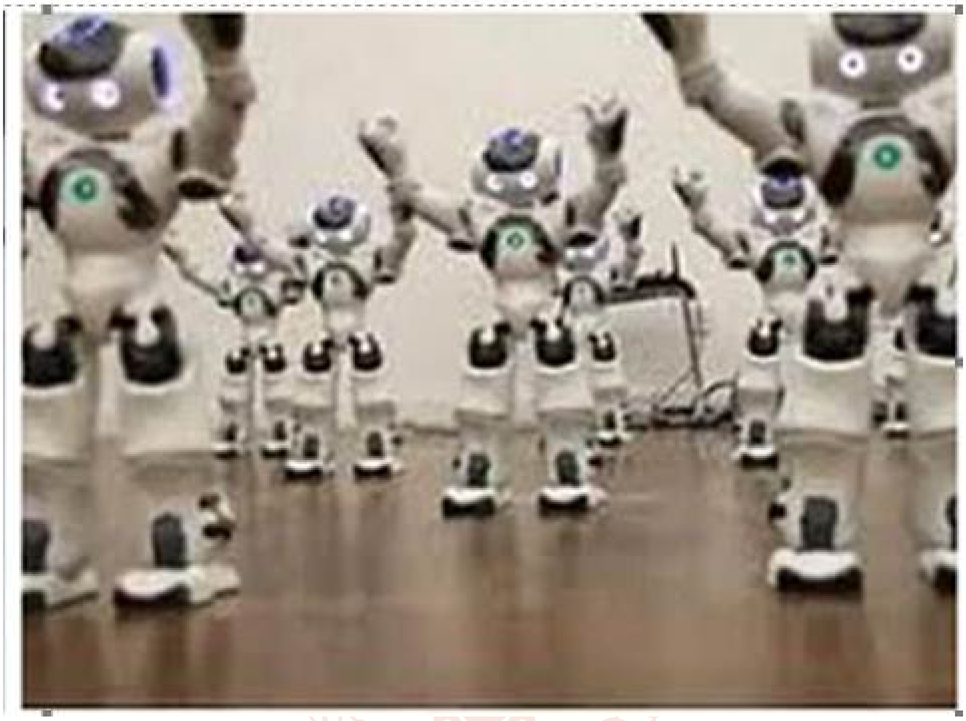

Figure 4 Swarm robotics in action [2].

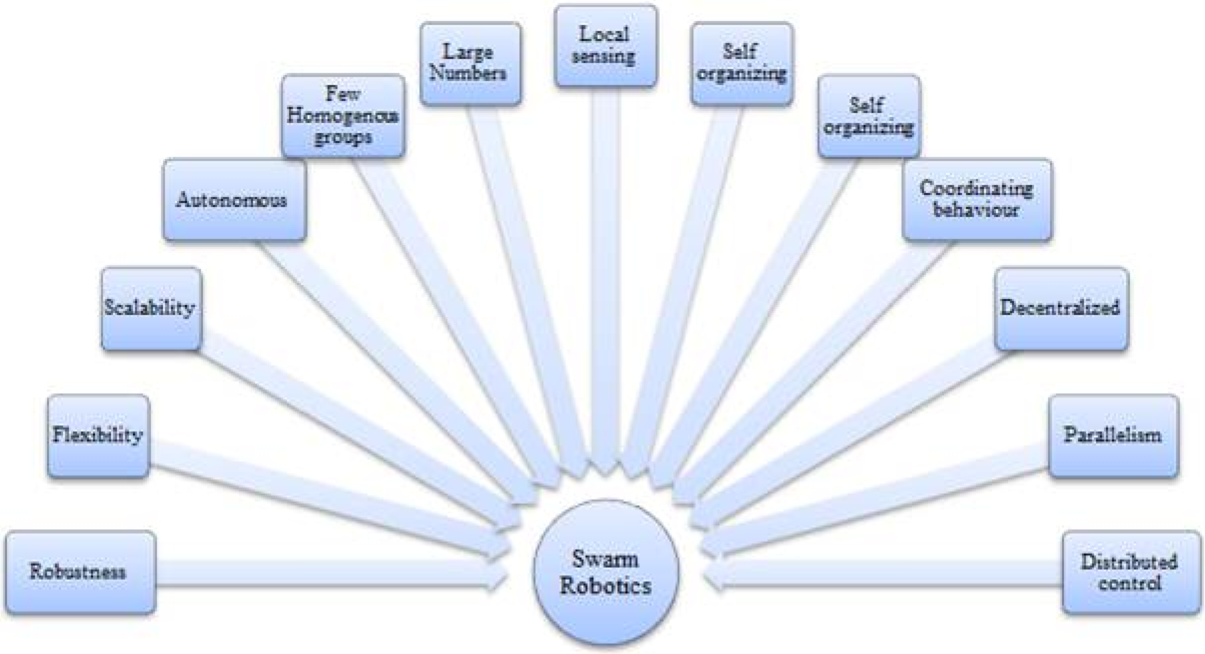

Figure 5 Some characteristics of Swarm Robotics [17].

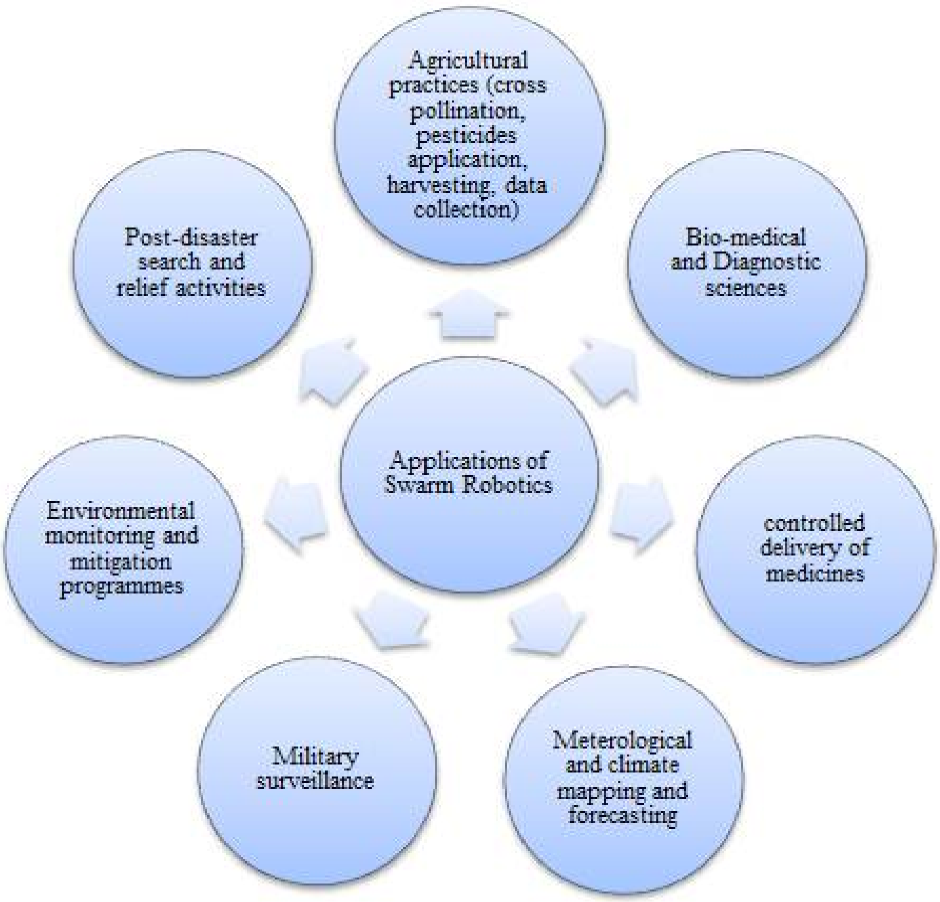

Figure 6 Application of swarm robotics in real world [17]