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Swam Robotics: Moving from Concept to Application

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Abstract. Humans have always been inspired by their environment to solve their problems. When it directly imitates the behavior of living things, it is called biomimicry. Biomimicry seeks to identify winning life strategies to apply them in our world to solve challenges. It is a practice that learns from and mimics the technique used by species alive today. Fish, birds, bats, bees, fireflies, many animals, and insects provide us with a permanent demonstration of a phenomenon as simple as it is complex and will be discussed in this reading: swarms. Swarm intelligence is a subfield of computer science that draws inspiration from the behavior of swarms to solve problems. It is possible to characterize a swarm as a structured set of individuals with limited individual capacities who offer collective intelligence to solve complex problems. Swarm robotics is an application of swarm intelligence. By applying the concept to multi-robot systems, behaviors similar to those observed in the living world are reproduced and make it possible to solve problems, propose new approaches or improve existing ones. This paper reviews the swarm robotics approach from its history to its future. First, we review several Swarm Intelligence concepts to define Swarm Robotics systems, reporting their essential qualities and features and contrasting them to generic multi-robotic systems. Then, we discuss the basic idea of swarm robotics, its important features, simulators, real-life applications, and some future ideas.

Keywords: Swarm Robotics, Particle swarm optimization, Internet of Thigs, Industrial Internet of Things, 5G.

1 Introduction

The term swarm intelligence was first used in 1989. Beni and Wang use it in the field of cellular robotic systems to then define a set of autonomous, and unsynchronized robots which attempt to achieve a global goal in a cooperative manner [1].

In the field of artificial intelligence, swarm intelligence will be defined as the collective behavior of self-organized and decentralized systems. We can therefore broadly define swarm intelligence as a collection of simple agents interacting with other agents and the environment using decentralized and self-organized management, with the aim of achieving a common objective [2].

Inspired by the collective and social behaviors of the animal kingdom but also of human societies, swarm intelligence is now a fully-fledged branch of the field of artificial intelligence. Its main applications will be the design of multi-agent systems such as with swarm robotics or optimization networks [3]. Like any multi-agent system, it is important to stress that swarm intelligence is to be seen as a collective entity and not as an isolated entity. Indeed, since it arises from a set of interactions between a multitude of individuals in a social context (or environment), swarm intelligence can be considered as a broader concept of intelligence [4].

The literature gives us different definitions of swarm intelligence:

- *Definition 1:* "Swarm intelligence refers to a kind of problem-solving ability that emerges in the interactions of simple information processing units. The information processing units that make up a swarm can be animate, mechanical, computational, or mathematical; they can be insects, birds, or humans; they can be real or imagined. Their coupling can have a wide range of characteristics, but there must be an interaction between the units" [4].

- *Definition 2:* "Swarm intelligence is a highly bio-inspired field whose goal is to model, by means of multi-agent systems, the mechanisms of self-organization and adaptation observed in living organisms. These models eventually give rise to algorithms that simulate natural phenomena in software (on a computer) or hardware (with robots), or serve as meta-heuristics for artificial intelligence problems." [5].

- *Definition 3:* "From a methodological point of view, swarm intelligence is a set of heuristic solutions inspired by the behaviors of animal swarms and capable of providing empirical solutions to many challenging computational problems belonging to several disciplines" [6].

The authors in [7] give us the properties that characterize swarm intelligence:

- *Flexibility:* Flexibility is defined as the ability of a swarm to solve different actions in different environments. This capacity is a direct consequence of the redundancy of the system and the absence of centralized control. Thus, the adaptability of swarms allows them to be flexible to the environment and to the task requested.
- *Error tolerance:* Another consequence of the redundancy of the system and the absence of centralized control is the robustness of the system. Because of the multitude of agents, the data collected follows Gaussian laws and thus reduces errors. Even if an agent performs a wrong action and reacts differently than the whole set of agents, its action will be diluted by the total number of agents that will perform a corrective action.
- *Scalability:* This characterizes the ability of a swarm to solve problems at different scales, regardless of the number of agents involved.

This paper explores the field of swarm intelligence and its application through swarm robotics. The first part will look at swarm intelligence and various optimization algorithms developed. The second part will introduce swarm robotics according to its different characteristics. Finally, the last part will few applications allowing the real deployment of the robot swarm.

This paper is organized as follows. Section 2 describes the information transfer and interactions within the swarm. Section 3 the algorithms based on swarm intelligence. Section 4 introduces the terminology and description of swarm robotics. Some applications of swarm robotics are given in Section 5. Finally, Section 6 presents our conclusions.

2 Information Transfers and Interactions within the Swarm

We can define two modes of information transfer within swarms. First, the agents have limited and straightforward capacities. The interactions within the swarm must thus follow the same characteristics.

Indirect information transfer or stigmergy uses an environment as an information medium. Although the agents do not interact directly with each other, they will modify their environment. These modifications of the environment are visible to the other agents, who can then modify their actions. This communication process leads to near-perfect coordination of the agents [2].

This experiment perfectly illustrates the indirect interaction mode. Each agent modifies its environment locally and can distinguish the modifications of the other agents. Moreover, by recurrence effect, there is the coordination of the agents without them communicating with each other.

On the other hand, direct information transfer represents the set of close interactions between individuals. It is based on the ability of agents to transmit information within a restricted perimeter and their ability to listen to a potential message coming from a close neighbor. The message transmitted is not fixed in the environment or in time. Therefore, this mode of communication is not influenced by the environment and mainly governs the self-organization behaviors in the space of a group.

This mode of communication can be observed with flocks of birds or schools of fish. Fast and straightforward communication from close to close within the school allows the fish to form only one entity and realize perfect coordination in movements and trajectories.

3 Algorithms Based on Swarm Intelligence

Currently, there are multiple applications of swarm intelligence such as robotics in testing, which will be studied in the next part of this reading, optimization problems, but also simulated crowds, military applications, road safety, data mining [8]-[12]. Therefore, different algorithms used in these domains will be developed in this section.

(a) Artificial Bee Colony (ABC)

Artificial Bee Colony is an optimization algorithm classified as a meta-heuristic. The algorithm is based on the model of Tereshko and Loengarov of the foraging of a bee colony [13]. Three main elements compose the model: employed and non-employed foraging bees and food sources. It also distinguishes two main behaviors essential to intelligence and collective self-organization: the positive feedback from hiring foragers to rich food sources and the negative feedback from foragers abandoning poor sources.

When ABC is applied to an optimization problem, it is necessary to first convert it into a problem consisting of finding the parameter vector and minimizing the objective function. Then the agents (bees) randomly explore a universe of solution vectors and iteratively improve them using a neighborhood search mechanism and abandoning wrong solutions (i.e., food sources) [14].

One of the famous mating and breeding behavior of honey bees inspired algorithm is Marriage in Honey Bees Optimization (MBO). The MBO algorithm, which is a swarm intelligence based and metaheuristic algorithm predicated on the marriage and fertilization of honey bees. The MBO is an annealing algorithm is used during the queen bee's mating flight, mating with drones, generation of new genotype, and adding these into the spermatheca [15]-[17].

(b) Ant Colony Optimization (ACO)

Ant Colony Optimization (ACO) is also a metaheuristic. It is inspired by the behavior of ant colonies in their search for food. It mainly exploits the behaviors related to the deposit and tracking of pheromones. Artificial ants are then stochastic procedures that use pheromone information (tailored to each problem) to build candidate solutions [18].

(c) Bacterial Foraging Optimization Algorithm (BFOA)

The Bacterial Foraging Optimization Algorithm is a global optimization algorithm. It is inspired by the foraging strategy of the E. Coli bacterium. As for the bacterium, the algorithm positions several agents in space. From a mathematical point of view, the latter moves to find a good area for swarming to reduce the cost function as much as possible [19].

(a) Firefly Algorithm (FA)

The Firefly algorithm was developed in 2008 by Yang [21]. The algorithm is inspired by the behavior of fireflies, which, in population, use light flashing activity to move, communicate, attract mates and warn of predator risks. By combining the characteristics of flashing and light intensity present in fireflies, the algorithm allows to generate a convergence of agents in several steps and thus to reach a global solution (as shown in the figure 1).

Although it is more recent than the other algorithms presented here, FA is highly appreciated for its efficiency in multimodal function formulation and thus for its effectiveness.

(a) Particle Swarm Optimization (PSO)

PSO is an optimization algorithm that mimics the behavior of birds or fish schools when searching for food. It is based on the principle that each individual has a share of experience and information that he can share with the rest of the group. It is a simple algorithm that does not use a gradient or a differential function. It is mainly used to find the extremum of an objective function defined on multidimensional vector spaces.

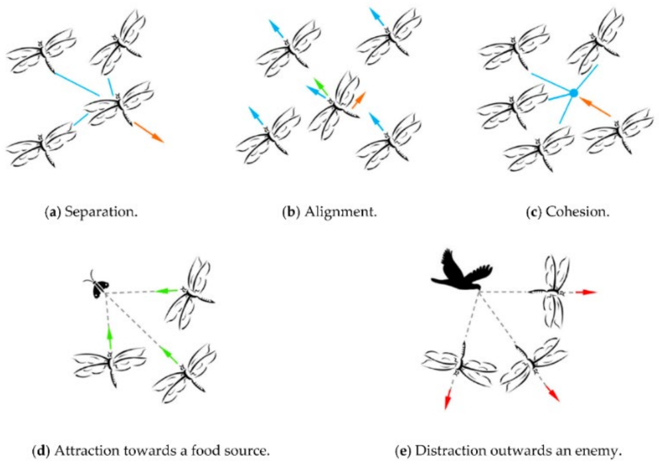

Figure 1. Dragonfly algorithm [20].

As show in the Fig 2, the basic principle proposes distributing particles (agents) randomly in the space, looking for an extremum. Then, at each iteration, each particle must search around the extremum point it has already found. (phase a) Then around the extremum point found by the whole swarm of particles (phase b). This leads to convergence to the function's extremum, excluding the local extrema (phase c).

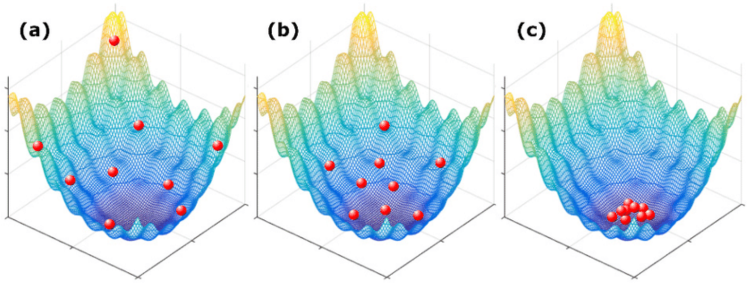

Figure 2. Particle Swarm Optimization (PSO).

4 Swarm Robotics

Swarm intelligence is a subpart of computer science, drawing inspiration from animal behavior to design optimization and problem-solving algorithms. Another direct application of swarm intelligence is swarm robotics.

Swarm robotics takes all the principles of swarm intelligence and applies them to the resolution of real situations. The agents, until now virtual, become real: mobile robots. Swarm robotics is a new method of the multi-robot system that addresses the many problems posed by designing a single robot to perform a task. Indeed, creating a single but powerful robot is generally long and expensive, and the flexibility in the face of situations is low. Therefore, deploying a collection of smaller, less powerful, and less costly robots to perform diverse but straightforward tasks makes more sense. The fields of application of robotics are mostly related to scale problems, which humans cannot solve alone. For example, the swarm of flying drones to locate victims in an accident area or after a natural disaster is an important research area of swarm robotics. We can also name the military and industrial sectors.

Definition 1: "Swarm robotics is defined following the principles that a swarm system should have a large number of robots, tasks should be solved and improved using a swarm system, and that the robots exchange local information through limited communication distances" [22].

Definition 2: "Swarm robotics is the study of how a large number of relatively simple physically embodied agents can be designed in such a way that a desired collective behavior emerges from local interactions among the agents and between the agents and the environment." [23].

Definition 3: "Swarm robotics is the study of how to create groups of robots that operate without dependence on external infrastructure or any form of centralized control. In a robot swarm, the collective behavior of the robots results from the local interaction between the robots and the environment in which they interact" [24].

(a) Characteristics

It is possible to define some important characteristics of swarm robotics. Since it represents a direct application of swarm intelligence, it inherits its features, notably its robustness to error.

- *Robustness:* Because of the large number of agents, the swarm multi-robot system is robust to error, a faulty agent, or a disturbance in the environment. In general, the swarm will always perform the requested action and converge towards its objective.
- *Evolutivity:* the number of individuals in the swarm does not influence the ability to solve the problem. The swarm can operate with many individuals and a small number of individuals.
- *Parallelism:* Swarm robotics allows the division of a complex task into sub-objectives that the agents can perform in parallel. The gain in efficiency is then important compared to a single robot having to realize all the tasks alone.
- *Flexibility:* A given swarm can perform many different actions.
- *Heterogeneity:* A swarm can contain robots that are different from each other and can be specialized for specific actions (like a colony of ants). This generates a heterogeneity of the swarm, improving its flexibility.
- *Absence of leader:* Compared with collective robotics, robot swarms do not have a leader. Each agent has the exact instructions and the same goals.

5 Applications of Swarm Robotics

For a given area, the swarm is sent to explore. Its objective is to map a zone, identify dangers, etc. Thanks to optimization algorithms and direct and indirect communications (see: Information transfer and interactions within the swarm), the exploration is optimized to be as fast and accurate as possible. This kind of application allows the exploration of areas humans cannot access for physical reasons: extreme conditions, small dimensions, rough terrain.

(a) Coordinated movement

Coordinated movement of agents is also an application of swarm robotics. The goal of common movement within the group requires constant estimation of group movement by each agent. Maintaining joint motion and group formation is helpful in transportation or logistics applications. Coupled with any other application, coordinated movement helps avoid collision between agents and serves as a navigation mechanism (returning all agents to a power charging area, maintaining a communication link with the operator) [25].

(b) Aggregation

Aggregation of a swarm consists of grouping all agents into a single close and compact group. The scope of application is very broad and can complement many of the applications cited here. This kind of displacement can also lead to the swarm regrouping around a given point (target, objective, threat to be eliminated) as to a specific organization of the swarm. This is known as morphogenesis: all the individuals in the group come together to form a single entity [25]. The Figure 3, show the morphogenesis approach on a real swarm of several kilobots.

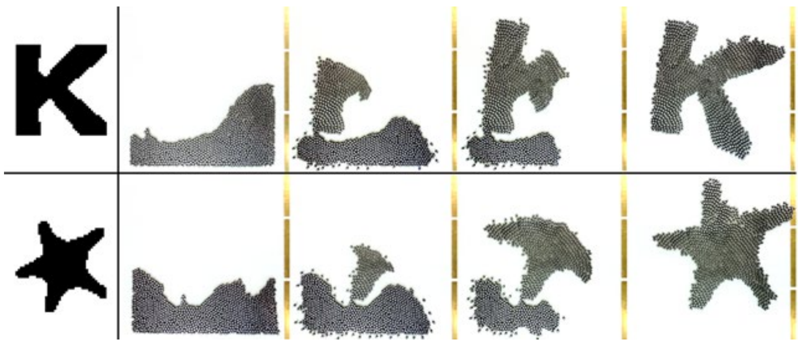

Fig. 3. Emergence of swarm morphologies kilobots

(c) Foraging

All search and collection operations are called foraging operations. The application areas range from foraging, victim finding, threat finding, cleaning operation.

(d) Localization

The localization of robots is an essential point. The agents must identify what surrounds them and where it is located. This perception problem is full-fledged in robotics, and swarms are no exception. However, by taking up the principles of data sharing within the swarm, it is possible to improve the agents' ability to perceive the environment. In this model, the agents will communicate the different locations they have visited so far. If two agents have seen the same place, they will pool data from both robots to update their maps.

(e) Example of applications

All these principles are mixed in real applications to solve complex tasks. It is possible to cite many real applications. The table below summarized few applications of swarm robotics. Table 1. They allow to investigate the application of swarm algorithms to robots.

Table 1. Classification of research platforms for swarm robotics.

Application	References
Autonomous Pollination of a Crop Field	[26]
Agriculture	[27]
Surveillance and Military Defense	[28]
Education	[29]
Traffic Monitoring	[30]
Oil Spill Cleanup and Detection	[31]
Medicine	[33]
Search and Rescue	[34]
Space Science	[35]

6 Conclusion

Swarm intelligence is a branch of artificial intelligence inspired by the living world to organize multi-agent algorithms. Swarm intelligence has become a recognized approach to optimization and problem solving for its robustness and adaptability. Swarm robotics is a physical application of swarm intelligence. Agents that have become real robots can perform complex tasks despite their simplicity. Aggregation, coordinated movement, exploration: robots act as a single unit to achieve their goals. Characterized by its heterogeneity as well as its ability to distribute and share information within it, a swarm can be deployed thanks to the implementation of several vital characteristics:

- The global consensus.
- The ability to localize.
- The ability to maintain communication chains and the implementation of long-term autonomy.

The fields of application of swarm robotics are already numerous and allow to perform operations that humans cannot do. With the capacity to explore and identify the environment being at the center of these devices, one can wonder what place swarms of robots will have in the phases of space explorations, notably on Mars in the years to come.

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