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A review of swarm robotics tasks

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ABSTRACT

Swarm intelligence principles have been widely studied and applied to a number of different tasks where a group of autonomous robots is used to solve a problem with a distributed approach, i.e. without central coordination. A survey of such tasks is presented, illustrating various algorithms that have been used to tackle the challenges imposed by each task. Aggregation, flocking, foraging, object clustering and sorting, navigation, path formation, deployment, collaborative manipulation and task allocation problems are described in detail, and a high-level overview is provided for other swarm robotics tasks. For each of the main tasks, (1) swarm design methods are identified, (2) past works are divided in task-specific categories, and (3) mathematical models and performance metrics are described. Consistently with the swarm intelligence paradigm, the main focus is on studies characterized by distributed control, simplicity of individual robots and locality of sensing and communication. Distributed algorithms are shown to bring cooperation between agents, obtained in various forms and often without explicitly programming a cooperative behavior in the single robot controllers. Offline and online learning approaches are described, and some examples of past works utilizing these approaches are reviewed.

1. Introduction

Swarm robotics is a field of research which studies how systems composed of multiple autonomous agents (robots) can be used to accomplish collective tasks, where the tasks either cannot be accomplished by each individual robot alone, or are carried out more effectively by the robots as a group. Dudek et al. [1] identified the following categories for tasks executable by robots: tasks that are inherently single-agent, tasks that may benefit from the use of multiple agents, tasks that are traditionally multi-agent, and tasks that require multiple agents. The swarm robotics discipline focuses on the last three categories, and past works have demonstrated in many application domains that using a multitude of agents to solve a task in a distributed manner allows working with significantly less complex agents at the individual level.

Three desired properties have been identified in a seminal paper by Şahin [2] as main motivations for swarm robotics studies: scalability, flexibility and robustness. The author defined a set of criteria to distinguish swarm robotics research from related disciplines: robots are autonomous, i.e. capable of moving and interacting with the environment without centralized control; the task at hand can be carried out collectively by a large number of robots, meaning that the system should be designed with scalability in mind; the swarm is made of relatively few homogeneous groups of robots, the focus being on large numbers of identical individuals rather than on centrally planned heterogeneous teams where each individual has a predefined role; the capabilities of a single robot (such as sensing, communication and computation capabilities) are limited compared to the difficulty of the collective task; and finally, sensing and communication are done by each robot at a local level, ensuring that interactions between swarm members are distributed and do not rely on coordination mechanisms that would hinder scalability. Swarm robotics takes inspiration from the collective behavior observed in nature in many living species, where local interactions between individuals and with the environment lead a group of autonomous agents to solve complex tasks in a distributed manner, without a central control unit. The locality of interactions and communication, which might be seen as a limitation, has a beneficial effect on scalability and robustness of the system, and is thus generally preferred over the use of global communication and sensing.

The expression “swarm intelligence”, which is now widely used in the field of swarm robotics, refers to the superior capabilities of a swarm of agents compared to its single individuals. The local events triggered by swarm members during execution of a task translate into a global behavior which often transcends the individual capabilities, to the point that many collective tasks can be successfully done by robots that are not explicitly programmed to execute those tasks: the global, macroscopic dynamics is said to *emerge* from interactions of swarm members between each other and with the environment.

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The possibility to achieve global objectives at the swarm level by means of distributed algorithms acting at the individual level comes at a price: it is often difficult to design the individual robot behavior so that the global performance is maximized. This problem has been widely studied by swarm robotics researchers, and has been addressed with simulation, modeling and learning approaches. Simulation, where a given multi-robot scenario is replicated in a virtual environment in which robot capabilities (sensors and actuators) and interactions are simulated by a computer program, allows assessing the performance of a robot swarm with repeated runs of an experiment, eliminating or mitigating the need for time-consuming experiments with real robots and facilitating algorithm optimization with a trial-and-error approach. Modeling (more precisely, macroscopic modeling) utilizes mathematical formulas to link individual-level control parameters to swarm-level dynamics; with such formulas, the impact of algorithm parameters can be evaluated directly, and often valuable insights on the global dynamics of the swarm can be intuitively obtained. Learning refers generically to adaptation of algorithm parameters based on previous experience; learning methods can be categorized in offline approaches, where the parameter optimization phase is part of the design of robot controllers, and online approaches, where robots dynamically update their control parameters based on their perception of the environment.

A widely used offline learning method is artificial evolution, which, starting from initial values of algorithm parameters, iteratively executes robot experiments evaluating for each experiment a fitness function which estimates the performance of the algorithm in executing a swarm-level task; the most performing parameter values at a given iteration are identified and used as a basis to program robots in subsequent iterations. Similar to what happens in nature with the evolution of species, robots are able to evolve their behavior across different “generations” and accomplish the given task. While neural networks are a common type of robot controllers used with artificial evolution, recent works explored the use of alternative methods such as rule-based grammatical evolution [3].

Online learning methods have been shown to be able to increase the flexibility of a swarm, i.e. its capability to adapt to different environment conditions. By definition, robots learning during task execution must have some form of memory which allows them to remember past experiences in order to adapt their future behavior; thus, inclusion of online learning methods in robot controllers implies an additional level of complexity in robot implementation. But generally the biggest difficulties encountered in this domain are due to different aspects: first, robots often have a limited and noisy perception of the environment and of the progression of a global task; second, as already discussed, the distributed nature of the problem makes it difficult to relate individual behavior to global performance. Two types of online learning methods can be identified in past works: reinforcement learning and parameter adaptation. Reinforcement learning is based on a model where robots, which can be in a given set of states and can execute a given set of actions, receive feedback on the results of their actions through a *reward*; the objective of robots is to choose a mapping between states and actions so as to maximize the reward. Using a local reinforcement paradigm, the reward is assigned only to robots which directly accomplish an objective, while with global reinforcement all the robots are rewarded for each accomplishment; local reinforcement is more coherent with swarm intelligence principles because it does not require sharing global information in the swarm. Other online learning methods can be described as based on dynamic adaptation of robot algorithm parameters triggered by observations of the environment.

In this paper, various tasks for which past works have proposed solutions using a swarm intelligence approach are surveyed, focusing on distributed control, locality of interactions and simplicity of individual robot controllers. The next section is dedicated to previous swarm robotics reviews; then, the subsequent sections describe the different tasks and the corresponding solutions proposed in past studies; finally, future research directions are outlined and concluding remarks are made in the last sections.

2. Previous work

In the last two decades, theoretical research on multi-robot systems has been fueled by technological advances that now allow building relatively cheap small robots. An early categorization of multi-robot systems is given by Dudek et al. [4,1], who identified swarm size, communication range, communication topology, communication bandwidth, swarm reconfigurability, swarm unit processing ability and swarm composition as taxonomy axes to classify natural or engineered multi-agent systems.

The fundamental notion of *cooperation* between robots plays a central role in determining whether a multi-robot system performs better than equivalent single-robot systems, and as such has been discussed in a number of existing surveys. For example, cooperation is the central topic in [5], where swarm robotics systems are analyzed in terms of group architecture of the swarm (indicating with this term properties such as centralization versus decentralization, homogeneity versus heterogeneity, direct or indirect communication between agents, and how agents model each other), interference problems due to sharing of common resources, origin of cooperation (with interesting examples of how cooperation can be achieved implicitly even if each agent acts to maximize its individual utility), and learning mechanisms (with focus on reinforcement learning and genetic algorithms); in addition, a number of studies are grouped under the category of geometric problems, such as multiple-robot path planning and formation and marching problems. Iocchi et al. [6] used cooperation as the first level of a multi-level characterization of robot swarms; cooperative systems are then further differentiated at the knowledge level, where systems with robots aware of the existence of other robots are distinguished from systems where each robot acts as if it was alone. The lower levels of the proposed taxonomy are the coordination level, describing how the actions of each robot take into account the actions of other robots, and the organization level, which determines whether decisions are taken in a centralized or distributed way; it is interesting to note that a centralized system may be compatible with swarm intelligence principles: more precisely, systems defined as *weakly centralized*, where one of the robots temporarily assumes the role of leader, can exhibit the desired property of fault tolerance provided that suitable mechanisms are in place to assign the leadership role.

While early papers provided characterization of swarm robotics systems mainly as an analysis tool to encourage further research and give guidance for the design of new systems, with the increasing number of published studies describing actual implementations of robot swarms, newer surveys have been able to propose taxonomies where each category is represented by several examples of existing works. An extensive review of the state of the art in the mid 2000s is provided in [7], where existing works are categorized based on analytical modeling approaches, design of individual robot behavior, type of interactions between robots, and problems being addressed by a robotic swarm. Gazi and Fidan [8] focused on the aspect of controlling robot movement, dividing existing works based on how the robot dynamics is modeled (i.e. how control inputs map to position variations) and how robot controllers are engineered; in addition, a further classification is done on the problem dimension. Previous works have been