Swarm Robotics

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Summary. Swarm robotics is a novel approach to the coordination of large numbers of robots and has emerged as the application of swarm intelligence to multi-robot systems. Different from other swarm intelligence studies, swarm robotics puts emphases on the physical embodiment of individuals and realistic interactions among the individuals and between the individuals and the environment. In this chapter, we present a brief review of this new approach. We first present its definition, discuss the main motivations behind the approach, as well as its distinguishing characteristics and major coordination mechanisms. Then we present a brief review of swarm robotics research along four axes; namely design, modelling and analysis, robots and problems.

1 Introduction

Swarm robotics represents a novel approach to the coordination of large numbers of robots whose main inspiration stems from the observation of social insects [10, 9]. These insects, such as ants, wasps and termites, are known to coordinate their behaviors to accomplish tasks that are beyond the capabilities of a single individual; ants can carry large preys to their nest; termites can build large mounds from mud within which a desired level of temperature and moisture is maintained [5]. The emergence of such synchronized behavior at the system level is rather impressive for researchers working on multi-robot systems, since it emerges despite the individuals being relatively incapable, despite the lack of centralized coordination and despite the simplicity of interactions.

The term swarm intelligence [4] was originally conceived as a "buzz word" by Beni in the 1980s [3] to denote a class of cellular robotic systems [2]. Later, the term moved on to cover a wide range of studies from optimization to social insect studies, losing its robotics context in the meantime. Recently the term swarm robotics has started to be used as the application of swarm intelligence to physically embodied systems.

2 What Is Swarm Robotics?

Given the plethora of terms being used for describing different approaches used in multi-robot systems, such as "distributed robotics" or "collective robotics," the distinguishing characteristics of swarm robotics from the rest need to be clarified. This concern was first explicitly stated in [10] and a definition was provided as follows.

Definition 1. *"Swarm robotics is the study of how a large number of relatively simple physically embodied agents can be designed such that a desired collective behavior emerges from the local interactions among the agents and between the agents and the environment."[9]*

2.1 System-Level Properties

The system-level operation of a swarm robotic system should exhibit three functional properties that are observed in natural swarms and remain as desirable properties of multi-robot systems.

- **Robustness.** The swarm robotic system should be able to operate despite disturbances from the environment or the malfunction of its individuals. A number of factors can be observed in social insects behind the robustness of their operation. First, swarms are inherently redundant systems; the loss of an individual can be immediately compensated by another one. Second, coordination is decentralized and therefore the destruction of a particular part of the swarm is unlikely to stop its operation. Third, the individuals that make up the swarm are relatively simple, making them less prone to failure. Fourth, sensing is distributed; hence the system is robust against the local perturbances in the environment.
- **Flexibility.** The individuals of a swarm should be able to coordinate their behaviors to tackle tasks of different nature. For instance, the individuals in an ant colony can collectively find the shortest path to a food source or carry a large prey through the utilization of different coordination strategies.
- **Scalability.** The swarm should be able to operate under a wide range of group sizes and support a large number of individuals without impacting performance considerably. That is, the coordination mechanisms and strategies to be developed for swarm robotic systems should ensure the operation of the swarm under varying swarm sizes.

2.2 Distinguishing Characteristics

We will now summarize the main distinguishing characteristics of swarm robotics research (see [9] for a full discussion). First, the research should be relevant to the coordination of a swarm of robots. That is, the individuals should have a physical embodiment, be situated, and be able to physically interact with their environment. Moreover, the coordination mechanisms being studied should promise to be scalable for a wide range of swarm sizes.

Second, the robotic system being studied should be rather homogeneous. That is, the individuals that makes up the swarm should be rather identical, at least at the level of interactions. Coordination strategies developed for heterogeneous multi-robot systems, which consist of individuals that differ in their interactions due to their physical embodiment or their behavioral control, fall outside of the swarm robotics approach.

Third, the individuals should be relatively simple. The simplicity criterion in the definition does not directly refer to the hardware and software complexity of the robots, but is rather meant to emphasize the limitations in their individual capabilities relative to the task. The members of the swarm system should be relatively incapable or inefficient on their own with respect to the task at hand. That is, either (i) the task should be hard or impossible to be carried out by a single robot, and the cooperation of a group of robots should be essential, or (ii) the deployment of a group of robots should improve the performance and robustness of the handling of the task.

Fourth, the individuals should have local interaction abilities. This constraint ensures that the coordination between the robots is distributed, and that it is more likely to scale with the size of the swarm. Mechanisms that rely on global interaction capabilities are likely to be bounded by the bandwidth and the range of communication channel and may create unscalable coordination mechanisms.

2.3 Coordination Mechanisms

Studies in physical and biological systems have revealed that there are a number of coordination mechanisms that are at work in natural systems which can act as sources of inspiration for coordinating swarm robotic systems. Two of the main coordination mechanisms are: self-organization and stigmergy.

Self-organization, defined as "a process in which patterns at the global level of a system emerge solely from numerous interactions among the lower-level components of the system" [5], is common in natural systems. Studies of self-organization in natural systems show that an interplay of positive and negative feedback of local interactions among the individuals is essential [4]. In these systems, positive feedback is typically generated through autocatalytic behaviors; that is the change inflicted in the swarm-environment system by the execution of a behavior increases the triggering of the very same behavior. Such a positive feedback cycle is then counterbalanced by a negative feedback mechanism, which typically stems from a "depletion of physical resources" [4]. In addition to these mechanisms, self-organization also depends on the existence of randomness and multiple interactions within the system.

Studies of self-organization in natural systems often develop models that are built with simplified interactions in the environment and abstract behavioral mechanisms in individuals. The self-organization models of social insects and animals have already been used as inspiration sources since, in a sense, swarm robotics can be considered as the engineering and utilization of self-organization in physically embodied swarms.

Stigmergy, defined as indirect communication of individuals through environment, was first proposed by Grasse [13] to explain the coordination mechanisms behind the building of nests in termites. Stigmergic communication is common in many social insects; ants are known to lay pheromones on the ground to mark the paths to food sources and these pheromones act as attractants to be followed by ants. Stigmergy is of interest to swarm robotics since it provides a communication mechanism that is local, distributed and scalable.

3 Research Directions

During the last 4-5 years, interest in swarm robotics has been on the rise. The growing interest in this new approach is being fueled by the advances in mechatronics and other technologies, such as MEMS, which have started to shrink the size and the cost of robots for mass production and opened the way towards the deployment of large-scale swarm robotic systems in real-world applications. In the discussion below, we will provide a brief review of the swarm robotics studies in four categories; namely design, modelling and analysis, robots, and problems.

3.1 Design

The main problem of a swarm robotic system can be stated as follows: How should one design individuals, both in terms of their physical embodiment as well as their behavioral control, such that a desired swarm-level behavior emerges from the interactions among the individuals as well as between the individuals and the environment? This goal, which can also be considered as the "engineering of self-organization" in multi-robot systems, is a challenging task that is difficult, if not impossible, to solve in general terms. The studies within this category can be grouped into two: *ad-hoc* and *principled* approaches.

In *ad-hoc approaches*, behaviors of individual robots are designed manually to achieve a desired swarm-level behavior. In this approach, usually, though not always, behaviors of social insects are usually adapted to the robots at hand. This process implicitly assumes that the behaviors used as inspiration are observed at a certain abstraction level that captures essential parameters that need to be adapted to robots and should yet reproduce similar swarm-level behaviors.

In *principled approaches*, instead of designing a specific swarm-level behavior, a general methodology through which desired swarm-level behaviors can be used to build necessary individual behaviors is proposed or utilized. One such approach is the use of artificial evolution. Evolutionary methods have been successfully used to develop behaviors within the Swarm-bots project [12]. In particular, the SwarmBot3D [22], a physics-based simulation environment for simulating the Swarm-bots robotic system at different levels of complexity, was used. In most of these studies, simple feedforward or recurrent multi-layer perceptrons were used to encode the behaviors. The evolved behaviors in the simulation environment were later successfully transferred to the physical robot system.

3.2 Modelling and Analysis

The behavior of a swarm robotic system at the system level emerges from the interactions of its individuals. These interactions, determined by the behaviors of the individuals and the environment, are inherently probabilistic. As a consequence of this, the behavioral outcome of swarm robotic systems is not straightforward and modelling and analysis of the swarm is desirable for at least two purposes. First, for a desired task to be accomplished, and for a proposed behavioral design at the individual level, one needs to obtain guarantees for system-level performance. Second, in most ad-hoc approaches, although the overall composition of individual behaviors may be known, the optimal values of the parameters may remain unknown. Systematic experiments with physical robots are often difficult to perform. Moreover, they can provide only limited guarantees and little insight into the operation of the system. The models that can be used towards this end can be reviewed in three groups. In *sensor-based modelling*, the sensing and actuation of the individual robots as well as robot-robot and robot-environment interactions are modelled. This kind of modelling, mostly used for building realistic simulators of robotic systems, allows us to conduct experiments in simulation and yet to obtain results that are in agreement with the ones obtained from physical robots. Although this type of modelling is common in building robotics simulators [21], models to be used in swarm robotics require more fidelity at the level of inter-robot interactions. However, the building of these models is subject to the trade-off between realism and simplicity – models and interactions need to be realistic to be useful, and, yet, at the same time they must be as simple as possible for speed.

One simulation platform built with all these issues in mind is Swarm-bot3D [22], a physics-based simulator specifically developed for the swarm-bot robotic system. The simulator contained models of the s-bot robot at different levels of complexity and was verified against the physical robot. The simulator was used both to generate behaviors for different problems using evolutionary methods (see the previous subsection) as well as to systematically analyze the resulting system-level behaviors. These simulations, even at the lowest level of complexity, proved to be computationally intensive, and a system that can parallelize the simulations over a cluster of computers was developed in [29].

This type of modelling can be used as a constructive means to design behaviors, and provide insight into the behavior of the swarm through systematic experimentation.

In *microscopic* modelling, similar to the sensor-based approach, modelling is carried out at the individual level. The states of the individuals and the transitions among these states are modelled analytically. Such a modelling takes into account the characteristics of the environment, the physical embodiment and the behavioral control of the robots. Through such modelling, instead of simulating the individual interactions within the system, the model evolves the states of the individuals in time.

An excellent example of this type of modelling in swarm robotics can be found in [16]. The authors studied the stick pulling problem, in which two robots have to collaborate to pull sticks. They proposed a probabilistic model to represent the changes in the states of the robots. The model, which is essentially a set of rate equations, was built using the physical characteristics of the robots, such as the body shape and size of the robot as well as the placement and characteristics of the sensors, and the environment. It also took into account the behavioral design of the individual robots and used it as a basis for the transitions among the different states. Microscopic modelling was reported to be much faster than the sensor-based modelling and yet provided means to link the behavioral parameters to the system-level outcomes.

In *macroscopic modelling*, unlike in the previous two approaches, modelling is done at the swarm level. This type of modelling, in which the behavior of some average quantities that represent the state of the system is represented, is common in physics and chemistry. Contrary to sensor-based and microscopic models, macroscopic models need to be solved only once to obtain the steady state of the model. This allows one to find the optimum behavioral parameters without conducting any systematic experiments with the robots and provides a theoretical guarantee over the system-level behavior of the swarm. One example of such modelling can be found in [19]. In this study, an analytical macroscopic model of the stick-pulling problem, mentioned above, is proposed. In this model, the number of robots in a certain state as well as the number of unextracted sticks are used to represent the state of the system and the rate equations describing the change in them are derived. Using such a model, the authors are able to determine optimal parameters for the behaviors of the individual robots without making any systematic experiments.

3.3 Robots

One major research direction has been the development of physical swarm robotic systems since the building of a swarm robotic system takes more than gathering a number of copies of a generic robot platform. All the studies towards this end, have focused on developing mobile robots that are aimed to provide a research platform and are not intended for real-world operation.

Below we will discuss the extra requirements (or wish list from the researchers' viewpoint) expected from robots that would be used in swarm robotic systems.

- **Sensing and Signalling.** The main emphasis in swarm robotics is the interaction among the robots as well as the interaction of the robots with their environment, resulting in extra constraints for the robots to be used. In particular, (i) the interference among the sensing systems of the robots and the effect of environmental factors on them should be minimal, (ii) the robots should be able to distinguish other kin-robots (preferably as easily as proximity sensing), and (iii) the robots should be able to leave "marks" in the environment and be able to sense them (i.e. stigmergy). Furthermore, it is preferable that the robots are equipped with (or extendable to) some form of generic sensing capability to allow the researcher to test novel sensing strategies.
- **Communication.** Unlike in stand-alone robotic systems, communication by plugging cables into the robots is no longer a feasible option. Therefore the robots have to support wireless communication (i) between a console and the robots, to allow easier monitoring and debugging of algorithms on individual robots, (ii) among robots such as in the form of ad-hoc networks. The robots should also be programmable in parallel through a wireless communication channel since control algorithms are mostly the same for all the robots and programming the swarm as a whole would be a big time saver.
- **Physical Interaction.** The robots should be able to physically interact with each other and the environment since this is required by possible tasks such as self-assembly and self-organized construction.
- **Power.** The robots should have a long battery life. In most studies, the swarm may need to operate for a period that is long enough for the collective behavior to emerge, and the goal to be reached.
- **Cost.** The robots should be as cheap as possible, since, unlike stand-alone robots, they will be sold at least in groups of tens.
- **Size.** Size does matter in swarm robotic systems. The robots should be small enough not to make it necessary to increase the size of the test arena when experimenting with the system, and yet big enough not to limit the expandability of the robot or increase the cost of the swarm robots due to miniaturization in components.
- **Simulation.** Swarm robotic systems require realistic simulators. They are essential for speeding up the development of new control algorithms. Such simulators need to model the interactions between the robots as well as the interactions of the robots with their environment in a realistic way that is also verified against the physical robots.

Developing a single robot platform that would realize the whole wish list is a difficult, if not impossible, challenge. The design choices made regarding one requirement, such as size, pose additional constraints towards the reaching of other requirements, such as power and communication. In the rest of this section, we review some of the existing mobile robot platforms that are developed (or can be used) for conducting swarm robotics research and evaluate them based on the wish list stated above.

- Alice [6] is a small rectangular mobile robot with dimensions 22×21 mm. The robot, driven by two high efficiency SWATCH motors for locomotion, hosts a PIC16F877 microcontroller with 8K words flash EPROM program memory. Alice has four IR proximity sensors for obstacle detection and a short-range robot-to-robot communication module as well as an IR receiver for remote control. There are also a wide variety of modules, such as a linear camera, RF, or gripper modules, for extending its capabilities. Ten hours of autonomy are reported with two button batteries and 20 hours of autonomy is achieved with an additional LiPoly battery. The robot model is available in the Webots simulator.
- e-Puck [8] is a circular robot with a diameter of 70 mm. The robot, driven by two stepper motors for locomotion, hosts a dsPIC 30F6014A microcontroller with 144 KB program memory and 8 KB of RAM. ePuck has eight IR sensors used for measuring proximity to objects as well as ambient light. It has a speaker for audible feedback and three directional microphones which can be used for sound localization and a three-axis accelerometer. The robot has a color camera, a number of LEDs to signal or show its state and Bluetooth as the main wireless communication channel. The robots can be programmed via this Bluetooth module. e-Puck also provides an expansion bus and has optional ZigBee communication modules. Three hours of autonomy are reported using a 5 Wh Li-Ion battery. The robot model is available in the Webots simulator.
- Jasmine [23] is a small rectangular robot with dimensions 23×23 mm. The robot, driven by two small gear head motors for locomotion, has six IR sensors for proximity sensing and proximal communication. There is one powerful IR LED for detailed analysis of an object of interest and an IR communication module with host. Jasmine III has a modular design in which different sensing modules such as an ambient light sensor, a color sensor and different locomotion modules can be utilized. Two hours of autonomy are reported with LiPoly batteries. A simulator called LaRoSim was built for conducting experiments in simulation.
- s-bot [22] has a circular shape having a diameter of 116 mm. The robots have a locomotion sub-system consisting of both wheels and tracks which are driven by two DC gear head motors. s-bots are equipped with two grippers for studying problems such as self-assembly and coordinated movement. The robots have sensors of different modalities, including 15 IR proximity sensors for obstacle detection, four IR sensors below the robot facing the ground, torque sensors on the wheels, a force sensor between the base and the wheels, a three-axis accelerometer, an omni-directional camera and eight RGB LEDs for messaging between the s-bots. The robot is equipped with a 400 MHz custom XScale CPU board, 32 MB of flash

memory and 64 MB of RAM. A Wi-Fi module is used for wireless communication. The robots have one hour battery life (Li-Ion). A custom-made simulator called SwarmBot3D is developed to simulate s-bots at different levels of complexity.

- Swarmbot [28] is a square-shaped robot with dimensions 130×130 mm. It has four wheels on each side driven by two DC gear head motors. The robot is equipped with an ARM Thumb CPU, an FPGA, eight bump sensors, four light sensors and a camera. The Swarmbot uses ISIS, an IR system that can sense the range, bearing and orientation of other neighboring robots. Additional modules are linear CCD, magnetic food and swarm-cam emitters which can be utilized on demand. There is an RF communication unit for debugging and programming purposes. The battery life of the robots is not reported.
- Centibots [25] are modified versions of Pioneer 2-AT and Amigobots. An inertial navigation system to estimate coordinates of the robots, a SICK laser range finder for map building and a CCD camera used to extend the sensing capabilities of the robots. An on-board computer, USB web cam for intruder and object-of-interest detection are added to Amigobots. There is a Wi-Fi wireless ad-hoc network between robots. An autonomy of three to six hours is reported for Pioneers and two hours for Amigobots.
- Kobot [34] is a circular mobile robot platform having a diameter of 120 mm. Two high-quality gear head DC motors are used for locomotion. Kobot has a modulated IR system that can provide proximity readings from objects and distinguish robots from obstacles. The sensing system, which uses modulated IR signals, is robust against environmental lighting conditions and minimizes interference among robots. Kobots use the IEEE 802.15.4/ZigBee protocol as wireless communication channel. Through this channel, the robots in a swarm can be programmed in parallel. Ten hours of battery life is reported with LiPoly batteries. A custom-made physics-based simulator is available.

3.4 Problems

So far, swarm robotics research is mostly confined to the development of proof-of-concept studies in simulators or robotic systems operating in laboratory environments. Below we will describe some of the problems that have been addressed in swarm robotics research and describe some of the exemplary studies addressing them.

- **Aggregation.** Self-organized aggregation, the grouping of individuals of a swarm into a cluster without using any environmental clues, is a common behavior observed in organisms ranging from bacteria to social insects and mammals. In swarm robotic systems it can be considered as one of the fundamental behaviors that can act as a precursor to other behaviors such as flocking and self-assembly. In [11, 30], aggregation behaviors were developed for myopic robots, robots that can perceive only a small part of the whole environment, confined to a large arena, using evolutionary approaches as well as a probabilistic controller inspired by social insects.

- **Dispersion.** Self-organized dispersion can be considered as the opposite of aggregation and is of interest in surveillance scenarios. In this problem (see, for example, [27, 26, 28]) the challenge is to obtain uniform spreading of a swarm of robots in a space, maximizing the area covered yet remaining connected through some form of communication channel.
- **Foraging.** This problem is inspired by the behavior of ants which search for food sources distributed around their nest. In this problem, the challenge is to find the optimum search strategies that maximize the ratio of returned food to the resources committed (such as the number of individuals performing foraging or signalling strategies) in an environment. Different foraging strategies have been explored and analyzed [31, 17, 20], and models of foraging have been developed [18, 15].
- **Self-assembly.** This behavior is observed in ants, where they form chains through connecting to each other to build bridges or float-like structures to stay above water. The problem of self-assembly can be defined as the self-organized creation of structures through the formation of physical connections among a swarm of individual robots. Self-assembly has been studied in physical robots [7, 24] such that a desired self-assembled structure is formed.
- **Connected Movement.** This problem can be described as follows: How can a swarm of mobile robots, physically connected to each other, coordinate their movement such that the group moves smoothly in an environment and avoids environmental obstacles, such as holes, in a coordinated way. This problem has been studied in [32, 33] as part of the Swarm-bots project. In these studies, evolutionary approaches were used to evolve behaviors that can control a number of connected robots to avoid holes within the environment. The robots, which are physically connected to each other through their grippers, were able to sense the forces acting on their bodies through traction sensors and were able to detect holes underneath them.
- **Cooperative Transport.** Ants are known to transport large preys to their nest through coordinating their pushing and pulling actions. Such a coordination ability is obviously valuable for swarm robotic systems since it allows individuals to join forces, generating a combined force large enough to pull a heavy object. This problem is partially related to the connected movement, with the difference that it includes a passive object that needs to be transported. In [14] a recurrent neural network controller is evolved to obtain solitary and group transport behaviors in a physics-based simulator. The angular position of the goal (marked with a light source) and the distance as well as the angular position of the prey and a connection sensor indicating whether the robot is connected to other robots or not were used to control the motors of the robot.

- **Pattern Formation.** This is a rather generic term for the problem of how a desired geometrical pattern can be obtained and maintained by a swarm of robots without any centralized coordination. Pattern formation may refer either to geometric or to functional pattern formation. In geometric pattern formation, the challenge is to develop behaviors such that individuals of a swarm form a desired geometrical pattern, similar to the formation of crystals. In this task, the environment is assumed to be uniform and the focus is on the use of inter-robot interactions to create such patterns. In functional pattern formation, the pattern to be formed is dictated by the environment. In natural swarms, the surrounding of a prey by a group of predators or the formation of pulling chains by weaver ants can be considered as examples of functional pattern formation, where the geometrical shape or size of the patterns formed are partially determined by the task at hand.
- **Self-organized Construction.** This problem can be formulated as follows: How can a number of passive objects, randomly distributed in an environment, be clustered together by a swarm of robots. This problem, sometimes also referred to as "aggregation," has been one of first problems studied. Beckers et al. [1] studied how a swarm of physical robots can cluster frisbees spread in an environment, and showed that despite the lack of communication and signalling among robots, frisbee clusters can be obtained.

4 Conclusion

In this chapter we provided a brief review of swarm robotics as a new approach to the control and coordination of multi-robot systems. We stated the inspiration behind this approach, the desirable properties, and the requirements to clarify the defining characteristics of this approach in relation to other existing studies. Then we reviewed the studies in this new field, grouping them into four categories. Due to the lack of a good review article in this rather new field, we have opted to present the reader with an overall picture of the field in rather general terms and pointed out some of the most interesting studies.

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