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# Guest Editorial

Swarm robotics can be loosely defined as the study of how collectively intelligent behavior can emerge from local interactions of a large number of relatively simple physically embodied agents. Swarm robotics studies are often inspired by the observation of social insects—ants, termites, wasps and bees—which stand as fascinating examples of how collectively intelligent systems can be generated from a large number of simple individuals. Despite noise in the environment, errors in processing information and in performing tasks, and the lack of global communication system, social insects can coordinate their actions to accomplish tasks that are beyond the capabilities of a single individual: termites build large and complex mounds, army ants organize impressive foraging raids, ants can collectively carry large prey. Researchers soon realized that understanding the functioning of system-level characteristics of social insects, such as robustness against failures of individuals, flexibility to adapt to changes in the environment, and scalability over a wide range of group sizes, can provide insight on how to implement such desirable capabilities in multi-robot systems. Biologists, computer scientists and roboticists teamed up to transfer their knowledge of social insects behavior to the design of controllers for multi-robot systems. This combined, multidisciplinary effort gave birth to the field of research known as swarm robotics.

There already is a plethora of terms labeling different flavors of multi-robot research such as “collective robotics”, “distributed robotics”, “robot colonies”, with often vague and overlapping meanings. Here, we would like to put forward a set of criteria for distinguishing swarm robotics research from other multi-robot studies. First, the study should be relevant for the coordination of large numbers of robots. Therefore, studies that are applicable to the control of only a small number of robots and do not aim for scalability, fall outside swarm robotics. Second, the robotic system being studied should consist of relatively few homogeneous groups of robots, and the number of robots in each group should be large. That is, studies that are concerned with highly heterogeneous robot groups, no matter how large the group is, are considered to be less “swarm robotic”. Third, the robots being used in the study should have difficulties in carrying out or completing the considered tasks on their own, and their performance should improve when they cooperate. Note that this criterion does not impose any restrictions on the hardware and software complexity of the robots; however, the robots should be relatively simple and incapable with respect to the task considered. Fourth, the robots being used in the study should only have local and limited sensing and communication abilities. In fact, the use of global communication channels within the robot group is likely to result in unscalable coordination mechanisms and would therefore act against the first criterion mentioned above.

However, the reader should keep in mind that these criteria are not meant to be used as a checklist for determining whether a particular study is a swarm robotics study or not. Instead, they should be used as yardsticks for measuring the degree to which the term “swarm robotic” might apply. We would also like to warn the reader that this list humbly expresses our current understanding of this newly emerging term with the hope that it will act as a seed for further discussion which will promote a better definition of “swarm robotics”.

## Contributed Papers

This issue compiles a number of papers on the analysis and synthesis of swarm robotic systems, both from software and hardware points of view. How to design and implement distributed controllers for performing typical swarm robotics activities such as clustering objects, uniformly covering the environment, or coordinated motion, is the subject of most of the papers, while particular attention to the design principles behind a novel type of swarm robotic artifact, the *swarm-bot*, is the subject of Mondada et al.’s contribution. In the following we briefly summarize the contribution of each of these papers.

Wilson et al. study the sorting of different types of objects into an annular pattern by a swarm of robots. Their inspiration comes from the brood-sorting behavior of *Leptothorax* ants which are observed to sort their brood into circular patterns, based on the stage of the brood, inside the almost two dimensional rock crevices that they inhabit. Three different mechanisms are proposed for a swarm of minimalist robots to construct annular patterns similar to those observed in ants. The robots, both simulated and real, have sensors that allow them to avoid walls of the arena or other robots (without the ability to distinguish them from each other), and the ability to carry and drop single pucks, but with no explicit communication between each other. The first mechanism uses a clustering behavior which makes the robots drop pucks that they carry when they collide with other objects or with walls. This mechanism tests the idea that the differences in the sizes of the objects, not in the clustering behavior, is responsible for the segregation of the objects. The second mechanism, called "extended differential pullback", extends the first mechanism by using different durations between the collision and the dropping of the pucks based on the type of the pucks carried. The third mechanism adds a leaky integrator mechanism that adaptively changes the durations for different objects based on the recent history of objects dropped. Measures between the different aspects of the annular pattern are proposed, and the performance of the three mechanisms, implemented both on simulated and real robots, is analyzed.

Spears et al. propose a framework called "physicomimetics" for controlling large numbers of mobile agents to spread themselves uniformly over a region for the purpose of sensing or surveillance. In this framework, each agent senses and reacts to virtual forces, motivated by the natural physical laws, induced on itself by other agents. Spears et al. apply this framework for constructing various regular geometric patterns with simulated agents and analyze the effect of certain parameters of the control law on the overall behavior of the system. By using concepts from physics, such as potential and kinetic energies, they demonstrate how the well-studied analysis methods of physics can be utilized for a better understanding of their system. They also implement some of the behaviors on a small group of physical robots to verify the results obtained in simulation.

Agassounon et al. study the macroscopic modeling of collective aggregation experiments using fixed and time-varying robotic team sizes. They present a methodology on how a discrete-time macroscopic model of the collective behavior of a group of robots can be calibrated and built incrementally by verifying the match with the data obtained from a realistic, sensor-based, embodied simulator. A case study on the gathering of small objects in an arena by a group of robots endowed with a simple threshold-based algorithm regulating their activity is used to demonstrate the modeling methodology. Their results show that the models constructed make correct predictions about the dynamics of the system without using any free parameter and that a simple steady-state analysis achieves conclusions which go beyond intuitive reasoning.

Mondada et al. present a new robotic concept, called a *swarm-bot*, which is a self-assembling and self-organizing artifact composed of a swarm of *s-bots*, mobile robots with the ability to connect to and disconnect from each other. They discuss the requirements for such a robotic concept and present a detailed mechatronics description of the s-bot platform developed. Designed as a robust and versatile platform with good rough terrain mobility, the s-bot has two capabilities that set it apart from other mobile robot platforms. First, it is equipped with two grippers which can be used to grip objects for retrieval or other s-bots for self-assembly. Second, it has a traction sensor that can be used to measure the intensity of the pulling and pushing forces applied to the s-bot body. Mondada et al. also present physics-based simulation models of the physical s-bot at different levels of detail which are used in the studies presented in Dorigo et al.'s companion paper.

Dorigo et al. study the use of artificial evolution as a methodology to develop behaviors for the swarm-bot concept described above. Using physics-based simulation models of the *s*-bots implemented at different levels, as described in Mondada et al.'s paper, they evolve two fundamental behaviors for the control of a swarm-bot: aggregation and coordinated movement. The aggregation behavior requires a swarm of *s*-bots randomly distributed over a closed arena to aggregate and is essential for the swarm-bot since it is a precondition to self-assembling. They show that evolution is able to discover aggregation behaviors that can scale beyond the size of the group that the behavior was evolved for. The coordinated movement behavior allows a swarm-bot, which consists of a group of *s*-bots assembled together, to move in a coordinated way. It is shown that evolution can find scalable and generalizable strategies for coordinated motion by exploiting the *s*-bot's traction sensor mentioned above.

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