Reflections on the future of swarm robotics

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One-sentence abstract:

After two decades of research, it is time for swarm robotics to move out of the lab and to real-world applications, by leveraging heterogeneous and hierarchical self-organization.

Text:

Hardly a day goes by without a news story on how robots are conquering new grounds—a new application, a new environment, or a new level of performance. With few exceptions, these stories are about single robots, or just a few. Large groups of robots that coordinate and cooperatively solve a problem or perform a task remain a challenge. For the last two decades, overcoming that challenge has been the goal of swarm robotics, a research field that takes inspiration from natural self-organizing systems such as social insects, fish schools, or bird flocks, and attempts to recreate the emergence of collective behavior from simple local interaction rules. Its goal is to make multi-robot systems more robust, fault-tolerant, and flexible than single robots. The swarm robotics field finds its roots in a few seminal works published in the 1990s [1,2], but it started to grow significantly only after the year 2000, moving from a small domain featuring studies with a clear biological inspiration to a mature research field involving many labs and researchers worldwide.

As of today, robot swarms have been demonstrated in lab settings, frequently employing a small number of robots with compact size [3,4]. While technological innovations are pushing the boundaries towards ever smaller scales [5,6] and larger numbers [7,8], the path towards real-word applications is still long and arduous. Future robot swarms will exist and operate at many different scales: physical scale—from micro/nano robots to large ground, aerial, and aquatic robots; group scale—from a few dozens to millions of individuals composing the swarm; temporal scale—from swarms that display fast intervention and quick adaptation in a rapidly evolving environment, to robots that endlessly operate on months-long missions (e.g., on a distant planet); and spatial scale—from deployments in small confined spaces to missions across expansive unbounded fields. To design and manage such a wide range of possible systems, the key challenge will be to define a rigorous engineering methodology to program the individual robots so that the swarm as a whole acts as desired. This is no easy task, as the characteristics of swarms at different scales might require radically different approaches.

To grasp the variety of possible systems and applications, we suggest a few general design principles that remain valid across scales. First, the increasing complexity of swarm systems is such that their design cannot be accomplished solely by traditional approaches. The more robot swarms will be confronted with uncertain/unpredictable environments and will rely on intricate patterns of interactions, the more automated design methodologies will be necessary to obtain desired behaviors, as they can be employed to generate individual rules and evaluate them for their effects on swarm performance [9]. Machine learning with data-driven approaches becomes relevant whenever model-based solutions are too demanding, for instance when it is difficult to provide a precise model of the robot-environment interactions (e.g., due to complex

physical interactions among micro/nano robots, or due to unpredictable environmental dynamics as caused by underwater currents). To address self-organized control, the learned control architectures need to suitably integrate robot perceptions with information asynchronously received from (possibly hundreds of) peers and with memory of past states. Hybrid systems mixing model-free and model-based approaches will likely provide additional power, allowing to extract from data those aspects that are peculiar to the problem at hand (e.g., the response of a noisy communication medium characterizing the target application). Overall, automated methods hold the potential to liberate the designer from tedious trial and error or parameter tuning, and to better deal with the specific swarm scales required by the task, resulting in a general engineering methodology that can be suitably applied across different application domains.

Second, in order for robot swarms to perform ever more complex tasks, they will likely need to be heterogeneous, both in the hardware features and in the roles that individual robots can play within the swarm [4]. Physical heterogeneity can equip the robot swarm for tasks that require different hardware (e.g., fast moving drones for collaborative monitoring that cooperate with slow ground robots capable of modifying the environment). Behavioral heterogeneity can enable specialization (possibly via local learning mechanisms), and can underlie phase transitions that make the emergent collective behavior more flexible, adaptive to new conditions, and resilient to external perturbations. By abandoning the traditional homogeneity of hardware and control, flexibility and autonomy can be improved for small and large swarms, and operations expanded to address a wider spectrum of spatial and temporal scales. The additional dimensions introduced by heterogeneity (i.e., number of different roles and their proportion within the swarm) entail increased complexity in the design, and further motivate the exploitation of automated techniques.

Finally, robot swarms should include mechanisms to allow hierarchical forms of control beyond traditional pure self-organization. While the latter features a flat organizational structure, a hierarchical control approach assigns a few individuals larger responsibilities, flexibly adapting the hierarchy to the task execution demands [10]. In this way, it could be possible to more efficiently address task allocation, creation of task-oriented teams within the swarm, coordination of specific activities, or interaction with human users. Such hierarchies should however not be imposed from the outside. Rather, they should be themselves the result of self-organizing processes where some robots in the swarm may take leading roles depending on their specific characteristics, on the task being performed, and on the environmental conditions in which they are placed. In this respect, leveraging heterogeneity for robot swarm control—as advocated above—becomes even more consequential.

An (automated) engineering methodology for heterogeneous, hierarchically self-organized robot swarms is still missing to date, but is crucially needed to successfully transition from laboratories to real-world applications (see Table: "Timeline of the swarm robotics research domain"). We believe that the first deployments of these novel robot swarms will be in precision agriculture, infrastructure inspection and maintenance, and non-combat military applications. Precision agriculture features expansive fields where different types of robots can operate in parallel and can collaborate in heterogeneous teams to perform important actions such as weeding, fertilizing, or harvesting. Infrastructure inspection can benefit from the parallel operation carried out by large numbers of small robots exploring different areas and collectively identifying the presence of faults or damage. Non-combat defense operations will benefit from swarms that—by exploiting hierarchical self-organization—are difficult to shut down as they can flexibly re-organize and self-repair. Later in the next decade, aquatic surface and underwater robots will be mature enough to be deployed at sea, carrying out inspection, ecological monitoring, deep-sea exploration, and sustainable fishing. Robot swarms will then likely enter our cities, taking over service and entertainment tasks in a coordinated and self-organized way, while interacting with human workers and citizens. The use of robot swarms in space missions could come next, and could play a key role in large-scale exploration of the Moon and Mars by 2040.

Another possible future direction takes advantage of miniaturization and novel materials, possibly exploiting bio-hybrid solutions [11]. Soft-bodied robots enable novel forms of interaction and physical self-organization that can be exploited for unprecedented innovation. For instance, swarms of soft-bodied, biodegradable, millimeter-scale robots could be deployed in agricultural fields and coordinate to attack pests or harmful soil nematodes without damaging the crops, or in the sea to harvest microplastics by self-assembling into

macroscopic structures to be later collected by larger water-cleaning robots. The last—and more challenging—frontier would be medical applications, requiring extreme miniaturization and biocompatibility. Considering the current advancements [5,6], nanoscale robot swarms could be ready for testing by the mid-21st century. The successful deployment of robot swarms in these and other applications could pave the way for self-organized, bioinspired swarm robotics to become a mainstay of engineering in the second half of the century, possibly establishing itself as *the* standard way of designing complex robotic systems.

Table: Timeline of swarm robotics research
The most relevant milestones reached by swarm robotics research in the past, and projections of future developments. For each milestone, we indicate whether it entails innovation in software (SW), hardware (HW) or both.

1990-2000	A new paradigm is tested in which collaboration is emergent from simple (often bioinspired) behaviors. First experiments with robots demonstrating self-organization by means of indirect (stigmergic) and local interactions, with clear inspiration from swarm intelligence.	SW
2000-2005	The possibility to design robots cooperating in a swarm is extended to several new tasks, entailing manipulation of objects, task allocation, and tasks that strictly require collaboration in order to be solved.	SW
2002-2006	The *Swarm-bots* project demonstrates robot swarms capable of self-assembly, extending to physical forms of collaboration. Robots are capable of building pulling chains and large structures that can deal with terrain roughness.	HW & SW
2004-2008	Initial demonstrations of the automatic design of robot swarms by means of evolutionary algorithms, leading to the establishment of the evolutionary swarm robotics approach.	SW
2005-2009	First attempts at developing standard swarm robotics platforms (e-pucks), as well as miniature robots for swarm robotics research (alice, jasmine).	HW
2006-2010	The *Swarmanoid* project demonstrated for the first time heterogeneous robot swarms composed of three groups of robots: flying, climbing, and ground-based robots.	HW & SW
2010-2015	Different approaches appear for the design of robot swarms: advanced methods for automatic design (AutoMoDe, novelty search), design patterns, mean-field models, and optimal stochastic approaches.	SW
2014-2019	The "control without computation" approach develops swarm robotics behaviors with direct sensor-actuator mapping and no computation whatsoever.	SW
2016-2020	Swarms of flying drones become available for research, and decentralized solutions are studied and deployed.	HW & SW
2020-2025	*First demonstration of robot swarms capable of autonomously learning a suitable collective behavior for a given class of problems.*	*SW*
2020-2030	*First civil applications of robot swarms to precision agriculture and infrastructure inspection and maintenance. Military applications largely use non-combat unmanned drones to cooperatively accomplish information gathering and mission support actions.*	*HW & SW*
2025-2030	*Deployment of robot swarms for maritime and deep-sea applications, providing support to ecological monitoring, surveillance, and fishing.*	*HW*
2025-2035	*The entertainment sector uses robot swarms for interactive, immersive displays. Robot swarms are employed within the city, sharing the environment with operators and citizens. Robots will be insect- or pet-like devices that will collaborate to carry out service tasks such as cleaning, grazing, or delivering goods.*	*HW & SW*
2030-2040	*First space exploration mission on the Moon and Mars with miniature rover swarms, expanding the explored area and demonstrating on-site construction abilities.*	*HW*
2030-2045	*Millimeter-scale soft-bodied robot swarms enter agricultural fields for pest control, or in aquatic environments to collect microplastics.*	*HW & SW*
2035-2050	*Microscopic robot swarms are demonstrated for medical applications such as targeted drug delivery, and clinical trials with human subjects begin.*	*HW & SW*

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