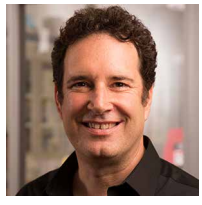
SWARM ROBOTICS

From individual robots to robot societies



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Most of today's robots operate in isolation. The coordinated motion of tens of robotic arms in manufacturing plants, hundreds of wheeled robots on warehouse floors, or thousands of drones in night skies is no different: Each of those robots is unaware of its conspecifics and obeys orders issued by a central computer that leaves no room for unexpected interactions or unsolicited initiatives of the individuals, not to speak of emerging collective behaviors.

Robotic and biological individuals, however, have limited energetic autonomy, strength, perception, and decision-making abilities when taken on their own. The transition from solitary individuals to societies has been described as one of the eight major transitions in the evolution toward higher levels of biological complexity (*1*). There is ample evidence from biology that self-organized groups of individuals with limited capabilities can act as super-organisms that are more robust to individual failures and more resilient to environmental change and that can carry out more complex tasks and build more complex structures.

Computer scientists have taken inspiration from principles of biological self-organization among interacting agents with limited capabilities, loosely labeled as swarms, to devise distributed and adaptive algorithms capable of solving complex, noisy, and changing computational problems (*2*). The more recent field of swarm robotics shares similar scientific roots and ambitions (*3*), as described by Robin Murphy in her article on swarm robotics in science fiction, but the physical instantiation of robots brings new challenges and opportunities that are specific to their scale of embodiment and situatedness. The four articles in this special issue address two aspects of robot swarms across scales: the role of physical interactions in robots of different dimensions and technical capabilities and the role of communication among several situated individuals in collective problem solving.

Boudet *et al.* demonstrate a premier example of such a transition across scales of hardware. They show a group of primitive robots that are individually capable only of simple sensing and motion. However, when a dozen or so of these robots are placed inside a flexible membrane, their motion becomes mechanically coupled. Together, they can cause the membrane to move, deform, and vibrate. This "superstructure" comprising the group of robots and their enclosing membrane can perform tasks that none of the individual robots could do alone. For example, the superstructure can carry objects, transverse obstacles as a group, or follow a light source. The transition from single robots to small, confined groups is one transition. We now wonder: What would happen if these superstructures themselves were then placed inside yet another, even larger, membrane? What would that super-superstructure be able to accomplish that the simpler superstructures could not?

Another example of a mechanical transition across scales is demonstrated by Ozkan-Aydin *et al.* A simple robot capable of locomotion is first demonstrated. Each robot uses compliant mechanisms as legs and joints. However, even with such appendages, each single robot is sometimes unable to traverse certain kinds of obstacles, such as wide gaps and protrusions larger than its own foot span, but when multiple robots join into a train, the larger super-robot can overcome obstacles greater than any individual robot. Again we ask: What if these super-robots themselves were combined into yet another, even larger, super–super-robot? With new kinds of connectors, such networked structures could likely be able to accomplish tasks that the simpler super-robot could not.

Communication provides an advantage to societies because it enables sharing of information that may not be locally available to some individuals. Talamali *et al.* consider a population of scouting robots that must identify as soon as possible the location of the best-of-*n* site, a problem that occurs in several applications of swarm robotics, such as search and rescue, mining, and environmental monitoring. The authors show that in physical environments, where the best site may gradually deplete or a new best site may arise, robots are more effective at locating the best site when they reduce the communication range, thus reducing the number of communication links, albeit at the cost of slower consensus reaching. The reduction of communication links is also convenient in physical robots where wireless communication packets that arrive simultaneously can be lost.

Castello Ferrer *et al.* instead address the problem of security in robot swarms where each robot is a vulnerability point, thus producing higher risk for larger swarm size. For example, one or few robots may be stolen, and the mission secrets revealed, or may be hacked to communicate wrong information to other robots, thus jeopardizing the entire mission. The authors propose the use of Merkle trees, a form of hash-based tree structure, to share information among untrusted parties that is used in blockchain algorithms. The idea is to give each robot only the template of the mission without the detailed sensory-motor actions, whose hash links must be

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discovered and communicated through a distributed verification-proof process by the robots. At this stage, the method described by the authors is applicable only to sequential missions, but it paves the way for a new stream of cybersecurity research in robotics that will become increasingly important when robotic swarms will be deployed in the real world.

The robot societies considered in these articles are homogeneous: They all have the same, or similar, physical characteristics and control algorithms. This means that the range of emergent collective behaviors is limited by the sensory and actuation domains of the individual robots, and some robots may be idle when a task is performed by other robots. More complex behaviors and efficient use of the group members could be achieved by heterogeneous societies made of robots with specialized perceptual, motor, and control systems that are capable of adaptive division of labor.

Looking forward, it is clear that if robotic systems are to continue to perform increasingly complex tasks, they must—like any other organism on Earth—transition from single individuals working alone or under centralized control to groups of self-organizing and loosely coupled teams of individuals working together. Single cells transitioned to multicellular organisms about 600 million years ago, ushering one of the most profound advances of life on Earth. More recently, we—*Homo sapiens*—transitioned from a relatively insignificant ape on the African savanna to become the most dominant lifeform on Earth by harnessing the ability to communicate and work together using loosely coupled intersubjective realities (*4*). Whatever robots learn to do, they should also learn to do it hierarchically.

– Dario Floreano and Hod Lipson

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