SOFT ROBOTS

Robot swarms meet soft matter physics

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Principles of soft matter physics can be leveraged to develop swarms of active robots with unique properties.

What is a robot? Most familiar to us—from factory robot arms to legged locomotors—are individual robots traditionally composed of rigid components. Such devices are typically confined to controlled environments. Once such a robot's design is in place, neither its morphology nor its construction changes—a motor remains a motor and an arm remains an arm. In a modification of this paradigm, the past several decades have seen researchers discover that robots constructed from mixtures of traditional hard components and "soft" materials like elastomers can display capabilities and complexity that result from the ability of materials to undergo large deformations. However, such devices are still largely unchangeable—once a soft robot crawler has been constructed, it remains in its current morphology.

Suppose we broaden our definition of a robot to anything that can function in the real world to perform work via movement, manipulation, and so on. Now, we might consider a swarm of robotic bodies to compose a single robot, that is, a collective that takes on a new character or capabilities that differ from the character or capabilities of its components, an example of "more is different" à la condensed matter physicist Philip Anderson. Most research in swarm robotics has focused on dilute collections of agents that do not physically interact and thus can be viewed as a collective that can act as a gas (or fluid) (*1*). Analogous literature has developed in physics in the form of "active matter," which is focused on the statistical mechanics and hydrodynamics of large numbers of "active" (driven) agents at relatively low density (*2*). In both fields, many bodies flow while undergoing short-range interactions, and thus, hydrodynamic concepts can be used/modified to direct global dynamics.

There have also been efforts to make and understand "swarms" at higher density; for example, the field of modular robotics develops groups of strongly mechanically interacting agents (*3*). These dense collectives tend to have regular connections between entities, thus displaying more solid-like properties and potentially limiting rapid reconfigurability. This feature has recently also appeared in the physics literature in the form of (for example) "active solids" (*4*).

Between the extremes of dilute swarms and regular aggregates, robot collectives encounter properties of matter between fluid and solid, those of so-called "soft matter" like glasses, polymers, liquid crystals, and sand. Soft condensed matter as a field of physics originated in the 1960s largely via the pioneering efforts of Pierre Giles de Gennes and Sam Edwards. This field brings contributions from engineering and materials science as well as physics and augments traditional condensed matter physics with principles of mechanics and flow of materials that can undergo large strains. A key feature of soft materials that allows such diversity of mechanical behaviors is that their structure is not typically crystalline, but amorphous. What began as a field largely studying polymeric systems has evolved into efforts to discover properties and principles of systems as diverse as origami, knits and knots, mechanical metamaterials, and granular media.

In their recent paper, Saintyves *et al.* (*5*) propose that principles from soft matter, specifically aspects of ensembles of particles (granular media), can be leveraged to develop a swarm of active cohesive robots that can rapidly change shape, material properties, and even locomotor strategy (Fig. 1). In this way, the individual robots form a new "robot" whose properties emerge from simple, often uncoordinated interactions among individuals. To do so, the authors have developed what they term "Granulobots," a few centimeter-scale cylindrical robots with toothed outer surfaces. The robots each contain an internal actuator that rotates an off-center magnet around the circumference and a second magnet that rotates freely along the circumference as well. When magnets from two robots come close, the robots attract and can roll without slipping against each other. The robots also contain controllers that can monitor the angular position of the actuated motor as well as the accelerations and rotations of the robots.

Both open- and closed-loop algorithms result in a diversity of fascinating behaviors even in a relatively small collective (~10 robots). These include swarms that can flow actively or passively, deform like viscoplastic/elastic solids/fluids, and self-oscillate. Importantly, these states can be of use; for example, an actively flowing aggregate spontaneously deforms around an obstacle to resist being impeded in its locomotion, and a solid-like aggregate can resist deformation with either fluid- or solid-like features. Importantly, no single robot has the material properties of the collective, and functional solid- and fluid-like properties emerge from relatively simple control schemes followed by each robot.

The emergence of function in collectives is an important theme in organismal and robophysical collectives. In recent years, studies have demonstrated such features in cohering and entangling active granular systems. For example, ensembles of fire ants can form floating "living materials" (*6*) whose mechanical properties can lead to functional benefits. Ensembles of elongated worms (*7*) can form "materials" that can prevent desiccation of the collective, generate large internal stresses, and even locomote without a fixed "engine." At a different length scale, organisms like the slime mold *Dictyostelium discoideum* form functional entities (slugs and fruiting bodies) from collections of cells. In robotics, such ideas have been developed in studies of "supersmarticles" in which enclosed collections of individually immotile but shape-changing robots could achieve stochastic phototaxis of the collective via collisional interactions of a smarticle "fluid" (*8*). Related to the work of Saintyves *et al.* is that of Li *et al.* (*9*), who introduced a system of even simpler active cohesive granular robots termed "BOBbots" (to honor granular media pioneer Bob Behringer) that demonstrated gas-, fluid-, and solid-like properties and could spontaneously aggregate and swarm to form a solid-like (but malleable) material to transport objects.

These advances present tantalizing possibilities for future connections to soft matter

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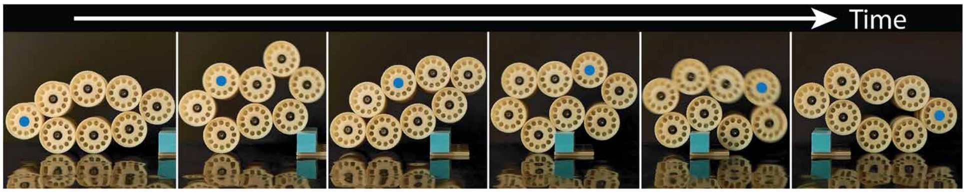

Fig. 1. Locomotion of Granulobot. An image showing the locomotion of Granulobot over an obstacle.

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physics, which has focused on how a system's properties are determined not only by its composition but by its geometric structure, suggesting a rich range of functionality for reconfigurable robot collectives. In metamaterials research, repeated structural motifs can lead to novel mechanical responses (*10*). Borrowing concepts from broad areas of physics can lead to new types of deformation originating in topological states or conformal symmetry (*11*). Metamaterials research is inspired by the maxim "The material is the machine," (*12*) in which the desired mechanical response can be achieved not by macroscopic assemblages but by repeated microscopic structures. Dense robot collectives seem to follow an inverted principle: "The machines are the material," in which individual robots can come together to form and reform new and powerful structures [a "smart active matter" (*13*)] in ways previously achieved only by biology.

Thus, as typified by the work of Saintyves *et al.*, leveraging the physics of soft matter can simplify control in dense swarms, leading to reconfigurable, resilient emergent "robots." Reciprocally, these physics disciplines can inherit insights from robotics, which can lead to new systems to analyze and search for principles of active (and potentially) living systems. Concepts in soft matter are often scale agnostic: Principles of fluid and solid-like aggregates can be used at the macroscale (as in the current study) and potentially at the microscale, as in the recent work on "colloidal" robots (*14*). To provably control these systems, the inclusion of advances by computer scientists [via concepts from distributed algorithms (*14*)] will be critical to go further and generate "algorithmic matter."

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