

From control to collective intelligence

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Drones have rapidly moved from technological curiosities to highly capable autonomous systems, transforming fields as diverse as environmental monitoring, infrastructure inspection, entertainment, and, increasingly, warfare. What makes them so compelling is not merely their mechanical sophistication, but the broader scientific questions they raise.

At first sight, the challenge seems to be one of control. How do we make a flying machine perceive its environment, make decisions, and execute them reliably? As Carlo Bosio and Mark Mueller illustrate in this issue, autonomy is already a remarkable systems-engineering achievement, where mechanics, sensing, computation and control must be carefully integrated. But as soon as one moves from individual drones to swarms, the problem changes in nature.

As stressed by Gábor Vásárhelyi centralized architecture offers predictability, global optimization, and clear human oversight. Such systems have demonstrated extraordinary capabilities, from coordinated drone shows involving thousands of units to highly reliable industrial deployments. Yet nature teaches us a very different lesson. Fish schools, bird flocks, insect swarms, or human crowds do not rely on a central planner. Coordination emerges from local interactions, imperfect information, and decentralized decisions. As explored in this issue, the scientific community is increasingly drawing inspiration from such natural systems to design drone swarms capable of robust, decentralized coordination.

The contrast between centralized and decentralized control is intellectually stimulating, but perhaps it is not the deepest one. Both remain, ultimately, paradigms of control. Whether decisions are imposed from above or negotiated locally, the behavioural rules remain fixed by design. The next conceptual leap may lie elsewhere: in systems able not merely to follow prescribed rules, but to modify them through experience. This is where social learning enters the picture.

In many biological systems, information propagates socially: through imitation, communication, shared environmental traces, or collective inference. A group becomes more capable than its members because experience becomes a distributed collective resource. The question is no longer simply how to coordinate agents, but how to allow a collective to adapt, discover, and improve under uncertainty. In such systems, intelligence is not localized in a central controller, nor entirely within each unit. It emerges in the interactions themselves.

Once phrased this way, the implications go far beyond drones. The same conceptual questions now arise across material science, robotics, and complex engineered systems. Can a material adapt its function rather than merely execute a design?

Physicists may find these questions familiar. After all, our discipline has long sought to understand how collective behaviour emerges from local interactions. From this point of view, collective intelligence is a form of collective behaviour that emerge from social interactions.

This opens extraordinary possibilities. Adaptive robotic collectives, intelligent metamaterials, autonomous infrastructures, responsive biohybrid systems: the prospect is not simply to build machines that act, but systems that become.

And yet, in the case of drones, this promise comes with an unavoidable shadow. The same technologies that may improve disaster response, environmental exploration, or collective logistics are also rapidly reshaping modern conflict. Autonomous swarms can extend human capabilities—but also amplify destruction, reduce accountability, and shift critical decisions ever further from direct human control. As often in physics-driven innovation, the scientific questions are fascinating, the technological possibilities immense, but the societal consequences impossible to ignore. ■