Collective Motion: from Active Matter to Swarms in Natural and Engineered Systems

Cristian Huepe

Abstract:

Animal groups, such as bird flocks, fish schools, or insect swarms, often exhibit complex, coordinated dynamics that result from individual interactions. The elegance of their collective motion has long fascinated observers, who see a level of coordination that is hard to conceive without centralized control. A current challenge of complexity research is to understand how simple individual rules can achieve such synchronized, scalable, robust, and fast-responding behavior, and to explore its role in natural and artificial systems.

In recent years, there has been growing interest in the study of collective motion, driven by the convergence of new analysis tools, models, experimental data, and applications in biology and engineering. Biological studies on collective motion have benefited from new tracking techniques that allow the simultaneous monitoring of individual trajectories in large groups of moving microscopic or macroscopic agents; swarm robotic systems composed of multiple robots that coordinate to achieve a given task are being built in several engineering research labs; many numerical algorithms displaying collective motion have been introduced; various modeling approaches, such as using hydrodynamic-like equations to describe multiple self-propelled agents as a fluid, are being explored. However, despite this progress, we are only beginning to understand the many rich features displayed by these systems: the role of their nonstandard interactions and dynamics is still poorly understood and the debate is still open on the benefits of collective motion for sensing and decision-making.

In this talk, I will overview current work in the fast-growing field of collective motion and describe some of our own contributions to different aspects of this research. I will first provide some historical background on how the biological, engineering, and complex systems perspectives converged towards a common research effort and outline the main challenges that remain in each discipline. This overview will also include other areas of application, in addition to the analysis of groups of moving biological agents or swarm robotic studies described above, such as swarm intelligence optimization algorithms, pedestrian and vehicular traffic, computer graphic swarm animations, and even multi-satellite formation control. I will then describe the following three specific contributions in which I have been involved:

1. A data-driven analysis of social interaction forces in fish schooling experiments: We used large datasets from recent experiments developed with Prof. Iain Couzin and his group at Princeton University to unveil specific effective ‘social’ interaction forces and collective decision-making processes in a well-controlled experiment with up to one thousand golden shiners.
2. An adaptive-network approach that focuses on the switching interaction or communication network that underlies collective motion processes: This approach allows us to explore the properties of these systems in an analytically tractable way. It is based on a toy model developed with Dr. Thilo Gross and his group at the Max Planck Institute in Dresden to capture the basic components of a generic swarming transition.
3. A new active-solid model that explores an alternative mechanism that produces collective motion: This model includes strong attraction-repulsion interactions but no explicit alignment rules. It achieves collective polar or rotational motion through a novel elasticity-based mechanism.

I will conclude by discussing some of the common features that make collective motion systems interesting and unique. Conceptually, an important unifying factor is that all these systems have their

energy injected at the smallest scales, thus requiring self-organization before coherent work can be produced. Furthermore, most of them display a similar nontrivial coupling between the individual state of each agent (its heading direction) and its interactions with other agents, which suggest that a common description may be possible. A final common aspect of the current research in this field is that it has been fueled by new experimental data and the expectation of a number of future applications.