Network analysis of collective motion

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Collective motion is characterized by coordinated behavior between the individuals of a group [1]. For instance, in ecology, flocks with tens of thousands of birds have been observed to fly in unison at high speeds and execute complex collective maneuvers. How the individuals communicate and change their behavior to sustain such organized motions is still unclear [2]. A common approach to describe these phenomena is to define differential equations of the position, the speed and the direction of each individual according to time. In these equations, the laws of motions typically depend on the distances between neighbors, which is considered to be a crucial factor for ordered motion [1, 3]. While the (distance-based) connections between individuals in these collectives necessarily form a *network*, few studies have taken full advantage of Network Science tools to systematically unravel the interaction patterns that shape collective motion in ecology. Since Network Science has been used to characterize a wide range of complex systems [4], it appears that a Network Science of Collective Motion is a promising venue for further insights.

We propose a method to extract a temporal network from the positions of collectively moving individuals. We focus our study on motion that characterizes flocking (i.e., where the individuals' positions and velocities are closely aligned). To do this, we simulate a series of self-propelled collectives of flocking particles, using a model known as the Couzin model [3]. This produces time series of positions for each individual in the collective. Then, at each time step, t, we compute the distances between each pair of individuals, from which we create an adjacency matrix, A_t, that describes the temporal network at each slice in time. With the dominant eigenvectors of A_t for all t, we investigate which individuals are more or less central in the network. We found that there is only a specific group of individuals that share dominant centrality according to time [FIG. 1. (a)]. This suggests that there is a *core* of individuals that interact with more neighbors than the individuals in the *periphery*. To validate this intuition, we obtain the backbone of the temporal network by averaging A_t across time and using the method proposed in Ref. [5] [FIG. 1. (b)]. Interestingly, the degree distribution of the backbone network [FIG. 1. (c)] clearly distinguishes two groups of individuals, one with a mean degree of 50 and another with a mean degree of 90. These observations suggest that there is a strongly connected core of leading individuals paving the way for close followers in the flock. These results stimulate further exploration of network structures in real collective motion time series.

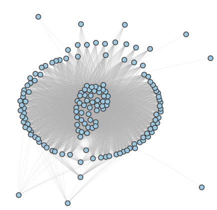

FIG. 1. (a) Index of the individual with optimal eigenvector centrality value in the network A_t for each time t. The average maximum eigenvector centrality value according to time is 0.12 and the average minimum eigenvector centrality value according to time is 0.010. We observe that only some individuals, i.e., those indexed from 0 to 75, share the maximum centrality value for $t \in [0, 2000]$. (b) Remaining fraction of nodes (blue curve) and links (orange curve) according to different values of backbone threshold . The backbone threshold $= 0.25$ (gray dashed lines) is selected to ensure that the thresholded network had the same number of nodes as the original. This produced a network with $N = 150$ nodes and $M = 4453$ links. (c) Degree distribution of the backbone network. (Inset) Temporal network backbone, using a Kamada-Kawai layout.

[1] T. Vicsek and A. Zafeiris. Collective motion. *Phys. Rep.*, 517:71–140, 2012.

[2] A. Attanasi, A. Cavagna, L. Del Castello, I. Giardina, T. Grigera, A. Jelic, S. Melillo, L. Parisi, O. Pohl, E. Shen, and M. Viale. Information transfer and behavioural inertia in starling flocks. *Nat. Phys.*, 10:691–696, 2014.

[3] I. Couzin, J. Krause, R. James, G. Ruxton, and N. Franks. Collective Memory and Spatial Sorting in Animal Groups. *J. Theor. Biol.*, 218:1–11, 2002.

[4] M. E. J. Newman. *Networks*. Oxford University Press, second edition, 2018.

[5] M. Á. Serrano, M. Boguñá, and A. Vespignani. Extracting the multiscale backbone of complex weighted networks. *Proc. Natl. Acad. Sci. U.S.A.*, 106:6483–6488, 2009.