Leader-Follower Relationships from Trajectory Data – a Case Study

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Abstract

The leader-follower phenomenon is natural for many mobile objects acting collectively. It is possible to find the leader of such collective motion from trajectory data and use it to understand the motion pattern of the group. This work proposes a technique for detecting leader-follower relationships from trajectories of mobile objects, and represents them as a graph sequence. We apply this method to analyze the leader-follower behavior of a herd of cows based on their GPS traces.

1 Introduction

Massive amounts of mobility data are becoming widely available through vehicles, mobile phones and GPS devices in the form of trajectories. In many cases, a mobile object moves by following others in the neighborhood, such as groups of people in a shopping mall and animals traveling in herds. The action of one object, including accelerating, stopping or changing directions, can propagate to its followers, causing the *leader-follower phenomenon*. Distinguishing leaders from followers for a certain group action provides us an abstraction of the complex group motion. It is also useful for determining the social roles of individual objects through their leader-follower relationships.

In most real-life trajectory data, it is rare to have a stable assignment of leaders and followers. One object may be followed by different objects at different instances in time. The action of following another is also limited by spatial constraints such as the visibility of the environment, and temporal constraints such as time delay between the leader action and the follower action. Disentangling leader-follower relationships that meet these constraints at a local, transient-level is the goal of this project.

2 Related Work

Leader-follower interactions of mobile objects based on local information have been frequently studied in flock simulation and multi-agent robot control theory. Classical applications include formation coordination of spacecrafts [2] and unmanned vehicles [3].

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Detecting leader-follower relations from observed trajectories is the inverse problem of motion modeling. Correlation analysis has been used for detecting coordinated motion patterns [5]. However, it alone can not distinguish between a leader-follower pair. The work by Andersson et al. [1] defines a leadership pattern based on the geometric arrangement of mobile objects over consecutive time-steps. Our method employs both geometric rules and motion correlations to compute local leader-follower relations.

3 Our Results

We consider n trajectories each describing the motion of an object moving in a 2D terrain. Let M be the number of frames (a.k.a. time-steps) in each trajectory. For each $1 \leq j \leq M$, denote by $S_j = \{x_{i,j} \in \mathbb{R}^2,\ i = 1, \ldots, n\}$ the positions of mobile objects in Frame j. Let $v_{i,j}$ be the approximated velocity of the ith object in this frame.

3.1 Defining the *follow* relation

Since leader-follower relationships emerge and disappear over time, we subdivide the trajectories into many overlapping time intervals of uniform length. For each interval of m frames, we find pairs of objects involved in a leader-follower relationship.

Let $N_k(i, j)$ be the set of k nearest neighbors of $x_{i,j}$ in each S_j. We consider *follow*, an asymmetric relation between i and i' in $N_k(i, j)$ with both spatial and temporal constraints. The spatial constraint restricts i' to be within the visible range of i. We approximate this constraint by partitioning $N_k(i, j)$ with a line l perpendicular to $v_{i,j}$. The *constrained k-neighborhood of i*, $CN_k(i, j)$ is the space on the same side of l as $v_{i,j}$. (See Figure 1.) In practice, we use a variation of this constraint that tolerates approximation errors.

The temporal constraint restricts the velocity of i to be similar with the velocity of i' within a few frames of delay. Denote the ith velocity sequence over frames $t_1 \ldots t_m$ by $\{v_i\}_{t_1}^{t_m} = v_{i,t_1}, \ldots, v_{i,t_m}$. We express this similarity as the *d-shifted correlation* between velocity sequences of i and i':

$$corr_{[t_1,t_m]}(i, i', d) = corr\left(\{v_i\}_{t_{d+1}}^{t_m}, \{v_{i'}\}_{t_1}^{t_m-d}\right)$$

We choose d, the number of delayed frames, to be the value that maximizes the d-shifted correlations of all

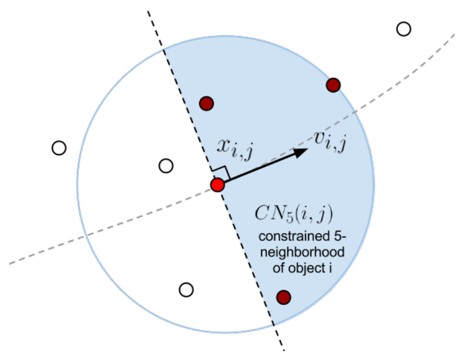

Figure 1: Constrained neighborhood of i.

(i, i') pairs, while satisfying the spatial constraint in the defined time interval. We write this relation formally:

Definition 1 (follow) *Given trajectories of objects i and i' during a time interval $[t_1, t_m]$. Let k and d be as previously defined. For any $0 \leq r \leq 1$, i **follows** i' during $[t_1, t_m]$, if $x_{i',j} \in CN_k(i,j)$ for all $t_1 \leq j \leq t_m$, and $corr_{[t_1,t_m]}(i,j,d) > r$, where r is the **correlation cutoff value**.*

The *follow* relationship induces a directed graph $G = (V, E)$ on all n objects in the group during time interval $[t_1, t_m]$. By constructing the leader-follower graphs for all time intervals, we obtain a sequence of graphs that show how the leadership and the internal structure of the group change over time.

3.2 Case study: leader-following behavior in cows

The spontaneous movement of group-living animals exhibits the leader-follower phenomenon [4]. Besides animal behavior research, the problem of determining leaders of herd movement from sensor data also has practical applications in cattle management.

Our dataset contains the trajectories of $n = 34$ cows recorded by mount-on GPS units during a 2-day experiment ($M = 90655$). We computed the leader-follower graph sequence with $k = 7$, $r = 0.7$, and time intervals of 30 frames with 10-frame overlaps. Figure 2 shows an instance of the graph when the group is making a clockwise turn.

We observed sudden increases in the number of followers for individual cows during fast and cohesive movements. In addition, cows with the most number of followers alternate over time. It confirms the statement in [4] that the leader-follower relationship in cattle's spontaneous group movement has little correlation with the dominance status, which is a much more stable assignment within a herd.

4 Conclusion

The above case study shows that our algorithm discovers reasonable leader-follower relationships in practice.

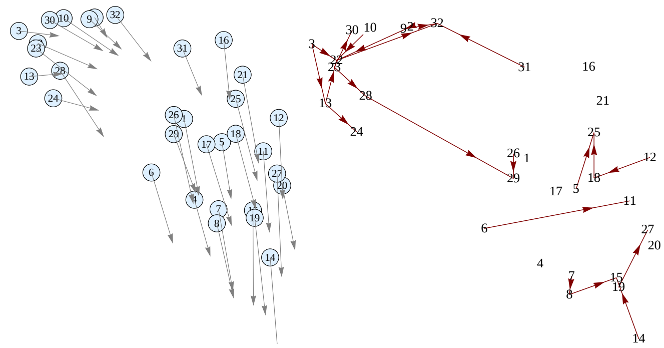

Figure 2: Left: A snapshot of cows. (velocity vectors are shown as scaled arrows.) Right: The corresponding leader-follower graph.

For the future work, we will consider using an adaptive correlation cutoff parameter r. This will improve the granularity of the algorithm when trajectories vary in speed and cohesiveness. For instance, we could consider all possible values of r, and select leader-follower pairs that persist through a long range of r values.

We are also interested in finding the time when critical changes to the leader assignment occur. This idea is related to the evolution of spatial-temporal graphs, which has been studied in areas including computational geometry, information theory and computational topology. Nevertheless, very few have worked on graphs induced by causal relations, such as the leader-follower interaction. Solving this problem allows us to associate a follower community to a leader with a precise lifespan. It also creates a natural way to cluster mobile objects and segment their trajectories simultaneously.

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