25th International Congress on Modelling and Simulation, Darwin, NT, Australia, 9 to 14 July 2023
mssanz.org.au/modsim2023

Modelling collective states and individual-level interactions in small sheep flocks

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Abstract: Flocking sheep can produce impressive visual displays with movements that are synchronized and coordinated, allowing the group moving as a cohesive unit. These movement patterns emerge without a central point of control and are shaped by the interactions and decisions of the individuals participating in the flock. Collective movement serves a functional purpose, as it allows the flock to move efficiently and stay together, providing protection from predators by diluting the risk of attack to the individuals. This study builds upon previous work (Ginelli et al., 2015) by investigating the emergent collective movement properties exhibited by small flocks of sheep and inferring the underlying interactions that drive the observed emergent behaviours. Data was collected from three randomly selected flocks of four individuals using collar-mounted, Real-Time Kinematic (RTK) satellite navigation receivers running at a sample rate of 10Hz. The flocks were left grazing pasture un-interrupted and isolated from other sheep across the observation period of 1-day each. The resulting dataset contains a mixture of flock-level behaviour including actively grazing/foraging and marching between locations in the pasture. The data was transformed using the Universal Transverse Mercator (UTM) coordinate system and the polarisation and angular momentum order parameters (which measure the degree of alignment between individuals and group rotation respectively), along with the mean group speed and the area of the flock's convex hull were calculated for each time step to characterise the emergent group-level behaviour. The changes in speed and direction of motion for all possible pairs of sheep were calculated at each time step, breaking them down into component form. This method has been extensively detailed in previous studies (Mudaliar and Schaerf, 2020) and is applied here to map the social forces that govern each individuals motion in response to the relative position of flock mates. An agent-based collective motion model was then developed to simulate that movement dynamics of a small flock in the grazing state. This model captures a range parameters that control individual motion, such as movement speed, maximum turning speeds and distances over which individuals experience social forces (e.g. repulsion/attraction). A sensitivity analysis was conducted to understand the impact of these parameter on the emergent properties.

The initial findings from this study show that the flock exhibits two key collective states. The flock adopts either a highly ordered *marching* state where the flock moves at a higher mean speed (ranging from 0.5 through 1.5msec^{-1}) with high polarisation/low angular momentum or a *grazing* state with a lower mean group speed (ranging from 0.0 through 0.5msec^{-1}) and a lower degree of collective order with a wider distribution of polarisation/angular momentum values. The grazing state is characterised by a pattern of expansion and contraction of the convex hull area, where individuals move away from each other while foraging and then spontaneously collapse back to a compact flock. When in the marching state, a flock remains relatively compact. Analysis of the changes in speed and direction show that an attraction force drives the emergent trends in both states. This force appears to be weaker and less consistent in the grazing state to facilitate exploration. These results demonstrate the trade-off between the need to forage and explore in the grazing state, and the survival imperative of remaining part of a cohesive group. The agent-based model developed was able to replicate the group-level emergent behaviour and social forces observed in the data. The sensitivity analysis on the model revealed that interaction ranges between individuals plays a key role in shaping the group-level emergent properties.

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Keywords: *Sheep flocks, collective motion, interactions, complex systems*