Supplementary for Impact of Individual Defection on Collective Motion

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Abstract. Collective motion modelling has attracted significant attention for gaining insights into the mechanisms of collective behaviour and its potential to inspire control strategies for swarm robotics. Most of the existing models assume that individuals within a group strictly adhere to the interaction rules. However, individuals in artificial and natural collectives could occasionally fail to follow the interaction rules, which is distinct from noisy actions. This study analyses how the presence of individuals who occasionally defect affects the ordered phase of the group during collective motion. Using Monte-Carlo simulations, we study two collective motion models, a non-spatial and a spatial model. In the non-spatial model, increasing the individuals' probability of defecting increases both the time required by the agents to reach motion coherence (group motion polarisation) as well as the average energy cost of the group to maintain such motion coherence (average energy consumption at high group motion polarisation). In the spatial model, there are conditions where agents with a given probability of defection can simultaneously reduce the time required by the collective to get highly polarised and the average energy cost in the polarised state. These findings not only enhance our understanding of probabilistic defective behaviour in biological systems but can also inspire innovative, efficient, and controllable approaches in swarm robotics.

1 Defection in the Pairwise Interaction Model

Note that in Figure 1, the polarisation time required for agents to get polarised increases with increasing probability of defection, P_D.

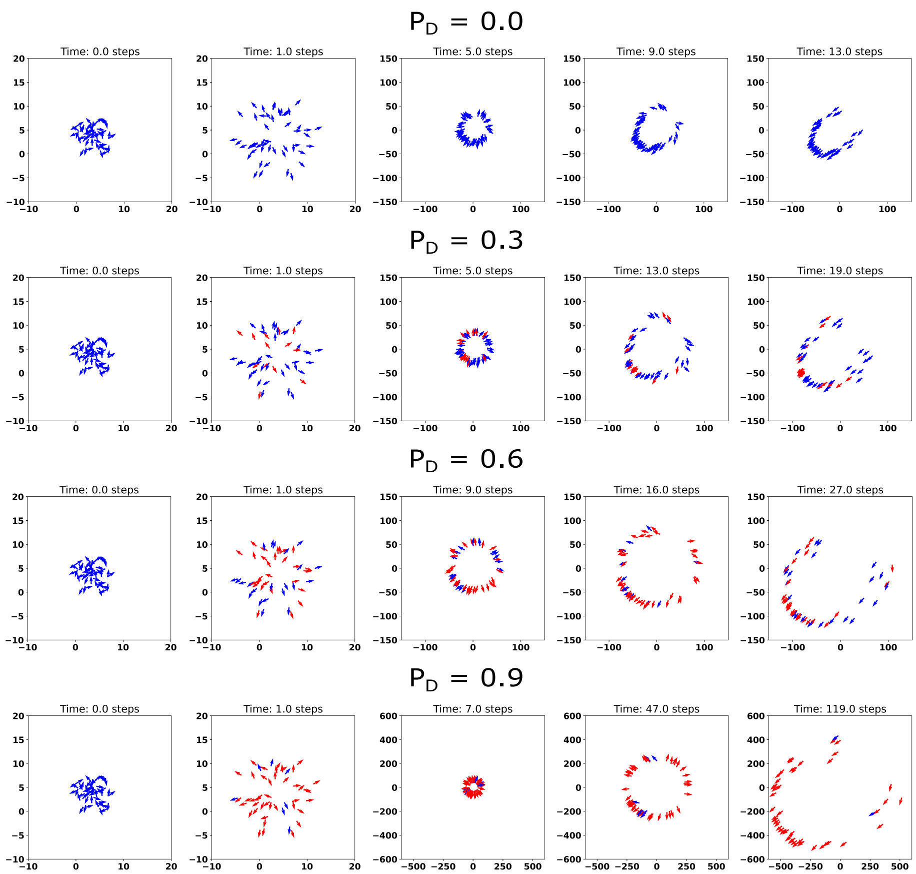

Fig. 1. The timelapse of a collective of size $N = 50$ consisting of agents that defect with a certain probability of defection, P_D, and interact through pairwise interaction model. In this figure, 1.0 steps correspond to 1.0 *sec*.

2 Defection in the Couzin Model

Note that in Figure 2, the polarisation time required for agents to get polarised decreases at certain probability of defection, P_D. With increasing values of P_D, the group becomes prone to split into higher number of clusters at earlier stages of the alignment process.

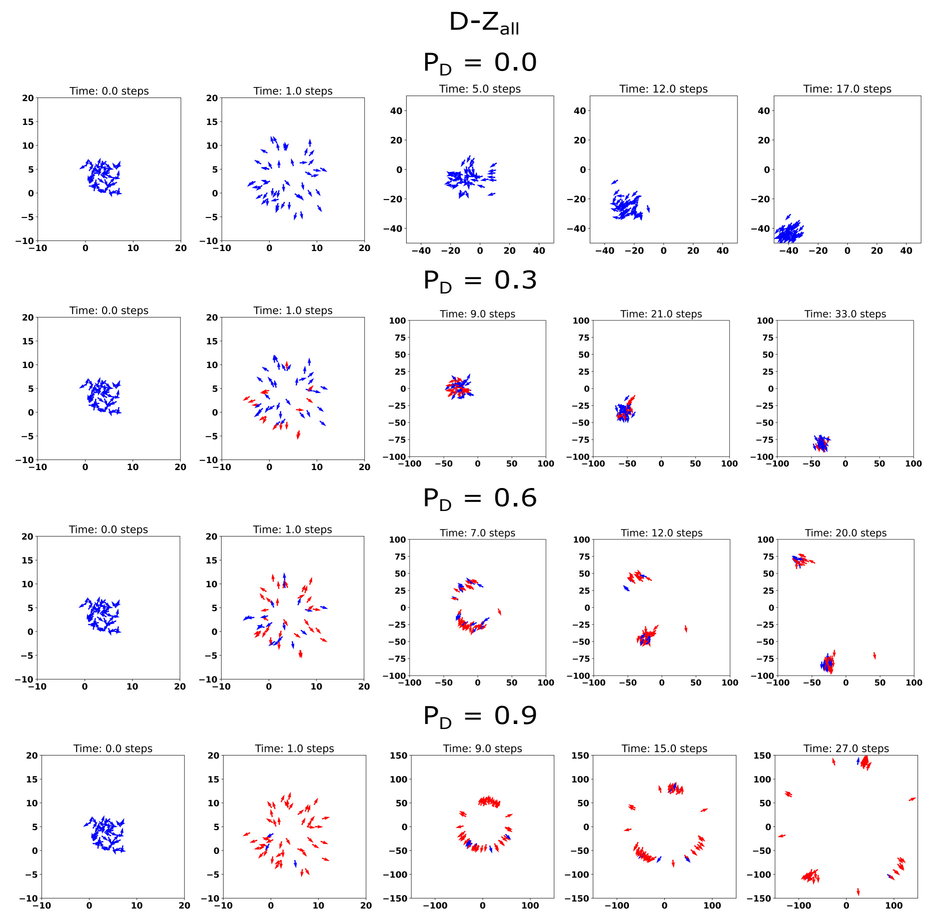

Fig. 2. The timelapse of a collective of size $N = 50$ consisting of agents $(D - Z_{all})$ that defect with a certain probability of defection, P_D. The agents interact as dictated by the Couzin model. In this figure, 1.0 steps correspond to 1.0 *sec*.

Further, in Figure 3, the polarisation time required for agents to get polarised decreases with increasing probability of defection, P_D. With increasing values of P_D, the group takes formation more similar to that of the pairwise interaction model.

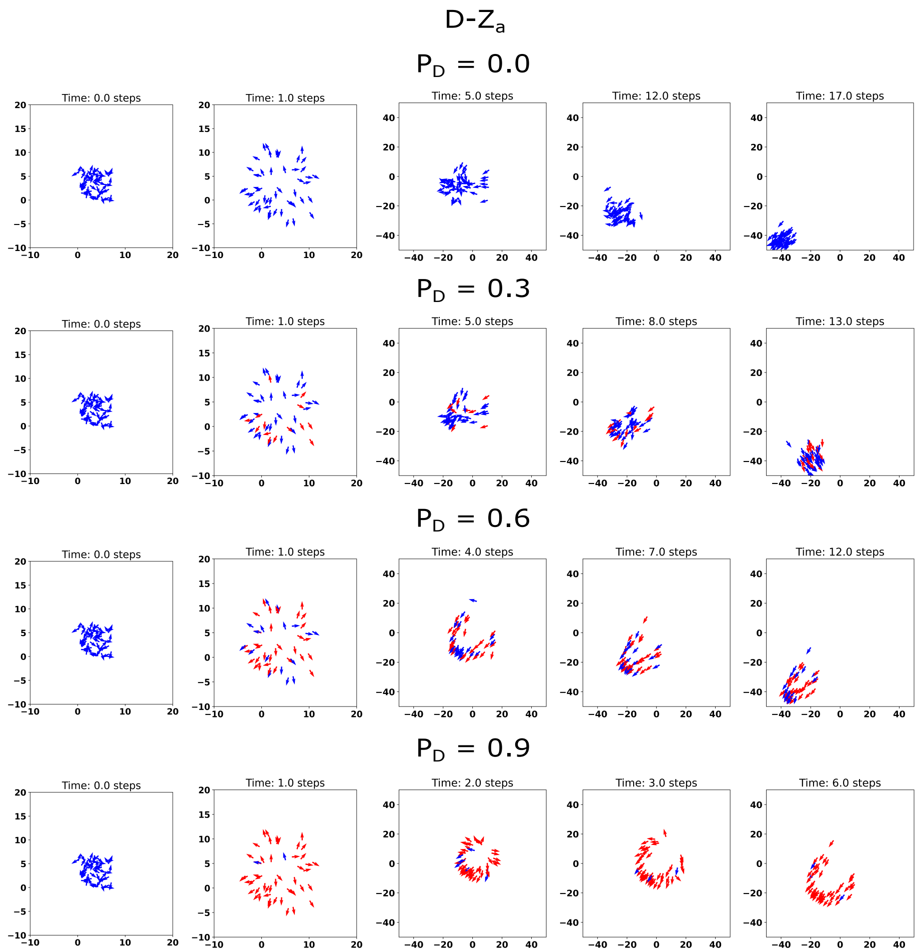

Fig. 3. The timelapse of a collective of size $N = 50$ consisting of agents $(D - Z_a)$ that defect with a certain probability of defection, P_D. The agents interact as dictated by the Couzin model. In this figure, 1.0 steps correspond to 1.0 *sec*.

In Figure 4, the polarisation time required for agents to get polarised increases with increasing probability of defection, P_D. There are certain values of P_D where the group transitions partially to the milling formation of the Couzin model.

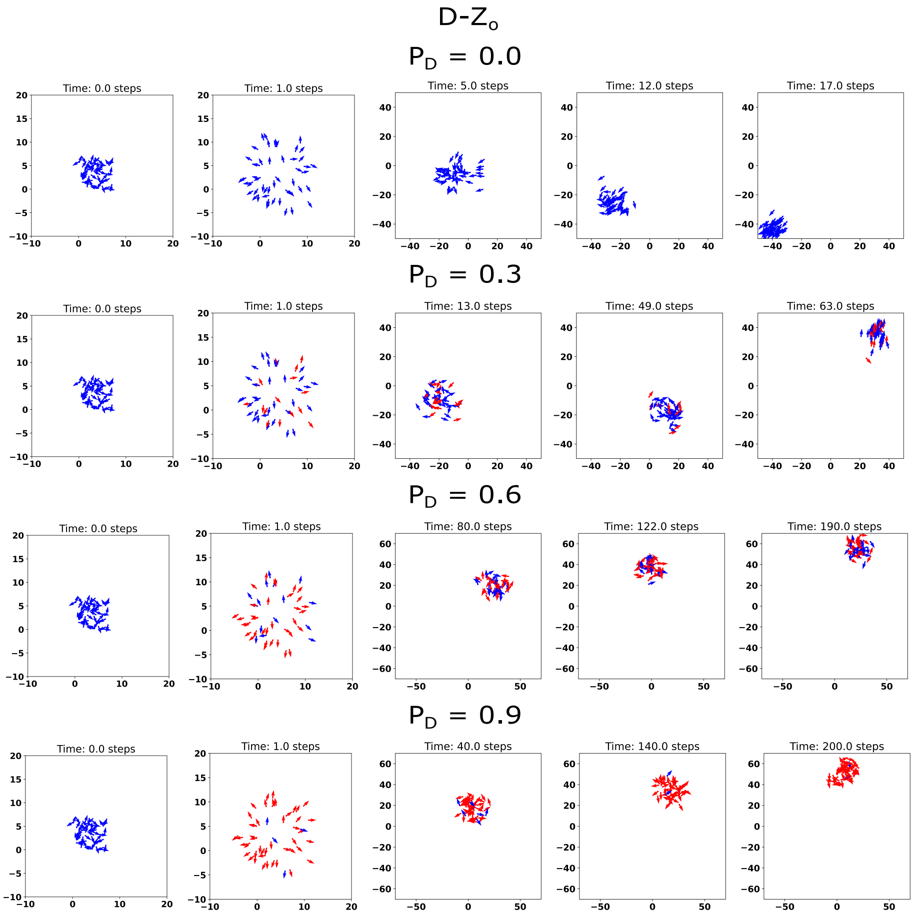

Fig. 4. The timelapse of a collective of size $N = 50$ consisting of agents $(D - Z_o)$ that defect with a certain probability of defection, P_D. The agents interact as dictated by the Couzin model. In this figure, 1.0 steps correspond to 1.0 *sec*.

Further, in Figure 5, the polarisation time required for agents to get polarised decreases with increasing probability of defection, P_D. With increasing values of P_D, the group gets densely packed.

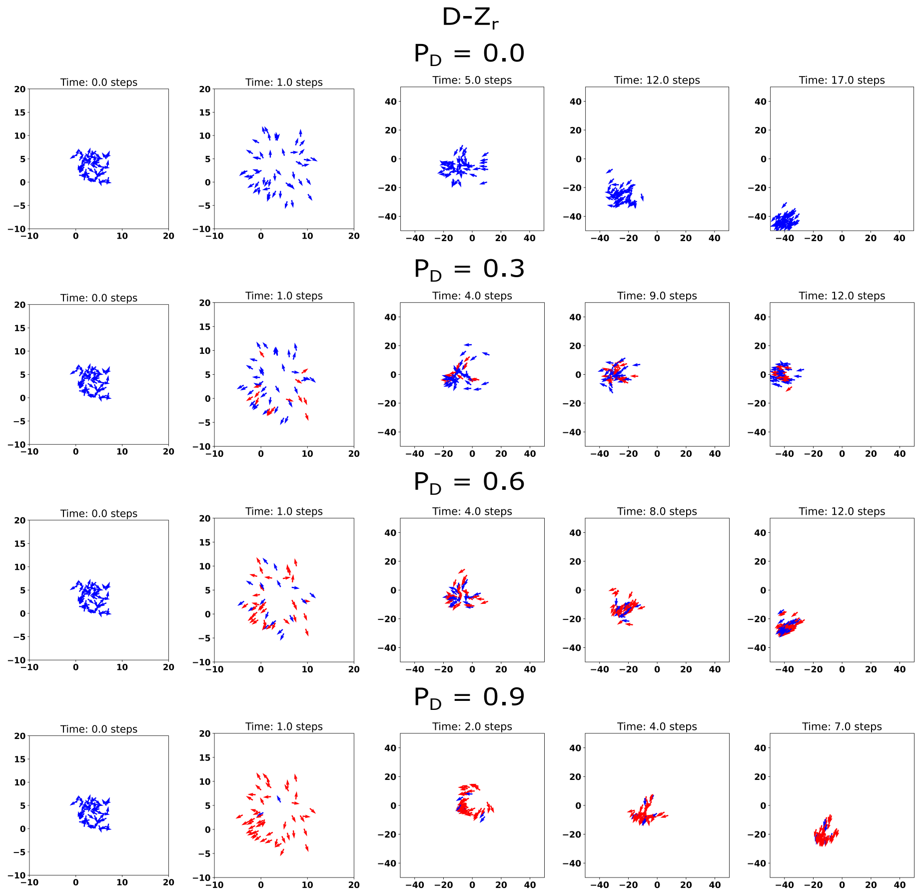

Fig. 5. The timelapse of a collective of size $N = 50$ consisting of agents $(D - Z_r)$ that defect with a certain probability of defection, P_D. The agents interact as dictated by the Couzin model. In this figure, 1.0 steps correspond to 1.0 *sec*.

Figure 6 shows the impact of defectors on the collective motion when the group size is $N = \{20, 50, 80\}$. When the agents defect in all the zones simultaneously, the resistance of the collective to the defectors decreases slowly with increasing group size. Whereas for the defection of type $D - Z_a$ and $D - Z_r$, the resistance to the defectors decreases at a smaller probability defect at higher group size. However, in the defection of type $D - Z_o$, the resistance to defectors decreases fast with increasing group size. Hence, we conclude that the impact of defectors get amplified at larger group sizes in unexpected ways.

Moreover, in the case of group size, $N = 80$, the polarisation time decreases when defection is of type $D - Z_a$ and $D - Z_r$ (Figs. 7(c, e)) with the increase in probability of defection. Whereas, for the defection of type $D - Z_{\text{all}}$, it decreases and then increases with a minimum at $P_D = 0.3$. Moreover, the average energy

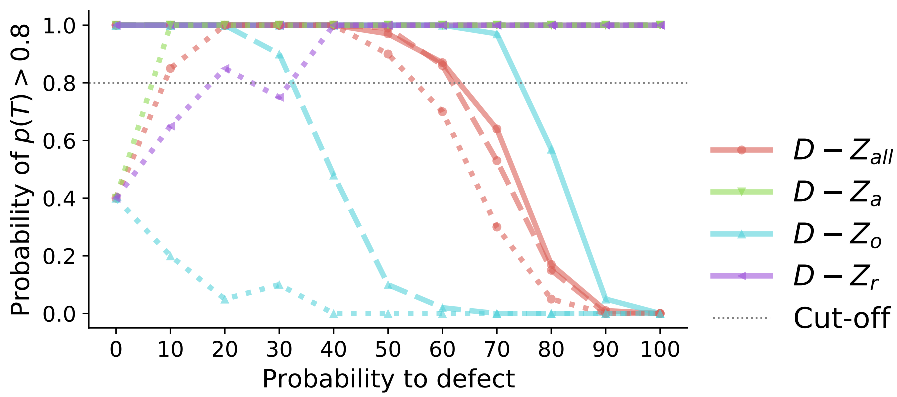

Fig. 6. The plot shows the probability of $p(T) > 0.8$ as a function of the probability of defection. The solid lines are for $N = 20$, the dashed lines are for $N = 50$, and the dotted lines are for $N = 80$.

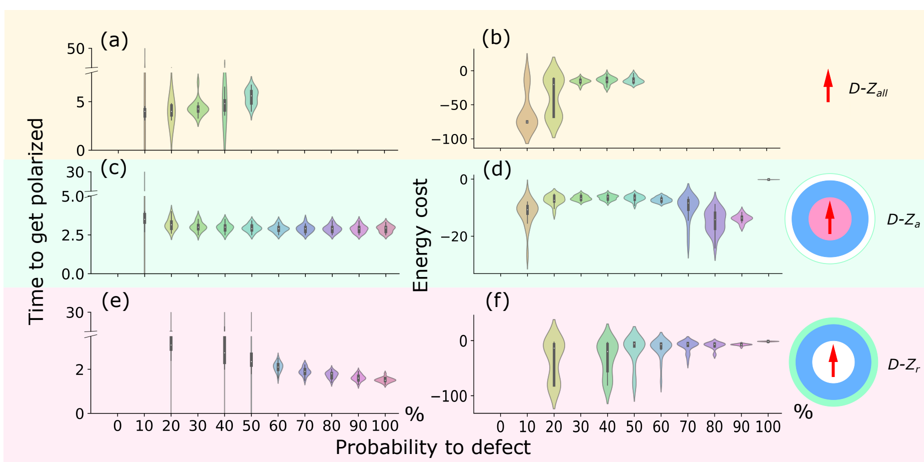

Fig. 7. The polarisation time (T) and the average group energy cost ($\Sigma_{t,N} e(t > T)$) across three types of defection for a group of size, $N = 80$. Each violin depicts a distribution of values from 100 iterations.

cost decreases for the defection of type $D - Z_{all}$ and $D - Z_r$ (Figs. 7(b, f)) with increasing probability of defection. On the other hand, in the case of $D - Z_{\mathrm{a}}$ (Fig. 7(d)), the energy cost decreases and then increases (with a minimum around $P_D = 0.4$) with the increasing probability of defection. In case of the defection of type $D - Z_o$, the collective fails to get polarised above the threshold probability of $p(T) > 0.8$ irrespective of whether the agents defect or not.

Counterintuitively, in $D - Z_r$, both the polarisation time and the average energy cost both decrease, indicating the benefits of incorporating defective behaviour with $P_D = 0.4$ (Figs. 7(e, f)).