Swarm deadlock for symmetric choices over three or more options

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Abstract. We consider a model of decentralised value-sensitive consensus decision-making, based on observations of house-hunting honeybees and proposed for swarm robotics applications. This model has been shown to adaptively maintain or break deadlock between equal options in binary choices, as a function of their quality, under the control of a single distributed decision parameter. We show that this model cannot break deadlock between three equal alternatives, as currently formulated.

Model. We study a model of decentralised decision-making [1] inspired by the observation of cross-inhibitory stop-signalling behaviour in swarms of house-hunting honeybees choosing between multiple potential nest-sites [2].

The general model for N options is:

$$\begin{cases} \frac{dx_i}{dt} = \gamma_i\, x_u - \alpha_i\, x_i + \rho_i\, x_u\, x_i - \sum_{j=1}^{N} x_i\, \tilde{\beta}_{ij}\, x_j \,, \qquad i \in \{1, \ldots, N\} \,, \\ x_u = 1 - \sum_{i=1}^{N} x_i \end{cases} \tag{1}$$

where x_i represents the subpopulation committed to option i and x_u the uncommitted subpopulation. γ_i represents the discovery rate for option i, α_i the abandonment rate for option i, ρ_i the recruitment rate for option i and $\tilde{\beta}_{ij}$ the cross-inhibition rate from subpopulation j to subpopulation i. By defining

$$\gamma_i = k\, v_i \,, \qquad \alpha_i = k\, v_i^{-1} \,, \qquad \rho_i = h\, v_i \,, \qquad \tilde{\beta}_{ij} = \tilde{\beta} \,, \qquad \frac{\tilde{\beta}}{k} = \beta \tag{2}$$

and applying (2) to (1), we obtain:

$$\begin{cases} \frac{dx_i}{d\tau} = v_i\, x_u - \frac{x_i}{v_i} + r\, v_i\, x_u\, x_i - \beta \sum_{j=1}^{N} x_i\, x_j \,, \qquad i \in \{1, \ldots, N\} \,, \\ x_u = 1 - \sum_{i=1}^{N} x_i \end{cases} \tag{3}$$

where $r = h/k$ is the ratio of interaction over spontaneous transitions, and $\tau = k\, t$ is the dimensionless time. The parameterisation of (2) is a generalisation of that in [1], since, using $r = 1$, the system (1) reduces to the original, and thus displays the same dynamics.

Due to its simplicity and its adaptive decision-making characteristics, this model is particularly interesting for the design of large-scale decentralised systems (e.g.,

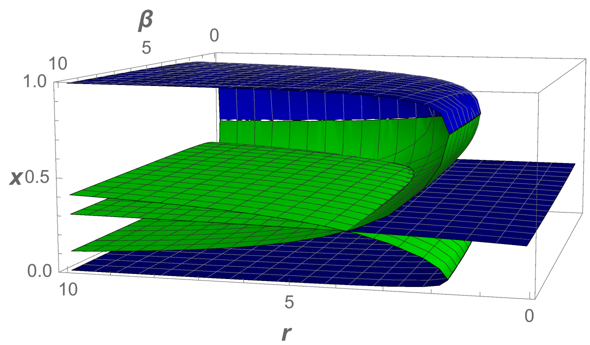

Fig. 1. Bifurcation diagram in 3D of the system (3) with $N = 3$ equal-quality options (i.e., $v_1 = v_2 = v_3 = v$) as a function of $r = h/k \in (0, 10]$ and $\beta \in (0, 10]$. The vertical axis shows $x \in [0, 1]$, which represents the proportion of bees committed to one of the three identical options. Blue surfaces represent stable equilibria, and the green surface unstable equilibria. For $r = 1$, the decision deadlock is stable for any tested value of β (see [5] for a proof).

robot swarms or wireless sensor networks) able to make consensus decisions [3]. A recent work has implemented the model of [1] on a swarm of 150 kilobot robots [4].

Results. A bifurcation analysis of (3) shows that for $r \leq 1$ there is no value of β that breaks the decision deadlock in the case of $N = 3$ same-quality options (see Fig. 1). A formal proof for N = 3 and $r = 1$ is provided in [5]. This result motivates the change of parameterisation with respect to previous work [1]. A full analysis of the resulting collective decision dynamics in both symmetric decisions, with N equal options, and best-of-N decisions, with one best option and N − 1 inferior distractors, is provided in [5].

Our results emphasise that r, the ratio of interactions over spontaneous behaviour, is the key parameter that allows, or prevents, the swarm to make a decision. Scarce communication hampers the attainment of consensus within the swarm, while frequent signalling between peers provides them a constant feedback from others that results in a coordinated collective response, in our case a consensus decision. We believe this finding may both help the better understanding of natural swarms and the design of large-scale decentralised systems.

References

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