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Flocking fragmentation formulation for a multi-robot system under multi-hop and lossy ad hoc networks

Key words: Multi-robot flocking; Flocking fragmentation probability; Fragmentation prediction; Multi-robot communication networks

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Background

- Multi-robot flocking (MRF) allows a robot swarm to perform tasks collaboratively, such as attacking targets, hunting prey, and transporting supplies.
- The Olfati-Saber (O-S) model is generally employed in MRF due to its superiority in guaranteeing the safety and stability of the system, requiring robots to obtain the state information (i.e., position and velocity) of a virtual leader and their neighbors first for posture adjustment and stability achievement.
- When parts of robots cannot obtain the virtual leader's state information (LSI), the fragmentation phenomenon may appear, leading to instability and failure of flocking.

Tendency and challenges

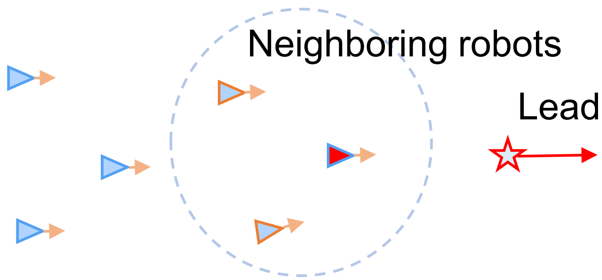
- Several connectivity-preserved control algorithms have been proposed to prevent fragmentation, which can guarantee the spatial connectivity when the communication network is ideal; i.e., the successful transmission probability (STP) is 1 for all communication links.
- However, in practice, the successful transmission of information over each link is a random event due to the unstable communication environment. Thus, lossy LSI announcements may still happen, leading to control errors and flocking fragmentation.

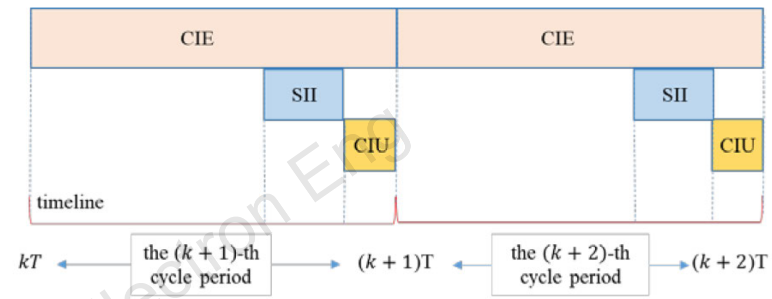
Motivation and main idea

- Except for spatial connectivity preservation, it is necessary to rationally design and optimize the network topology parameters, such as the relay hop count features and STP of LSI, to prevent multi-robot flocking fragmentation.
- For flocking-stability-oriented network design and optimization, a fundamental problem is to ascertain how the key network topology characteristics affect the multi-robot flocking fragmentation phenomenon, which motivates us to formulate the relationship between the flocking fragmentation probability (FFP) and the network parameters.

System model

Communication–computation–execution cycles in each robot





Communication: state information interaction (SII)

Neighbor's state information (NSI): transmitted through one-hop broadcast links → p_s → $P_r(l_{ij}(\mathrm{k}) = 1) = p_s$

Leader's state information (LSI): transmitted through multi-hop broadcast links → p_b → $P_r(h_i(\mathrm{k}) = 1) = p_b^{H_i}$

STP in each link

The final STP

The minimum relay hop count

Each robot can acquire the LSI only if the transmission over all hops is successful.

Computation: control instruction updating (CIU)

$$u_i(k) = \sum_{j \in N_i(k)} l_{ij}(k)\left(k_1\left(\|\boldsymbol{q}_{ij}(k)\| - d_e\right)\frac{\boldsymbol{q}_{ij}(k)}{\|\boldsymbol{q}_{ij}(k)\|} + k_2\boldsymbol{p}_{ij}(k)\right)$$

$$-h_i(k)[c_1(\boldsymbol{q}_i(k) - \boldsymbol{q}_r(k)) + c_2(\boldsymbol{p}_i(k) - \boldsymbol{p}_r(k))]$$

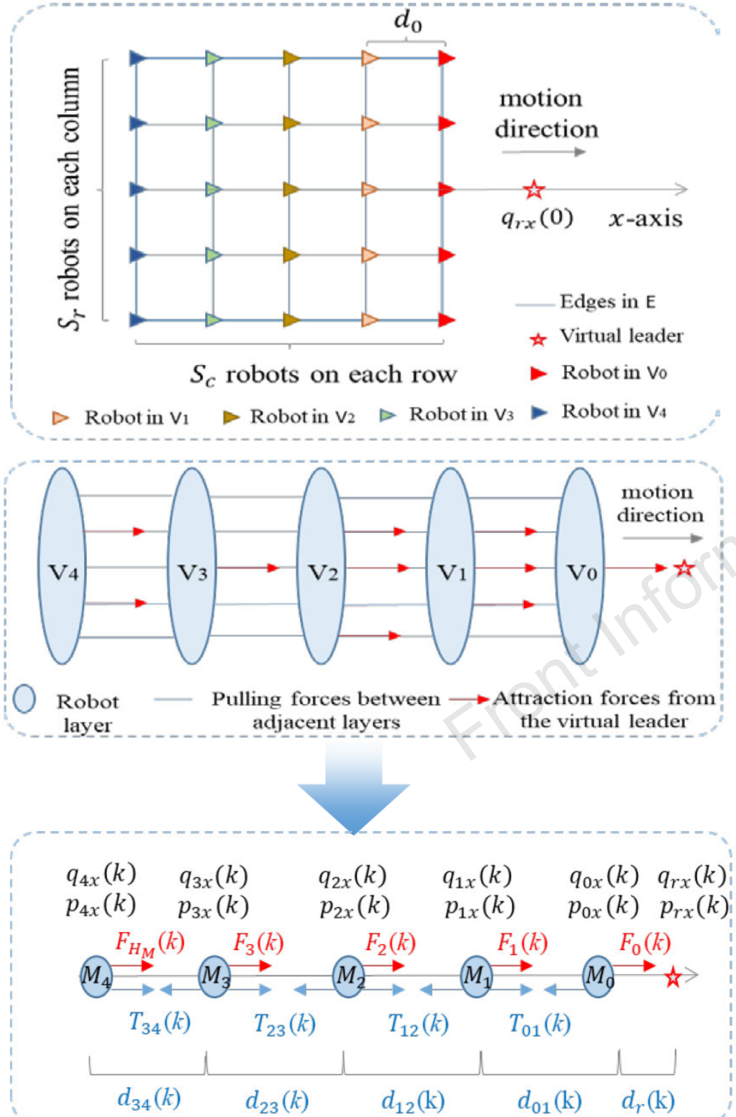
Execution: control instruction execution (CIE)

$$q_i(k+1) = q_i(k) + p_i(k) \times T + \frac{1}{2}u_i(k)T^2$$

$$p_i(k+1) = p_i(k) + u_i(k)T$$

Flocking fragmentation probability formulation

◻ Fragmentation analysis for specific flocking scenarios



Proposing a method based on layer division and spatial linearization

Robots are classified into different layers according to the minimum relay hop count

Conduct force analysis on centroid M_h of each layer

$$F_h(k) = a_h\left[c_1\left(d_r(k) + \sum_{j=0}^{h-1} d_{j(j+1)}(k)\right) + c_2\left(v_r(k) + \sum_{j=0}^{h-1} v_{j(j+1)}(k)\right)\right]m$$

$$T_{h(h+1)}(k) = e_{h(h+1)}\left[k_1\left(d_{h(h+1)}(k) - d_e\right) + k_2 v_{h(h+1)}(k)\right]m$$

Calculate the acceleration of centroid M_h

$$u_{hx}(k) = \begin{cases} \dfrac{F_h(k) - T_{h(h+1)}(k)}{n_h \times m}, h = 0 \\ \dfrac{F_h(k) + T_{(h-1)(h)}(k) - T_{h(h+1)}(k)}{n_h \times m}, 0 < h < H_M \\ \dfrac{F_h(k) + T_{(h-1)(h)}(k)}{n_h \times m}, h = H_M \end{cases}$$

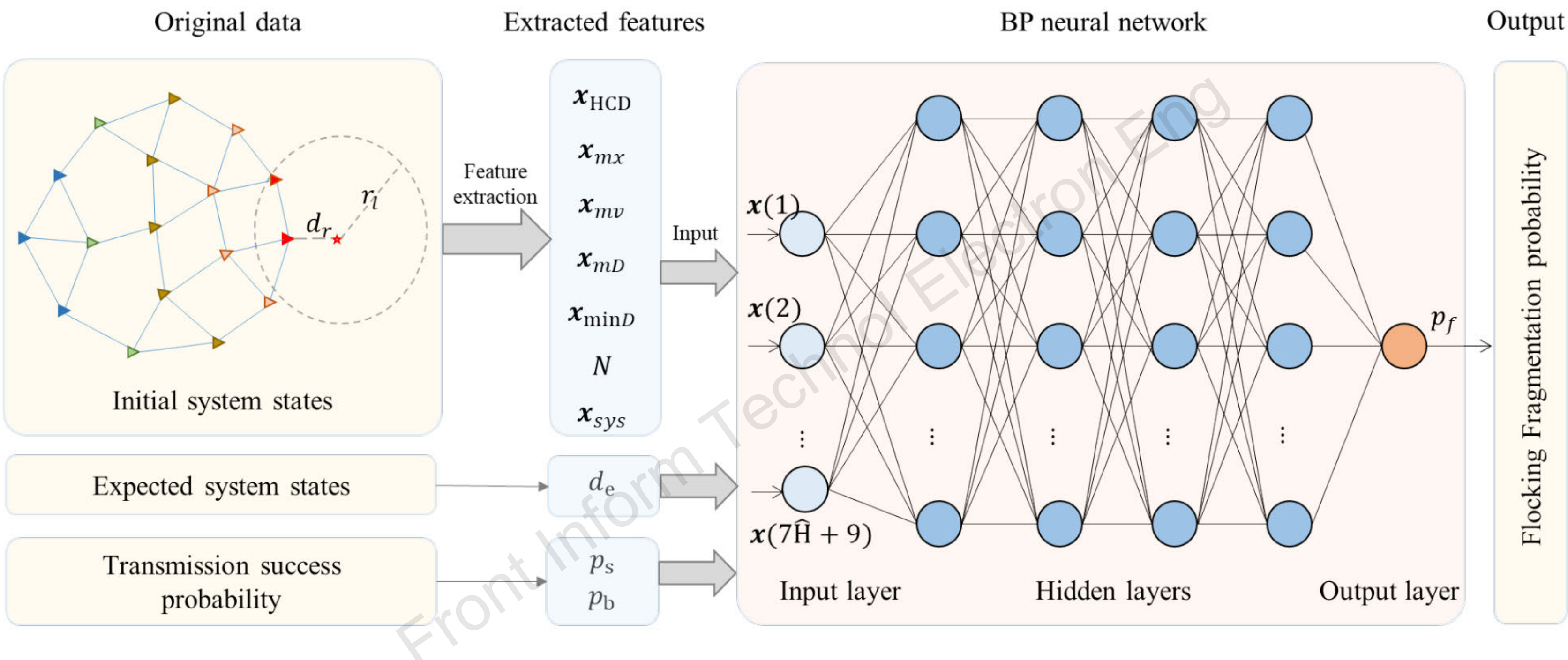
Derive the discrete-time state updating equation

$$s_{dv}(k+1) = \mathbf{A} \times s_{dv}(k) - \mathbf{B}$$

The derived fragmentation prediction model (FPM) can be employed to judge if flocking fragmentation appears

Flocking fragmentation probability formulation

◻ FFP formulation for general flocking scenarios



We develop a data fitting model based on a back propagation (BP) neural network to formulate the FFP. The neural network takes key network topology parameters extracted from FPM as the input features, which makes the formulation applicable to robot swarms of different sizes with changeable and random initial states.

Major results

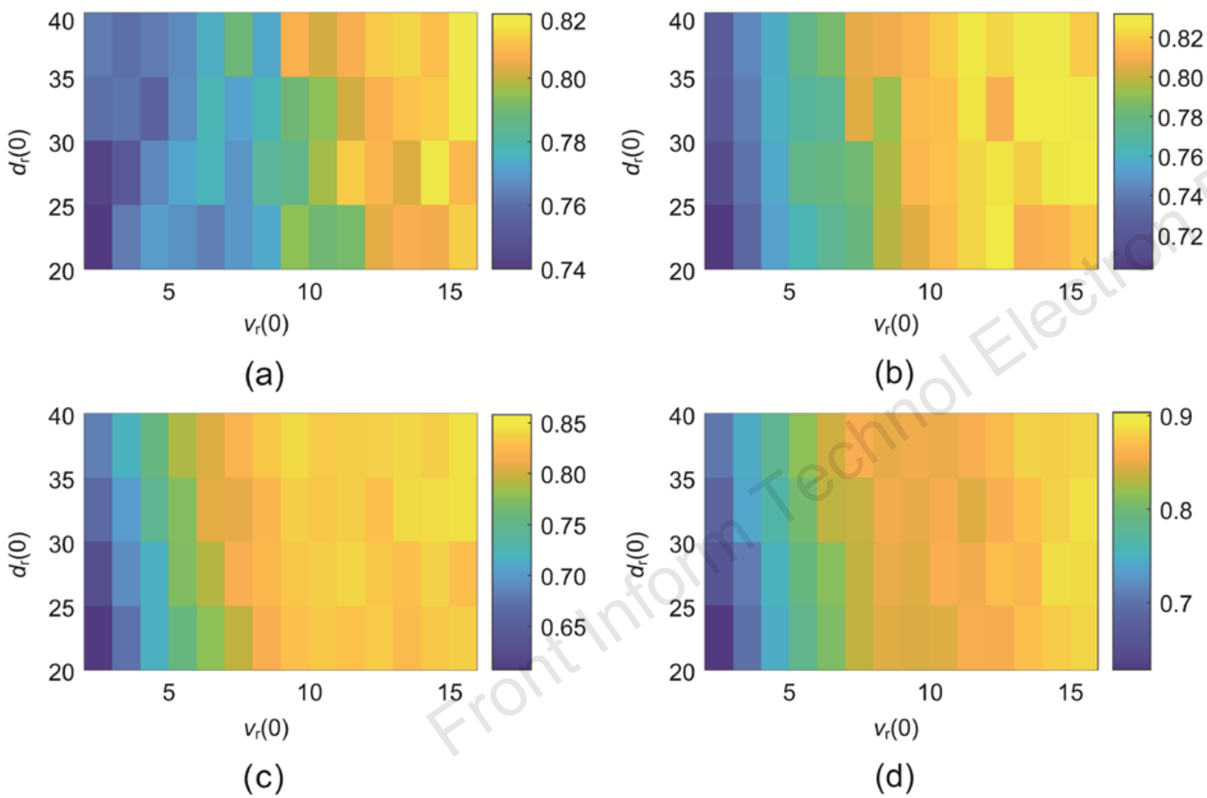
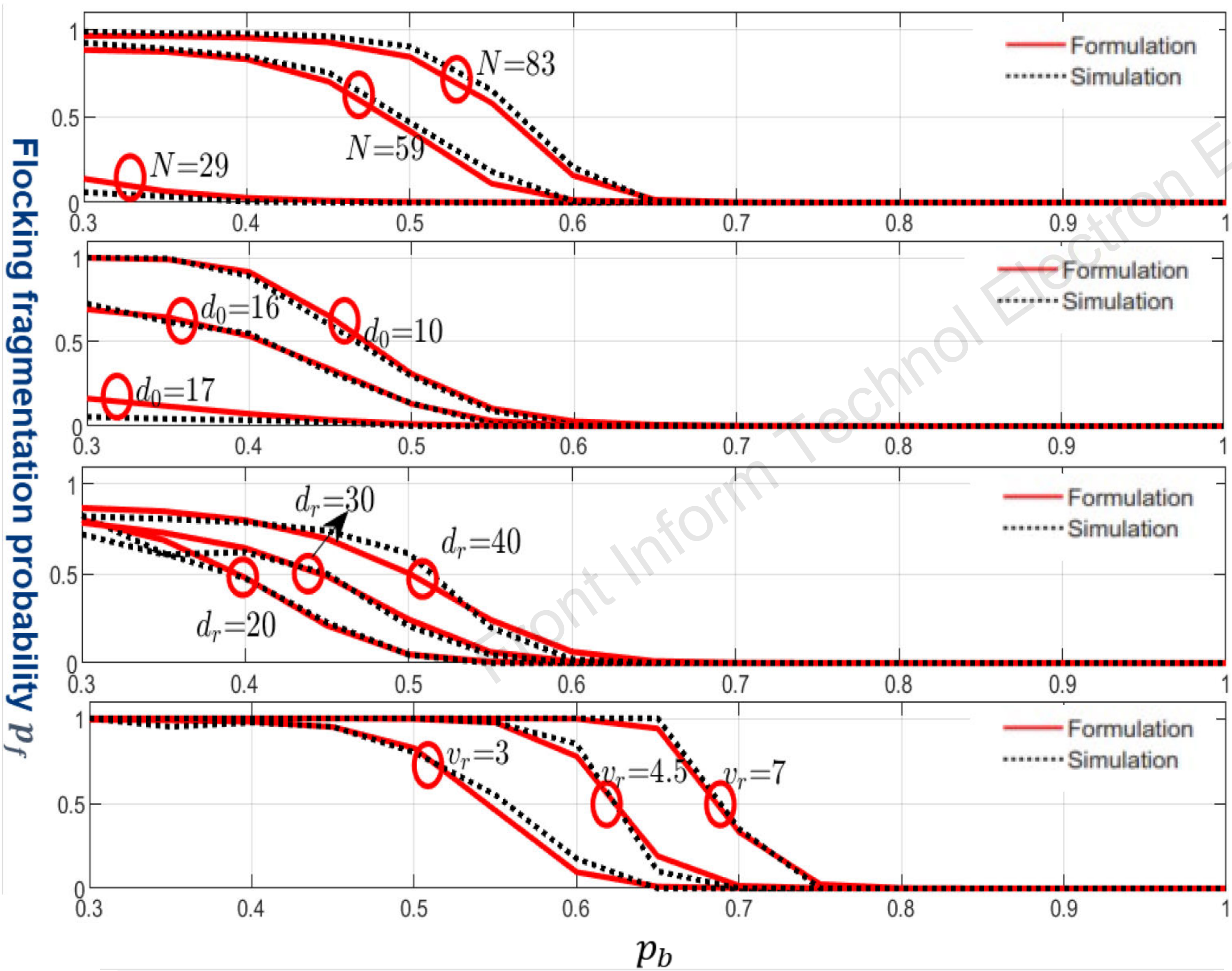


Fig. 4 Prediction accuracy of FPM under different value situations of vector [d_0, $d_r(0)$, $v_r(0)$]: (a) d_0=8.5; (b) d_0=9; (c) d_0=10; (d) d_0=11

From Fig. 4, we ascertain that a large proportion of prediction accuracy values are kept within the interval [0.7, 0.8] under a wide range of parameter settings. This implies that our FPM analysis has a certain degree of precision and that the extracted key initial system or network state features do affect the final trend of flocking swarms.

Major results

- Effect analysis of key features on FFP



① Good coincidence → The model is accurate.

② p_b ↑ p_f ↓

The global announcement of LSI benefits fragmentation prevention.

③ p_f=0 when p_b reaches the critical threshold

It is not necessary to realize the absolute transmission success of LSI over each hop. Nevertheless, when designing the communication network for a multi-robot flocking system, appropriate technologies should be selected and improved to achieve the critical performance of links.

Conclusions

- The transmission of LSI and NSI in communication networks is crucial to guarantee multi-robot flocking stability. Specifically, when the global delivery of LSI cannot be guaranteed, the flocking is likely to demonstrate fragmentation phenomena and cannot reach stability. Since LSI's transmission performance depends on the topology structure and parameter configuration of multi-robot communication networks, we analyze the impact of network topology parameters (including hop count features and STP) on flocking fragmentation by formulating their relationship.
- We first present a CCE protocol to describe the interaction and control process of multi-robot flocking, where an extended discrete-time O-S model is employed to achieve flocking control in multi-hop and lossy ad hoc networks.

Conclusions

- We put forward the FPM for specific flocking scenarios, and furthermore develop the FFP formulation for generalized flocking scenarios.
- Simulation validates the effectiveness of our proposed method. The developed FFP formulation has excellent accuracy and generalization capability, and is applicable to robot swarms of different sizes with changeable and random initial states. The results indicate that a higher STP and an overall small hop count can prevent flocking fragmentation and ensure final stability.