



Distributed Event-Triggered Formation Control for a Multi-robotic Fish System

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Abstract. This paper investigates the formation control problem for a multi-robotic fish system and a distributed event-triggered-based formation control framework is proposed. The framework consists of a communication topology, a distributed formation control law, and a dynamic event-triggered communication mechanism. In particular, a position-based formation control law is presented to drive the multi-robotic fish system to an anticipated configuration based on local measurements while keeping pace with a moving target. Meanwhile, a dynamic event-triggered mechanism is utilized to measure importance of the interactive information and decide the communication timing. The proposed formation control method shows its merits to greatly reduce communication consumption with a limited loss of formation control performance. Finally, simulations with quantitative comparisons are presented to verify the effectiveness of the proposed framework. This formation control framework provides a solid foundation for future marine cooperative control of the multi-robotic fish system.

Keywords: Robotic fish · Underwater multi-agent systems · Formation control · Event-triggered mechanism

1 Introduction

To meet the ever-increasing demands in marine exploration and underwater operation, autonomous underwater vehicles (AUVs) are filled with high expectations to accomplish more complicated underwater assignments autonomously and intelligently [1, 2]. Inspired by social insect colonies, bird flocks, and fish schools in nature, increasing underwater multi-agent robotic systems come to the fore [3–5]. These multi-agent systems make up flaws in low sensor accuracy and limited operating capacity of a single underwater robot to some extent.

As a familiar deployment problem of the multi-agent system, formation control has attracted extensive attention owing to its wide applications in exploring, patrolling, detecting, and rescuing with multiple unmanned robots [6]. Thereby, tremendous research efforts have been made to propose several formation control laws, including leader-follower-based schemes, virtue structure methods, artificial potential field techniques, and consensus-based strategies [7, 8]. For instance, He *et al.* addressed a decentralized leader-follower formation control problem for unmanned surface vehicles, where each vehicle converged to its leader considering obstacle avoidance under external disturbances [9]. Falconi *et al.* presented a consensus-based control strategy to gather formation for a group of differential-wheeled robots, where the stability was demonstrated by means of analytical proofs [10]. Spears *et al.* provided a distributed methods based on virtual potential field, where the control forces were motivated by natural physics laws and agents could finally construct predefined geometric lattice configurations [11].

Due to the hostile environment, most AUVs suffer from bandwidth-constrained and energy-constrained occasions during marine operation assignments. In these cases, event-triggered mechanism (ETM) proves effective to mitigate the unnecessary waste of communication resources. Zhu *et al.* proposed an event-triggered formation control strategy using dynamic state observers, and continuous communications between neighboring agents were avoided [12]. Chen *et al.* presented an event-triggered scheme for surface vessels and overcame the nonlinearity problem by neural networks and auxiliary variables [13].

Regarded as a special bionic AUV, robotic fish enables fish-like agility, maneuverability, and propulsive efficiency. However, the restricted assembly space curtails its widespread use in marine applications. Hence, sustaining a trade-off between desired control performance and satisfactory resource consumption, formation control problem is more complicated for the robotic fish. In previous work, the researches rarely focused on control assignments with multiple robotic fish. Besides, owing to the underactuated locomotion, some traditional formation control methods might not pertain to the robotic fish. What is more, communication restriction and resource consumption should be taken into account for the formation control of a multi-robot fish system.

Motivated by the above observations, this paper aims to carry out three-dimensional (3-D) formation control assignments for a multi-robotic fish system. Firstly, considering the underactuated fish-like locomotion, a dynamic model of agents in the multi-robotic fish system is described. Thereafter, an event-triggered formation control framework is proposed. In particular, a distributed position-based formation control law is utilized and a moving target is introduced as a virtue leader in the meanwhile. Further, a dynamic event-triggered mechanism (dETM) is presented to measure importance of the interactive information and decrease communication consumption to a great extent. Simulations are finally carried out to validate effectiveness of the proposed formation control method with elaborate comparisons and analyses.

The rest of the paper is organized as follows. In Sect. 2, the formation control problem for the multi-robotic fish system is sketched out. Section 3 discusses

the proposed 3-D formation control framework. Simulation verification with the multi-robotic fish system is introduced in Sect. 4. Finally, the conclusions and future work are summarized in Sect. 5.

2 Preliminaries and Problem Formulation

As a typical manifestation of the deployment task, pattern formation makes rational use of limited resources and boosts operation efficiency. Considering a multi-robotic fish system with N robotic fish, every robotic fish maneuvers and occupies a specified relative position, where ensemble of the system composes as an anticipated geometric shape globally. The capability to sense relative states or interact with neighbors from a local perspective substantially enhances flexibility of the formation in particular. Hence a distributed formation controller based on local communication topology is propitious in various and complex environment.

To describe interactions of the multi-robotic fish system intuitively, an undirected digraph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ is declared, where $\mathcal{V} = \{1, 2, \dots, N\}$ is a vertex set and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is an edge set. \mathcal{A} is a weighted adjacency matrix where $\mathcal{A} = [a_{ij}]_{N \times N}$. $(i, j) \in \mathcal{E}$ means two agents i and j are associated with each other with $a_{ij} = 1$, and $a_{ij} = 0$ otherwise. With aforementioned communication topology, every robotic fish receives states of other agents from neighbors and shares its own states if necessary. Furthermore, control objectives of the formation control task are depicted as follows:

- *Formation producing*: In view of enormous fading of the signals in underwater environment, a faster formation producing favors the system to set up a reliable communication topology. Hence, robotic fish in the multi-robotic fish system makes quick convergence and constitutes a predefined shape globally.
- *Formation keeping*: For guiding the whole system to a designated area, a moving target is introduced as a virtue leader. Robotic fish swims while keeping pace with each other to realize a locomotion to the moving target globally.

It is assumed that formation configuration is defined in a two-dimensional (2-D) space in this paper, represented by $\Delta = [\delta_{ij}]$, and the configuration can also be described as $\delta_{ij} = \delta_i - \delta_j$. Note that orientations of the agents keep consistent in the predefined configuration, so $\tilde{\delta}_{ij} \in \mathbb{R}^2$ is used as a 2-D configuration, where $\delta_{ij} = [\tilde{\delta}_{ij}^T, 0]^T$. A position vector $\eta_i = [x_i, y_i, \psi_i]^T$ is introduced for agent i to indicate relative position of robot, where $p_i = [x_i, y_i]^T$ is a 2-D coordinate with respect to the world coordinate frame and ψ_i represents the yaw angle, respectively. Corresponding speed vector is deduced by $v_i = [\dot{x}_i, \dot{y}_i, \dot{\psi}_i]^T$ as a derivative of η_i . Similarly, states of the moving target are expressed as $\eta_l = [x_l, y_l, \psi_l]^T$ and $v_l = [\dot{x}_l, \dot{y}_l, \dot{\psi}_l]^T$. Therefore, the formation control problem can be specified as follows:

Definition 1. *Agents achieve the desired formation with an anticipated configuration if equations exit for agent i that*

$$\lim_{t \rightarrow \infty} \|\eta_i(t) - \eta_j(t) - \delta_{ij}\| = \mathbf{0}, (i, j) \in \mathcal{E} \quad (1)$$

$$\lim_{t \rightarrow \infty} \|\bar{\eta}(t) - \eta_i(t)\| = \mathbf{0} \quad (2)$$

where $\bar{\eta}(t) = \sum_{i \in \mathcal{V}} \eta_i(t)/N$ denotes geometric center of the multi-robotic fish system. Using $\delta_{il} = \delta_i - \delta_l$ to denote a desired relative position to the center, (2) can also be depicted as

$$\lim_{t \rightarrow \infty} \|\eta_i(t) - \eta_l(t) - \delta_{il}\| = \mathbf{0}. \quad (3)$$

According to the definition mentioned above, formation error ε_e is introduced to measure a deviation of the formation process, which is formalized as follows:

$$\varepsilon_e = \sum_{i \in \mathcal{V}} \|\eta_i(t) + \delta_{il} - \eta_l(t)\|. \quad (4)$$

Remark 1. At least one of the agents can detect the moving target and broadcast its states through communication topology \mathcal{G} on demand, in the meanwhile, a spanning tree is constructed from this agent as a root node.

3 Event-Triggered Formation Control System

3.1 3-D Formation Control Framework

Figure 1 depicts an overview of the proposed formation control framework. Each robot in the multi-robotic fish system moves in 3-D space with sensors collecting data in real time. Robotic fish broadcasts pivotal measurements through the communication topology. Moreover, onboard computing element integrates all the measurements from neighbors and updates the distributed formation control law. Pursuing a moving target as a virtue leader, the formation control law drives each robot to constitute a predefined configuration while keeping the same depth with the leader. In consideration of the bandwidth-constrained and energy-constrained occasion in complex ocean environment, an ETM is proposed. Further, the event detector determines when to broadcast current states, which mitigates the unnecessary waste of communication resources to a great extent. Therefore, the multi-robotic fish system can keep an anticipated formation while arbitrating between control precision and communication consumption by this event-triggered formation control framework.

3.2 Position-Based Formation Control Law

Robotic fish does not have direct control forces in the sway and heave directions, which means some traditional ways, such as consensus-based and potential field-based methods, can not be utilized directly for the multi-robotic fish system.

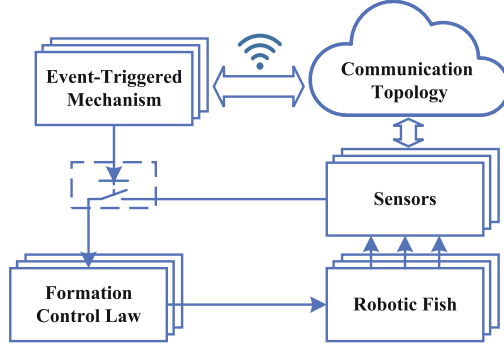


Fig. 1. Overview of the event-triggered formation control framework.

Therefore, a position-based formation control law is proposed, where the desired formation configuration is converged intuitively.

It is derived from the problem description in (1)–(3) that aiming at different neighbors, desired positions of agent i are represented as a set that

$$\hat{\eta}_{di}(t) = \underbrace{\{\eta_1(t) + \delta_{i1}, \dots, \eta_j(t) + \delta_{ij}, \dots, \eta_l(t) + \delta_{il}\}}_{(i,j) \in \mathcal{E}}. \quad (5)$$

Concentrating on agent j as one of its neighbors, Fig. 2 delineates locomotion tendency of the robotic fish i in regard to j . Agent i is supposed to reach a 2-D position as $p_i \rightarrow p_{ij}$ while keeping a same yaw angle that $\psi_i \rightarrow \psi_j$, where $p_{ij} = p_j + \tilde{\delta}_{ij}$. Moreover, speed vectors \dot{p}_i and \dot{p}_j are introduced as a derivative of p_i and p_j , respectively. For reasons of speed consistency and a smooth transition when agent i reaches p_{ij} , an extension is made in the direction of \dot{p}_j with a lookahead distance d_{lij} , thus p_{rij} is set as a new target to complete formation control. To drive the orbits tangent to \dot{p}_j in p_{ij} , d_{lij} is designed adaptively. The shorter distance between p_i and p_{ij} , the longer d_{lij} is selected, which is depicted as follows:

$$d_{lij} = \overline{d}_l e^{-\|p_i(t) - p_{ij}(t)\|} \quad (6)$$

where \overline{d}_l is an upper limit. Likewise, the speed of i , represented by $U_i = \|\dot{p}_i\|$, is converging to a desired speed that $U_i \rightarrow U_{dij}$, which is given by

$$U_{dij} = \frac{U_j}{e^{-\|p_i(t) - p_{ij}(t)\|}}. \quad (7)$$

In conclusion, considering the influence of all the neighbors, (5) is redefined by a desired 2-D position set \hat{p}_{di} and a desired surge speed set \hat{U}_{di} as follows:

$$\hat{p}_{di}(t) = \underbrace{\{p_{ri1}(t), \dots, p_{rij}(t), \dots, p_{ril}(t)\}}_{(i,j) \in \mathcal{E}} \quad (8)$$

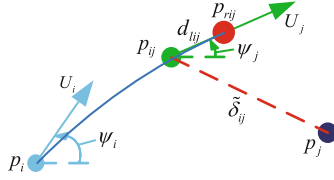


Fig. 2. Locomotion tendency of the robotic fish i in regard to neighbor j .

$$\hat{U}_{di}(t) = \{U_{di1}(t), \dots, \underbrace{U_{dij}(t), \dots}_{(i,j) \in \mathcal{E}}, U_{dil}(t)\}. \quad (9)$$

Ascribing a definite weight to each element in the sets above, the desired position $p_{di}(t)$ and desired speed $U_{di}(t)$ of agent i are finally deduced as

$$p_{di}(t) = \sum_{j \in \mathcal{V} \cup \{l\}} a_{ij} w_{ij} p_{rij}(t) \quad (10)$$

$$U_{di}(t) = \sum_{j \in \mathcal{V} \cup \{l\}} a_{ij} w_{ij} U_{dij}(t) \quad (11)$$

where $a_{il} = 1$ means agent i can get states of the moving target. w_{ij} is a weight coefficient where $\sum_{j \in \mathcal{V} \cup \{l\}} a_{ij} w_{ij} = 1$. By following aforementioned references, agents in the multi-robotic fish system move to the desired position with specified speed and constitute the configuration globally.

3.3 Event-Triggered Mechanism

It is amenable to produce a predefined formation in finite time and make the multi-robotic fish system pursuit towards a moving target with the proposed formation control law. However, the situation is pretty grim in hostile underwater environment. On the one hand, due to an attenuation of the signal, communication quality withstands uncertainty and the bandwidth is constrained. On the other hand, assembly space of the robotic fish is too restricted to hold a high capacity battery. In a word, it is crucial to evaluate importance of the sending messages and transfer information selectively. Therefore, an ETM is proposed to reduce energy consumption by sacrificing acceptable control precision.

In accordance with the commonly used communication equipment of the robotic fish, a node-based ETM protocol is selected. Once the event detector determines a triggering occasion, robotic fish, such as agent i , broadcasts its states to all its neighbors in \mathcal{E} , where the sequence of triggering times is represented as $\{t_0^i, t_1^i, \dots, t_{k_i}^i, \dots\}$. The triggering occasion is determined by

$$t_{k_i}^i = \inf \{t > t_{k_i-1}^i : \Gamma_i(t) \geq 0\} \quad (12)$$

where $\Gamma_i(t)$ is the event triggered function. It means once $\Gamma_i(t) < 0$ is violated, the state information is published and the triggering time $t_{k_i}^i$ is recorded.

States at triggering times are saved in comparison with the real-time states, where the trigger error vectors are defined as $e_i = [e_{\eta_i}^T, e_{v_i}^T]^T$, made up of $e_{\eta_i}(t) = \eta_i(t_{k_i}^i) - \eta_i(t)$ and $e_{v_i}(t) = v_i(t_{k_i}^i) - v_i(t)$. Different from the traditional static event-triggered mechanism (sETM), dETM exists its ability to further reduce the number of events without sacrificing excessive control performance. Based on dynamic threshold parameters (DTPs) [14], a dETM is proposed as follows:

$$\begin{aligned} \Gamma_i(t) &= \left\| \Phi^{\frac{1}{2}} e_i(t) \right\|^2 - \mathcal{T}_i(\hat{z}_i(t)) \\ &= \left\| \Phi^{\frac{1}{2}} e_i(t) \right\|^2 - \sigma_i(t) \sum_{j \in \mathcal{V} \cup \{l\}} \left\| \Phi^{\frac{1}{2}} \hat{z}_i(t) \right\|^2 \end{aligned} \quad (13)$$

where $\mathcal{T}_i(\hat{z}_i(t)) = \sigma_i(t) \sum_{j \in \mathcal{V} \cup \{l\}} \left\| \Phi^{\frac{1}{2}} \hat{z}_i(t) \right\|^2$ is the threshold function. Φ is a positive symmetric weighting matrix. $\sigma_i(t)$ is a time dependent dynamic parameter while $\hat{z}_i(t)$ is the data of interest represented by $\hat{z}_i(t) = a_{ij} \left(\xi_i(t) - \xi_j(t_{k_j}^j) \right)$, where $\xi_i = [\eta_i^T, v_i^T]^T$.

When $e_i(t)$ suffers from large fluctuation, a smaller $\sigma_i(t)$ is selected to verify a timely information interaction. Moreover, when the formation control system converges to the equilibrium point, a larger $\sigma_i(t)$ is prescribed to reduce unnecessary message transmissions. The forms of the adaptive continuous $\sigma(t)$ is formalized by

$$\sigma_i(t) = \underline{\sigma} + (\bar{\sigma} - \underline{\sigma}) e^{-k_\sigma \sum_{j \in \mathcal{V} \cup \{l\}} \left\| \Phi^{\frac{1}{2}} \hat{z}_i(t) \right\|^2} \quad (14)$$

where $\underline{\sigma}$ and $\bar{\sigma}$ are lower limit and upper limit of $\sigma_i(t)$, respectively. k_σ is a non-negative constant. As demonstrated in [15], the asymptotic stability of the dETM is guaranteed.

Remark 2. For a neat and convenient implementation of the proposed event-based controllers, event-triggered transmission (ETT) is utilized to realize a Zeno-freeness control [16]. In particular, the continuous-time system states are firstly sampled at discretized and equidistant instants of time $\{kh : k \in \mathbb{N}\}$ with a constant sampling period $h > 0$. Therefore, it is clear that the event detectors only work at sampled time and the minimal inter-event time (IET) T_{min} satisfies that $T_{min} \geq h > 0$, which eliminates the Zeno behavior.

4 Simulation Analysis

For the sake of validity illustration of the proposed formation control framework, simulation environment is established in Robot Operating System (ROS) and extensive simulations are carried out. In order to implement the formation control task, four robotic fish is coordinated together, whose initial positions are set as $\eta_1 = [0.1, 3.8, -0.3]^T$, $\eta_2 = [0.8, 3.6, -1.5]^T$, $\eta_3 = [0.6, 2.5, -0.8]^T$, $\eta_4 = [0.3, 3.2, 0.9]^T$. The 2-D anticipated configuration is set as $\tilde{\delta}_l = [0, 0]^T$,

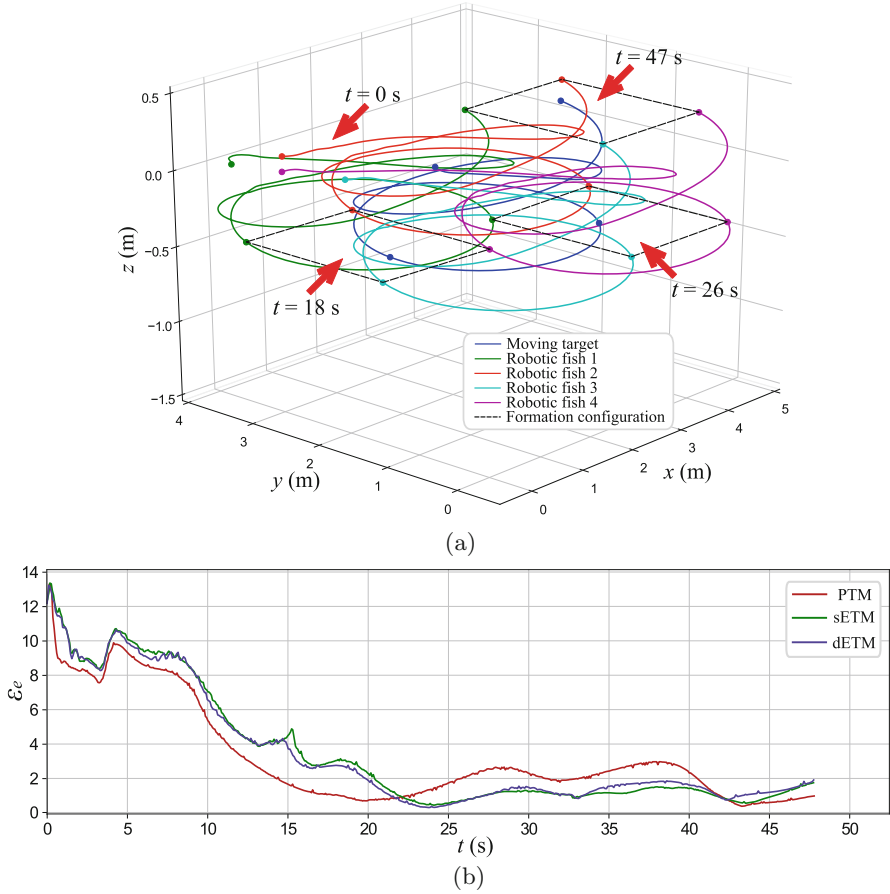


Fig. 3. Simulation results. (a) Formation control results with dETM. (b) Comparisons of the formation errors of different triggering mechanisms.

$\tilde{\delta}_1 = [-1, 1]^T$, $\tilde{\delta}_2 = [1, 1]^T$, $\tilde{\delta}_3 = [-1, -1]^T$, $\tilde{\delta}_4 = [-1, 1]^T$. Note that in the subsequent simulations, the communication topology \mathcal{G} is strong connected, which means each robotic fish can interact with all the other agents, in the meanwhile, receive information about the virtue leader at triggering times. The moving target starts at $\eta_l = [1.8, 2.1, -1.6]^T$, and the scheduled trajectory is set as a 3-D helical path, which is parameterized by $x(\varpi) = 2.5 + 1.7 \cos(\varpi)$, $y(\varpi) = 2 + 1.3 \sin(\varpi)$, $z(\varpi) = -0.5 \sin(\varpi/4 + \pi/8)$ with $\varpi \in [-0.5\pi, 4\pi]$. The control period and constant sampling time are set to 60 ms. Afterwards, upper limit of the lookahead distance is set as $\bar{d}_l = 0.5$ m and weight coefficient is selected as $w_{ij} = 0.25$. Simultaneously, weighting matrix of the triggering mechanism is set as a unit matrix with $\Phi = I_{6 \times 6}$. Bounds of $\sigma(t)$ are set as $\underline{\sigma} = 0.006$ and $\bar{\sigma} = 0.03$ with $k_\sigma = 2$, respectively.

Table 1. Triggering numbers and quantitative analysis during formation control process

Items	Total triggering numbers					RMSE
	Leader	1	2	3	4	
PTM	957	957	957	957	957	4.34
sETM	352	731	668	723	578	4.90
dETM	276	598	583	608	528	4.96

Figure 3(a) shows simulation results with the proposed formation control law based on dETM. In comparison, periodic-triggered mechanism (PTM) and sETM are also employed with the same control law. Note that PTM is triggered at every sampling time, and sETM is set the same as (13) with a constant coefficient $\sigma = 0.01$. The formation error ε_e is selected as a pivotal index to measure the formation control performance for these different mechanisms in Fig. 3(b). Further, root mean square error (RMSE) is utilized for quantitative analysis, where the analysis results and total triggering numbers are both recorded in Table 1. It reveals intuitively that the proposed formation control law based on dETM copes well with the formation control task. Compatible with locomotion of the moving target, the predefined shape is initially produced at $t = 18$ s. Agents in the multi-robotic fish system keep pace in the following formation keeping process and ε_e converges to an acceptable range gradually. The other two based on PTM and sETM also get ideal formation control performance.

Specifically, PTM-based formation control method has the best performance with the lowest RMSE at 4.34. Nevertheless, despite loss of formation performance less than 15%, triggering numbers of two ETM-based schemes are dramatically reduced, where over 36% communication consumption is saved. PTM has faster rate of convergence indeed at the first 22 s. However, with a higher communication frequency, the formation performance is unexpectedly poor when approaching the equilibrium state. In a word, by regulating communication intervals with triggering mechanism, utilization of the interactive information can improve effectively on the one hand. On the other hand, high-frequency communication is not necessarily favorable to the control performance. It means some superfluous control commands are issued, especially near the equilibrium state.

Moreover, in comparison with the sETM-based method, dETM-based method manifests significantly lower triggering numbers with the same level of control performance. As for sETM, the threshold function $\mathcal{T}_i(\hat{z}_i(t))$ composed of state deviations provides standard to measure relative magnitude of the triggering errors. However, the formation is not configured with high state deviations at the outset, hence the triggering frequency is low at that time. It is a typical downside to produce formation rapidly. Under the supervision of DTPs, dETM-based method shows its merit to decrease the threshold function and increase the convergence speed when suffering from large fluctuation while reducing inessential communication afterwards. Therefore, the proposed method with dETM is

validated to preserve a reliable formation control performance while mitigating the unnecessary waste of communication resources to a great extent.

5 Conclusion

In this paper, we have proposed a 3-D distributed formation control framework for a multi-robotic fish system to constitute an anticipated configuration guided by a moving target. To formulate the control objectives, the formation control process is analyzed firstly. Thereafter, an event-triggered formation control framework is proposed. In particular, the communication topology is set up and a position-based formation control law is utilized based on local measurements. Further, sustaining a trade-off between formation control performance and communication consumption, a dETM is presented to measure importance of the interactive information and mitigate unnecessary wastes. Moreover, adequate simulations are carried out to validate effectiveness of the proposed method with elaborate comparisons. In summary, the proposed formation control framework is effective in the formation control task for a multi-robotic fish system.

Future work will concentrate on a more complicated real-world formation control task while further reducing the communication consumption.

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