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A novel strategy to solve communication constraints for formation control of multi-AUVs

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Dear editor,

Interest in terms of research on formation control of multiple autonomous underwater vehicles (multi-AUVs) has gained considerable attention in recent years [1–5], owing to its extensive applications in deep sea inspection, ocean sampling and localization.

The formation control objective cannot be realized without information (i.e., position and velocity) exchange between AUVs. Owing to the particularity of underwater environments, acoustic communication is the most effective data transmission mode. However, this mode still has many drawbacks, such as long propagation delays, high transmission losses, packet drops, and limited bandwidth. Reducing the amount of data is an effective way of decreasing the impact of such defects. Generally speaking, there are two main strategies to decrease the amount of data in general communication systems. First is to reduce the data in each packet, and the second is to reduce the amount of data packets.

A reasonable way to approach the first strategy is removing the transmission of speed information between AUVs. Owing to environmental disturbances and/or technology limitation, the accurate velocity measurement of AUVs is more difficult than position measurement. To obtain the velocity of AUVs, the observer is a common way, which is used in many studies [4,5]. In [4], a high-gain observer-based cooperative path following control approach was developed without measuring the velocity of vehicles. In [5], a global finite-time convergent observer was proposed to reconstruct vehicle velocity. Neither the linear observer in [4] nor the nonlinear observer in [5] can guarantee convergence within the setting time.

An effective way to approach the second strategy is to reduce the communication frequency between different subsystems. To this end, some new communication mechanisms have been proposed in [6, 7]. Among these methods, event-triggered communication mechanism is of significant interest. The key idea of the event-triggered theory is to sample and update the controller only when certain conditions are violated. If the threshold is set properly, this scheme can reduce the required computation cost while maintaining satisfactory control performance.

With regard to the above observations, this study proposes a novel strategy to solve the communication constraint problem. This new strategy combines the event-triggered transmission scheme with the velocity observer method. This strategy is capable of not only decreasing the data in each packet but also can reducing the amount of data packets.

Kinematics and dynamics model of AUV. The kinematics and kinetics of the AUV can be described as [8]

$$\begin{cases} \dot{p} = J(\Theta)\upsilon, \\ M\dot{\upsilon} = -C(\upsilon)\upsilon - D(\upsilon)\upsilon + \tau, \end{cases} \tag{1}$$

where $p = [x, y, z]^{\mathrm{T}}$ and $\Theta = [\phi, \theta, \psi]^{\mathrm{T}}$ denote the position and attitude vectors expressed in the earth-fixed reference frame $\{E\}$, respectively; $J(\Theta)$ is a rotation matrix from the body-fixed reference frame $\{B\}$ to the earth-fixed reference frame $\{E\}$; $\upsilon = [u, v, \omega]^{\mathrm{T}}$ denotes the velocity vector expressed in the body-fixed reference frame; $\tau = [\tau_u, \tau_v, \tau_\omega]^{\mathrm{T}}$ denotes the control input; M and $D(\upsilon)$ represent the inertia matrix and the nonlinear damping matrix, respectively. For simplicity, the dynamics model can be rewritten as follows:

$$\dot{\upsilon} = \varphi + M^{-1}\tau, \tag{2}$$

where $\varphi = [\varphi_u, \varphi_v, \varphi_\omega]^{\mathrm{T}}$ and $\varphi = M^{-1}(-C(\upsilon)\upsilon - D(\upsilon)\upsilon)$.

Assumption 1. There is a known and positive constant ϱ_* that satisfies

$$|\varphi_*(*_1(t), t)| - |\varphi_*(*_2(t), t)| \leqslant \varrho_* | *_1(t) - *_2(t)|, \tag{3}$$

where $* = u, v, \omega$ and let $\varrho = \mathrm{diag}(\varrho_u, \varrho_v, \varrho_\omega)$.

Lemma 1 ([9]). Consider the following nonlinear dynamic system:

$$\dot{x} = f(x),\ f(0) = 0,\ x(0) = x_0,\ x \in \mathbb{R}^n, \tag{4}$$

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where $x = [x_1, x_2, \ldots, x_n]^{\mathrm{T}} \in \mathbb{R}^n$ is the state vector, and $f(x) : \mathbb{R}^n \longrightarrow \mathbb{R}^n$ is a nonlinear function. Suppose $f(x)$ is a homogenous vector function in the bi-limit with associated triples (r_0, k_0, f_0) and $(r_\infty, k_\infty, f_\infty)$. If $\dot{x}_0 = f_0(x)$ and $\dot{x}_\infty = f_\infty(x)$ are globally asymptotically stable (GAS), then the following statements hold:

(1) The origin of (4) is fixed-time stable when the condition $k_\infty > 0 > k_0$ holds;

(2) Let d_{V_0} and d_{V_∞} be real numbers such that $d_{V_0} > \max_{1\leqslant i\leqslant n} r_{0,i}$ and $d_{V_\infty} > \max_{1\leqslant i\leqslant n} r_{\infty,i}$. There exists a continuous and positive definite function $V(x)$ such that the function $\frac{\partial V}{\partial x_i}$ is homogeneous in the bi-limit associated with triples $(r_0, d_{V_0} - r_{0,i}, \frac{\partial V_0}{\partial x_i})$ and $(r_\infty, d_{V_\infty} - r_{\infty,i}, \frac{\partial V_\infty}{\partial x_i})$, and the function $\frac{\partial V}{\partial x} f(x)$ is negative definite.

Triggering event design. Before the event-triggered communication mechanism is given, a binary variable σ is introduced to describe the communication mode (i.e., continuous or periodic) between AUVs.

The binary variable σ is represented as follows:

$$\sigma = \begin{cases} 1, & \text{if } f_i(t) \geqslant 0, \\ 0, & \text{else}, \end{cases} \tag{5}$$

where $\sigma = 1$ indicates the continuous communication mode adopted between AUVs, and periodic communication is selected when $\sigma = 0$.

The position tracking error vector $\tilde{e}(tk)$ is defined as follows:

$$\tilde{e}(tk) = p_l(t_{kh}) - p_f(t) - d_{lf}, \tag{6}$$

where $\{t_{kh}\}$, $k = 1, 2, \ldots, N$ are the time instants at which data transmission takes place between AUVs. Here, h and d_{lf} denote the sampling period and the desired formation configuration in the global coordinate frame $\{E\}$, respectively.

By denoting $\{t^0, t^1, \ldots, t^k\}$ to be a sequence of triggering instants for following AUVs, the triggering instant t^k is iteratively defined by

$$t^{k+1} = \inf\{t > t^k : f_i(t) \geqslant 0\}, \tag{7}$$

where $f_i(t)$ is the event triggering function which defined as

$$f_i(t) = |\tilde{e}(tk)| - \delta|d_{\min}|, \tag{8}$$

in which $d_{\min} = [d_{x\min}, d_{y\min}, d_{z\min}]^{\mathrm{T}} \in \mathbb{R}^3$ is a positive definite constant vector, $\delta = \tanh(x) + 1$ is the dynamic threshold parameter with $x = \Sigma \frac{\gamma_* |\tilde{e}_*(tk)|}{|d_{*\min}|}$ and $\delta|d_{\min}|$ being the minimum threshold of the triggering event. Here, $\gamma*$ denotes the weight with $\Sigma\gamma_* = 1$, $* = x, y, z$.

Remark 1. Compared with the continuous communication mechanisms of [1, 3–5], the event-based communication scheme can significantly decrease the communication burden. Furthermore, compared with the mechanisms of [6, 7], the proposed dynamic event-triggered mechanism can achieve a better trade-off between reducing data transmissions and preserving favorable formation performance.

When the event is triggered, the leader will continuously send data to followers, and to exclude the Zeno behavior, the continuously communication mode will be maintain h.

To further reduce the communication burden, a fixed-time velocity observer is proposed to estimate the velocity υ of the leader AUV in the continuous communication mode. Before the observer design, a coordinate transformation is first given.

Coordinate transformation. Define the actual velocity vector as follows:

$$\zeta = J(\Theta)\upsilon, \tag{9}$$

where $\zeta = [\zeta_u, \zeta_v, \zeta_\omega]^{\mathrm{T}}$. Here, we rewrite $J(\Theta)$ as J in the following content.

Together with the AUV dynamics in (1), the transformed model can be written as follows:

$$\begin{cases} \dot{p} = \zeta, \\ \dot{\zeta} = f(p, \zeta) + u, \end{cases} \tag{10}$$

where $f(p, \zeta) = JM^{-1}(-D(J^{-1}\zeta)J^{-1}\zeta - J)$, and $u = JM^{-1}\tau$.

Based on the transformed dynamics of the AUV, a velocity observer will be designed in the following content.

Velocity observer design. To estimate the velocity vector $\zeta = [\zeta_u, \zeta_v, \zeta_\omega]^{\mathrm{T}}$, the observer is constructed as follows:

$$\begin{cases} \dot{\hat{p}} = \hat{\zeta} + k_1 e_1 + k_2 e_1^{\alpha} + k_3 e_1^{\beta}, \\ \dot{\hat{\zeta}} = u + \lambda_1 e_1 + \lambda_2 e_1^{\bar{\alpha}} + \lambda_3 e_1^{\bar{\beta}} + f(p, \hat{\zeta}), \\ \hat{\upsilon} = J^{-1}\hat{\zeta}, \end{cases} \tag{11}$$

where $e_1 = p - \hat{p}$, $e_2 = \zeta - \hat{\zeta}$, $k_i \in \mathbb{R}^{3\times 3}$, $\lambda_i \in \mathbb{R}^{3\times 3}$ $(i = 1, 2, 3)$ are positive definite diagonal matrices and the parameters α, β, $\bar{\alpha}$, and $\bar{\beta}$ are given as follows:

$$\alpha = \frac{1 + 2\epsilon}{2},\ \beta = \frac{2 + \epsilon}{2},\ \bar{\alpha} = 2\epsilon,\ \bar{\beta} = \epsilon + 1 \tag{12}$$

with $\epsilon \in (0, \frac{1}{2})$.

In light of Lemma 1, Theorem 1 is obtained.

Theorem 1. Consider the proposed velocity observer (11) with parameters defined in (12) under Assumption 1. If elements of matrices k_i and λ_i satisfy the following feasibility conditions:

$$\begin{aligned} &\lambda_2 > k_2,\ \lambda_3 > k_3,\ \frac{\lambda_1}{4k_1} - \frac{3}{2}\varrho > 0, \\ &k_1 - \frac{2\lambda_1}{k_1} - \frac{\varrho}{2} - \frac{k_1(k_2 + k_3)}{2} > 0, \end{aligned} \tag{13}$$

then the states $(\hat{p}, \hat{\zeta})$ of the observer (11) will converge to the actual states (p, ζ) within fixed time.

The proof of Theorem 1 is given in Appendix A, and the designed observer is testified by numerical simulations, as shown in Appendix B.

Remark 2. Here, the designed observer not only can estimate the speed of the leader AUV within settling time regardless of the initial states of the system, but also can be used to estimate the speed information of the following AUV with appropriately modifying parameters.

Conclusion. This study focused on the problem of communication constraints in multi-AUV formation systems. A novel strategy that integrates the event-triggered intermittent communication with a velocity observer was proposed. Event-triggered theory is more effective than the traditional time-scheduled control approach, as it can not only reduce the communication burden but also ensure satisfactory system performance. To further resolve the communication constraints, a fixed-time theory based estimation approach was presented to estimate the velocity of the leader AUV. Actual speed can be precisely estimated within fixed time under the action of a velocity observer. Finally, numerical examples were provided to illustrate the theoretical results.

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Supporting information Appendixes A and B. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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