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Network-based modelling and dynamic output feedback control for unmanned marine vehicles in network environments☆

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ABSTRACT

This paper is concerned with network-based modelling and dynamic output feedback control for an unmanned marine vehicle in network environments. A network-based model for the unmanned marine vehicle in the network environments is established for the first time by taking sampler-to-control station packet dropouts, network-induced delays, and packet disordering into account. This model is then extended to the unmanned marine vehicle system in the network environments subject to control station-to-actuator, and both sampler-to-control station and control station-to-actuator packet dropouts, network-induced delays, and packet disordering. Based on these models, dynamic output feedback controllers are designed to attenuate the oscillation amplitudes of the yaw velocity error and the yaw angle. It is shown through a benchmark example that (i) compared with the unmanned marine vehicle without control, the designed dynamic output feedback controllers can attenuate the oscillation amplitudes of the yaw velocity error and the yaw angle; and (ii) the designed dynamic output feedback controllers can provide much smaller oscillation amplitudes of the yaw velocity error and the yaw angle than a proportional–integral controller.

1. Introduction

Marine vehicles are widely used in military operations, transportation, fishing, tourism, environmental monitoring, oil and pollution clean-up, scientific characterization, exploration, and so on. Manned/unmanned marine platforms can provide cost-effective solutions to coastal and offshore problems. Because of an increasing demand for high accuracy and reliability in practical applications, motion control of marine vehicles has received much attention (Fossen, 1994) and there are some interesting results available in the literature, e.g., roll stabilization (Ren, Zou, & Wang, 2014), heading control (Kahveci & Ioannou, 2013), mooring control (Chen, Ge, How, & Choo, 2013), tracking control (Katayama & Aoki, 2014), and dynamic positioning (Johansen, Bø, Mathiesen, Veksler, & Sørensen, 2014).

Note that manned marine vehicles were investigated in the above mentioned literature. Compared with manned marine vehicles, unmanned marine vehicles (UMVs) can provide more flexibility in practical applications. Some interesting results dealing with UMVs were reported in Adamek, Kitts, & Mas (2015), Fischer, Hughes, Walters, Schwartz, & Dixon (2014), Kim, Kim, Shin, Kim, & Myung (2014), Liu & Bucknall (2015), Mahacek, Kitts, & Mas (2012) and Sohn, Oh, Lee, Park, & Oh (2015). When carrying out tasks such as scientific characterization and exploration, a UMV may be stopped and anchored. However, external disturbance, such as waves, wind, and current, may induce the oscillation of the yaw velocity error and the yaw angle of the UMV, where the yaw velocity error denotes the difference between the actual yaw velocity and the constant yaw velocity reference. Obviously, the oscillation of the yaw velocity error and the yaw angle is not desired in practical applications. For a UMV, how to propose an appropriate control scheme to attenuate the oscillation amplitudes of the yaw velocity error and the yaw angle is practically valuable and attractive.

Based on a remote land-based control station, one can control the motion of a UMV in network environments. The communication between the UMV and the remote control station is completed through communication networks. In the last decade, because of several attractive advantages, such as lower cost, more flexibility and higher reliability, networked control systems (NCSs) have been found a wide range of applications in areas including transportation systems, power systems, offshore platforms (Zhang, Han, & Zhang, 2016), multi-agent systems (Ding, Han, Ge, & Zhang, 2018;

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He et al., 2017), spring–mass systems (Yan, Qian, Zhang, Yang, & Guo, 2016), and Markov jump systems (Zhu, Han, & Zhang, 2014). There are many results in the literature, see the survey papers (Ge, Yang, & Han, 2017; Zhang, Han, & Zhang, 2017). For an NCS, controller-to-actuator network-induced delays whose length is smaller than a sampling period were taken into account in Jungers, Castelan, Moraes, & Moreno (2013), while packet dropouts were not considered. As observed from Du, Sun, & Wang (2014), both packet dropouts and network-induced delays were taken into consideration. For the UMV controlled through communication networks, how to take sampler-to-control station and control station-to-actuator packet dropouts, network-induced delays, and packet disordering into account, and to establish network-based models are of paramount importance and unresolved. Addressing these issues is the first motivation of the current study.

State feedback control of an NCS was studied in Peng & Han (2013, 2016). In some practical situations, controlled plants' states may not be always measurable. Thus, it is significant to study observer-based control of systems under consideration (Du et al., 2014; Wang & Han, 2016; Wang, Wang, & Han, 2016) and dynamic output feedback control of systems under consideration (Jungers et al., 2013; Zhang, Han, & Jia, 2015). For a UMV, if the surge velocity, sway velocity, and the yaw velocity are not measurable, how to propose an appropriate dynamic output feedback controller (DOFC) design scheme to attenuate the oscillation amplitudes of the yaw velocity error and the yaw angle is significant and has received no attention in the literature, which is the second motivation of the current study.

The non-uniform distribution characteristic of interval time-varying delays was considered in Wang & Han (2014) and Yue, Tian, & Han (2013) to study the stabilization of systems. For the UMV in network environments, packet dropouts and network-induced delays may be non-uniformly distributed. Note that the non-uniform distribution characteristic of packet dropouts and network-induced delays can be implied by the non-uniform distribution characteristic of an interval time-varying delay (Zhang & Han, 2013). If such a characteristic is considered, how to establish network-based models for the UMV, and how to construct appropriate integral inequalities for products of vectors which are introduced in DOFC design are of paramount importance.

In this paper, we will address issues about network-based modelling and dynamic output feedback control for an unmanned marine vehicle in network environments. We will establish a network-based model for the UMV for the first time by introducing a state tracking system, and taking sampler-to-control station packet dropouts, network-induced delays, and packet disordering into account. Then we will extend this model to the UMV with control station-to-actuator, and both sampler-to-control station and control station-to-actuator packet dropouts, network-induced delays, and packet disordering. Based on these models, we will design DOFCs to attenuate the oscillation amplitudes of the yaw velocity error and the yaw angle. We will adopt the non-uniform distribution and Wirtinger-based integral inequality approach to derive less conservative DOFC design criteria. We will show through a benchmark example that (i) the designed DOFCs can attenuate the oscillation amplitudes of the yaw velocity error and the yaw angle; and (ii) compared with the proportional–integral controller, the designed DOFCs can provide much smaller oscillation amplitudes of the yaw velocity error and the yaw angle.

Notation: $\mathbb{R}^n$ denotes n-dimensional Euclidean space. I and 0 represent an identity matrix and a zero matrix, respectively. E stands for the expectation operation. $*$ denotes the entries of a matrix implied by symmetry. Matrices, if not explicitly stated, are assumed to have appropriate dimensions.

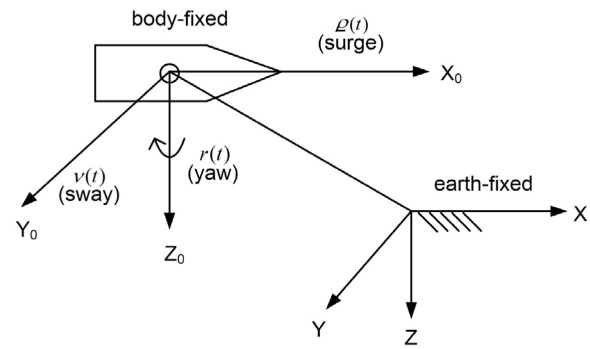

Fig. 1. Body-fixed and earth-fixed reference frames.

2. Network-based modelling for a UMV

The dynamics of a marine vehicle in 6 degrees of freedom include surge, sway, heave, roll, pitch, and yaw. The first order model of Nomoto is the simplest model to describe the dynamics of the marine vehicle. Due to the nominal high order state-space model's resemblance of the Nomoto model, this paper investigates an anchored marine vehicle, which is equipped with thrusters (Grovlen & Fossen, 1996; Kahveci & Ioannou, 2013). Consider the body-fixed and earth-fixed reference frames presented in Fig. 1, where X_0, Y_0, and Z_0 denote the longitudinal axis, transverse axis, and normal axis, respectively; X, Y, and Z denote earth-fixed reference frames.

The body-fixed equations of motion in surge, sway, and yaw are described as

$$M\dot{\nu}(t) + N\nu(t) + G\eta(t) = u(t) \tag{1}$$

where $\nu(t) = [\varrho(t)\ \upsilon(t)\ r(t)]^T$ with $\varrho(t)$, $\upsilon(t)$, and $r(t)$ denoting the surge velocity, sway velocity, and yaw velocity, respectively; $\eta(t) = [x_p(t)\ y_p(t)\ \psi(t)]^T$ with $x_p(t)$ and $y_p(t)$ denoting positions and $\psi(t)$ denoting the yaw angle. The control input vector $u(t) = [u_1(t)\ u_2(t)\ u_3(t)]^T$ with $u_1(t)$ and $u_2(t)$ denoting the forces in surge and sway, respectively, and $u_3(t)$ denoting the moment in yaw provided by the thruster system; M denotes the matrix of inertia which is invertible with $M = M^T > 0$; N introduces damping; the matrix G represents mooring forces; and

$$\dot{\eta}(t) = J(\psi(t))\nu(t) \tag{2}$$

where

$$J(\psi(t)) = \begin{bmatrix} \cos(\psi(t)) & -\sin(\psi(t)) & 0 \\ \sin(\psi(t)) & \cos(\psi(t)) & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

Let $A_1 = M^{-1}G$, $A = -M^{-1}N$, $B = M^{-1}$, and $x(t) = \nu(t)$. Then the system (1) can be expressed as

$$\dot{x}(t) = Ax(t) + Bu(t) - A_1 f(t, x(t)) \tag{3}$$

where $f(t, x(t)) = \eta(t)$ with $f(t, x(t))$ denoting a time-varying, nonlinear vector-valued function of $x(t)$. If the disturbance, denoted as $\tilde{D}(t)$, induced by waves, wind, and current, is taken into account, the system in (3) is converted to

$$\dot{x}(t) = Ax(t) + Bu(t) + \tilde{D}(t) - A_1 f(t, x(t)). \tag{4}$$

As mentioned in the Introduction, a marine vehicle may be stopped and anchored when carrying out tasks such as scientific characterization and exploration. Whenever the yaw angle $\psi(t)$ is small enough, one has that $\cos(\psi(t)) \approx 1$, $\sin(\psi(t)) \approx 0$, and