Ocean Engineering 115 (2016) 159–167

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Robust fault–tolerant tracking with predefined performance for underactuated surface vessels

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ARTICLE INFO

Article history:
Received 8 April 2015
Accepted 3 February 2016
Available online 22 February 2016

Keywords:
Fault–tolerant control
Predefined performance
Underactuated surface vessels
System faults
Actuator faults

ABSTRACT

This paper investigates a robust fault–tolerant tracking (FTT) problem of uncertain underactuated surface vessels (USVs) with unknown faults in nonlinear dynamics and saturated actuators. All nonlinearities, external forces, and faults in USVs are assumed to be unknown. Compared with the existing literature, the main contribution of this paper is to present a predefined performance design methodology for FTT of USVs that are nonholonomic systems. The predefined performance bounds, which characterize the convergence rate, maximum overshoot, and steady-state response of control errors, are integrated with error surfaces in consideration of underactuated constraints. A new FTT control scheme using the integrated error surfaces is designed without applying any function approximators to estimate unknown nonlinearities including faults and requiring the repeated differentiation of virtual controllers where auxiliary variables are derived to ensure the predefined performance of underactuated systems. Thus, compared with the previous controllers for USVs, a simple controller design can be derived regardless of unknown nonlinearities, their faults, and actuator faults. It is shown that tracking errors are preserved within bounds guaranteeing predefined transient and steady-state performance.

1. Introduction

There are challenging problems for trajectory tracking of uncertain underactuated surface vessels (USVs). One of them is that the motion of USVs possesses three degrees of freedom whereas there are only two available controls. Thus, the trajectory tracking control of USVs has been received great attention from the control community. Jiang (2002) proposed two constructive tracking solutions based on the Lyapunov's direct method and passivity scheme. In Lefeber et al. (2003), a global tracking result was obtained by applying a cascade approach. These works assumed that the yaw velocity is nonzero, but it is very restrictive because the straight line cannot be tracked. Though this problem was overcome in Do et al. (2002), the control methods presented in Jiang (2002), Lefeber et al. (2003) and Do et al. (2002) still assume that the mass and damping matrices of USVs are diagonal not to destroy the cascade structure. To relax this assumption, the state transformation method was proposed in Do and Pan (2005). Another problem is that it is difficult to find coefficients in the damping matrix (Skjetne et al., 2005; Do and Pan, 2006) and environmental disturbances are inevitable. Therefore, various control algorithms such as adaptive control (Li et al., 2008), sliding mode control (Ashrafiuon et al., 2008; Yu et al., 2012), disturbance observer (Do, 2010; Yang et al., 2014), switching control (Wu et al., 2014), model predictive control (Yan and Wang, 2012), a linear algebra approach (Serrano et al., 2014), and intelligent control (Zhang and Zhang, 2014) were proposed to deal with the model uncertainties and external disturbances.

The fault–tolerant control problem of USVs has been received relatively little attention than the tracking problem. Many underwater vehicles have actuators more than required DOFs. This is usually not just for backup in the event of failure but rather related with hardware design aspect (Podder and Sarkar, 2001). However, this traditional approach increases the cost, weight, and volume of USVs and complicates the allocation of actuator forces (Polycarpou and Helmicki, 1995). Thus, some analytical fault–tolerant control approaches have been proposed for USVs where unexpected faults causing substantial damage in systems are compensated by using the adaptive technique or function approximators (Chen and Tan, 2013; Chen et al., 2016). Despite these efforts, these approaches increase the complexity of the control system due to the use of the function approximators or the adaptive tuning laws. Furthermore, the transient performance of control errors cannot be ensured when the faults occur at unknown time instants.

On the other hand, recent advancement of nonlinear control theories has been allowed to impose the certain specifications on

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http://dx.doi.org/10.1016/j.oceaneng.2016.02.006
0029-8018/

the control performance of nonlinear systems. Specifically, these specifications mean the performance indices such as overshoot, convergence rate, and steady-state error that affect the transient and steady-state performance of control errors. Prescribed performance control introduced in Bechlioulis and Rovithakis (2008) is an efficient tool, which achieves the preassigned transient and steady-state performance via a control error transformation integrating predefined performance functions. This methodology has been applied to control several classes of nonlinear systems (see Bechlioulis and Rovithakis, 2010, 2013; Kostarigka and Rovithakis, 2012 and references therein). However, although these aforementioned works considered some nonlinear systems, their methods can only deal with fully-actuated systems. Namely, there have been still no research results available for the predefined performance design problem of underactuated systems.

Motivated by the observations above, we develop a predefined performance design methodology for fault–tolerant tracking (FTT) of USVs with multiple faults in both nonlinear dynamics and saturated actuators. It is assumed that all nonlinearities, external forces, and faults in USVs are unknown. Control errors are incorporated into predefined performance bounding functions where auxiliary variables are defined to deal with underactuated constraints. On the basis of the incorporated errors, we recursively design a FTT control scheme by deriving update laws of auxiliary variables for the predefined performance design of USVs. It is shown that the tracking errors remain within performance bounds predefined by adjusting design parameters of performance functions. The main contribution of this paper is three-fold: (i) compared with the previous works related to prescribed performance control (Bechlioulis and Rovithakis, 2008, 2010, 2013; Kostarigka and Rovithakis, 2012), a design methodology for underactuated systems is firstly developed in this paper; (ii) contrary to the previous control methods for USVs with uncertainties or unknown nonlinearities (Yan and Wang, 2012; Zhang and Zhang, 2014), the proposed FTT scheme is simply designed without employing any function approximators to estimate unknown nonlinearities and the adaptive technique to compensate for uncertainties, and requiring the repeated differentiation of virtual controllers; and (iii) compared with all existing approaches for fault–tolerant control of USVs (Chen and Tan, 2013; Chen et al., 2016), the proposed approach can ensure transient performance at the moments when unknown multiple faults occur, because of control errors constrained by prescribed performance bounds.

This paper is organized as follows. In Section 2, we present the predefined performance problem for FTT of USVs with unknown multiple faults. The error transformation and the FTT system with predefined performance are developed in Section 3. A simulation result is discussed in Section 4. Finally, Section 5 gives some conclusions.

2. Problem formulation

Consider the kinematics and dynamics of USVs with unknown faults in both nonlinear dynamics and saturated actuators as follows (Fossen, 2002):

$$\dot{\eta} = J(\psi)\nu,$$
$$M\dot{\nu} = -C(\nu)\nu - D(\nu)\nu + H(\nu) + \tau_d + F_p\tau_s(\tau), \qquad (1)$$

where $\eta = [x, y, \psi]^\top$ is the state vector denoting the position (x, y) and the yaw angle ψ of USVs in the earth-fixed frame, $\nu = [u, v, r]^\top$; u, v, and r denote the surge, sway, and yaw velocities of USVs in the body-fixed frame, respectively, see Fig. 1; $\tau_d = [\tau_{d,u}, \tau_{d,v}, \tau_{d,r}]^\top$ denotes the external forces such as wind and ocean currents, $\tau = [\tau_u, 0, \tau_r]^\top$ is the control vector consisting of the surge force τ_u

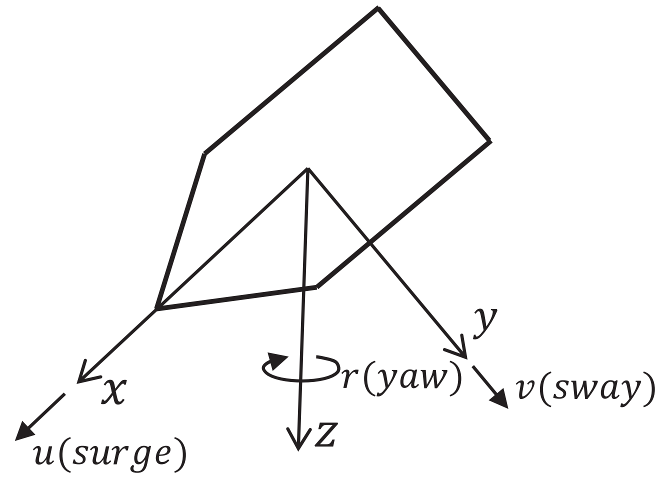

Fig. 1. The coordinate system for USVs.

and the yaw moment τ_r, $\tau_s = [\tau_{s,u}, 0, \tau_{s,r}]^\top$ is the saturated control vector defined as

$$\tau_{s,i} = \begin{cases} -\tau_{i,M}, & \tau_i \le -\tau_{i,M} \\ \tau_i, & -\tau_{i,M} < \tau_i < \tau_{i,M} \\ \tau_{i,M}, & \tau_i \ge \tau_{i,M} \end{cases} \qquad (2)$$

where $i = u, r$; $\tau_{i,M} > 0$ are the limit bounds of control inputs, and $F_p = \mathrm{diag}[f_1, 0, f_2] \in \mathbb{R}^{3\times3}$ denotes the actuator fault vector that occurs at T_a where

$$f_i = \begin{cases} 0 < f_i < 1; & \text{if the thrusters are in partial failure,} \\ 1; & \text{if the thrusters are not in failure.} \end{cases}$$

In (1), the matrices $J(\psi)$, $D(\nu)$, $C(\nu)$, $S(\nu)$, and M are represented by

$$J(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad D(\nu) = \begin{bmatrix} d_{11}(u) & 0 & 0 \\ 0 & d_{22}(v,r) & d_{23}(v,r) \\ 0 & d_{32}(v,r) & d_{33}(v,r) \end{bmatrix},$$

$$C(\nu) = \begin{bmatrix} 0 & 0 & -m_{22}v - m_t r \\ 0 & 0 & m_{11}u \\ m_{22}v + m_t r & -m_{11}u & 0 \end{bmatrix}, \quad H(\nu) = \begin{bmatrix} h_{1,f} \\ h_{2,f} \\ h_{3,f} \end{bmatrix},$$

$$M = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & m_{23} \\ 0 & m_{32} & m_{33} \end{bmatrix}, \qquad (3)$$

where

$$m_{11} = m - X_{\dot{u}}, \quad m_{22} = m - Y_{\dot{v}}, \quad m_{23} = mx_g - Y_{\dot{r}},$$
$$m_{32} = mx_g - N_{\dot{v}}, \quad m_{33} = I_z - N_{\dot{r}},$$
$$m_t = (m_{23} + m_{32})/2, \quad d_{11}(u) = -(X_u + X_{|u|u}|u|),$$
$$d_{22}(v,r) = -(Y_v + Y_{|v|v}|v| + Y_{|r|v}|r|),$$
$$d_{23}(v,r) = -(Y_r + Y_{|v|r}|v| + Y_{|r|r}|r|),$$
$$d_{32}(v,r) = -(N_v + N_{|v|v}|v| + N_{|r|v}|r|),$$
$$d_{33}(v,r) = -(N_r + N_{|v|r}|v| + N_{|r|r}|r|),$$
$$h_{i,f} = \sum_{k=1}^{N} \beta(t - T_{i,k})\varpi_{i,k}(\nu), \quad i = 1, 2, 3.$$

In these expressions, X_u, $X_{u|u|}$, Y_v, $Y_{|v|v}$, $Y_{|r|v}$, Y_r, $Y_{|v|r}$, $Y_{|r|r}$, N_v, $N_{|v|v}$, $N_{|r|v}$, N_r, $N_{|v|r}$, and $N_{|r|r}$ are the linear and quadratic drag coefficients, m is the mass of USVs, $X_{\dot{u}}$, $Y_{\dot{v}}$, $Y_{\dot{r}}$, $N_{\dot{v}}$ and $N_{\dot{r}}$ are added masses, x_g is the center of gravity in the body-fixed frame, I_z is the inertia with respect to the vertical axis, and M is invertible. The unknown nonlinear term $\varpi_{i,k}(\cdot) \in \mathbb{R}$ denotes the change of nonlinear functions in system dynamics due to the kth fault. Additionally, $\beta(t - T_{i,k})$ is the corresponding time profile of the fault occurring at some unknown time $T_{i,k}$ satisfying $\beta(t - T_{i,k}) = 0$ if t