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Thruster fault-tolerant control for dynamic positioning of vessels

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ABSTRACT

This paper proposes a fault-tolerant control (FTC) scheme for dynamic positioning (DP) of vessels under thruster faults. A fault state observer is constructed to estimate the unknown fault states. An integrated FTC design method based on the fault state observer is presented for the DP system using the dynamic surface control (DSC) approach. Furthermore, the FTC forces and moment computed from the designed FTC law are allocated to individual thrusters through applying the Lagrange multiplier method. By means of Lyapunov functions, it is proved that the FTC law can maintain the vessel position and heading at the desired values, while guaranteeing the uniform ultimate boundedness of all signals in the closed-loop DP FTC system of vessels under thruster faults. Finally, simulation studies on a 1:70 scale model of a supply vessel are carried out to demonstrate the effectiveness of the proposed FTC scheme.

1. Introduction

Dynamic positioning (DP) is the technology that maintains the position and heading of a vessel at a fixed point or along a predetermined track exclusively using its thrusters [1,2]. Compared with the traditional anchor moored positioning, DP technique is not limited by the water depths and has high maneuverability and excellent positioning accuracy, thus gaining wide application in the marine engineering. The development of advanced DP techniques has attracted considerable attention in recent years, with many results reported in the literature, such as neural network control [3,4], fuzzy control [5], sliding mode control [6] and backstepping [7,8]. However, most researches on the DP control did not consider the possibility of the occurrence of thruster faults. In practice, thrusters inevitably undergo faults due to the long time operation in the complex ocean environment, which can lead to the reduction of the DP accuracy, even the instability of DP control system. The fault-tolerant control (FTC) can maintain the control system stability and safety in the event of component faults [9]. The FTC for DP of vessels in the presence of thruster faults can enhance the DP control system reliability and has important practical significance for the wide applications of the DP technique in marine engineering.

In [10], the thruster faults were regarded as one part of the composite uncertainties which also included external environmental disturbance and dynamic uncertainties, and the interval type-2 fuzzy logic system was employed to reconstruct the composite uncertainties for the FTC problem of the dynamically positioned vessels. In [11], a proportional-derivative FTC scheme was proposed for the DP of vessels with partial loss of actuator effectiveness faults. In [10,11], the fault information cannot be obtained. To obtain the fault information, the fault detect and diagnosis (FDD) unit is involved in [12–17]. In [12], an observer-based fault detection filter and controller coordinated design criterion were derived for under-actuated unmanned surface vehicles. In [13], a robust fault detection observer and a time-varying detection criterion were presented to detect the actuator faults distinguished from uncertainties in nonlinear dynamics and external disturbances for under-actuated surface vessels, further an adaptive fault accommodation scheme based on the dynamic surface control (DSC) was designed to compensate the detected faults. But the proposed methods in [12,13] cannot be used to diagnose the thruster faults of over-actuated DP of vessels. [14] proposed a fault diagnosis method based on graph-theory and fault-tolerant control for the station keeping of a marine vessel in the presence of multiple failures in sensors or actuators. For an autonomous underwater vehicle, [15] diagnosed the thruster fault by comparing the errors between the inputs and the outputs of the thrusters with a fault detection threshold. [16] used an unknown input observer to detect and isolate the thruster faults for the over-actuated vessels. In [17], a discrete-time variable-structure FTC scheme with the pre-set fault isolation logic was developed for DP of vessels with uncertain external disturbances. There exists the time delay problem in the FTC strategies in [15–17] due to using the fault detection and

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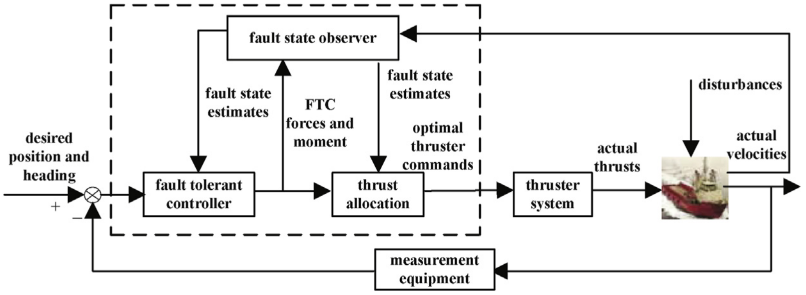

Fig. 1. Schematic of FTC scheme for DP system.

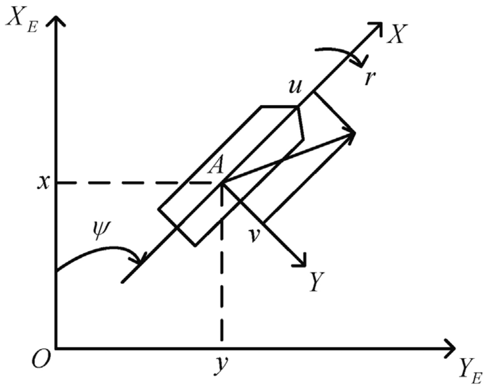

Fig. 2. Earth-fixed frame and body-fixed frame.

isolation (FDI) module.

For the above problem, this paper introduces the thruster effectiveness coefficients to express the fault states, which are assumed to be unknown. A fault state observer is constructed to provide the online estimates of the unknown effectiveness coefficients for overcoming the time delay problem, based on which, an integrated FTC scheme for DP systems is developed. The schematic of proposed scheme in this paper is shown in Fig. 1. The actual position and heading of the ship are the controlled or output variables of the DP control system. The vessel may be subject to the environmental disturbances and thruster faults, which results in that the position and heading of the vessel deviate from desired values. Based on this deviation and the thruster fault information estimated by the fault observer, the DP fault tolerant controller calculates the appropriate forces and moment to maintain the vessel at the desired position and heading, and the control allocation unit assigns these forces and moment to individual thrusters as the thruster commands applying the Lagrange multiplier method. The main contributions of the proposed scheme are summarized as: (1) The proposed FTC scheme in this paper obtains the location and amplitude of the thruster faults under multiple thruster faults. (2) Under the partial loss-of-effectiveness faults of thrusters, the remaining execution capacity of fault thrusters can be still utilized to generate certain forces and moment. (3) Compared with the FTC schemes in [15–17], our proposed scheme integrating fault estimation and FTC can avoid the FDI time delay problem, which improves the reliability of the whole FTC system.

The rest of this paper is organized as follows. Section 2 presents the mathematical model to capture the nonlinear motion of a dynamically position vessel. Section 3 proposes the FTC scheme for DP system of vessels under thruster faults. Section 4 provides simulation studies with comparisons on a 1:70 scale model vessel. Section 5 concludes this paper.

2. Nonlinear motion mathematical model of dynamically positioned vessels

The reference coordinate frames of vessel motion is illustrated in Fig. 2, the earth-fixed reference frame is denoted as X_EOY_E and the body-fixed frame is XAY. The coordinate origin O of the earth-fixed reference frame is the original position of the vessel. The axis OX_E is directed to the north and the axis OY_E is directed to the east. The coordinate origin A of the body-fixed frame is located at the gravity center of the vessel. The axis AX is directed from aft to fore and the axis AY is directed to starboard. The kinematics and kinetics equations of a dynamically positioned surface vessel can be described, respectively, by the following equations:

$$\dot{\eta} = R(\psi)\upsilon \tag{1a}$$

$$M\dot{\upsilon} = -D\upsilon + \tau + d(t) \tag{1b}$$

where $\eta = [x, y, \psi]^T$ denotes the position vector of the vessel in the earth-fixed frame, consisting of the transverse position x, longitudinal position y, and the yaw angle $\psi \in [0, 2\pi)$. $\upsilon = [u, v, r]^T$ denotes the vessel's velocity in the body-fixed frame, consisting of the surge velocity u, the sway velocity v, and the yaw rate r of vessels. The rotation matrix $R(\psi)$ is

$$R(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

with the property $\|R(\psi)\| = 1$. $\|\cdot\|$ denotes the 2-norm of a vector or a matrix. M is the inertia matrix with added mass, which is invertible, symmetric and positive definite. D is a linear damp matrix. $\tau = [\tau_1, \tau_2, \tau_3]^T$ is the control forces and moment vector, consisting of the control forces τ_1 in surge and τ_2 in sway, and moment τ_3 in yaw. $d(t) = [d_1(t), d_2(t), d_3(t)]^T$ is the environmental disturbance vector due to wind, currents and waves, where $d_1(t)$ and $d_2(t)$ are the disturbance forces in surge and sway respectively, and $d_3(t)$ is the disturbance moment in yaw. The environmental disturbance $d_i(t)$ $(i = 1, 2, 3)$ is unknown yet unbounded with $|d_i(t)| \leq \bar{d}_i$, where $\bar{d}_i$ $(i = 1, 2, 3)$ is a positive constant. Notate $\bar{d} = [\bar{d}_1, \bar{d}_2, \bar{d}_3]^T$.

For a dynamically positioned vessel equipped with m azimuth thrusters, the control forces and moment vector τ is expressed by

$$\tau = G(\alpha)u_p \tag{3}$$

where $u_p = [u_{p_1}, \ldots, u_{p_m}]^T \in R^m$ with u_{p_i} being the thruster command of the ith thruster, and $G(\alpha) \in R^{3\times m}$ is the configuration matrix defined by

$$G(\alpha) = \begin{bmatrix} \cos(\alpha_1) & \cdots & \cos(\alpha_m) \\ \sin(\alpha_1) & \cdots & \sin(\alpha_m) \\ l_1 & \cdots & l_m \end{bmatrix} \tag{4}$$

where $l_i = l_{x_i}\sin(\alpha_i) - l_{y_i}\cos(\alpha_i)$, α_i is the orientation angle of the ith thruster, $\alpha_i \in [0, 180^\circ]$ denotes that the orientation angle is clockwise from the forward direction of the vessel, and $\alpha_i \in [-180^\circ, 0]$ denotes that the orientation angle is counterclockwise from the forward direction of the vessel. (l_{x_i}, l_{y_i}) is the location of the ith thruster in the body-fixed frame. Then, (1b) can be rewritten as follows

$$\dot{\upsilon} = -M^{-1}D\upsilon + M^{-1}G(\alpha)u_p + M^{-1}d(t) \tag{5}$$

In this paper, we consider the situation that there are the thruster