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Event driven tracking control algorithm for marine vessel based on backstepping method

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A B S T R A C T

In this paper, an event driven tracking control algorithm based backstepping method is proposed for marine vessel. A tracking controller is designed by using backstepping method at the beginning to guarantee global asymptotic tracking of the desired position or trajectory. The proposed event driven tracking control algorithm is achieved by extending the designed continuous time tracking controller. The event driven conditions are developed to determine the updated time instants of the event driven controller. The proposed event driven tracking controller could ensure that the error of tracking is uniform ultimately bounded and no Zeno behavior. Compared to the existing continuous or discrete controller, the communication quantity will be reduced by introducing the event driven conditions, and meanwhile it will lead to little executions of actuator. The performance of this algorithm is finally demonstrated through the simulation results.

1. Introduction

This paper investigates the problem of tracking control for marine vessel. There are many research results about control method of dynamic position, trajectory tracking or path following for marine vessel [1,2]. The backstepping method is often used to research the marine control in view of the fact that it is a better way to deal with nonlinearity problem and it is convenience for the further design of adaptive control schemes. Related results can be referred to the literatures as [3,4]. In the existing research results, the designed controllers broadly fall into two categories: continuous and discrete control. In particular, discrete control has been widely used in practical applications in view of the lower installation cost of microprocessors. The relative studies on discrete control for marine vessel could refer to the literatures [5,6]. These discrete control approaches depend on periodic sampling of the sensors and execution of control law, which requires to communicate the state (which includes the actuator state) information at every sampling instant. This will lead to unnecessary energy consumption and the wear of actuator due to the frequent changes of actuator status.

Some other control mechanisms have recently attracted significant attention, such as data driven control [7,8] and event driven control [9]. The data driven is widely used in some areas [10,11]. The event driven control could be considered as sampled-data control which may be aperiodic sampling. Compared with the periodic sampling of traditional discrete-time control, the sampling of calculation or execution of the event driven control is activated only when certain events occur or meet certain conditions. For the practical applications of the marine vessel, it is no doubt that the event driven tracking controller can make better use of the communication resources and extend the service life of propellers or thruster. Thus the event driven control will be more suitable for some applications of marine control.

Relevant studies on the event driven control are widely discussed recently. The state-feedback event driven control scheme [12–14,17] and model-based event driven control strategy [15] are proposed for the linear systems, respectively. The theoretical studies on event driven control are carried out for nonlinear systems [16]. Specifically, event driven control method is developed for input–output linearizable nonlinear systems which have internal dynamics, and applied to practical reactor temperature [18]. A robust event driven approach is proposed for nonlinear uncertain systems in the strict-feedback form based small-gain method, the designed controller is robust to the external disturbances [19]. The decentralized asynchronous event driven control methods are proposed for linear system and nonlinear system, respectively. The architecture in which is a system with full state feedback and with distributed sensors [20]. The small-gain approach to event driven control is also developed for nonlinear systems with state feedback and output feedback [21]. A framework and a universal

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formula are proposed for event driven stabilization of nonlinear systems [22,23]. The above theoretical results of event driven control for nonlinear system is useful for the practical applications. The issues of event driven tracking control for nonlinear systems are studied in [24,25], the proposed event driven control scheme is achieved by extending the continuous-time tracking control law, and assuming a reference system with exogenous input, the solution of which is desired trajectory. Recently, the applications of the event driven tracking control are investigated for unicycle mobile robots and fully actuated surface vessel in [26] and [27], respectively. The event driven control has great potential applications in marine control in view of the limited communication resources and the requirement of service life. However, existing results of event driven control are extremely rare.

The main contribution of this paper is that an event driven tracking control algorithm is proposed for marine vessel to ensure that the error of tracking is uniform ultimately bounded and no Zeno behavior. The continuous-time nonlinear tracking controller is firstly designed using backstepping method. The proposed algorithm is achieved by constructing the event driven conditions and extending the designed continuous-time tracking controller. Compared with the traditional tracking controller for the marine vessel, the designed control input is updated only when meet certain event conditions. The proposed event driven control method could significantly reduce the controller implementation frequency and the communication quantity. Thus the efficient energy consumption could be guaranteed and the service time of vessel could be improved, meanwhile it can ensure that the tracking performance is similar to that of the conventional method, if not better.

The remainder sections are organized as follows. Section 2 presents the mathematical model of marine vessel. Section 3 discusses the proposed event-triggered trajectory tracking control algorithm. In Section 4, simulations are carried out to validate the developed tracking algorithm. Finally, Section 5 provides the conclusions.

2. Mathematical model of marine vessel

In this paper, the tracking operations for marine vessel is focused on low-speed applications, so 3 degrees of freedom (DOF) model for marine vessel is considered. For marine vessel, $\eta = [N,\ E,\ \psi]^T$ represents north, east locations and heading in the frame of earth reference. $\nu = [u,\ v,\ r]^T$ denotes the velocities of surge, sway and yaw in the frame of body reference. The mathematical model for marine vessel is as follows [1]:

$$\begin{aligned} \dot\eta &= R(\psi)\nu \\ M\dot\nu + C(\nu)\nu + D(\nu)\nu &= \tau \end{aligned} \tag{1}$$

$R(\psi)$ is a matrix that used to transform from body to earth reference frame, the form of which is:

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

It satisfies $RR^T = R^T R = I_3$. $M \in \mathbb{R}^{3\times 3}$, $C(\nu) \in \mathbb{R}^{3\times 3}$ and $D(\nu) \in \mathbb{R}^{3\times 3}$ are system inertia, Coriolis-centripetal and damping matrices, respectively. τ is the control input of forces and torques to vessel.

3. Event driven tracking algorithm

In order to reduce costs, the new designed tracking control algorithm is better to expand and deepen the existing controller, due to nonlinear kinematic and nonlinear dynamics that are included in the maneuvering model of marine vessel. In the practical applications, the controller are often designed using the backstepping method. Therefore, in this section, the tracking controller is designed based on backstepping method firstly, and then the event driven tracking controller is achieved by extending the designed control law.

3.1. Tracking controller design based on backstepping method

Define the position tracking error is:

$$\tilde\eta = \eta - \eta_d \tag{3}$$

Differentiating the above equation, then we have:

$$\dot{\tilde\eta} = \dot\eta - \dot\eta_d \tag{4}$$

Assume that a reference velocity of marine vessel is ν_r, define the velocity error as:

$$\tilde\nu = \nu - \nu_r \tag{5}$$

Define a Lyapunov function as:

$$V_1 = \frac{1}{2}\tilde\eta^T\tilde\eta \tag{6}$$

Differentiating the above equation yields:

$$\dot V_1 = \tilde\eta^T R(\psi)\tilde\nu + \tilde\eta^T R(\psi)\nu_r - \tilde\eta^T\dot\eta_d \tag{7}$$

The reference velocity is chosen as:

$$\nu_r = R^T(\psi)(\dot\eta_d - \Lambda\tilde\eta) \tag{8}$$

where Λ is a parameter matrix which is positive definite.

Define a Lyapunov function as:

$$V_2 = V_1 + \frac{1}{2}\tilde\nu^T M\tilde\nu \tag{9}$$

The derivative of above equation is as:

$$\dot V_2 = \tilde\eta^T R(\psi)\tilde\nu - \tilde\eta^T\Lambda\tilde\eta + \tilde\nu^T[\tau - C(\nu)\nu - D(\nu)\nu - M\dot\nu_r] \tag{10}$$

The control input can be chosen as:

$$\tau = C(\nu)\nu + D(\nu)\nu + M\dot\nu_r - R^T(\psi)\tilde\eta - \Gamma\tilde\nu \tag{11}$$

where Γ is the parameter matrix which is positive definite.

Then Eq. (10) can change to be:

$$\dot V_2 = -\tilde\eta^T\Lambda\tilde\eta - \tilde\nu^T\Gamma\tilde\nu \le 0 \tag{12}$$

The above control input can guarantee the tracking operation is performed.

3.2. Event driven tracking controller design

Define

$$S = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

to facilitate the following expressions. Derivative of the reference velocity as Eq. (8) is:

$$\dot\nu_r = -rS\nu_r - R^T(\psi)\Lambda R(\psi)\nu - R^T(\psi)\Lambda\dot\eta_d + R^T(\psi)\ddot\eta_d \tag{13}$$

Then the control input is rewritten to be: