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Event triggered trajectory tracking control approach for fully actuated surface vessel

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ABSTRACT

This paper proposes an event-triggered trajectory tracking control approach for fully actuated surface vessels based on guidance-control structure. In which, a guidance system is designed to provide the desired trajectory with an exogenous input while a control system is designed to guarantee uniform ultimately bounded tracking error and to ensure no Zeno behavior of execution times. The proposed approach reduces the amount of computation and communication, and in the meantime it results in little controller executions. The effectiveness of the approach is finally illustrated by the simulation results.

1. Introduction

Traditional studies on ship control mainly focus on two broad categories, namely continuous control and discrete-time control [1,2]. Due to the fact that digital microprocessors are regularly used in actual systems for lower installation cost, discrete-time control strategy is widely applied for practical applications. Relevant research achievements are fruitful, for example, sampled-data dynamically positioning control in [3,4], discrete-time trajectory tracking control in [5], etc.. However, the mechanism of discrete-time control requires to adjust actuator state at every sampling instant, which may cause unnecessary energy consumption and even actuator attrition because of the frequent changes in the state of actuator. On the other hand, in practical marine operations, the period of sampling is usually determined by external situations, while the execution rate of actuator heavily depends on the present position and velocity of the ship. Therefore, the discrete-time control strategy may not be the optimal choice. In recent years, some other triggered mechanisms have attracted continuous attention, such as data-driven [6,7] and event-triggered [8] techniques. Especially, the nature of the latter determines that it may be more suitable for some application cases of ship control. In the mechanism of event-triggered control, the actuator state of a ship is modulated only when specified events happen or certain conditions are satisfied, such that it can guarantee efficient energy consumption to improve the service time of the operational ship.

The event-triggered control is a hot topic in the past few years. Relevant studies in linear systems have been reported in [9,10], in which state feedback strategy is adopted by assuming no exogenous input for target systems. Considering the universality of non-linearities, reference [11] proposes an event-triggered scheme for a class of non-linear systems that can be input–output linearizable; reference [12] proposes a robust event-triggered approach for non-linear systems with uncertainties. The applications of event-triggered control in nonlinear systems with state feedback and output feedback are also studied by references [13]. Meanwhile, the related topic of switched stochastic systems is also studied in recent years [14–16]. References [17] propose a framework for event-triggered stabilization of non-linear systems. Compared with the traditional tracking control method [18], references [19,20] study the issues of event-triggered trajectory tracking. Reference [21] investigates the stabilization of time-varying trajectories for unicycle mobile robots using event-triggered controllers. Although the event-triggered control also has great potential application values in ship control, existing achievements are extremely rare. Inspired by [19,20], this paper aims to solve the problem of trajectory tracking for surface vessels by using event-triggered control technology. Compared with the existing works of event-triggered control, the guidance system is designed independently in this paper, and the event-triggered controller is designed based on the guidance system. The designed controller is universal for a variety of mission mode of operational vessels due to the introduction of guidance system. Then the

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design can make debugging convenient, improve the manoeuvering performance and reduce the cost.

The core of the proposed approach is based on a guidance-control structure in which a guidance system is designed to provide the desired trajectory with an exogenous input and a control system is governed by an event-triggered controller to guarantee the tracking error to be uniform ultimate bounded and the inter-execution time to be bounded greater than zero. The force input of thruster is modulated only when certain event-triggered conditions are satisfied. Considering the nature of the proposed event-triggering strategy, it could significantly reduce the frequency of controller executions as well as the amount of communication to guarantee efficient energy consumption to improve the service time, and in the meantime it could ensure similar, if not better, tracking performances as the traditional methods.

The rest of this paper is organized as follows. In Section 2, the mathematical model of the surface vessel is given. The detailed procedures of the proposed event-triggered trajectory tracking control approach is presented in Section 3. In Section 4, simulations on a literature example are carried out. Finally, the conclusions are summarized in Section 5.

2. Mathematical model of surface vessel

The tracking issue of surface vessel considered in this paper is a low-speed application. According to the literature [1], a three degrees of freedom (DOF) non-linear maneuvering model for marine vessel is as follows:

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

$$M\dot{v} + C(v)v + D(v)v = \tau \tag{2}$$

where $\eta \in \mathbb{R}^3$ denotes the vector of position and heading which is decomposed in the NE reference frame, and $\eta = [N, E, \psi]^T$, N represents the north position, E represents the east position, ψ represents the heading. $v \in \mathbb{R}^3$ denotes the vector of linear velocity and angular velocity which is decomposed in the body-fixed frame. $R(\psi) \in \mathbb{R}^{3\times3}$ is the rotation matrix from the body-fixed frame to the NE reference frame, the form of which is as follows:

$$R(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

It satisfies $RR^T = R^T R = I$, where I is a three-dimensional unit matrix. $M \in \mathbb{R}^{3\times3}$ is system inertia matrix, $C(v) \in \mathbb{R}^{3\times3}$ is Coriolis-centripetal matrix, $D(v) \in \mathbb{R}^{3\times3}$ is damping matrix. $\tau \in \mathbb{R}^3$ is the vector of forces and torques to vessel in body-fixed frame.

The kinematics model Eq. (1) can be re-expressed in vessel parallel coordinates as follows:

$$\eta_p = R^T(\psi)\eta \tag{4}$$

where η_p is the vector of position and heading expressed in the body-fixed reference frame.

Thus, the three DOF vessel model can be re-written as:

$$\dot{\eta}_p = v \tag{5}$$

$$\dot{v} = -M^{-1}C(v)v - M^{-1}D(v)v + \tau \tag{6}$$

3. Event-triggered trajectory tracking approach

3.1. Guidance system design

The detailed event-triggered trajectory tracking controller is designed based on the guidance-control structure. Guidance system is a better choice for surface vessel to track smooth trajectory in practical applications, which can improve operational performance and reduce costs. The structure diagram of the event-triggered control loop and the detailed relationship between guidance system and control system are shown in Fig. 1.

According to the second-order non-linear vessel model Eqs. (5) and (6), the guidance system is used to provide reference trajectory and reference velocity for the vessel. The input of the guidance system is from external input. In this section, a simple guidance system is designed as follows:

$$\dot{\eta}_d = v_d \tag{7}$$

$$\dot{v}_d = \omega \tag{8}$$

where $\eta_d \in \mathbb{R}^3$ is the desired trajectory in the vessel parallel coordinates, $v_d \in \mathbb{R}^3$ is the desired velocity in the body-fixed frame, $\omega \in \mathbb{R}^3$ is the external input signal. Notice that, η_d in the vessel parallel coordinates and η_d in the NE reference frame are uniform when $\psi_d = 0$. This is convenient for designing the following event-triggered tracking controller.

From a practical point of view, we can assume that $\|[\eta_d^T, v_d^T, \omega^T]^T\| \le a$, $a \ge 0$ for all time $t \ge 0$. In addition, the input ω is differentiable and $\|\dot{\omega}\| \le b$, $b > 0$ for all time $t \ge 0$.

3.2. Event-triggere d trajectory tracking controller design

Based on the reference signals generated from the above guidance system, an event-triggered tracking controller is designed as follows. Define position tracking error in the vessel parallel coordinates as:

$$\tilde{\eta}_p = \eta_p - \eta_d \tag{9}$$

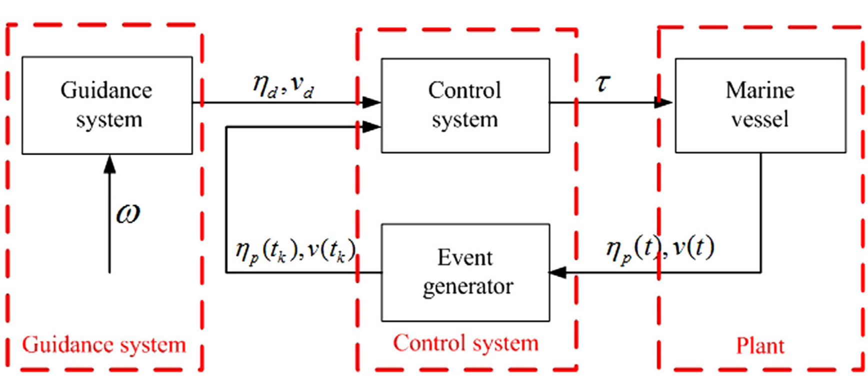

Fig. 1. The event-triggered control loop.