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GESO based robust output tracking controller for marine vessels

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ABSTRACT

In this paper, a novel design for robust steering autopilot for marine surface vessels is proposed. As the uncertainties and disturbances acting on the ship due to external environmental effects, model inaccuracies, parametric variations, and nonlinearities of rudder movement are matched as well as mismatched, Generalized Extended State Observer (GESO) is used to estimate them. A composite design consisting of an output tracking state feedback controller augmented by GESO derived disturbance compensation term is formulated. Stability of the resulting closed-loop system is established and the efficacy of the controller is demonstrated through simulations by considering various practical circumstances. The results show that the controller offers highly satisfactory tracking performance in the presence of significant matched as well as mismatched uncertainties and disturbances.

1. Introduction

When a ship is under way, its course is maintained automatically by deflection of rudder through the application of steering autopilot system. Effective autopilot of marine vessels will have a positive impact directly on economy by reducing fuel consumption, manpower requirement, security, machine maintenance and also providing comfort to the crew. In the case of maneuvering of marine vessels, the external and internal factors vary with time. Winds, tides, waves, underwater ocean currents, depth below keel, various sailing orders akin to changes in loading, trim, ballast, speed etc. and other exogenous factors alter the hydrodynamic coefficients and other parameters associated with the ship dynamics. Yaw velocity constraint also needs to be considered as large yaw velocity can generate severe roll and sway thereby causing cargo damage and sea sickness (Li and Sun, 2012). Further, un-modeled dynamics and nonlinearities at the input are present. Lastly, the movement of rudder is mechanically restricted and the speed at which it moves is governed by the speed of hydraulic pump and opening of its discharge valve. These practical limitations on actuator impose Saturation (SAT) and Slew Rate Limits (SRL) on the rudder which are of great importance since they can cause significant deterioration in controller performance. Constraints in maneuvering capability of controller also arise due to vessel's bulk and restricted size of rudder (McGookin et al., 2000). Owing to all these issues, designing a robust and effective steering controller for marine vessels poses a challenging task.

Though the first commercial autopilots were designed based on PID control, they may not offer satisfactory performance in rough seas. The controllers need adjustments in their settings with varying conditions which is not only time consuming and tedious, but also may not be accurate enough. To address the issues in order to obtain better performance, various approaches have been proposed in the literature for design of ship autopilots. Designs based on adaptive control (Amerongen and Cate, 1975; Amerongen, 1984; Yang et al., 2003; Lauvdal and Fossen, 1998; Tzcng, 1999), self-tuning control (Lee et al., 2013), optimal control (Grimble, 1980; Johansen et al., 2008), neural network (Burns, 1995; Dai et al., 2012), fuzzy logic (Rigatos and Tzafestas, 2006; Yang and Ren, 2003), backstepping (Fossen and Strand, 1999; Do et al., 2002), sliding mode control (McGookin et al., 2000; Yuan and Song Wu, 2010), H_∞ approach (Sheng et al., 2006; Katebi et al., 1997), predictive control (Tao and Jin, 2012) etc. are some examples to cite. While it has been shown that the controllers offer improved performance, there exists certain issues that need attention. Frequently, controllers have been designed by ignoring the rudder servo dynamics. The resulting design, therefore, may not offer satisfactory performance in practice. Next, many of the controllers need a priori information on certain characteristics of uncertainty and disturbances to achieve robustness. Additionally, some approaches require availability of accurate plant model as well as complete state information. In practice, the requirements may not be easy to fulfill always.

In this work, a robust steering controller for ship based on the Generalized Extended State Observer (GESO) (Li et al., 2012) is proposed. The mathematical model considered for controller

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design includes ship as well as rudder servo dynamics. Using the plant model, an output tracking state feedback controller is designed to follow commanded heading angle profile. The controller, however, needs all the states for its implementation. Also, it lacks robustness in the face of uncertainties and disturbances. To address the issues, GESO is used for estimation of states as well as the matched and mismatched effects of uncertainties and disturbances in an integrated manner. A composite steering control law consisting of the state feedback output tracking controller designed for nominal system and augmented by a GESO based disturbance compensation term is formulated. An important feature of the proposed design is that it does not require any specific information about the uncertainties and disturbances. As the GESO also provides estimate of state vector, the issue of requirement of state availability is addressed. Closed-loop stability for the controller–observer structure is established. Effectiveness of GESO in estimation of the states and uncertainties and in robustifying the output tracking controller in the presence of parametric uncertainties, external disturbances, un-modeled dynamics and measurement noise is illustrated by simulation.

The remaining paper is organized as follows: In Section 2, mathematical model of ship including rudder actuator and the statement of problem is presented. Design of a state feedback output tracking controller augmented by GESO based disturbance compensation term is discussed in Section 3. In Section 4, closed loop stability analysis results are presented. The proposed design is validated by simulations and the results are given in Section 5. Lastly, Section 6 concludes this work.

2. Problem formulation

In this work, the ship dynamics is augmented by rudder servo dynamics to form the plant model used in controller design. To this end, a brief on the ship dynamics followed by the actuator dynamics is presented in this section.

2.1. Ship dynamics

The linearized dynamics describing the model of marine vessel (Davidson and Schiff, 1946) is given by

$$M_y(\dot{v} + ur) = Y_v v + Y_{\dot{v}}\dot{v} + Y_r r + Y_{\dot{r}}\dot{r} + Y_{\delta_r}\delta$$
$$I_{zz}\dot{r} = N_v v + N_{\dot{v}}\dot{v} + N_r r + N_{\dot{r}}\dot{r} + N_{\delta_r}\delta \tag{1}$$

where Y_v, $Y_{\dot{v}}$, … denote the hydrodynamic force and moment coefficients, u and v represent the surge and sway velocities respectively, r represents the yaw rate and δ represents the rudder angle. Assuming uniform speed and eliminating sway velocity yields the second order Nomoto model (Nomoto et al., 1957) as

$$\frac{\dot{\psi}}{\delta} = \frac{K(1 + T_3 s)}{(1 + T_1 s)(1 + T_2 s)} \tag{2}$$

where T_1, T_2, T_3 are the time constants and K is the rudder gain and are functions of the hydrodynamic coefficients (Davidson and Schiff, 1946). Because of the ill conditioning arising due to the near pole-zero cancellations, (2) is simplified into the first order Nomoto model as

$$\frac{\dot{\psi}}{\delta} = \frac{K}{(Ts + 1)} \tag{3}$$

where $T = T_1 + T_2 - T_3$ is known as the effective yaw rate time constant. First order Nomoto model gives practically precise description of the course-keeping yaw dynamics for a large class of ships and is frequently used as a nominal model for ship steering autopilot design (Amerongen, 1982). Since r is the time derivative of yaw angle, ψ, (3) can be re-written as

$$\frac{\psi}{\delta} = \frac{K}{s(Ts + 1)} \tag{4}$$

which, in time domain, can be expressed as

$$T\ddot{\psi} + \dot{\psi} = K\delta \tag{5}$$

During the course-changing maneuver where large rudder angle is involved, a considerable non-linear relation is observed and to account for the same, the yaw dynamics described in (5) is modified as Amerongen (1982)

$$T\ddot{\psi} + H(\dot{\psi}) = K\delta \tag{6}$$

where

$$H(\dot{\psi}) = \alpha_0 + \alpha_1\dot{\psi} + \alpha_2\dot{\psi}^2 + \alpha_3\dot{\psi}^3 \tag{7}$$

and α_0, α_1, α_2 and α_3 are known as Norrbin's coefficients. Because of the symmetrical nature, most ships have the property that $\alpha_2 = \alpha_0 = 0$. The value of α_1 is $+1$ for stable and -1 for unstable ships while the value of α_3 can be determined via spiral test (Cheng et al., 2006).

2.2. Actuator dynamics

The movement of rudder is controlled by steering machine and the rate at which rudder moves depends mainly on the speed of steering pump and the opening of its discharge valve. The hydraulic fluid flow is controlled by the movement of swash plate, governed by telemotor system. Due to this limitation of hydraulic steering pump, the rudder remains to be a low bandwidth actuation device. In addition to rate saturation, it also has magnitude limitation. Attributable to these hard nonlinearities like saturation (SAT) limit and slew rate limit (SRL), rudder dynamics should be integrated in the controller design. In some of the earlier works (Cheng and Ran, 2002; Cheng and Ying, 2004; Lei and Guo, 2015) effect of steering dynamics is considered as time delay. In this work, the servo dynamics has been considered in the plant model used in controller design. The dynamics (Amerongen, 1984, 1982; Burns, 1995; Guorui and Fengyu, 2009; Amerongen et al., 1990; Xiao et al., 2011; Yuan and Song Wu, 2010; Lim and Forsythe, 1983; Lauvdal and Fossen, 1998) is given by

$$\delta(s) = sat\left(\frac{1}{s\tau_\delta + 1}\right)\delta_c(s) \tag{8}$$

The typical values of saturation and slew rate limit are

$$\delta_{max} = 35°; \tag{9}$$

and

$$\dot{\delta}_{max} = 2 - 7\ (\text{deg/s}) \tag{10}$$

where δ and δ_c represent the actual and commanded rudder angles respectively and sat(·)=sign(·)min(δ_{max}, |·|). Since the gain of transfer function as shown in rudder dynamics is of unity value, it follows that if $\delta_c \le \delta_{max}$, $t \ge 0$ then $\delta \le \delta_{max}$, $t \ge 0$. In view of this limitation and stalling of rudder, large control gain cannot solve stability problem of a vessel due to inadequate rudder (Triantafyllou and Hover, 2003). Accordingly, assuming that $\delta_c \le \delta_{max}$, rudder dynamics can be treated linear as

$$\frac{\delta(s)}{\delta_c(s)} = H_a(s) = \left(\frac{1}{s\tau_\delta + 1}\right) \tag{11}$$

In the design of the controller, care needs to be taken to ensure that the derivative of the output signal of the controller is less than the maximum rudder speed in order to prevent phase lag.