Ocean Engineering 143 (2017) 125–132

Contents lists available at ScienceDirect

Ocean Engineering

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

Robust model predictive control for path-following of underactuated surface vessels with roll constraints

Jun Zhang[a], Tairen Sun[a,*], Zhilin Liu[b]

[a] School of Electrical and Information Engineering, Jiangsu University, Zhenjiang, China
[b] College of Automation, Harbin Engineering University, Harbin, China

ARTICLE INFO

Keywords:
Underactuated surface vessels
Path following
Sage-Husa Kalman
Model predictive control
Disturbance observer

ABSTRACT

Abrupt maneuvering or strong disturbances from sea waves probably lead to large roll motion of underactuated surface vessels, which severely affects stability of surface vessels. A novel path-following control for vessels with roll constraints is proposed by combining Kalman filter, disturbance observer and robust constrained model predictive control method. Firstly, a switched linear uncertain model with coupled surge, sway, roll and yaw is constructed for underactuated surface vessels. Then, an improved Sage-Husa Adaptive Kalman Filter is proposed to estimate vessels' full states by partial states information and eliminate the effects of measurement noises. Next, the disturbance observer, which is used to estimate low-frequency disturbances from wind, waves and oceans, is combined with constrained model predictive control to improve the robustness of the closed-loop control system. In this paper, the effectiveness of the proposed algorithm is verified by theoretical analysis, simulations and experiments.

1. Introduction

More and more control has been designed based on the methods such as sliding mode control (Ashrafiuon et al., 2008; Fahimi, 2007),time-varying feedback control (Ashrafiuon et al., 2010; Do, 2010), dynamic surface control (Zhang et al., 2015; Xu et al., 2015) for underactuated surface vessels, due to their applications in mine countermeasures, anti-terror, surveillance, reconnaissance, anti-submarine warfare and so on. The under-actuated nature of these problems, namely with more variables to be controlled than the number of control actuators. How to design control law for underactuated surface vessels is an significant research topic, on account of the fact that such a system is not locally linear controllable and can not be asymptotically stabilized by any smooth time-invariant control law due to the limitations imposed by Brockett's condition (Ma, 2009).

Nowadays, there has been lots of results on control design for underactuated surface vessels (Ashrafiuon et al., 2008, 2010; Fahimi, 2007; Do, 2010; Zhang et al., 2015; Xu et al., 2015). However, there are some deficiencies in the literature. On one hand, the considered systems are mostly deterministic systems (Ashrafiuon et al., 2008, 2010; Fahimi, 2007; Do, 2010). Factually, marine surface vessels are disturbed by sea wind, sea waves and sea currents, which are with stochastic characteristics. Thus, the system models of surface vessels are stochastic systems in fact. On the other hand, most of these results didn't consider roll damping (Ashrafiuon et al., 2010; Do, 2010; Zhang et al., 2015; Xu et al., 2015). In fact, when sailing in sea, stability of the surface vessels may be severely affected by large roll motions, which is caused by abrupt maneuvering and strong disturbances from wind, waves and oceans. The roll motion also produces high acceleration and is considered as the principal villain for the seasickness and cargo damage. Therefore, designing control for stochastic models of surface vessels with roll constraints becomes an important design consideration.

Up to now, to reduce roll effects on vessels, the composite control of rudder-roll damping and fin stabilizer, rudder-roll damping based on (Wang and Zhang, 2011) and inner mode control (Alarin, 2007) have been proposed. However, the above control (Wang and Zhang, 2011; Alarin, 2007) did not take roll constraints explicitly into account, and the control effects on roll damping were achieved through numerical simulations and trial-and-error tuning of the controller parameters. Therefore, how to ensure the roll angles of vessels in safe range in advance is of great value. Model predictive control (MPC) is one of the most effective control methods to solve the constraints problem and it can realize the multi-objective optimal control with the multi-variable coupling (Oh and Sun, 2010). In Li and Sun (2012); Li et al. (2009), rudder-roll damping was achieved by adding roll angle constraints in MPC design. The roll angles of vessels were ensured in safe range in advance due to the advantages of MPC. However, there are some deficiencies in the MPC for surface vessels. Firstly, the considered system is linear deterministic system, which doesn't accord with

* Corresponding author.

http://dx.doi.org/10.1016/j.oceaneng.2017.07.057
Received 21 November 2015; Received in revised form 28 March 2017; Accepted 27 July 2017

stochastic characteristic of disturbances from wind, wave and oceans. Secondly, though the constraints are satisfied in the designed MPC, stability can not be guaranteed and no theoretical proof for stability was given. Thirdly, the MPC design were based on the premise of obtaining all motion states of vessels. However, it is impractical to measure all motion states of vessels precisely and directly, because marine surface vessels are highly susceptible to the disturbances of sensors measurement noise, system noise, low-frequency wind, wave and currents.

In this paper, Kalman filter estimation and disturbance observer are combined with robust MPC to design control for surface vessels to achieve rudder stabilization and path following. The main contributions of this paper include:

1) the design of robust MPC for stochastic models of surface vessels with roll constraints to guarantee path-following and rudder-roll damping;
2) estimation full states of vessels from partial states by Sage-Husa adaptive Kalman Filter and designing disturbance observer to estimate disturbances from wind, wave and currents;
3) theoretical analysis of the effectiveness of the proposed method, including feasibility and stability of the designed control.

The design process of this paper is organized as follows. In Section 2, the objective of this paper is stated. In Section 3, adaptive Kalman filter is used to estimate the full state from partial state based on the stochastic model. A disturbance observer is designed to estimate the disturbances and the disturbances estimation is used to compensate uncertainties feed forwardly. In Section 4, control law is designed by MPC and disturbance compensation to guarantee path following and rudder-roll damping. Section 5 presents simulation and experiment results. At last, conclusions are given in Section 6.

2. Problem statement

In the open literature, path following of surface vessels has been addressed with two different approaches: one is to design the controller directly using the error dynamics in the inertial frame, the other is to research on it in the Serret-Frenet frame. The introduced Serret-Frenet frame is to simplify the controller design in some ways. Fig. 1 shows the frame $\{SF\}$ used for path following control of the surface vessel. Ω is the given target path, ψ_{SF} is the path tangential direction, and ψ is the heading angle of the vessel. The origin of the frame $\{SF\}$ is located at the closest point on the curve Ω from the origin of the body-fixed frame $\{B\}$. The error dynamics of the path following in the Serret-Frenet frame are given by

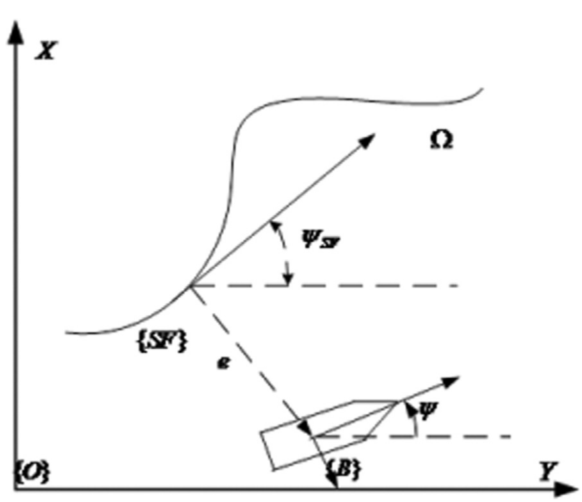

Fig. 1. The Serret-Frenet frame of the surface vessel.

$$\begin{cases} \dot{e} = u\sin(\overline{\psi}) + v\cos(\overline{\psi}) \\ \dot{\overline{\psi}} = \dot{\psi} - \dot{\psi}_{SF} = \frac{\kappa}{1-e\kappa}(u\sin(\overline{\psi}) - v\cos(\overline{\psi})) + r \end{cases} \tag{1}$$

where e, $\overline{\psi} = \psi - \psi_{SF}$ are referred as the cross-track error and heading error, respectively. u, v are the body-fixed linear velocities (surge and sway), and r is the yaw rate, κ is the curvature of the given path. In most path following problems for surface vessels in open sea, the path is often a straight line or a way-point path, which consists of piecewise straight lines with the curvature $\kappa = 0$. In ship maneuvering, the sway velocity is relatively small compared with other motion variables (Fossen, 2012). Therefore, we assume that the sway velocity was small enough to be neglected, which means v=0. Then, the error dynamics (1) can be simplified as

$$\begin{cases} \dot{e} = u\sin(\overline{\psi}) \\ \dot{\overline{\psi}} = r \end{cases} \tag{2}$$

Notice the control objective for path following of marine surface vessels is to drive e and $\overline{\psi}$ to zero. To decrease the complexity of the vessel model, it is assumed that the surge velocity u is constant, which was adopted by many researchers (Pettersen and Lefeber, 2001). Then, the control objective is converted into designing r to drive heading angle error $\overline{\psi}$ converging to zero, and then the convergence of the error e can be obtained.

When sailing in sea, stability of the surface vessels may be severely affected by large roll motions, and roll dynamics must be established to ensure the roll angle of the underactuated vessels in the safe range. The coupled nonlinear dynamics with four degrees of freedom between steering and rolling are given by

$$\begin{aligned} & m(\dot{u} - vr - X_G r^2 + Z_G pr) = X \\ & m(\dot{v} + ur + X_G\dot{r} - Z_G\dot{p}) = Y \\ & I_{XX}\dot{p} - I_{XZ}\dot{r} - mZ_G(\dot{v} + ur) = K - WGM_T\phi \\ & I_{ZZ}\dot{r} - I_{XZ}\dot{p} + mX_G(\dot{v} + ur) = N \end{aligned} \tag{3}$$

where m is the ship mass, I_{XX} and I_{XZ} are the coupling moment of inertia, p is the roll velocity and ϕ is the roll angle. X_G and Z_G are the location of the center of gravity in the x-axis and z-axis, W is the ship displacement, GM_T is transverse metacentric height. The hydrodynamic forces X,Y and moments K,M are usually the third order Taylor series polynomials for nonlinear hydrodynamic constants, the definitions in detail can be referred in the literature (Fossen, 2012). For simplicity, it is usually assumed that the only external forces and moments are caused by a single rudder whereas the rudder angle is denoted by δ (Fossen, 2012).

Since the model (3) is a nonlinear system with strong disturbances and big uncertainties, it is difficult to design control directly based on it. In ship path tracking, the rudder angle range is usually limited in the range $|\delta| \le 35°$. In this paper, to facilitate the control design for the ship, the complex nonlinear system model is converted into a switched linear system according to the following polytopes (Li et al., 2009)

$$\begin{aligned} & \Omega_1 = \{\delta | -10° \le \delta \le 10°\}, \Omega_2 = \{\delta | 10° \le \delta \le 35°\}, \\ & \Omega_3 = \{\delta | -35° \le \delta \le -10°\}. \end{aligned} \tag{4}$$

The switched linear system is stated as follows

$$\begin{aligned} & \dot{x} = A_i x + B_i\delta + d_1 + C\omega, \ i = 1, 2, 3 \\ & y = Hx + V \\ & x \in X \\ & \delta \in U \end{aligned} \tag{5}$$

where the ith model will be active if $\delta \in \Omega_i$, and

$$A_i = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & a_{i11} & a_{i12} & a_{i13} & a_{i14} \\ 0 & a_{i21} & a_{i22} & a_{i23} & a_{i24} \\ 0 & a_{i31} & a_{i32} & a_{i33} & a_{i34} \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \quad B_i = \begin{bmatrix} 0 \\ b_{i1} \\ b_{i2} \\ b_{i3} \\ 0 \end{bmatrix} \tag{6}$$