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Linear Parameter Varying Adaptive Control of an Unmanned Surface Vehicle

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Abstract: For the investigation of unmanned surface vehicle (USV) with sudden changes in system dynamics (mass variation), an adaptive gain-scheduling control design methodology is developed in this paper. First, a linear parameter varying (LPV) control method is devised to operate a USV under variation in its overall mass. Then, an adaptive parameter estimation mechanism is designed to estimate the online information of mass variation. Finally, a LPV controller with adaptive parameter estimation and adaptation capabilities is synthesized to properly manoeuvre USV. Numerical simulations are carried out to verify the effectiveness of the proposed approach. The results demonstrate that the proposed methodology enables USV to deal with sudden change in mass without significant deterioration in terms of system performance.

Keywords: Unmanned surface vehicle, Linear parameter varying, Mass variation, Linear matrix inequality, Adaptive control.

1. INTRODUCTION

In the last decade, the global positioning system (GPS) has become more compact, effective and affordable, while more affordable, long range and higher bandwidth wireless data systems have been developed as well (Manley, 2008). These developments have made unmanned surface vehicles (USVs) to be more capable for more sophisticated marine applications. Actually, USVs have increasingly attracted tremendous attention from commercial market, universities, institutes, and military. Numerous USVs have also been developed and demonstrated their capabilities in various applications such as environmental sampling, resources exploration, boarder patrol and surveillance, military missions, and post-disaster search and rescue (Breivik, 2008; Roberts, 2006; Svec, 2012).

In real life situations, the mass of USV may suddenly and dramatically change due to payload deployment, aircraft taking-off and landing, as well as missile launching. It may also gradually alter over a period of time due to fuel consumption and water sampling. These factors can directly lead to the variation of system dynamics (inertia and Coriolis and centripetal effects), and may ultimately deteriorate the performance of USV controller that is designed on the basis of a static internal model. More seriously, it may likewise result in missions being aborted and the possibility of threatening the safety of other marine crafts and personnels in the vicinity (Annamalai, 2014). In order to cope with such events and successfully accomplish assigned missions without significant performance degradation, the development of an efficient and effective gain-scheduling control methodology with adaptive dynamics updating capabilities is highly demanded. Unfortunately, the variation of mass is normally unknown in advance and is responsible for the significant deterioration in terms of controller performance, which should be precisely estimated in real-time. Few research to date involves in this topic, only a recent publication is found in Annamalai (2014), in which a model predictive control (MPC) combining with three parameter estimation algorithms (including gradient descent, least squares, and weighted least squares) is developed.

Most of the existing USVs control approaches are based on linear models or the linearization of nonlinear systems around a specific operating point. But for systems with a wide operating range, the linearized methods may fail to achieve satisfactory performance. Alternatively, the linear parameter varying (LPV) control (Shamma, 2012) capable of effectively solving numerous nonlinear control problems has progressed steadily into a mature tool (Hoffmann, 2014). It has a significant advantage over the fixed-gain controllers since its feedback control gains can be scheduled along with the variation of dynamics, which contributes to less conservativeness of the controller as well. In industrial applications, LPV control method has been widely adopted to solve variety of practical problems due to its capability of guaranteeing system stability and performance over a wide range of operating conditions (Wu, 2006). The idea of LPV is firstly appeared in Shamma (1988) which is to analyse the interpolation and realization issues in the traditional gain-scheduling control approaches. In the successive development, many

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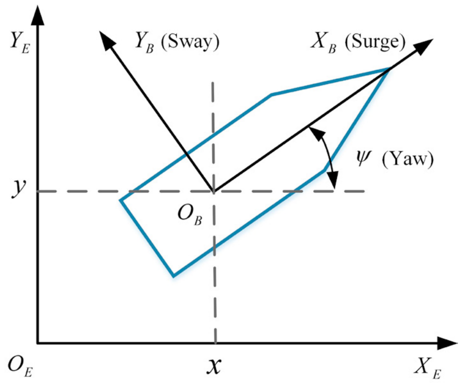

Fig. 1. Illustration of USV's planar motion

methodologies are gradually developed to contribute to the LPV control design including linear matrix inequality (LMI) (Wu, 2001), stable realizations (Blanchini, 2010), and set-invariance methods (Blanchini, 2007).

In order to overcome the challenges addressed above, this paper investigates the design of an adaptive gain scheduling control method for USV tackling the sudden change in mass, which includes the following components: 1) a LPV state feedback controller is designed to control USV under different operating conditions (variation of overall mass). In this study, USV's overall mass is considered as the scheduling variable in controller design; 2) an adaptive parameter estimation mechanism is devised to provide the real-time information of mass variation during the maneuver of USV; 3) finally, a LPV state feedback controller capable of adaptively estimating system parameter variation is synthesized to guarantee the satisfactory mission performance in the absence/presence of sudden and dramatic change in dynamics. The effectiveness of the proposed control approach is validated in a nonlinear USV model. The contribution of this paper includes: 1) the variation of mass is considered in the controller design which can significantly improve the USV system performance; 2) an adaptive estimation scheme is proposed to obtain the *prior* unknown variation of mass in real-time.

The rest of this paper is organized as: Section 2 addresses some preliminaries. Section 3 presents the control design procedure. Numerical simulations are conducted in Section 4. Conclusions are summarized in the last section.

2. PRELIMINARIES

2.1 USV Dynamics

In this paper, only surge/forward, sway/lateral, and yaw are considered in planar motion of USV since the primary concern of USV control is usually the position and orientation (as shown in Fig. 1).

Employing the most widely used ship model in Fossen (1994), a common USV dynamical model can be described as follows:

$$M\dot{\nu} + D(\nu)\nu = \tau, \tag{1}$$

where $M = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & m_{23} \\ 0 & m_{32} & m_{33} \end{bmatrix}$, $D(\nu) = \begin{bmatrix} d_{11} & 0 & 0 \\ 0 & d_{22} & d_{23} \\ 0 & d_{32} & d_{33} \end{bmatrix}$, $\nu = [u_u \; u_v \; r]^T$, and $\tau = [\tau_u \; \tau_v \; \tau_r]^T$. $m_{11} = m - X_{\dot{u}}$, $m_{22} = m - Y_{\dot{\nu}}$, $m_{33} = I_z - N_{\dot{r}}$, $m_{23} = m\chi_g - Y_{\dot{r}}$, and $m_{32} = m\chi_g - N_{\dot{v}}$. Whilst $d_{11} = -X_u - X_{u|u|}|u_u|$, $d_{22} = -Y_v$, $d_{33} = -N_r + (m\chi_g - \frac{1}{2}N_{\dot{v}} - \frac{1}{2}Y_{\dot{r}})u_u$, $d_{23} = -Y_r + (m - X_{\dot{u}})u_u$, and $d_{32} = -N_v + (X_{\dot{u}} - Y_{\dot{v}})u_u$. The terms m_{11}, m_{22}, m_{23}, m_{32}, and m_{33} represent the USV inertia. While d_{11}, d_{22}, d_{23}, d_{32}, and d_{33} represent the hydrodynamic damping forces. Assuming the fore/aft symmetry, the non-diagonal terms in M and $D(\nu)$ can be eliminated, and (1) can then be rewritten as follows:

$$\begin{aligned} \dot{u}_u &= \frac{m_{22}}{m_{11}}u_v r - \frac{d_{11}}{m_{11}}u_u + \frac{1}{m_{11}}\tau_u \\ \dot{u}_v &= -\frac{m_{11}}{m_{22}}u_u r - \frac{d_{22}}{m_{22}}u_v \\ \dot{r} &= \frac{m_{11} - m_{22}}{m_{33}}u_u u_v - \frac{d_{33}}{m_{33}}r + \frac{1}{m_{33}}\tau_r, \end{aligned} \tag{2}$$

where u_u, u_v, and r denote the velocity of surge, sway, and yaw, respectively. τ_u and τ_r denote the surge force and yaw moment, respectively.

2.2 USV Linear Parameter Varying Model

Assumption 1: It is reasonable to neglect the sway velocity (this derives $u_v = 0$) since it is much smaller than the surge velocity in the case of underactuated USV.

Based on *Assumption 1*, the following simplified USV model consisting of surge and steering dynamics can be achieved:

$$\begin{aligned} \dot{u}_u &= A_u u_u + B_u \tau_u \\ \dot{\psi} &= r \\ \dot{r} &= A_r r + B_r \theta, \end{aligned} \tag{3}$$

where ψ is yaw angle, and θ denotes rudder deflection. $A_u = -d_{11}/m_{11}$, $A_r = -d_{33}/m_{33}$, $B_u = 1/m_{11}$, $B_r = N_\theta/m_{33}$.

In addition, the parameters $d_{33} = -N_r + (m\chi_g - \frac{1}{2}N_{\dot{\nu}} - \frac{1}{2}Y_{\dot{r}})u_u$ and $m_{11} = m - X_{\dot{u}}$ are functions of system overall mass m. When selecting m as a time-varying parameter, (3) is exactly a LPV model (Skjetne, 2004).

Without loss of generality, (3) can be written into the following state-space form:

$$\begin{cases} \dot{x}(t) = A(\rho)x(t) + B(\rho)u(t) \\ y(t) = C(\rho)x(t), \end{cases} \tag{4}$$

where $u(t) = [\tau_u \; \theta]^T \in \Re^m$, $x(t) = [u_u \; \psi \; r]^T \in \Re^n$, and $y(t) \in \Re^p$ represent the system's control input, state, and output vector, respectively. $A(\rho) = \begin{bmatrix} A_u & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & A_r \end{bmatrix}$, $B(\rho) = \begin{bmatrix} B_u & 0 \\ 0 & 0 \\ 0 & B_r \end{bmatrix}$, $C(\rho) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, and $x(t) = \begin{bmatrix} \psi \\ r \end{bmatrix}$. Additionally, ρ is a time-varying vector of real parameters that contains all possible trajectories of system.

The linearized USV model can then be expressed as:

$$\begin{aligned} (A(\rho), B(\rho), C(\rho)) &= \sum_{i=1}^{N} \mu_i (A_i, B_i, C_i) \\ &\in Co\{(A_i, B_i, C_i) : i = 1, ..., N\} \end{aligned} \tag{5}$$

with the convex coordinates $\mu_i > 0$ and $\sum_{i=1}^{N} \mu_i = 1$, $(A_i, B_i, C_i)(i = 1, ..., N)$ are unknown constant matrices