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Modified observer backstepping controller for a dynamic positioning system

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ABSTRACT

A procedure for attenuating the control law of a vessel dynamic positioning system, based on the observer backstepping methodology, is proposed. The motivation is the appearance of an undesirable on–off behavior on the signal sent to the actuators when their saturation is considered and the control law is dependent on estimated state variables. Two gain matrices associated with the error variables are introduced to achieve the desired attenuation. Stability is proven through Lyapunov stability analysis. Numerical simulations confirm the effectiveness of the proposed controller to render the control law compatible with the limitations of the actuators.

1. Introduction

Dynamic Positioning Systems (DPS) are intended to control the horizontal motions of a vessel by exclusive means of propellers and thrusters (Fossen, 1994). Increasing operational range and performance requirements have stimulated the research community to improve on control strategies, especially to cope with challenges such as the nonlinearity of the multivariable mathematical model, stochastic perturbations, constraints on the mechanical systems (e.g., saturation of the actuators) and accurate estimation of state variables. Vessel motions are assumed to be composed of low- and wave-frequency motions. Thus, position and heading measured signals have to be filtered before they are used as an input for the controllers, since the wave-frequency component of motions is not intended to be compensated by the actuators. Early versions of DPSs adopted a notch filter to separate the low-frequency components from the total motion, while PID controllers were used to calculate the control loads assuming surge, sway and yaw motions independent from each other (Fossen, 2011). Later Balchen, Jenssen, and Saelid (1976) proposed applying a Kalman Filter (KF) to estimate the low-frequency motions of the vessel, using optimal control theory to calculate the control loads. This approach was extended and improved upon by Balchen, Jenssen, and Saelid (1980), Saelid, Jenssen, and Balchen (1983), Grimble, Patton, and Wise (1980), Fung and Grimble (1983) and Sorensen, Sagatun, and Fossen (1996). The advantage of the KF technique lies in the reduction of the phase lag induced by the filtering process (as compared to conventional low-pass or notch filters), in the possibility of implementing sensor fusion, in performing optimal estimations of the position and heading of the vessel based on sensor signals, and in the estimation of the environmental loads acting on the vessel. However, an important drawback is the need to linearize the vessel's equations of motions around a set of constant yaw angles, which imposes a time-consuming procedure for tuning of parameters and precludes assurance of global stability for the system (Fossen & Strand, 1999a; Tannuri & Pesce, 2002).

Nonlinear controllers have been considered for DPS to overcome linearization problems. Grovlen and Fossen (1996) proposed an approach with a nonlinear observer and the backstepping methodology. Fossen and Grovlen (1998) improved this idea by treating the problem in vector form, but without consideration of either filtering of wave-frequency motions or environmental loads estimation. Those works assume a stable sway–yaw dynamics condition that is removed by Robertsson and Johansson (1998). A passive nonlinear observer for both the low-frequency motions of the vessel and the environmental loads was developed by Fossen and Strand (1999a). Passivity is attained by convenient tuning of the observer gains based on a notch filter effect introduced in the mathematical model, and the observer has proven to be globally exponentially stable. Aarset, Strand, and Fossen (1998) then proposed a nonlinear controller for a DPS comprising the passive nonlinear observer and the backstepping methodology with additional integral action, but without considering the actuators dynamics. Fossen and Berge (1997) included actuator dynamics in the controller based on backstepping for tracking of marine vessels, since the bandwidths of both the actuators and vessel dynamics were close to each other. However, the controller is fed with uncorrupted position and heading signals.

An alternative nonlinear strategy for DPS was presented by Tannuri, Donha, and Pesce (2001, 2010), who proposed a controller

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based on the Sliding Mode Control (SMC) theory. This approach showed to be robust in addressing the variations in loading and environmental conditions, as well as modeling errors. Additionally, the tuning of the SMC control parameters is simple and intuitive. However, an approach ensuring global stability for a system comprising both the controller and a state observer has yet to be presented.

Backstepping methodology involves the attainment of global stability by defining an error variable and a corresponding stabilizing function of each sub-system in association with a Lyapunov function in a systematic manner to achieve the control law. The approach also allows the introduction of additional nonlinearities into the control laws for compensation of undesirable ones (Fossen & Strand, 1999b; Khalil, 2002; Krstic, Kanellakopoulos, & Kokotovic, 1995; Marques, 2003). In DPS applications, however, the controller may induce an undesirable high-amplitude oscillatory signal. This behavior is due to the lack of a gain matrix multiplying some of the error variables that in turn may be corrupted with a parcel of wave-frequency components "leaked" from the observer estimates—an expected scenario under real situations. This aspect was observed by Zakartchouk and Morishita (2009) during the experimental evaluation of a DPS in which the controller was based on the work by Aarset et al. (1998). Preliminary analysis indicated that the reason for this behavior was the saturation of the actuators. To overcome this problem, the introduction of a gain matrix was suggested to lower the values of the deviation of the estimated positions from their desired values (an error variable) in the control loop, but no formal proof of stability was presented.

In order to achieve a more realistic DPS control law, the thrust allocation among the actuators and their saturation should be considered. Direct inclusion of such effects (specially saturation) in the control laws is a rather difficult task. In many cases, once the control law signals are defined, the thrust allocation is performed, and the saturation is subsequently imposed on the signal for each actuator. Alternatively, the thrust allocation and the corresponding saturation can be treated as an optimization problem (Johansen, Fossen, & Tondel, 2005). A proposal to consider the actuator saturation in a controller based on backstepping methodology is presented by Bateman, Hull, and Lin (2009), although neither wave-frequency motion filtering nor thrust allocation is addressed. For additional details on this subject, see Fossen (2011) and Sordalen (1997).

The main object of this paper is to propose a controller based on the observer backstepping methodology for a DPS in which both a nonlinear observer for wave-frequency motions and the actuator dynamics are included in the plant model. Besides, the controller allows a convenient tuning of the gains for the control signal to be compatible with the limitation of the actuators. In this sense, a slight modification in the controller based on observer backstepping for a DPS introduced by Aarset et al. (1998) is proposed and as a result two new gain matrices associated with error variables are included in the control structure. These matrices replace the identity gain matrices of the controller based on the conventional backstepping methodology.

The saturation of the actuators is not included in the control structure, but it is cascaded with the controller. A formulation based on a pseudo-inverse matrix is applied for dealing with the over-actuated system. The stability of the observer–controller set is proven using Lyapunov stability analysis. The assessment of the controller performance is carried out by means of dynamic simulations that consider a realistic model for the vessel dynamics and environmental loads rather than the simplified plant model considered in the design of the controller.

The text is organized as follows: Section 2 briefly presents a mathematical model of the plant for controller design purposes. In Section 3 the modified formulation for the controller based on observer backstepping is proposed. Next, stability is proven using Lyapunov stability analysis, and the rationale for the inclusion of two new gain matrices is presented. Section 4 discusses the results of the simulations, and conclusions are drawn in Section 5.

2. Mathematical model

Under assumption of small motions and considering the ship as a slender body with port/starboard symmetry, its horizontal and vertical motions may be decoupled from each other so that only the surge, sway and yaw motions—those to be controlled by the DPS—are considered in the mathematical model (Lewis, 1989; Sorensen & Strand, 2000). The vessel responses to the environmental and actuator loads are then calculated through a set of equations of motions derived in two different coordinate systems, as shown in Fig. 1. The first, *OXYZ*, is an Earth-fixed frame that can be considered as inertial for the present problem. The other frame ($GX_GY_GZ_G$) is a body-fixed one, whose axes coincide with the ship's principal axes of inertia. Both systems are assumed to be parallel to the water surface, and the direction of current, wind and waves are defined according to their orientation related to the *OX*-axis. As a DPS is exclusively intended to control low-frequency motions, only those loads due to current and the slowly varying components of wind and waves are to be considered in the models for both the controller and the observer, together with those induced by the actuators. A mathematical model suitable for the design of the controller based on observer backstepping is presented below. A more complete mathematical model for the dynamics of the vessel considered in the simulation is briefly described in Appendix A.

2.1. Low-frequency motions

The three degrees-of-freedom mathematical model for the vessel low-frequency motions consists of state-space representations of a position vector $\boldsymbol{\eta} = [X\ Y\ \psi]^T$ and a velocity vector $\boldsymbol{\nu} = [u\ v\ r]^T$, with X, Y and ψ being the coordinates for the vessel position and heading in the inertial frame and u, v, r the surge, sway and yaw velocities in the body-fixed frame respectively. For the purpose of designing the observer–controller model the environmental loads are assumed as slowly varying first-order Markov processes. The actuator dynamics are modeled through first-order differential equations. Thus, the state equations of the system are (Fossen, 1994)

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{\nu} \tag{1}$$

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{D}\boldsymbol{\nu} = \boldsymbol{B}\boldsymbol{f}_{\boldsymbol{p}} + \boldsymbol{J}^T(\boldsymbol{\eta})\boldsymbol{b} \tag{2}$$

$$\dot{\boldsymbol{b}} = -\boldsymbol{T}_{\boldsymbol{b}}^{-1}\boldsymbol{b} + \boldsymbol{\theta}\boldsymbol{n} \tag{3}$$

$$\dot{\boldsymbol{f}}_{\boldsymbol{p}} = \boldsymbol{T}_{\boldsymbol{p}}^{-1}(\boldsymbol{f}_{\boldsymbol{d}} - \boldsymbol{f}_{\boldsymbol{p}}) \tag{4}$$

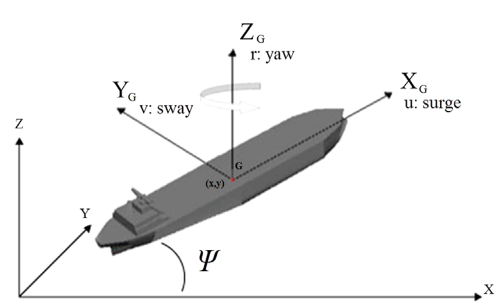

Fig. 1. Definition of the earth-fixed and body-fixed frames.