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Iterative lead compensation control of nonlinear marine vessels manoeuvring models

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ABSTRACT

This paper addresses the problem of control design and implementation for a nonlinear marine vessel manoeuvring model. The authors consider a highly nonlinear vessel 4 DOF model as the basis of this work. The control algorithm here proposed consists of a combination of two methodologies: (i) an iteration technique that approximates the original nonlinear model by a sequence of linear time varying equations whose solution converge to the solution of the original nonlinear problem and (ii) a lead compensation design in which for each of the iterated linear time varying system generated, the controller is optimized at each time on the interval for better tracking performance. The control designed for the last iteration is then applied to the original nonlinear problem.

Simulations and results here presented show a good performance of the approximation methodology and also an accurate tracking for certain manoeuvring cases under the control of the designed lead controller. The main characteristic of the nonlinear system's response is the reduction of the settling time and the elimination of the steady state error and overshoot.

1. Introduction

The design of autopilots based on proportional–integral–derivative (PID) methodologies has been in use since 1920s [10] with the help of gyrocompasses which measured the vehicle's heading angle for feedback purposes. The major challenges confronted in the design of ship autopilots are mainly the existing surrounding environmental uncertainties such as waves, wind, ocean currents and the high nonlinear ship dynamics. In addition to these, the rudder dynamics also present saturation-type nonlinearities on its rate and deflection angle.

Several articles deal with the design and implementation of PID based autopilots, in which linearizations for the vessel's manoeuvring model are performed, see [10,17,29,18,23,22] as the most representative. In the case of low speed applications, it is acceptable to neglect the nonlinear dynamics on the ship's manoeuvring model due to linear terms predomination. However, for high speed applications, tight turns, large sideslip angles or in the presence of currents, nonlinear effects become pronounced and thus neglecting them may degrade the controller's performance and robustness.

On the other hand, different nonlinear methods [10] have been presented for course-keeping autopilot's design such as state feedback linearization [12], nonlinear backstepping [2,38], sliding mode control [20], output feedback [21], H_∞-control [16], particle swarm optimization [31], genetic algorithms [20], fuzzy logic methods [5], etc. For most of these type of applications, nonlinear manoeuvring models in 1 degree of freedom (DOF) are considered, see [25] or [3] as example, still in these contributions, the coupling existing between the various variables is obviously not taken into account. Due to the complexity of some of the above-cited nonlinear methods, the implementation may be tedious and time consuming from the computational point of view.

The aim of this article is to design a control method for a nonlinear marine vessel manoeuvring model without performing any simplification in the model's nonlinearities or variable's couplings. The authors propose a control strategy based on an optimized lead compensation control methodology combined with an iteration technique used to approach the original nonlinear system. This iteration technique was initially presented in [33,34] and has been used to solve various nonlinear control problems such as optimal control [35], observers design [15], nonlinear optimal tracking [8], etc. One of its advantages is the fact that it maintains the inherent nonlinear characteristics of the system's behaviour, providing the grounds for a robust control implementation where modelling uncertainties are removed. The iteration technique is applied to a 4 DOF nonlinear manoeuvring ship model. This opens the novel possibility of course-keeping autopilot design based on lead compensation methodology

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Table 1
Notation for the ship's displacement variables.

Movement	Force	Linear speed	Position
Surge	X	u "b-frame"	x_n "n-frame"
Sway	Y	v "b-frame"	y_n "n-frame"
Rotation	Moment	Angular speed	Angle
Roll	K	p "b-frame"	ϕ euler
Yaw	N	r "b-frame"	ψ(heading) Euler

applied to a nonlinear model. This approach exists without the limitations of the linear models previously indicated, and keeps the simplicity of the lead compensation design and implementation. Furthermore, based on a preliminar study, the use of a lead controller instead of a conventional PID is justified. By an appropriate optimization technique, a trade off between the overshoot and time response is achieved without stationary state error.

The objective is to design a lead compensation controller for nonlinear systems of the form:

$$\dot{x} = f(x) = A(x)x(t) + B(x)u_c(t, \theta_c), \quad x(0) = x_0 \tag{1}$$

where $u_c(t, \theta_c)$ is the control action, θ_c is the set of controller's parameters, $x(t)$ is the state vector, $A(x)$, $B(x)$ are matrices of appropriate dimensions and $x(0)$ are the initial conditions. Replacing the nonlinear system by a sequence of "i" linear time varying (LTV) systems, a sequence of corresponding feedback laws $u_c^{(i)}(t, \theta_c)$ is generated: for each of them, the closed-loop response for the ith LTV system at each time of the time interval is controlled by the designed lead controller $u_c^{(i)}(t, \theta_c)$. From the convergence of the sequence of LTV solutions [33], the last iterated control law $u_c^{(i)}(t, \theta_c)$, (corresponding to the ith iteration), will provide lead controller stability objectives satisfaction when it is applied to the nonlinear system.

The structure of the article is as follows: Section 2 contains the detailed description of the nonlinear model for the vessel under consideration. Details on the hydrodynamic, propulsion and control forces are given. Section 3 provides details on the iteration technique and the convergence theorem is stated. Section 4 shows the application of this technique to the nonlinear vessel model by using a 20–20° zig-zag manoeuvre example to illustrate the ideas. Section 5 presents the control algorithm design and implementation. Section 6 shows the performance of the control methodology on the vessel's nonlinear model. This section contains the simulations carried out and a discussion on the results obtained. Conclusions and further research guidelines are provided in Section 7.

2. The mathematical model

The nonlinear dynamical model described in this section is classified as what is known as manoeuvring. Manoeuvring deals with the ship's motion in absence of waves excitation (calm water) [27]. The motion results from the action of control devices such as control surfaces (rudders, fins, T-foils) and propulsion units.

In manoeuvring theory, the motion of 4 DOF ship models requires from four independent coordinates in order to fully determine the position and orientation of the vehicle, which is considered to be a rigid body. These coordinates represent the longitudinal and lateral positions and speeds as well as and their derivatives along the respective coordinate frames. The variables describing the vessels's dynamics are provided in Table 1 and Fig. A1 following the notation found in [32], which will be adopted for remaining of this article.

The four degrees of freedom under consideration in this work describe the ship's motion (surge, sway and yaw) on the horizontal plane and the roll in the vertical plane. Two coordinate frames are used: the n coordinate system (earth-fixed), O_n, is used to define the ship position and the system b, (body-fixed) O_b, helps to define the ship's orientation [27] (see Fig. A1).

The rigid-body equations of motion of the 4 DOF model are given by [28]:

$$\begin{aligned} m[\dot{u} - y_g^b\dot{r} - vr - x_g^b r^2 + z_g^b pr] &= \tau_X \\ m[\dot{v} - z_g^b\dot{p} + x_g^b\dot{r} + ur - y_g^b(r^2+p^2)] &= \tau_Y \\ I_{xx}\dot{p} - mz_g^b\dot{v} + m[y_g^b vp - z_g^b ur] &= \tau_K \\ I_{zz}\dot{r} + mx_g^b\dot{v} - my_g^b\dot{u} + m[x_g^b ur - y_g^b vr] &= \tau_N \end{aligned} \tag{2}$$

The subindex $_g$ refers to the center of gravity and the superindex ^{b} to the b-frame. Details of the parameters included in Eq. (2) can be found in Appendix A. These equations of motion are formulated about the b-frame, which is fixed to the point determined by the intersection of the port-starboard plane of symmetry, the waterline plane and the transverse vertical plane at $L_{pp}/2$ (see Appendix A for hull dimensions).

The force terms on the right hand side of Eq. (2) can be described as the total contribution of the hydrodynamic, propulsion and control forces:

$$\tau = \tau_{hyd} + \tau_p + \tau_c \tag{3}$$

These terms will be described next.

2.1. Hydrodynamic forces

The hydrodynamic forces considered in this section, τ_{hyd}, are those appearing due to the motion of the vessel in calm water. The following equations correspond to the model established by [6] that proposed a simplified version of the model in [24], preserving in this way the most important hydrodynamic coefficients so that the model describes a wide variety of manoeuvring regimes in spite of some minor simplifications. Hydrodynamic forces are mainly composed by surge, sway, roll and yaw terms:

- *Surge terms*

$$\tau_{Xhyd}^b = X_{\dot{u}}\dot{u} + X_{vr}vr + X_{u|u|}u|u| \tag{4}$$

- *Sway terms*

$$\begin{aligned} \tau_{Yhyd}^b =\; & Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{\dot{p}}\dot{p} + Y_{|u|v}|u|v + Y_{ur}ur + Y_{|v|v}|v|v + Y_{|v|r}|v|r \\ & + Y_{|r|v}|r|v + Y_{\phi|uv|}\phi|uv| + Y_{\phi|ur|}\phi|ur| + Y_{\phi uu}\phi u^2 \end{aligned} \tag{5}$$

- *Roll terms*

$$\begin{aligned} \tau_{Khyd}^b =\; & K_{\dot{v}}\dot{v} - K_{\dot{p}}\dot{p} + K_{|u|v}|u|v + K_{ur}ur + K_{|v|v}|v|v + K_{|v|r}|v|r \\ & + K_{|r|v}|r|v + K_{\phi|uv|}\phi|uv| + K_{\phi|ur|}\phi|ur| + K_{\phi|uu|}\phi u^2 \\ & + K_{|u|p}|u|p + K_{p|p|}p|p| + K_p p - K_{\phi\phi\phi}\phi^3 + \rho g \nabla GMt\phi \end{aligned} \tag{6}$$

- *Yaw terms*

$$\begin{aligned} \tau_{Nhyd}^b =\; & N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_{|u|v}|u|v + N_{ur}ur + N_{|v|v}|v|v + N_{|v|r}|v|r \\ & + N_{|r|v}|r|v + N_{\phi|uv|}\phi|uv| + N_{\phi u|r|}\phi u|r| + N_{|p|p}|p|p \\ & + N_{|u|p}|u|p + N_{\phi u|u|}\phi u|u| \end{aligned} \tag{7}$$

Note that $\dot{\psi} = r$ and $\dot{\phi} = p$.