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Identification-based simplified model of large container ships using support vector machines and artificial bee colony algorithm

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ABSTRACT

The 6 degrees of freedom (DOF) model with a high degree of complexity for capturing ship dynamics is generally able to track the nonlinear and coupling dynamics of ships. However, the 6 DOF model makes challenges in estimating model coefficients and designing the model-based control. Therefore, simplified ship dynamic models within allowed accuracy are essential. This paper simplified the 6 DOF nonlinear dynamic model of ships into two decoupled models including the speed model and the steering model through reasonable assumptions. Those models were tested through maneuvering simulations of a container ship with a 4 DOF dynamic model. Support vector machines (SVM) optimized by the artificial bee colony algorithm (ABC) was used to identify parameters of speed and steering models by analyzing the rudder angle, propeller shaft speed, surge and sway velocities, and yaw rate from simulated data extracted from a series of maneuvers made by the container ship. Comparisons with the first order linear and nonlinear Nomoto models show that the simplified nonlinear steering model can capture more complicated dynamics and performs better. Additionally, comparisons among three different parameter identification methods demonstrate similar identification results but the different performance involving the applicability and effectiveness. SVM optimized by ABC is relatively convenient and effective for parameter identification of ship simplified dynamic models.

1. Introduction

With the development of advanced control techniques such as the linear quadratic Gaussian control (LQG), the state feedback linearization, the integrator backstepping, and the sliding-mode control [1], model-based control has become the state-of-the-art for steering and positioning ships to enhance performance of ships. Due to the high cost and risk of using full-size ships to test advanced control methodologies, a scaled-model ship is always applied to evaluate ship control approaches [2]. These studies, to some degree, can facilitate the effectiveness of their control techniques, but the scale effect caused by differences between scaled-model ships and large ships makes the application of these control techniques to large ships a challenging task. A large container ship [3] is used to remedy this situation in this paper. The dynamics of this container ship in 4 degrees of freedom (4 DOF), i.e., translational motions of surge and sway, and rotational motions of roll and yaw, are described in reality by a set of complex differential equations which will be presented in the next section. These sufficiently accurate equations satisfy simulation study purposes about assessing maneuverability of ships. With respect to the ship control, however, they will exponentially increase complexity of the control designs, and make the reasonable estimation of parameters of the ship dynamic model a tough task. An adequate ship dynamic model with reasonable parameters is imperative for the studies of control designs and simulations.

Therefore, aiming at determining a desirable ship dynamic model with relatively acceptable complexity for control designs, this paper addresses the simplifications of the nonlinear and coupling dynamic model for a large container ship by only considering the decoupled speed and steering motions. Recently, studies have been reported on applying the simplified ship dynamic model to ship control designs. For instance, Zwierzewicz [4] linearized the nonlinear ship model of Norrbin type, and then applied it to adaptive control approaches to test the ship course-keeping control system. Besides, Sonnenburg [5] used a backstepping trajectory

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controller to track the Ribcraft USV's trajectories generated by the first order linear Nomoto model with the linear sideslip model and simplified speed model, and the references therein. Obviously, the authors are mainly using scaled-model ships for their work, which in turn illustrates that the goal of this paper about simplifying the complex model of large ships is meaningful.

After selecting the suitable ship dynamic model for control designs, parameter identification of the ship dynamic model is another task of much importance. The main methods for estimating the maneuvering model include towing-tank experiments, captive model experiments [6], computational fluid dynamics (CFD) and system identification combined with full-scale or free-running model [7]. Among these methods, system identification combined with full-scale or free-running model is becoming an attractive and sufficient technique for estimating ship maneuvering model due to its relatively high cost-effectiveness.

System identification is a very large topic with different techniques that depend on the characters of models to be estimated: linear, nonlinear, hybrid, nonparametric, etc. [8]. Various conventional system identification methods such as the least squares method (LS) [7], the maximum likelihood method (ML) [9] and the extended Kalman filter (EKF) [10] have been successfully applied to estimate the ship maneuvering model. During recent years, a variety of new methods based on the modern artificial intelligent technology, such as the artificial neural network (ANN) [11], the genetic algorithm (GA) [12] and the support vector machines (SVM) [13,14] have been successfully used to system identification of the ship maneuvering model. Comparatively, SVM directs at finite samples, which requires no initial identification of parameters but has good generalization performance and global optimum. Note that the coefficients of variables in the regression model are sensitive to the structural parameters in SVM, such as the insensitivity factor, the regularization parameter, and kernel parameters. Using trails is a general way to determine parameters in SVM. In contrast, it seems a cost-effective way to optimize parameters in SVM by intelligent algorithms instead of using trails. Taking the research [15] as an example, the particle swarm optimization algorithm (PSO) is incorporated into SVM to obtain the optimized structural factors in SVM, and the SVM regression results agree well with the experimental results. Inspired by this research, and the better performance of ABC than PSO [16,17], this paper is the first proposing SVM optimized by ABC to identify the simplified dynamic model of large ships by using simulated data.

The main contributions of this paper are summarized as follows: First, the nonlinear and coupling dynamic model of ships is simplified into a 3 DOF nonlinear dynamic model including decoupled speed and steering models. This model can be easily modified to either a 3 DOF model for the large ship trajectory tracking, and path following, etc., or a steering model for large ship autopilot control designs. Furthermore, to date, SVM optimized by ABC is the first time to be used for parameter identification of the simplified dynamic model of large container ships. This boosts the application of SVM in marine research field while declaring the solution of optimizing structural parameters in SVM. To the best knowledge of authors, the application of SVM optimized by ABC to parameter identification of the ship dynamic model has not been considered in open literatures.

This paper is organized as follows. Section 2 describes an overview of the nonlinear model of a container ship, and addresses the simplification of the complex model. In Section 3, the formulations of SVM and ABC, and construction of samples for identification are presented, respectively. The simulated maneuvers of the large container ship are used in Section 4 as training samples and validation samples for parameter identification of the simplified ship dynamic model, and comparisons among three steering models, and three parameter identification methods are carried out, respectively. Finally, concluding remarks are summarized in Section 5.

Table 1
Notation from SNAME.

DOF	Motions	Forces	Linear velocity	Positions
1	Surge	X	u	x
2	Sway	Y	v	y
3	Heave	Z	w	z
	Rotations	Moments	Angular velocity	Rotation angles
4	Roll	K	p	φ
5	Pitch	M	q	θ
6	Yaw	N	r	ψ

2. Dynamic model of ships

For ships moving in 6 DOF, six independent coordinates are necessary to determine the position and orientation. The first three coordinates and their time derivatives correspond to the position and translational motion along the x, y and z, while the last three coordinates and their time derivatives are used to describe the orientation and rotational motion [1]. Generally, the two reference frames shown in Fig. 1 consisted of a body-fixed frame and an earth-fixed frame are used to describe 6 DOF dynamics which can be analyzed through the Newton–Euler formulation. The nonlinear 6 DOF dynamic model of a ship can be expressed in the body-fixed frame as [3]

$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\boldsymbol{\upsilon}, \tag{1}$$

$$\boldsymbol{M}\dot{\boldsymbol{\upsilon}} + \boldsymbol{C}(\boldsymbol{\upsilon})\boldsymbol{\upsilon} + \mathbf{D}(\boldsymbol{\upsilon})\boldsymbol{\upsilon} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau}_{ext} + \boldsymbol{\tau}, \tag{2}$$

where $\boldsymbol{\upsilon} = [u, v, w, p, q, r]^T$ is the spatial velocity state vector, $\boldsymbol{\eta} = \left[x, y, z, \varphi, \theta, \psi\right]^T$ presents the position and orientation states, $\boldsymbol{J}(\boldsymbol{\eta}) = f(\varphi, \theta, \psi)$ is the transformation matrices between variants in the body-fixed frame and earth-fixed frame, $\boldsymbol{M}$ is the mass matrix, $\boldsymbol{C}(\boldsymbol{\upsilon})$ is the Coriolis and centripetal matrix, $\boldsymbol{D}(\boldsymbol{\upsilon})$ is the damping matrix, $\mathbf{g}(\boldsymbol{\eta})$ manifests the effects of buoyancy's interaction with gravity, $\boldsymbol{\tau} = [X, Y, Z, K, a, N]^T$ denotes the actuator forces and moments generated by a set of propellers with revolutions per second $\mathbf{n} = [n_1, n_2, \ldots, n_{p1}]^T$ and a set of control surfaces with angles $\boldsymbol{\delta} = [\delta_1, \delta_2, \ldots, \delta_{p2}]^T$, $\boldsymbol{\tau}_{ext}$ is the external disturbances from currents, wave, etc. The notation from SNAME used in this paper are presented in Table 1.

2.1. Nonlinear model of a large container ship

The study of the maneuverability of surface ships are mainly considered for studying the horizontal motions of ships such as surge, sway and yaw with more importance given to the last two highly coupled motions, known as the steering model. However, for the high speed container ship, the roll effects cannot be ignored. Hence, the nonlinear roll-coupled steering model for the high speed container ship is written as [18]

$$(m - X_{\dot{u}})\dot{u} - (m - Y_{\dot{v}})vr = X, \tag{3}$$

$$(m - Y_{\dot{v}})\dot{v} + (m - X_{\dot{u}})ur - Y_{\dot{r}}\dot{r} = Y, \tag{4}$$

$$(I_x - K_{\dot{p}})\dot{p} = K - WG\bar{M}_T\varphi, \tag{5}$$

$$(I_z - N_{\dot{r}})\dot{r} + N_{\dot{v}}\dot{v} = N, \tag{6}$$

where

$$\begin{aligned} X = {} & X(u) + (1-t)T + X_{vr}vr + X_{vv}v^2 + X_{rr}r^2 \\ & + X_{\varphi\varphi}\varphi^2 + X_{\delta}\sin\delta + X_{ext}, \end{aligned} \tag{7}$$