Applied Ocean Research 48 (2014) 55–65

Contents lists available at ScienceDirect

Applied Ocean Research

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

Target Path Iteration method for trajectory control of ships

S.K. Bhattacharyya*, Deepak Kumar Gupta

Department of Ocean Engineering, Indian Institute of Technology Madras, India

ARTICLE INFO

Article history:
Received 28 June 2013
Received in revised form 23 July 2014
Accepted 23 July 2014
Available online 21 August 2014

Keywords:
Trajectory control
Automatic control
Nonlinear
Maneuvering
Ship

ABSTRACT

A trajectory control algorithm, termed "Target Path Iteration (TPI) algorithm" is proposed for maneuvering of surface ships and its performance studied. A mathematical model for nonlinear maneuvering of cargo ships has been used in conjunction with the proposed algorithm. The TPI method works with one error measure, namely, the average mean square error, which is minimized to obtain the desired rudder angle. The proposed control scheme has been verified for a variety of straight line and curved trajectories and its performance has been found excellent.

1. Introduction

Various modern control techniques have been applied to large ships to improve the autopilot performance over a ship's operating envelope. The conventional techniques of autopilot design, such as those based upon PID (Proportional, Integral and Derivative) based controllers and their variants have remained in use for many years because of their simplicity, reliability and low cost. This is despite the widely held view that the steering characteristics of PID controllers are fundamentally unsatisfactory, mainly due to the necessity for user adjustment to accommodate changes in ship loading conditions and the operating environment.

The optimal control theory provided an alternative route to autopilot design and a number of solutions were proposed based on this. Other approaches that have gained limited use are autopilots based upon adaptive methods such as model reference and self-tuning.

More recently attempts to combine the attributes of adaptive and optimal control, designing 'robust' autopilots using the H_∞ methodology has gained currency. Fuzzy logic, with its origin in human reasoning process, is being actively pursued for autopilot design since it has the potential to replicate experienced helmsmen, thereby producing a robust and nonlinear autopilot. Identification algorithms are often combined with appropriate control laws to construct automatic control systems. Neural network based controllers have also been studied for the automatic maneuvering problem. For a brief history and contemporary advances in ship autopilot design paradigms one is referred to [1,2].

Combinations of controllers are being actively investigated these days in pursuit of controllers that can work with changing environmental conditions and system parameters. It is worth mentioning that the problem of ship maneuvering control is made complex because of ever changing environmental conditions (i.e. winds, waves and currents) and the changes in the system behavior with changes in draft, trim, heel, water depth, marine growth on the hull, etc.

An outline of neuro-fuzzy controllers is presented in [1]. Recent studies involve the use of traditional PID controllers in conjunction with modern fuzzy control [3,4]. The controller constantly switches between PID and fuzzy control based on the deviations from the desired trajectory. The two quantitative measures of error are 'heading error' and 'rate of change of heading error'. For small deviations from the target trajectory, PID control is preferred while fuzzy control is preferred when the errors are large.

Robust controllers based on H_∞ [5] and Quantitative Feedback Theory (QFT) [6] methodologies have been used with linear ship maneuvering models. A major drawback of using the classical control theories is that they can be easily applied to linear systems or simple nonlinear systems but not to complex nonlinear systems. Linear ship models sufficiently describe a ship in deep waters but as the ship comes into the shallow waters (i.e. harbor region) nonlinear effects gain prominence and a full-fledged nonlinear model is necessary to describe ship dynamics.

Several authors have applied stochastic approach to analysis and control of ship motion [7–9]. More recently, a new method for constructing ship autopilots based on combination of the Recursive

* Corresponding author at: Department of Ocean Engineering, Indian Institute of Technology Madras, Chennai 600036, India. Tel.: +91 44 22574803; fax: +91 44 22574802.
E-mail address: skbh@iitm.ac.in (S.K. Bhattacharyya).

0141-1187/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2014.07.012

Least Square (RLS) algorithm with the Linear Quadratic Gaussian (LQG) optimal control algorithm has been formulated [10].

Neural networks have been found wanting in effective maneuvering control of ships because of their lack of generalization. They tend to produce better results on the training data set than with a new set of data. Some researchers have turned toward Support Vector Machines (SVMs) because the generalization abilities of SVMs are better than those of neural networks [11,12].

The first ship autopilot designed with fuzzy set theory considered two different inputs and a fixed rule base [13] and various developments such as the first commercially available autopilot design [14] and the first version of fuzzy autopilot for track keeping [15] have been proposed. Later, improved fuzzy autopilots for track keeping [16,17] using three inputs (heading error, rate of change of heading and offset from desired path) were proposed. A fuzzy autopilot that works with two error inputs (heading error and the offset from the desired path) has also been studied in conjunction with a linear ship model that includes a damping term in yaw [18]. In a recent paper [19], a fuzzy autopilot was proposed which worked well for continuously curved target trajectories. Typically, except [19], in all papers the target trajectories that had been considered consisted of a series of straight line paths between the so called way-points with a radius included at the intersection of two straight lines, i.e. at each way-point. A continuously curved target path in fuzzy controlled maneuvering such as a path that the ship takes in a turning circle maneuver was treated in [19]. Another striking aspect is that seldom it has been the case that a comparison of the path taken by the ship during the control simulation vis-à-vis the target trajectory has been presented in literature. Such a comparison is probably the best judge for the performance of an autopilot at first glance.

A control strategy that has now become the industry norm for control of systems with slow dynamics is the Model Predictive Control (MPC). In MPC, the control action at any time is determined by optimization of a system-specific 'cost function' over future time. MPC is computationally intensive and often system dynamics, which may be nonlinear in nature, is assumed to be linear to cut-down the resource utilization. An implementation of MPC with a linear ship model has been recently presented in [20] where the 'cost function' is a quadratic combination of the control input and the offset of the ship from the given target path.

In this paper, for path control of ships, a new algorithm, called "Target Path Iteration" (TPI) algorithm, has been proposed with a 'one input' (average mean square error of the future path of some length) – 'one output' (command rudder angle) system and tested by simulation. The implementation considers direct nonlinear time domain simulation of the differential equations of motion to implement the control algorithm. Extensive testing of the proposed control algorithm has shown excellent behavior for a well-known nonlinear ship maneuvering model [21–23] which can describe the behavior of a wide class of cargo ships. Whereas in earlier works based on fuzzy control, e.g. [15–17], trajectories consisting of straight lines only have been studied, in this paper attempt has been made to study the performance of the path following algorithm over continuously curved target trajectories in addition to the trajectories consisting of a path joining two straight lines. It should be noted that waypoint trajectories are easily reproduced by all control strategies but curved target trajectories, such as a circular path obtained from turning circle maneuver, offer more demanding test for the controller to follow.

2. Nonlinear ship maneuvering model

The mathematical model of ship dynamics in the horizontal plane involving coupled surge-sway-yaw motions is essential both for numerical simulation and investigation of different control algorithms. In this paper, the model of a Mariner class vessel is adopted which can describe the dynamics of a wide variety of cargo ships. The nondimensional equations of this model are nonlinear and are given below [19,21–23] in the ship-fixed coordinate system (X, Y, Z):

$$\begin{aligned}
&(m - X_{\dot u})\Delta\dot u = \Delta X_F\\
&(m - Y_{\dot v})\Delta\dot v + (mX_G - Y_{\dot r})\Delta\dot r = \Delta Y_F\\
&(mX_G - N_{\dot v})\Delta\dot v + (I_Z - N_{\dot r})\Delta\dot r = \Delta N
\end{aligned}\tag{1}$$

where

$$\begin{aligned}
\Delta X_F ={}& X_u\Delta u + X_{uu}\Delta u^2 + X_{uuu}\Delta u^3 + X_{uvv}\Delta u\Delta v^2 + X_{uvr}\Delta u\Delta v\Delta r + X_{uv\delta}\Delta u\Delta v\Delta\delta + X_{urr}\Delta u\Delta r^2 + X_{ur\delta}\Delta u\Delta r\Delta\delta + X_{u\delta\delta}\Delta u\Delta\delta^2\\
&+ X_{vv}\Delta v^2 + X_{vr}\Delta v\Delta r + X_{v\delta}\Delta v\Delta\delta + X_{rr}\Delta r^2 + X_{r\delta}\Delta r\Delta\delta + X_{\delta\delta}\Delta\delta^2\\
\Delta Y_F ={}& Y_u\Delta u + Y_v\Delta v + Y_r\Delta r + Y_\delta\Delta\delta + Y_{uu}\Delta u^2 + Y_{uuv}\Delta u^2\Delta v + Y_{uur}\Delta u^2\Delta r + Y_{uu\delta}\Delta u^2\Delta\delta + Y_{uv}\Delta u\Delta v + Y_{ur}\Delta u\Delta r + Y_{u\delta}\Delta u\Delta\delta\\
&+ Y_{vvv}\Delta v^3 + Y_{vvr}\Delta v^2\Delta r + Y_{vv\delta}\Delta v^2\Delta\delta + Y_{vrr}\Delta v\Delta r^2 + Y_{vr\delta}\Delta v\Delta r\Delta\delta + Y_{v\delta\delta}\Delta v\Delta\delta^2 + Y_{rrr}\Delta r^3 + Y_{rr\delta}\Delta r^2\Delta\delta\\
&+ Y_{r\delta\delta}\Delta r\Delta\delta^2 + Y_{\delta\delta\delta}\Delta\delta^3 + Y_0 + Y_{0u}\Delta u + Y_{0uu}\Delta u^2\\
\Delta N ={}& N_u\Delta u + N_v\Delta v + N_r\Delta r + N_\delta\Delta\delta + N_{uu}\Delta u^2 + N_{uuv}\Delta u^2\Delta v + N_{uur}\Delta u^2\Delta r + N_{uu\delta}\Delta u^2\Delta\delta + N_{uv}\Delta u\Delta v\\
&+ N_{ur}\Delta u\Delta r + N_{u\delta}\Delta u\Delta\delta + N_{vvv}\Delta v^3 + N_{vvr}\Delta v^2\Delta r + N_{vv\delta}\Delta v^2\Delta\delta + N_{vrr}\Delta v\Delta r^2 + N_{vr\delta}\Delta v\Delta r\Delta\delta + N_{v\delta\delta}\Delta v\Delta\delta^2 + N_{rrr}\Delta r^3\\
&+ N_{rr\delta}\Delta r^2\Delta\delta + N_{r\delta\delta}\Delta r\Delta\delta^2 + N_{\delta\delta\delta}\Delta\delta^3 + N_0 + N_{0u}\Delta u + N_{0uu}\Delta u^2
\end{aligned}\tag{2}$$

$$u = u_0 + \Delta u; \quad v = v_0 + \Delta v; r = r_0 + \Delta r; \quad \delta = \delta_0 + \Delta\delta \tag{3}$$

In the above, m is the mass of the ship, I_Z is its mass moment of inertia about Z axis (vertically downward with axis origin O amidships and on the centerline at free surface), u and v are velocities along X (toward forward) and Y axes (toward starboard) respectively, r is the yaw rate ($=\dot\psi$, where ψ is the yaw angle in the horizontal plane), an overdot denotes time (t) derivative, δ is the rudder angle, X_G and Y_G are the X and Y coordinates of ship's center of gravity (CG). Also, Δu, Δv, Δr and $\Delta\delta$ are small perturbations to their corresponding nominal values u_0, v_0, r_0 and δ_0, respectively. Specifically, u_0 is the service speed. Similarly, ΔX_F, ΔY_F and ΔN are the surge force, sway force and yaw moment perturbations respectively. All other quantities are constant hydrodynamic derivatives. The positive rudder angle is toward starboard (leading to starboard turn) and negative toward port (leading to port turn). This maneuvering model does not include any propulsion related parameters and as a result propulsion control is absent in the model. The only control possible in this model is rudder control. All quantities in the above equations are nondimensional and may be related to their