Adaptive Backstepping Autopilot for Way-point Tracking Control of a Container Ship in the presence of Time-varying Disturbances

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Abstract: Effective Control of ships in a designed trajectory, is always an important task for ship maneuvering. This article considers way-point tracking control of a container ship based on LOS method using adaptive backstepping. The uncertainty of model parameters in the presence of disturbances such as waves, winds and currents, dictate the application of techniques that take into account the nonlinear equations of ship’s motion and the presence of unknown parameters. In this sense, the adaptive backstepping procedure with tuning functions design is used for solving this problem. The simulation results show the suitability of this technique to compensate the time-varying disturbances effects in way-point tracking control.

Keywords: Adaptive Backstepping, Way-point Tracking, LOS Guidance.

1. INTRODUCTION

The way-point tracking control problem is an issue of high interest in research areas of ship maneuvering. In seaway, the path or trajectory is constructed by using a set of way-points that can be generated according to sail plan and weather data (minimum resistance or energy approach). The way-point tracking control problem is to make the ship follow the path planned with the way-points by controlling the rudder. A widely used method for way-point tracking control is line of sight (LOS) guidance. In this methodology, a LOS vector is computed from the ship position to the next way point for heading control (Fossen, 2000).

The way-point tracking control has been improved over several years. Reference (Petterson,2001) gives a yaw control law for ship way-point tracking control problem based on a full state feedback control approach. A new fuzzy autopilot for way-point tracking is proposed in [Cheng, 2006]. A way-point guidance algorithm by LOS, which calculates a dynamic LOS vector norm in order to minimize the cross track error, is presented in [Moreira, 2007].

The backstepping method is a recursive procedure which interlaces the control design problem with construction of Lyapunov functions in a step by step manner. The use of the backstepping method makes it possible to create, in an arbitrary way, additional nonlinearities and introduce them in to the control process to eliminate undesirable nonlinearities from the system (Fossen, 1998). This is of great importance in the case of ship control systems in which removing all nonlinearities would require information on accurate models of all existing nonlinearities, which is hardly available in practice. The backstepping method has been used in numerous engineering applications, among other cases, for designing a system that controls the flight trajectory (Harkegard, 2003), in the spaceship observation process (Krsti´c and Tsiotras, 1999), and in the design of industrial systems. In particular, the backstepping method can be an effective tool in adaptive control design for estimating parameters (Fang et al., 2004; Jiang, 2002).

In Adaptive backstepping with tuning functions; at each design step a virtual adaptation law known as tuning function is introduced, while the actual adaptation algorithm is defined at the final step in terms of all the previous tuning functions (Krestic´ et al., 1995). Moreover, the control algorithms based on the backstepping method make it possible to design a robust, nonlinear controller that limits the effect of disturbances acting in both deterministic and stochastic manners (Do et al., 2004; Skjetne et al., 2005). The work on adaptive backstepping control of ship can be found in (Casado, 2005) and (Godhavn,1998). This technique has been used to identify the ship model parameters based on the turning test trial and for tracking control of overactuated ships in the presence of constant disturbances.

In this paper, the problem of way-point tracking of container ship is considered. The disturbances such as winds and currents are regarded. This disturbance are time-varying and control problem has been solved using adaptive backstepping method.

The remainder of this paper is organised as follows. Section 2 deals with the modeling of ship and disturbances, Section 3 describes designing nonlinear controller, in section 4 the LOS guidance system is explained briefly, Section 5 discusses results and, finally, the conclusion is made in the last section.

2. EQUATIONS OF MOTION AND DISTURBANCES MODELING

2.1 Equations of Motion
In this section, the mathematical model of a single-screw high speed container ship is reviewed. A four degrees of freedom model in surge-sway-roll and yaw directions is considered (see Fig. 1). Considering various types of forces acting on a hull of a ship, which are the hydrodynamical forces caused by waves, winds, currents and finally the forces caused by a rudder and a propeller of a ship. To simplify, we consider a ship as a system with only one dimensional input vector i.e. the angle position of the rudder.

Fig.1. surge-sway-roll and yaw motion coordinate system

The ship equations of motion can be defined:

\[ m(\dot{u} - vr) = X \]  
\[ m(\dot{v} + ur) = Y \]  
\[ I_x \dot{r} = N \]  
\[ I_x \dot{\phi} = K \]

Where \( m \) is the mass of the ship, \( u \) and \( v \) are the surge and sway linear velocities, \( p \) and \( r \) are the roll and yaw angular velocities, \( I_x \) and \( I_z \) are the moments of inertia about the \( x \)-axis and \( z \)-axis respectively. The forces \( X \), \( Y \), and moments \( K \) and \( N \) can be expressed as functions of the states \( u, v, r, p \), their time derivatives \( \dot{u}, \dot{v}, \dot{r}, \dot{p} \) and the rudder angle \( \phi \) (Lewis, 1989). Hence,

\[ X = X(u, v, r, \dot{u}, \dot{v}, \dot{r}, \dot{p}, \phi, \dot{\phi}) \]  
\[ Y = Y(u, v, r, \dot{u}, \dot{v}, \dot{r}, \dot{p}, \phi, \dot{\phi}) \]  
\[ N = N(u, v, r, \dot{u}, \dot{v}, \dot{r}, \dot{p}, \phi, \dot{\phi}) \]  
\[ K = K(u, v, r, \dot{u}, \dot{v}, \dot{r}, \dot{p}, \phi, \dot{\phi}) \]

The state \( \phi \) is the roll angle, and it is the integration of the roll rate \( p \).

2.2 Disturbances Modeling

While moving in oceans, ships' motions are often influenced by environmental disturbances, therefore in order to control ships effectively, it is necessary to model the environmental disturbances such as winds and ocean currents (including tildals). Influence of each type of disturbances is derived separately and then the principle of superposition is applied to get the influences of environmental disturbances.

**Influences of Wind**

Forces and moments generated by the wind are given by the following system of equations:

\[ X_a = (1/2) \rho_A C_x (\theta_a) A_r V_A^2 \]  
\[ Y_a = (1/2) \rho_A C_y (\theta_a) A_L V_A^2 \]  
\[ N_a = (1/2) \rho_A C_n (\theta_a) L A_r V_A^2 \]

These forces and moments are added to right hand side of the equations of motion (1) to (3). Here, \( \rho_A \) is air density; \( A_T, A_L \) are transverse and longitudinal projected areas, respectively; \( \theta_a \) is wind relative direction; \( V_A \) is relative wind speed and \( C_x, C_y, C_n \) are forces and moment coefficients in \( X, Y, N \) directions, respectively. The relation between wind relative direction and forces and moment coefficients are shown in Fig. 2.

Fig.2. Relation between relative wind direction and forces and moment

**Ocean Currents**

Currents in the upper layers of the ocean are mainly generated by the atmospheric wind system over the sea surface. Current velocity can be expressed by velocity components of tildals, component generated by local wind, component generated by nonlinear waves (Stokes drift), component by major ocean circulation (e.g. Gulf Stream), component due to set-up phenomena and storm surges, and components governed by strong density jumps in the upper ocean:

\[ V_e = V_t + V_{\text{set-up}} + V_{\text{surf}} \]

Influences of forces and moments induced by currents can be included in the dynamic equations of ship motion by replacing the velocities in Equations (1) to (4) with relative velocities that is represented by:

\[ v_r = v - v_e \]

Where \( v_e = [u_e, v_e, w_e, 0, 0, 0] \) is a vector of irrotational body-fixed current velocities (Fossen, 1994).
3. DESIGNING NONLINEAR CONTROLLER

The control system is designed for steering a ship on the course. In this system, the controlled parameter is the ship course, \( \psi(t) \), while the controlling parameter is the rudder angle, \( \delta(t) \). For control purpose the Bech’s model is used. This model is obtained from the second-order Nomoto model, in which the angular velocity \( \dot{\psi}(t) \) was replaced by a nonlinear maneuvering characteristic \( H(\psi(t)) \), the coefficients of which can be determined from a spiral test.

The obtained model is given by the following equation (Amerongen, 1982):

\[
\ddot{\psi}(t) + \frac{1}{T_1} \dot{\psi}(t) + \frac{1}{T_2} H(\psi(t)) = K(\dot{T}_3 \delta(t) + \delta(t))
\]

(14)

where \( H(\psi(t)) \) is approximated by the following function:

\[
H(\psi(t)) = a \dot{\psi}(t)^3 + b \ddot{\psi}(t)
\]

(15)

Where \( a \) and \( b \) are real constants. Commonly, \( a \) and \( b \) are calculated based on a spiral test, but In this article, because of the presence of time-varying disturbances, the spiral test is not helpful to obtain these parameters. Identification of these parameters and also the control procedure is implemented by adaptive backstepping with tuning functions. (Krestic’et al., 1995).

To simplify control design, the Bech model is reduced to the Norbin model given by:

\[
T \dot{\psi}(t) + H(\dot{\psi}(t)) = K \delta(t)
\]

(16)

Where \( T = T_1 + T_2 - T_3 \)

(17)

In order to carry out the system description by the nonlinear state equations, it is preferable to define the following state variables: \( x_1 = \psi \) (yaw angle), \( x_2 = \dot{\psi} \) (yaw rate), and the output \( y = x_1 \). The kinematic equations of ship dynamics are

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= dU + a_1 x_2^3 + a_0 x_2 = dU + a^T Y \\
U &= \delta
\end{align*}
\]

(18) (19) (20)

The coefficient’s values are defined as:

\[
\begin{align*}
a_1 &= -\frac{a}{T} \\
a_0 &= -\frac{b}{T} \\
d &= K/T \quad \text{(23)}
\end{align*}
\]

\[
Y^T = [x_2 \ x_2^3] \\
\begin{bmatrix} 2 & 1 \end{bmatrix}
\]

(24) (25)

The control objectives are:

1. To force the output \( y = x_1 = \psi \) of the system to asymptotically track the reference output \( y_r(t) = \psi_r(t) \).
2. To keep the rudder angle in the acceptable range.

3.1 Adaptive Backstepping procedure

To implement the identification procedure by combining backstepping with tuning functions design, the following steps should be performed:

**STEP 1**

Introducing the variable \( z_1 \) representing the tracking error, and \( z_2 \) which means the error variable that expresses the fact by which \( x_2 \) is not the true control, both are defined by:

\[
\begin{align*}
z_1 &= x_1 - y_r \\
z_2 &= x_2 - \dot{y}_r - \alpha_1
\end{align*}
\]

(26) (27)

Eq. (26) yields

\[
\dot{z}_2 = z_2 + \alpha_1
\]

(28)

We design the virtual control law \( a_1 \) as

\[
a_1 = -c_1(x_1 - y_r)
\]

(29)

where \( c_1 > 1/2 \) is a positive design parameter. A positive Lyapunov function \( V_1 \) is defined as

\[
V_1 = \frac{1}{2} z_1^2
\]

(30)

Then the derivative of \( V_1 \) along with (28) and (29) is given as

\[
\begin{align*}
\dot{V}_1 &= -c_1 z_1 z_2 + z_2 z_2 \\
&\leq -c_1 z_1^2 + \frac{1}{2} z_2^2 + \frac{1}{2} z_2^2 \\
&= -\overline{c}_1 z_1^2 + z_2^2
\end{align*}
\]

(31)

Where \( \overline{c}_1 = c_1 - \frac{1}{2} > 0 \)

**STEP 2**

Without loss of generality, we assume that the sign of \( d \) in Equation (19) is positive (i.e. \( \text{sgn}(d) > 0 \)). From (19) and (27), we obtain

\[
\dot{z}_2 = U + a^T Y - \dot{a}_1 - \dot{y}_r
\]

(32)

We design the adaptive control law \( U(t) \) as follows

\[
U = -c_2(x_2 - \dot{y}_r - \alpha_1) - \dot{a}^T Y + \alpha_1 + \dot{y}_r
\]

(33)

where \( c_2 \) is a positive design parameter satisfying \( c_2 > \frac{1}{2} \). \( \alpha \) is an estimate of \( a \). The parameter update law is designed as

\[
\dot{\alpha} = \Gamma Y z_2
\]

(34)

where \( \Gamma \) is a positive definite matrix. We define a positive Lyapunov function \( V \) as
\[ V = \sum_{i=1}^{2} \frac{1}{2} z_i^2 + \frac{1}{2} \bar{a}I^{-1} \bar{a} \]  
(35)

where \( \bar{a} = a - \bar{a} \). By assuming that the time varying disturbances cause a slowly time varying parameters in the ship model, the derivative of \( V \) along with (32) to (34) is given by

\[ \dot{V} = \sum_{i=1}^{2} z_i \ddot{z}_i + \bar{a}^T I^{-1} \bar{a} \]
(36)

\[ \leq -\sum_{i=1}^{2} \bar{c}_i z_i^2 + \bar{a}^T I^{-1} (\bar{Y} z_2 - \bar{a}) \]

\[ = -\sum_{i=1}^{2} \bar{c}_i z_i^2 \]

Where \( \bar{c}_2 = c_2 - \frac{1}{2} \)

This shows that \( V \) is uniformly bounded. Thus \( z_i, i = 1,2 \) and \( \bar{a} \) are bounded.

4. LOS GUIDANCE

Systems for guidance consist of waypoints that are used to generate a trajectory (path) for the ship. A widely used method for path control is LOS guidance. In this methodology, a LOS vector from the ship to the next way point is computed. The desired heading angle as a set point for autopilot system can be calculated through:

\[ \psi_d(t) = \tan^{-1}\left( \frac{y_d(k) - y(t)}{x_d(k) - x(t)} \right) \]  
(37)

Care must be taken to select the proper quadrant for \( \psi_d \). The next way point can be selected on a basis of whether the vessel lies within a circle of acceptance with radius \( \rho_0 \) around the way-point \( (x_d(k), y_d(k)) \). Moreover if the vessel location \( (x(t), y(t)) \) at the time \( t \) satisfies:

\[ |x_d(k) - x(t)|^2 + |y_d(k) - y(t)|^2 \leq \rho_0^2 \]  
(38)

The next way point \( (x_d(k+1), y_d(k+1)) \) should be selected. A guideline could be to choose \( \rho_0 \) equal to two ship lengths, that is \( \rho_0 = 2L \) (Fossen, 1994).

5. SIMULATION RESULTS AND ANALYSIS

Simulation results are shown in Fig 3 to 9. Fig 3 to 6 show the time-varying disturbances including current relative velocity in surge direction, current relative velocity in sway direction, Relative wind angle and Relative wind speed respectively which are generated based on the algorithm in (Fossen, 1994). Fig.7 gives the way-point tracking course for the adaptive backstepping autopilot in the presence of disturbances and without disturbances. These two courses are close to each other. Comparison of ship heading angle (rad) in the presence of disturbances and without disturbances and rudder angle (rad) for this way-point tracking are shown in Fig. 8 and 9 respectively. The maximum rudder angle for this container ship was 10 (deg) that is satisfied by the actuator limit.

6. CONCLUSIONS

The paper considers way-point tracking system in the presence of time-varying disturbances with adaptive backstepping approach. Because of the uncertainty in model parameters in the presence of disturbances, adaptive backstepping algorithm is proposed. The results show that this algorithm effectively implements the way-point tracking control.
Fig. 6. Relative wind speed.

Fig. 7. Comparison of simulation results of way-point Tracking: In presence of disturbances (dashed line), without disturbances (solid line).

Fig. 8. Comparison of simulation results of Ship heading angle: Desired heading angle for way-point tracking (dotted line), ship heading angle without disturbances (dash-dot line), ship heading angle in presence of disturbances (dashed line).

Fig. 9. Ship rudder angle in the presence of disturbances.

REFERENCES


