A Ship’s Automatic Maneuvering System Using Optimal Preview Sliding Mode Controller with Adaptation Mechanism

Naoki Mizuno*, Naoki Saka* and Takuya Katayama*

* Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan
(Tel: +81-52-735-5339; e-mail: nmzuno@nitech.ac.jp)

1. INTRODUCTION

During the cruise, there are many factors which affect the maneuverability for ships. For example, wind, wave and current disturbances make the ship deviate from the desired route and the variation of the load condition and fuel consumption have the long term effect for ship’s dynamics.

Therefore, the robust control techniques are expected to design the high performance route tracking control system.

For this kind of problem, the sliding mode control system (Edwards and Spurgeon, 1998), which is one of the robust control methods, has been applied for automatic maneuvering system.

In these previous researches, it is shown the sufficient robustness of the sliding mode control method to disturbances (Ohtsu, 2005), nonlinearity and uncertainty in ship’s dynamics (Yamato et al., 1996).

However, in some research, only the control the heading of the ship is investigated (Ohtsu, 2005) and in many researches, only the simulation results have been shown (Yamato et al., 1996).

On the other hand, the authors have proposed optimal maneuvering system based on the nonlinear model based predictive controller (Mizuno et al., 2004, 2015) but the method is time consuming and hard to implement by using conventional computer in the commercial autopilot.

For this situation, the authors have modified the basic sliding-mode control algorithm applicable to automatic maneuvering system under some disturbances by introducing the gain scheduling and adaptive gain tuning methods (Mizuno et al., 2013).

However, in some severe conditions, there has been non negligible overshoot after maneuvering.

In this paper, we propose an automatic maneuvering system based on the preview sliding mode control method (Sato et al., 2001) with adaptation mechanism. This method improves the transient response of the basic sliding mode control algorithm by introducing the optimal preview servo mechanism (Ikedo et al., 2004).

Moreover, adaptation mechanism keeps the tracking performance for variation and uncertainty of ship’s dynamics. These are new features of proposed system.

2. DESIGN OF OPTIMAL PREVIEW SLIDING MODE CONTROLLER

The sliding mode control (SMC) is one of the nonlinear robust control method based on the variable structure system (VSS) theory. The method forces the states of the system to slide on the hyper surface and to converge to the target states (origin of the state space) by using discontinuous (switched) control input depending on the system state (Edwards and Spurgeon, 1998).

It is well known that SMC achieves the robust system to the parameter uncertainty, nonlinearity and disturbances, since the state of the controlled system under sliding mode are constrained on the hyper surface.

Regarding the above property of sliding mode control, it is considered to be an effective control algorithm which has sufficient robustness to the nonlinear and uncertain problems of ship’s dynamics (Mizuno et al., 2013).

2.1 Optimal Preview Servo System

We assume that the controlled system can be modeled by the...
following linear discrete time system.

\[
x(k+1) = Ax(k) + Bu(k) \\
y(k) = Cx(k)
\]

Where,

\[
x(k): \text{ State vector of the system (}\begin{array}{c}
(n \times 1) \end{array}\)
\[
y(k): \text{ Output vector of the system (}\begin{array}{c}
(m \times 1) \end{array}\)
\[
u(k): \text{ Input vector of the system (}\begin{array}{c}
(r \times 1) \end{array}\)
\[
R(k): \text{ Set point vector (}\begin{array}{c}
(m \times 1) \end{array}\)
\]

Next, we define the error vector as,

\[
e(k) = R(k) - y(k)
\]

Using the above notation, we introduce the following error system.

\[
\begin{bmatrix}
e(k+1) \\
\Delta x(k+1)
\end{bmatrix} =
\begin{bmatrix}
I & -CA \\
-CB & A
\end{bmatrix}
\begin{bmatrix}
e(k) \\
\Delta x(k)
\end{bmatrix}
+ \begin{bmatrix}
0 \\
\Delta u(k)
\end{bmatrix} \Delta R(k+1)
\]

Where, \(\Delta\) denotes the difference operator.

Simply, we describe Eq. (4) as the following form,

\[
X_o(k+1) = \Phi X_o(k) + \Gamma \Delta u(k) \\
+ \Gamma P \Delta R(k+1)
\]

and construct the augmented system including the future set point as the state under the assumption that the \(M_p\) steps future values of the set point are available (Sato et al., 2001).

\[
\begin{bmatrix}
X_o(k+1) \\
X_R(k+1)
\end{bmatrix} =
\begin{bmatrix}
\Phi & \Gamma P_R \\
0 & A_R
\end{bmatrix}
\begin{bmatrix}
X_o(k) \\
X_R(k)
\end{bmatrix}
+ \begin{bmatrix}
0 \\
\Gamma
\end{bmatrix} \Delta u(k)
\]

Where,

\[
I_{PR} = \begin{bmatrix}
I_m & 0 & \cdots & 0 \\
0 & I_m & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & \cdots & \cdots & I_m
\end{bmatrix}
\]

\[
A_R = \begin{bmatrix}
0 & \cdots & \cdots & 0 \\
\vdots & \ddots & \cdots & \vdots \\
\vdots & \vdots & \ddots & \vdots \\
0 & \cdots & \cdots & I_m
\end{bmatrix}
\]

\[
X_R(k) = \begin{bmatrix}
\Delta R(k+1) \\
\Delta R(k+2) \\
\vdots \\
\Delta R(k+M_p)
\end{bmatrix}
\]

Or

\[
\bar{X_o}(k+1) = \bar{\Phi} \bar{X_o}(k) + \bar{\Gamma} \Delta u(k)
\]

To obtain the control input which stabilizes the augmented system, we adopt optimal regulator theory.

In this case, the following quadratic cost function is defined.

\[
J = \sum_{k=-M_p+1}^{\infty} \begin{bmatrix}
X_o^T(k) X_o(k) \\
\Delta u^T(k)H\Delta u(k)
\end{bmatrix}
\]

\[
+ \begin{bmatrix}
Q & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
X_o(k) \\
\Delta u(k)
\end{bmatrix}
\]

Where, \(Q\) is \((m+n)\times(m+n)\) semi positive definite matrix and, \(H\) is \(r \times r\) positive definite matrix.

By solving the optimal regulator problem described by Eqs. (6)-(11), we obtain the following optimal input.

\[
\Delta u(k) = \bar{F} \bar{X_o}(k)
\]

\[
= F_0 X_0(k) + \sum_{j=0}^{M_p} F_R(j) \Delta R(k + j)
\]

Where,

\[
\bar{F} = \begin{bmatrix}
F_0 & P_R \\
F_0(0) & 0
\end{bmatrix}
\]

\[
F_0 = -[H + \Gamma^T P R]^{-1} \Gamma^T P R \\
F_R(j) = -[H + \Gamma^T P R]^{-1} \Gamma^T [x^T(j) - \Gamma^T P R] [x(j) - \Gamma^T P R] \phi_p (j \geq 1)
\]

\[
P = Q + \Gamma^T P R - \Gamma^T P R [H + \Gamma^T P R]^{-1} \Gamma^T P R \phi_p
\]

2.2 Optimal Preview Sliding Mode Control System

In this subection, we design optimal preview sliding mode control system by combining the optimal preview control system designed in the previous subsection and the normal sliding mode control system (Ikedo et al., 2004).

To design the total control input \(u(k)\) which forces the state \(\bar{X_o}(k)\) to converge to 0, first, we design the structure of sliding mode controller and the hyper surface used in the controller.

In this case, the switching function in the state space is defined as follows.

\[
\tilde{\sigma}(k) = \bar{S} \bar{X_o}(k), \quad \bar{S} > 0
\]

The second step is to design the control input. To introduce the integral action in the controller, we design \(\Delta u\) instead of \(u\). \(\Delta u\) consist of two components: equivalent control, \(\Delta u_{eq}\) and non-linear one , \(\Delta u_{nl}\).

\[
\Delta u(k) = \Delta u_{eq}(k) + \Delta u_{nl}(k)
\]

In Eq. (15), \(\Delta u_{eq}\) is the equivalent control input which stabilizes the nominal linear system. This component makes the states reach to the sliding line. The non-linear part \(\Delta u_{nl}\) is switching control such that the state of the system remains on the hyper surface.

The two components of sliding mode control input are described as follows.

\[
\Delta u_{eq}(k) = -\tilde{\sigma} \tilde{S}^{-1} \tilde{S} \phi - I \bar{X_o}(k)
\]

\[
\Delta u_{nl}(k) = -\eta \tilde{\sigma} \tilde{S}^{-1} \tilde{\sigma}(k)
\]

To introduce the optimality into the sliding mode controller, we replace \(\tilde{S}\) in the switching function (14), by the feedback gain \(\bar{F}\) obtained by (13), extend the sliding mode controller as follows.

\[
\Delta u_{eq}(k) = -\tilde{\sigma} \tilde{F}^{-1} \tilde{S} \phi - I \bar{X_o}(k)
\]

\[
= -[F_0 \Gamma^T]^{-1} [F_0(\Phi - I) X_0(k) + [F_0 \Gamma^T - F_R(1)] \Delta R(k + 1) + \sum_{j=2}^{M_p} F_R(j) (j - 1) - F_R(j)] \Delta R(k + j)]
\]
\[ \Delta u_n(k) = -\eta(Sf)^{-1}\tilde{\sigma}(k) \]
\[ = -\eta(F_0^r)^{-1}[F_0^rX_0(k) + \sum_{j=1}^{\mathbf{M}_R} F_R(j)\Delta R(k + j)] \] (19)

Based on the optimal sliding mode controller (18), (19), we design the optimal preview sliding mode controller as follows.

\[ \Delta u(k) = \Delta u_{smc}(k) + \Delta u_{fr}(k) \] (20)
\[ \Delta u_{smc}(k) = -(F_0^r)^{-1}[F_0^r(\mathbf{I} - \eta F_0^r) + \eta F_0^r]X_0(k) \] (21)
\[ \Delta u_{fr}(k) = -(F_0^r)^{-1}\left[F_0^r\mathbf{M}_R[\Delta R(k + 1) + \sum_{j=1}^{\mathbf{M}_R} F_R(j)\Delta R(k + j)] \right] \] (22)

Where, \( \Delta u_{smc} \) is the optimal sliding mode control input and \( \Delta u_{fr} \) is the preview feedforward control input using the future values of the set points.

3. APPLICATION TO AUTOMATIC MANEUVERING SYSTEM

To apply the optimal preview sliding mode control method for automatic maneuvering system, we should generate the target route. Moreover, the \( \mathbf{M}_R \) steps future values of the target course which achieves the tracking to target route should be calculated on line.

3.1 Route Generation

In this paper, the parallel deviation maneuvering problem is considered as a simple example of the feasible study and the simple route generation algorithm based on the Helieme interpolation is adopted. This route generation algorithm can be implemented by on board computer and the future values of the set course are easily calculated in real-time.

3.1.1 Parallel deviation maneuvering

The parallel deviation maneuvering problem is defined as the maneuvering in which the initial course line is charged to the terminal one for constant speed ship as shown Fig. 1.

Where \( \ell \) is the distance between two parallel courses. \( x[m], y[m] \) are the coordinates of ship’s position. \( u[m/s], v[m/s] \) are surge speed and sway speed, respectively. \( \mathbf{P}[\text{deg}] \) is the ship’s heading and \( r[\text{deg/s}] \) is yaw rate.

3.1.2 Route generator using Hermit interpolation

In the Helieme interpolation, the route can be generated based on the initial position \((x_0, y_0)\), terminal position \((x_f, y_f)\), initial speed \(U_0\), \( v_r \); the \( x \) component of \( U_0 \), and the \( y \) component of terminal speed \( v_r \).

The generated route is described as the following equations (Mizuno et al., 2013).

\[ f(x) = ax^3 + bx^2 + cx + d \] (23)

\[ f'(x) = 3ax^2 + 2bx + c \] (24)

For parallel deviation maneuvering problem, \((x_v, y_v)\)\((0,0)\), \( v_r = f'(x) = 0 \). In this case, the coefficients of Eqs. (23), (24) are obtained by solving the following equations.

\[ ax^2 + bx - y = 0 \] (25)
\[ 3ax^2 + 2bx = 0 \] (26)
\[ c = 0 \] (27)
\[ d = 0 \] (28)

Using the solutions of the above equations, we can generate the route for parallel deviation maneuvering by assigning \((x_v, y_v)\).

Moreover, the target heading for proposed control system can be calculated by the following equation.

\[ \psi_r = a \tan \frac{\Delta y(t)}{\Delta x(t)} \] (29)

Where, \( \Delta y(t) = y(t + \Delta t) - y(t) \), \( \Delta x(t) = x(t + \Delta t) - x(t) \).

However, the route (function of coordinate) obtained by Helieme interpolation is only geometrically sufficient for parallel deviation maneuvering, but is not suitable as a time history of the route.

To modify the geometrical route obtained by Helieme interpolation into the feasible time history of the route, we introduce the second order filter regarding the ship’s dynamics as shown below.

\[ h_f = \frac{a^2}{(s^2 + 2\xi \omega_n s + \omega_n^2)^n} \] (30)

By assigning the appropriate parameters \( \xi \), \( \omega_n \) of the filter and applying the filtering process \( n \) times for deviation distance, the approximate optimal deviation route (deviation distances for each time instant) can be obtained with sufficient accuracy.

3.2 Target Heading Compensation For Course Tracking

In this control system, only the heading is controlled by sliding mode controller. However, if the transient heading error occurs due to the disturbance and uncertainty of the ship’s dynamics, the route tracking error does not converge to 0, although the heading tracked the desired value.

To force to converge the route error to zero, we introduce the compensation mechanism for target heading.

First, we obtain the error between the target position and the current ship’s position based on the following equation.

\[ e = -(x - x_r) \sin \psi_r + (y - y_r) \cos \psi_r \] (31)

Where, \( x, y \) : ship’s current position [m]
\( x_r, y_r \) : target position [m]
\( \psi_r \) : target heading [deg]
Moreover, to obtain the stable compensation for target heading, we introduce the dead band for position error.

Next, the modification angle \( \psi_d \) [deg] is calculated based on the position error.

\[
\psi_r = \arctan\left(-\frac{e}{\Delta}\right)
\]

(32)

Where, \( \Delta \) [m] is the recovery distance to target route.

Finally, the target heading \( \psi_d \) [deg] is determined based on the original heading \( \psi_r \) on target route and modification angle \( \psi_C \) as follows.

\[
\psi_d = \psi_r + \psi_C
\]

(33)

Figure 2 shows the compensation mechanism for target heading.

![Compensation of target heading](image)

In this figure,

\( (x_k, y_k) \): target position for \( k \) steps future[m]

\( (x_{k+1}, y_{k+1}) \): target position for \( k+1 \) steps future[m]

For preview control system, the \( M_k \) steps future values of the target heading are needed at each sampling instance.

To generate the future values of the target heading \( \psi_d \), we calculate the future values of modification angle \( \psi_r \) by using the following equations. Equation (34) means that the absolute value of modification angle for each sampling step decay exponentially like the method in reference (Fukuda and Ohtsu 2001).

\[
\psi_r(k+i) = \tan^{-1}\left(-\frac{e}{\Delta} \times \exp\left(-\frac{l_i}{\Delta}\right)\right)
\]

(34)

\[
l_i = \sqrt{(x_{r,k+i} - x_{r,k})^2 + (y_{r,k+i} - y_{r,k})^2}
\]

(35)

\[
\psi_d(k+i) = \psi_r(k+i) + \psi_C(k+i)
\]

(36)

\[
+ \left(\psi_r(k+i) - \psi_r(k)\right)
\]

\( (i = 0, 1, \ldots, M_k) \)

3.3 Implementation Of Optimal Preview Sliding Mode Controller

To implement the preview sliding mode controller for automatic maneuvering system, the linear model of the ship described by Eq. (1) and its nominal parameters are needed.

In this paper, we adopt the simple Nomoto’s model for the linearized ship’s dynamical model (Nomoto, 1957) as,

\[
T\dot{r} + r = K\delta
\]

(37)

Where, \( r \) is the yaw rate and \( \delta \) is the rudder angle. \( T \) denotes the time constant and \( K \) is the static yaw rate gain, respectively.

In this case, the discrete-time model corresponds to Eq. (1) is described as follows.

\[
\begin{bmatrix}
\psi(k+1) \\
r(k+1)
\end{bmatrix}
= \begin{bmatrix}
1 & 1 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
\psi(k) \\
r(k)
\end{bmatrix}
+ \begin{bmatrix}
0 \\
b
\end{bmatrix}
\delta(k)
\]

(38)

The parameters \( a, b \) in Eq.(38) depend on \( T, K \) in Eq.(37) and the sampling period.

Although the sliding mode control system is robust for variation of dynamics of the controlled system, the fixed model based design cannot achieve the sufficient performance under various operating conditions.

To improve the tracking performance, we investigate the adaptation mechanism based on linear approximate model.

3.4 Extension To Adaptive Control System

To estimate the parameters of the nominal model correspond to Eq. (38), we assume the following identification model.

\[
\begin{bmatrix}
\psi(k+1) \\
r(k+1)
\end{bmatrix}
= \begin{bmatrix}
1 & 1 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
\psi(k) \\
r(k)
\end{bmatrix}
+ \begin{bmatrix}
0 \\
b
\end{bmatrix}
\delta(k)
\]

(39)

The parameters in Eq.(39) can be estimated by using the following adaptation algorithm proposed by Landau (2011).

\[
\dot{\theta}(k) = \theta(k-1) - \Gamma(k-1)\zeta_\theta(k)\epsilon_\theta(k)
\]

(40)

\[
\epsilon_\theta(k) = \frac{\theta^T(k-1)\zeta_\theta(k) - \gamma_\theta(k)}{1 + \zeta_\theta^T(k)\Gamma(k-1)\zeta_\theta(k)}
\]

(41)

\[
\Gamma(k) = \frac{1}{\lambda_2(k)}
\]

(42)

\[
\lambda_2(k) = \lambda_1(k) + \lambda_2(k)\zeta_\theta^T(k)\Gamma(k-1)\zeta_\theta(k)
\]

(43)

\[
\zeta_\theta(k) = D(z^{-1})\zeta(k)
\]

(44)

\[
D(z^{-1}) = 1 o r 1 - z^{-1}
\]

(45)

Where, \( \dot{\theta} = [\dot{a}, \dot{b}] \), \( \zeta(k) = [r(k-1), \delta(k-1)]_T \). \( D(z^{-1}) \) is assigned \( 1 - z^{-1} \) for the case when the current disturbance cannot be neglected. The parameters in Eq. (42), \( \lambda_1(k) \) and \( \lambda_2(k) \) are assigned depending on the estimation condition.

If the measurement noise is small, the fixed trace algorithm is useful for time varying characteristics of ship’s dynamics.

On the other hand, if the measurement noise is not negligible, recursive least squares algorithm is preferred.

3.5 Total Structure of Proposed Control System

Figure 3 shows the schematic diagram of the proposed control system.
Fig. 3 Block diagram of proposed control system.

In this system, when the course direction and deviation distance are assigned by the user, the target route \((x_r, y_r)\) and heading \(\Psi_r\) is automatically calculated before maneuvering. During the automatic maneuvering, the target heading is modified based on the target ship’s position \((x_c, y_c)\) and current one \((x, y)\). The modified target heading \(\Psi_r\) is fed to the optimal preview sliding mode controller with adaptation mechanism.

The adaptation mechanism estimates the model parameters in Eq. (39) for various ship speed and cruise condition. The optimal preview sliding mode controller is updated by solving the optimal control problem described by Eqs. (6)-(11) using Matlab function within each sampling period based on the estimated parameters.

### 4. PRELIMINARY EVALUATIONS BY COMPUTER SIMULATIONS

Before implementing the proposed automatic maneuvering system, computer simulations of proposed system are performed for nonlinear dynamical model of the small training ship *Shioji Maru* (Shoji et al., 1993).

#### 4.1 Simulation Conditions

To evaluate the effectiveness of the proposed method, control performances of automatic maneuvering system using conventional sliding mode controller (SMC), optimal preview sliding mode controller (PSMC) and adaptive optimal preview sliding mode controller (APSMC) are compared.

In the simulations, the sampling period of the control system is 1 sec. The initial ship speed is set at 10 knot. The parallel deviation distances are assigned 100m, 150m and 300m. The disturbances in simulation are typical winds measured in previous sea tests (4 directions with variable speed about 8.3m/s). These values are typical in the bay.

In case of APSMC, the fixed trace adaptation algorithm is used. Moreover, some additional design parameters should be assigned. Table 1 shows the default parameters for simulations.

<table>
<thead>
<tr>
<th>( n )</th>
<th>Design parameters for proposed controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>45</td>
</tr>
<tr>
<td>( M_R )</td>
<td>12</td>
</tr>
<tr>
<td>( Q )</td>
<td>diag[1,0,0]</td>
</tr>
<tr>
<td>( \theta )</td>
<td>( \dot{a}(0) = 0.92 )</td>
</tr>
<tr>
<td>( \theta )</td>
<td>( \dot{b}(0) = 0.01183 )</td>
</tr>
<tr>
<td>( \theta )</td>
<td>( \dot{\Gamma}(0) = 10^{-1} )</td>
</tr>
</tbody>
</table>

Where, the initial values of estimated parameters in model (39) are determined based on the step response of the nonlinear dynamic model of the target ship.

#### 4.2 Simulation Results

The simulation results shows the practical effectiveness of the proposed method for all conditions. However, the advantage of proposed method for other methods depend on the direction of wind disturbance.

In this paper, only the critical results for tailwind case (Fig.4) is shown.

Fig. 4 Simulation results of right course shifting maneuvering with tail wind

In Fig. 4, the left figure shows the ship’s route (the black line is target route and the red and green lines are actual ones), the middle figures are order rudder, yaw rate, value of switching function in PSMC and wind direction in order from the top. The right figures are heading, route error, and value of switching function in APSMC and wind speed, respectively. In the middle and right figures, the red lines indicate the PSMC cases and the green lines the APSMC cases except for wind data. This result shows the superior control performance of APSMC.

5. ACTUAL SEA TEST

In order to evaluate the feasibility of the proposed control system, the actual maneuvering tests for parallel deviation were carried out at sea.

#### 5.1 Target Ship

The target ship is the Shioji Maru of Tokyo University of Marine Science and Technology (Fig. 5).

#### 5.2 Experimental Results

The experiments have been performed in the Tateyama bay or near the Hakkeijima island in Japan.

For all experiments, the main settings for the controller are same as the simulation except for the type of adaptation algorithm and its initial gain.

The adaptation algorithm is changed to recursive least squares and the initial gain is set at 0.1, taking the influence of wave disturbance.
disturbance into account. Figure 6 shows the typical experimental result using proposed control scheme. From this result, it can be seen that the proposed optimal preview sliding mode controller with adaptation mechanism is feasible for automatic maneuvering system in actual sea condition.

Moreover, to confirm the effectiveness of the adaptation mechanism, the performance of SMC and PSMC with and without adaptation mechanism are compared. Figure 7 shows that the tracking performance of SMC is inferior to PSMC but PSMC is similar to proposed APSMC. However, the performance index for each method in Table 2 show the effectiveness of adaptation mechanism.

From these results, it can be concluded that the proposed optimal preview sliding mode controller based automatic maneuvering system is feasible in actual sea conditions.

6. CONCLUSION

This paper presented an automatic ship’s maneuvering system using optimal preview sliding mode controller with adaptation mechanism. For the parallel deviation maneuvering, the system gives good tracking performance in actual sea tests.

Moreover, the total control scheme can be easily implemented in the auto pilot for small size ships without accurate knowledge about the dynamics of the ship.

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