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A Study on Automatic Berthing Control of an Unmanned Surface Vehicle

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Abstract

This study examined a PD controller and its application to automatic berthing control of an unmanned surface vehicle (USV). First, a nonlinear mathematical model was established for the maneuvering of the USV in the presence of environmental forces. A PD control algorithm was then applied to control the rudder and propeller during an automatic berthing process. The algorithm consisted of two parts, namely the forward velocity control and heading angle control. The control algorithm was designed based on longitudinal and yaw dynamic models of the USV. The desired heading angle was obtained using the “line of sight” method. Finally, computer simulations of automatic USV berthing were performed to verify the proposed controller subjected to the influence of disturbance forces. The results of the simulation revealed a good performance of the developed berthing control system.

Keywords: Berthing Control; unmanned surface vehicle (USV); PD controller; dynamic system

1. Introduction

Oceans are the source of life as well as transportation arteries. The 21st century will involve three challenges, namely the disparities caused by population explosion and limited living space, exhausted land resource and the growing requirement of social production, and eco-environmental degradation and human development. Intelligence motion platforms, such as unmanned surface vehicles (USVs), can be relied on for remote control or autonomous navigation and safety in a real marine environment and to complete various tasks. Additionally, several previous studies examined control algorithms to improve the dynamic characteristics of maritime vehicles (Roberts and Sutton, 2006; Fossen, 1994).

A marine literature review indicated that USV (or ship) berthing or maneuvering is considered an extremely complex mission with high pressure on a helmsman to ensure safe operations. Specifically, USV berthing requires many processes from the helmsman when compared with other missions such as autopilot for steering, position tracking (which includes the trajectory tracking and path following), and dynamic positioning or station keeping. It is necessary to maintain the USV velocity at an extremely low value during the stage where the vessel moves from the open sea to confined water; the controllability of actuators (main

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propeller, rudder and so on) is significantly reduced during this stage. Furthermore, when a USV is close to a jetty, then it is necessary for the USV master to accurately detect the USV position exactly as well as predict motions to prevent collision. Furthermore, it is necessary to consider a significant amount of information including maneuvering conditions, actuator characteristics, wind effects, and wave and current disturbances.

Given the aforementioned reasons, automatic berthing approaches were proposed from the early 1990s. Recent researches focused on developing intelligent control strategies without any information on the dynamic model such as fuzzy control (Takai and Yoshihisa, 1987; Kasasbeh et al., 1993) and neural network techniques (Zhang et al., 1997) owing to the difficulties involved in capturing the change in hydrodynamic coefficients. These approaches possess the advantages of embedded human experiences and knowledge about USV behavior with respect to control strategies. However, extant research does not focus on the limits of actuator controllability in a dead slow velocity condition, and thus it is dangerous to apply these methods with respect to real situations. Despite the advent of the application of new technologies, such as differential global positioning systems (DGPS) and camera sensing systems, in the fields of navigation or in propulsion manufacturing, to-date large USV (or ship) maneuvering in harbor areas is performed manually with the assistance of tugboats.

The motion of USV in the presence of environmental disturbances was considered to design a controller for USV (or ship) berthing. Environmental disturbances affecting the USV motion consisted of wind, wave motion, and current. In the present study, a robust controller based on a PD control was proposed with respect to the uncertainty and complexity of USV dynamics and environmental disturbances. The PD controller presented in this study guaranteed a robust performance and good stability relative to disturbances and dynamic uncertainty.

2. Mathematical model

2.1 Equations of motion

Extensive nonlinear equations of 3 DOF USV motions with PD control based on a mathematical model developed by Fang and Luo, 2005 are shown as follows:

$$m(\dot{u} - vr) = X \tag{1}$$

$$m(\dot{u} + ur) = Y \tag{2}$$

$$I_{zz}\dot{r} = N \tag{3}$$

The following set of equations corresponds to one of these expressions based on the coordinate system shown in Fig. 1 in which X, Y, and N denote the total hydrodynamic forces and moments generated by USV motions, propellers, rudder forces, and environment forces. The hydrodynamic terms can be expressed as follows:

$$X = X_{Hydrodynamics} + X_{Propeller} + X_{Rudder} + X_{Wave} + X_{Wind} + X_{Current} \tag{4}$$

$$Y = Y_{Hydrodynamics} + Y_{Propeller} + Y_{Rudder} + Y_{Wave} + Y_{Wind} + Y_{Current} \tag{5}$$

$$N = N_{Hydrodynamics} + N_{Propeller} + N_{Rudder} + N_{Wave} + N_{Wind} + N_{Current} \tag{6}$$

Here, the term with subscript "Hydrodynamics" denotes the hydrodynamic forces and moments produced by motions of the USV hull (without propeller and rudder) and acting upon it, the term with subscript "Propeller" denotes propeller forces and moments, the term with subscript "Rudder" denotes rudder forces and moments, and the term with subscript "Wave, Wind, Current" denotes disturbance environment forces and moments, respectively.

2.2 External environmental forces and moments

This section describes the related calculations of the external forces, including current force, wind force, and wave drifting force.

2.2.1 Current forces and moments

The current forces and moment acting on the USV in the ocean with respect to the relative speed and direction between the USV and current can be expressed as follows:

$$X_{current} = \frac{1}{2}\rho[(V_c\cos\alpha - \dot{x}_G)^2 + (V_c\sin\alpha - \dot{y}_G)^2]BdC_{cx} \tag{7}$$

$$Y_{current} = \frac{1}{2}\rho[(V_c\cos\alpha - \dot{x}_G)^2 + (V_c\sin\alpha - \dot{y}_G)^2]L_{pp}dC_{cy} \tag{8}$$

$$N_{current} = \frac{1}{2}\rho[(V_c\cos\alpha - \dot{x}_G)^2 + (V_c\sin\alpha - \dot{y}_G)^2]L_{pp}^2dC_{cn} \tag{9}$$

Here, F_{cx} and F_{cy} denote current forces related to the surge and sway modes, respectively, of the ship; N_c denotes the yaw moment; V_c denotes the current speed; α denotes the angle between the current and ship heading; $\dot{x}_G$ and $\dot{y}_G$ denote the horizontal components of the ship with respect to the center of gravity; B, D, and L_{pp} denote the breadth, depth, and length, respectively, between perpendiculars. The corresponding coefficients C_{cx}, C_{cy}, and C_{cz}, were obtained using empirical formulae. A similar concept was also applied to estimate the wind forces and moments on the ship as shown below.

2.2.2 Wind forces and moments

The wind forces and moments on the ship based on the formulae developed by Isherwood, 1973 are estimated as follows:

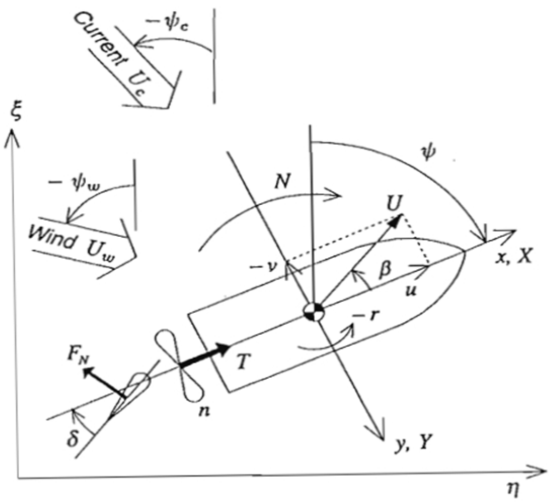

Fig. 1. Coordinate system

$$X_{Wind} = X_W(\gamma_R)\frac{1}{2}\rho_a A_f V_R^2 \tag{10}$$

$$Y_{Wind} = Y_W(\gamma_R)\frac{1}{2}\rho_a A_S V_R^2 \tag{11}$$

$$N_{Wind} = N_W(\gamma_R)\frac{1}{2}\rho_a A_S L V_R^2 \tag{12}$$

Here, X_{Wind}, Y_{Wind}, and N_{Wind} denote the wind forces and moments with respect to the surge, sway, roll and yaw, respectively; X_W , Y_W , and N_W denote nondimensional coefficients of the wind forces and moments with respect to the relative wind angle γ_R ; ρ_a denotes the air density; A_f and A_S denote the longitudinal and sideward projected areas, respectively, of the ship hull above the water surface; and V_R denotes the speed of the ship relative to the wind.

2.2.2 Wave drifting forces and moments

Based on the "weak scatterer" assumption, the nonlinear hydrodynamic forces are calculated using the same technique as that described by Salvesen, 1974 as follows:

$$\bar{F}(\omega_e) = R_e\left\{-\frac{1}{2}\rho\iint_{S_B}\left[\phi_B\frac{\partial}{\partial n}-\frac{\partial\phi_B}{\partial n}\right]\nabla\phi_1^* ds\right\} \tag{13}$$

where, ϕ_1^* denotes the complex conjugate of incident wave potential ϕ_1 , and ϕ_B denotes the body disturbance potential. The integral correpsonds to the ship body surface S_B.

The mean longitudinal and lateral nonlinear forces on the ship with respect to the wave heading μ in short-crested waves can be approximately estimated by the following expression:

$$X_{Wave} = \left|\bar{F}_D\right|\cos\psi \tag{14}$$

$$Y_{Wave} = \left|\bar{F}_D\right|\sin\psi , \tag{15}$$

where

$$\bar{F}_D = 2\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\int_0^{\infty}\frac{F(\omega)}{a^2}S_{aa}(\omega,\mu)d\omega d\mu \tag{16}$$

Here, $\bar{F}_D$ denotes the mean nonlinear hydrodynamic force on the ship in random waves, and $S_{aa}(\omega,\mu)$ denotes the ITTC-1978 wave energy spectrum of a short-crested wave. The yaw drifting moment N_{Wave} can be integrated from the sectional Y_{Wave} with respect to the LCG along the whole USV length.

2.3 Rudder Forces and Moments

The rudder forces and moments including the hydrodynamic forces and moments on the hull of the USV because of rudder action corresponded to X_{Rudder}, Y_{Rudder}, and N_{Rudder} and could be expressed as follows based on a study by Ogawa and Kasai, 1978:

$$X_{Rudder} = -(1-t_R)F_N \sin\delta \tag{17}$$

$$Y_{Rudder} = -(1-a_H)F_N \cos\delta \tag{18}$$

$$N_{Rudder} = -(x_R + a_H x_H)F_N \cos\delta \tag{19}$$

where

$$F_N = \begin{cases} \dfrac{\rho}{2} A_R f_\alpha U_R^2 \sin\alpha_R & (n \geq 0) \\ 0 & (n < 0) \end{cases}$$

and $f_\alpha = \dfrac{6.13\Lambda}{2.25+\Lambda}$

2.4 Propeller Forces and Moments

The propeller thrusts and moments are expressed as follows based on a study by Hasegawa and Kitera, 1993:

$$X_{Propeller} = \begin{cases} C_1 + C_2 J_s & (J_s \geq C_{10}\ and\ n > 0) \\ C_8 + C_9 J_s & (J_{st} < J_s < C_{10}\ and\ n > 0) \\ C_6 + C_7 J_s & (J_s \geq C_{10}\ and\ n < 0) \\ C_3 & (J_{st} < J_s < C_{10}\ and\ n < 0) \end{cases} \tag{20}$$

$$Y_{Propeller} = \begin{cases} A_1 + A_2 J_s & (J_{syn} \leq J_s \leq J_{syn0}) \\ A_3 + A_4 J_s & (J_s < J_{syn}) \\ A_5 & (J_{syn0} \leq J_s) \end{cases} \tag{21}$$

, and

$$N_{Propeller} = \begin{cases} B_1 + B_2 J_s & (J_{syn} \leq J_s \leq J_{syn0}) \\ B_3 + B_4 J_s & (J_s < J_{syn}) \\ B_5 & (J_{syn0} \leq J_s) \end{cases} \tag{22}$$

where $J_s = \dfrac{U}{nD_P}$

3. Controller model

3.1 LOS guidance

Guidance systems consist of a waypoint generator with a human interface that can be designed by storing the selected waypoints in a database and using the waypoints to generate a trajectory for the USV. Other systems can be linked to the waypoint guidance system in case of weather routing, collisions, and obstacle avoidance in which LOS guidance is widely utilized. Additionally, LOS schemes were applied to surface USVs.

When moving along a path, the next waypoint (x_{k+1}, y_{k+1}) can be selected based on whether a ship lies within a circle of acceptance with radius R_0 around the waypoint (x_k, y_k). If the vehicle positions ($x(t)$, $y(t)$) at time t satisfy Eq. (23), the next waypoint should be selected as follows:

$$\left[x_k - x(t)\right]^2 + \left[y_k - y(t)\right]^2 \le R_0^2 \tag{23}$$

However, a waypoint located far away from the ship will result in large cross-track errors in the presence of wind, current, and wave disturbances. The LOS position corresponds to the point along the path toward which the vessel should be pointed at. Therefore, the LOS vector can be defined as the vector from the vessel coordinate origin (x, y) to the intersecting point on the path (x_{los}, y_{los}) at a distance of n ship lengths L_{pp} ahead of the vessel. Thus, the desired yaw angle can be computed as follows:

$$\psi_d(t) = a\tan 2(y_{los} - y(t), x_{los} - x(t)) \tag{24}$$

The four quadrant inverse tangent function tan 2 (y, x) is used to ensure the following:

$$-\pi \le a\tan 2(y, x) \le \pi \tag{25}$$

The LOS coordinates (x_{los}, y_{los}) are given as follows:

$$\left[y_{los} - y(t)\right]^2 + \left[x_{los} - x(t)\right]^2 \le \left(nL_{pp}\right)^2 \tag{26}$$

$$\left(\frac{y_{los} - y_{k-1}}{x_{los} - x_{k-1}}\right) = \left(\frac{y_k - y_{k-1}}{x_k - x_{k-1}}\right) = constant \tag{27}$$

Equation (26) corresponds to the Pythagoras theorem, while Eq. (27) indicates that the slope of the path between the waypoints (x_{k-1}, y_{k-1}) and (x_k, y_k) was constant.

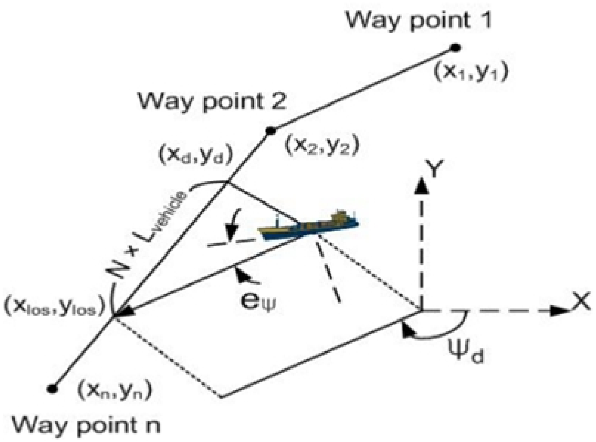

Fig. 2. Calculation of the LOS vector

3.2 PD Control for USV Berthing

In this study, the model of PD control for the USV berthing system is described in this section, and the related results were derived in the simulations.

The PID controller is usually expressed as follows:

$$y(t) = K_p e(t) + K_I \int_0^t e(t)dt + K_D \frac{de(t)}{dt} \qquad (28)$$

where y(t) denotes the output in the controller (for e.g., R.P.M of the thruster), and e(t) denotes the system error (for e.g., position and heading deviations). In the present study, only two control gains (i.e., proportional (K_P) and derivative (K_D)) were considered in the PD controller, while the control gain of the integral (K_I) was not included because the desired goals were fixed and independent of time (i.e., a steady-state error did not exist in the control system).

In the present study, the thruster T was based on the position and heading deviations. In the PD control, the R.P.M of the thruster (denoted as n of the thruster T) is as follows:

$$n(t) = K_{P,x}\left[x(t) - x(0)\right] + K_{D,v_x}\left[v_x(t) - v_x(t-1)\right] + K_{P,\psi}\left[\psi(t) - \psi(0)\right], \qquad (29)$$

where n denotes the R.P.M of the forward thrusters; $K_{P,x}$ and K_{D,v_x} denote the related control gains for surge and surge rate, respectively, and $K_{P,\psi}$ denotes the control gain for the heading deviation.

To obtain the optimal PD control, it is necessary to suitably adjust the above control gains to obtain a maximum control effect with respect to different sea states. If an optimal algorithm or good experience is not applied, then it is necessary to obtain the optimal gains by a trial and error method, which is complex and involves a considerable amount of time. The procedures of a trial and error method are described in this section. First, it was assumed that all the control gains were identical; simultaneously, an attempt was made to increase or decrease each gain based on the simulation results. Finally, the regularity was derived in which the control gain "K_D" was typically greater by one or two orders of magnitude than the control gain "K_P". However, the gains obtained from the trial and error method may not be optimal although they correspond to better results. Therefore, it is necessary to incorporate the PD control with other algorithms, such as neural networks, for an optimal control effect.

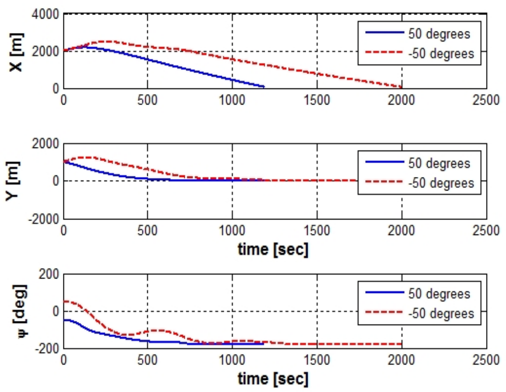

Fig. 3. Time history of the USV horizontal motions: the positions of USV in both cases

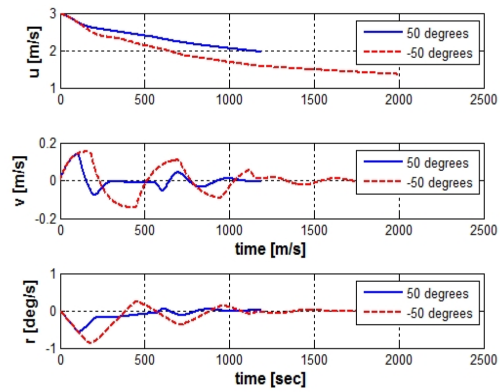

Fig. 4. Time history of the USV horizontal motions: the velocities of USV in both cases

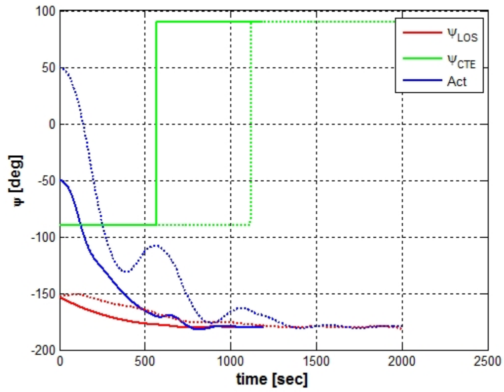

Fig. 5. USV yaw angles in both cases

4. Simulation and Discussion

This section describes the simulations that were performed involving two cases for the control of the USV yaw angle for navigations and berthing that generated two trajectories of the USV as shown in Fig. 6. The first case involved setting a condition of the USV moving from star point A (x = 2000 m, y =1000 m, yaw angle = 50 degrees) to goal point B (0 m, 0 m, -180 degrees). With respect to the other case, a condition was set such that the USV moved from star point A (x = 2000 m, y =1000 m, yaw angle = -50 degrees) to goal point B (0 m, 0 m, -180 degrees). In both cases, the initial velocities of the USV corresponded to $v_x = 3$ *(m/s)*, $v_y = 0$ *(m/s),* and $v_z = 0$ *(m/s)*. The simulation period corresponded to 2000 s with a start time of 0 s and finish time of 2000 s, with a time step of 0.01 s for the first case. The simulation time corresponded to 1200 s with a time step of 0.01 s for second case. Figure 6 shows the USV trajectories in both cases, and Fig. 5 shows the control input of the USV for the revolution of the thruster and the rudder angle. In further detail, the yaw angle of the USV as well as the position and velocity of the USV were observed as shown in Figs. 2, 3, and 4, respectively. The results evidently indicate that the time taken by the USV to reach goal point B in the first case (0 m, 0 m, -180 degrees) exceeded that in the second case given that the second case corresponded to a time period of 2000 s, while the first case corresponded to a time period of 1200 s. Additionally, the trajectory as well as the velocity and rudder angle of the USV in the second case was extremely complicated when compared with those in the first case. Generally, to ensure that the USV reached the goal point effectively, it was necessary to define the optimal yaw angle of the USV as well as to carefully control its rudder angle.

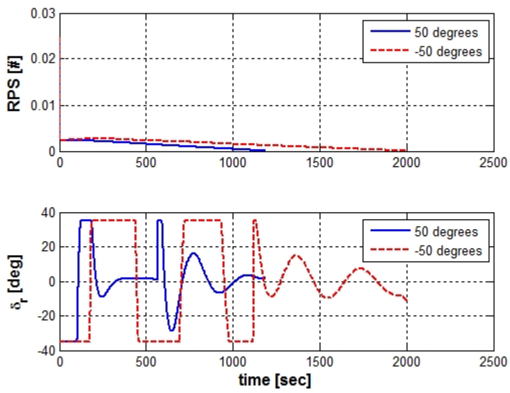

Fig. 6. USV thruster revolution and yaw angle in both cases

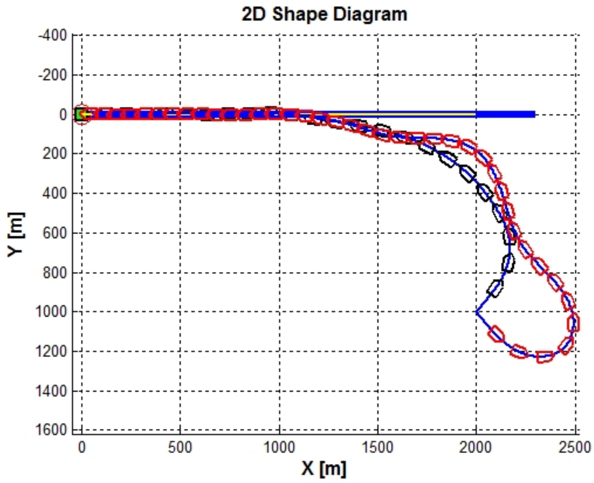

Fig. 7. USV trajectories in both cases

5. Conclusions

In this study, a mathematical model was first introduced as a model dealing with a non-uniform current and wind, and this was followed by the introduction of a mathematical model at a slow advance speed based on previous studies. The control algorithm was designed to control the longitudinal and yaw dynamic models of the USV. The desired heading angle was obtained by using a "line of sight" method. Finally, computer simulations of automatic USV berthing were performed to verify the proposed controller with the influence of disturbance forces. Finally, the USV model was applied for berthing control using a PD controller. The results indicated that both the modeling system and the control method were promising.

Acknowledgements

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