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Combined Yaw and Roll Control of an Autonomous Boat

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Abstract—**In this paper we try to develop a host-based system and study actual sea trials via rudder based roll control method. To authors' best knowledge, the boat we investigated is the smallest among those reported in the literature. An autonomous boat model is obtained by a system identification approach. The identified system is designed with frequency-shaped sliding mode control. The control scheme is composed of a sliding mode observer and a sliding mode controller. The stability and reachability of the switching function are proved by Lyapunov theory. Computer simulations and experiment show that successful course keeping and roll reduction results are achieved.**

I. Introduction

Unmanned surface vehicles (USVs) have been receiving attention for various applications and missions in recent years, for example: explorations of water depth, temperature, pollutant tracking and environmental hydrographic surveys in rivers, reservoirs, inland waterways and coastal waters. Particularly, applications in narrow lakes or coastal areas dangerous to manned vessels are more feasible for USVs. In military applications, a USV is utilized for homeland security, search and recovery, and coastline protection. Therefore, interest in control system of both merchant and naval USVs has increasingly grown and USV control systems are now an important area of research [1]-[3]. For consideration of USVs in the applications mentioned above, roll stabilization can be a decisive factor for the USVs because of the requirements of on-board equipment such as ultrasonic and video sensors and so on.

There are several approaches that can be used to reduce the roll motion, such as bilge keels, anti-rolling tanks, fin stabilizers and rudder roll stabilizers (RRSs). Since the rudder based approach requires no additional equipment and is thus a relative inexpensive solution, it has been analyzed by numerous studies with different control schemes, such as LQR[4][5] Gain schedule[6], IMC[7] and SMC[8]. All these methods, in some way, are mathematical models for which the parameters are derived from the Planar Motion Mechanism (PMM) and the results based on these models are rendered by computer simulations. Experimental studies including actual sea trials are very rare, especially for small-sized boats.

The problem of using a rudder to complete course keeping and roll reduction of an autonomous boat is a challenge. As is well-known, an estimation of a USV plant is strongly related to the accuracy of the hydrodynamic coefficients which specify the mathematical model of the rudder roll damping system. If experimental equipments of deriving USV plant parameters are not sufficient, the model may not be utilized because of its many uncertainties. For this reason, a system identification approach must be adopted to obtain a reasonable model. However, the states variables of the model will usually have no physical meaning and thus can not be measured in that case. Therefore, a controller based on an observer is produced. Particularly, a sliding mode observer due to its properties of insensitivity properties and robustness[8-11] has been widely studied and developed; for rudder roll damping control, the efficient strategy is to have the controller work better at frequencies close to the roll natural frequency. So the frequency-shaped sliding mode control is designed.

In this paper, we introduce a design of radio-controlled boat, the controller of which is calculated on the ground station, the control command is transmitted remotely via wireless modem to the boat. An identified system based on frequency-shaped sliding mode control scheme, is proposed for simultaneous course keeping and roll damping.

The paper is organized as follows: In Section 2, the boat setup, identified model and wave model are presented. In Section 3, the rudder roll damping control system design is described. The stability and reachability of the switching function are also proved. The performance is evaluated by numerical simulations and a sea trial test in Section 4. Finally, some conclusions and future research are presented in Section 5.

II. The Boat System

A. The Boat Description

The autonomous robotic boat investigated in this study is one meter long and 0.25 meter across(beam) as shown in Fig. 1. The draft is 0.135 meter. The maximum forward speed is about 1.2 m/s. A rudder with pintle is hung on the stern, and is actuated by a servo motor with an operating speed of 0.1 sec/60°, and the rudder aspect ratio is 2.1. A four-blade propeller is configured in the front of the rudder,

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which is a left-handed propeller that turns counterclockwise to produce forward thrust and is driven by two DC motors. The power source comes from two Ni-Mn batteries and the endurance under the cruising speed is about 60 minutes.

Fig. 1. Profile of robotic boat

B. Host-Based Communication Setup

Overview of the system design is demonstrated in Fig.2. The control architecture is a host-based approach. All control decisions are done at the ground station. Sensor data come from the boat side, and the control commands are generated by running the control algorithm at host, then the command is sent to the boat via the WLAN. The host is a Pentium III laptop running Windows XP with a 256 MB RAM. With this configuration, we can modify and test our control algorithm easily. There is no need to download program to the processor on boat side whenever any change takes place, as is the case when the controller locates at the boat side. It is useful for fast prototype phase in the development. The boat control system comprises three essential components: the boat, sensors and a ground station.

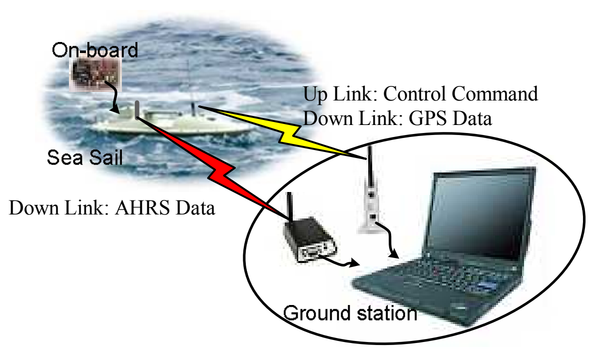

Fig. 2. Overview of host-based control system. Wireless LAN (WLAN) is in charge of interaction between the boat and the ground station.

C. Sensors package

The sensors used in the system include a rate gyro, a tilt-compensated 3-axis compass module that can measure rotational angles, and a GPS for measuring the boat speed. The gyro sensor used in this work is home-made, whereas commercial rate gyros such as ADXRS150 from Analog Devices, Inc. May also be suitable. The hardware of sensor module (except GPS) is shown in Fig 3.

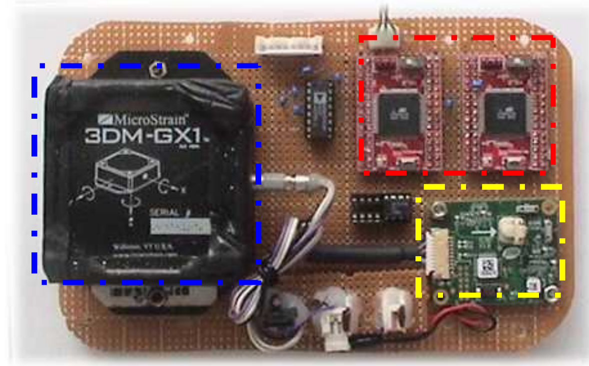

Fig. 3. The hardware integration of sensors. The unit in the blue dashed rectangle is the gyro, while the yellow is compass module, and the red means two ATM processors.

D. The Ground Station

The ground station consists of a ground computer and two wireless modems. Sail data is stored and displayed simultaneously. Calculated control commands (rudder deflection angle) by the ground computer are converted to pulse generator we developed independently and sent to the boat. The sensors data also can down link for the controller inputs use.

III. Control System Design

A. The Identification Model

A subspace-based state space identified model with three outputs (yaw, yaw rate, roll rate) is obtained by using the rudder steering angle, attitude data of yaw rate and roll rate. Converting the discrete-time state-space system to a continuous-time system, and write in the form:

$$\dot{x} = Ax + Bu \tag{1}$$

$$y = Cx \tag{2}$$

The identified model is confirmed by the data of one sea test. The yaw rate and roll rate matching results are shown in Fig. 4 and Fig. 5, respectively. The bode diagram of the open-loop system is shown in Fig. 6.

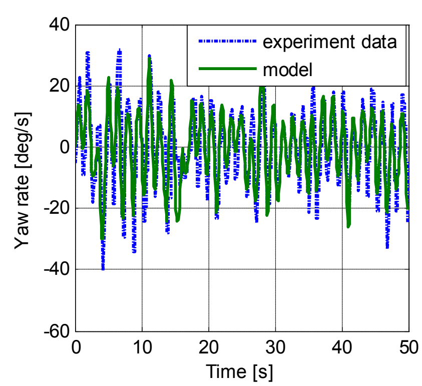

Fig. 4. Validation data for yaw rate

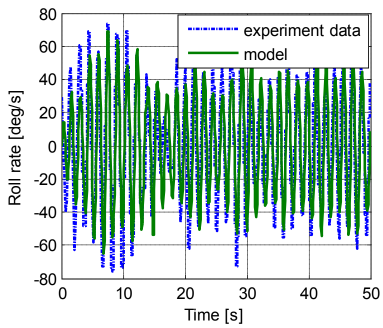

Fig. 5. Validation data for roll rate

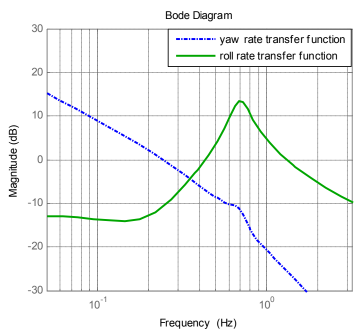

Fig. 6. Validation data for roll rate. It can be seen that there is a resonant peak at 0.7 Hz which indicates the oscillatory characteristics of the rudder roll damping system.

B. Wave Model

Wave and wind are the principle factors causing disturbances to a ship at sea. In terms of the boat rolling motion, the wave is the more important disturbance. By nature wave disturbance is taken as a random process, and the influence on ship motions can be adequately characterized through appropriate measurement of their spectral densities. The wave transfer function is simulated by a second-order linear approximation of the Pierson-Moskowitz spectral density function $h(s)$

$$h(s) = \frac{2\zeta\omega_0\sigma_w s}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \tag{3}$$

where σ_w is a constant describing the wave intensity, ζ is the damping coefficient, and ω_0 is the dominating wave frequency. The disturbance is driven by zero mean Gaussian white noise

$$w_\phi = h(s)w(s) \tag{4}$$

where $w(s)$ is Gaussian white noise.

C. Frequency-shaped Sliding Mode Controller Design

The output of the yaw attitude asymptotically tracks a constant reference r can be simply achieved via the integral control approach. Consider a course keeping control law for the identified system above, and the introduction of additional states that satisfy:

$$x_r = \int (r - y_r)dt \tag{5}$$

where the tracking signal is a scalar of constant demand, y_r is the tracking attitude of the system output. By augmenting the states of (1) and (5), the following is defined:

$$x_a = [x_r \quad x]^T \tag{6}$$

The augmented system can then be conveniently written in the form

$$\dot{x}_a = A_a x_a + B_a u + E_a r \tag{7}$$

where

$$A_a = \begin{bmatrix} 0 & -C_r \\ 0 & A \end{bmatrix},\ B_a = [0 \quad B]^T,\ E_a = [E \quad 0]^T$$

where $C_r$the yaw component in eq.(2). E the identity matrix. Consider a frequency-dependent compensator is introduced into the sliding mode. The weighting function for the roll rate is described in state-space with second-order as follows

$$\dot{x}_q = A_q x_q(t) + B_q x_{rr}(t) \tag{8}$$

$$z_q = C_q x_q(t) + D_q x_{rr}(t) \tag{9}$$

The roll rate weighting function design is given in Fig. 7.

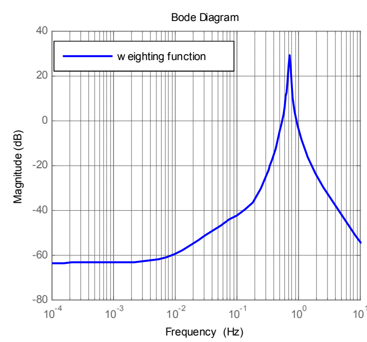

Fig. 7. Roll rate weighting function

The states of (6) and (8) are augmented and defined as

$$x_e = [x_q \quad x_a]^T \tag{10}$$

The augmented system can then be conveniently written in the form

$$\dot{x}_e = A_e x_e + B_e u + E_e r \tag{11}$$

$$y_e = C_e x_e \tag{12}$$

The cost function can be written in the frequency domain by using Parseval's theorem

$$J_{fs} = \frac{1}{2\pi}\int_{-\infty}^{\infty} X^*(j\omega)QX(j\omega)d\omega \tag{13}$$

in the time domain, presented as follows:

$$J = \int_{t_0}^{t} x_e^T Q x_e dt \tag{14}$$

Frequency-shaped sliding mode control (FSSMC) design, based on the idea of an optimal sliding surface, is achieved by formulating an optimal LQR problem with frequency-dependent weighting terms. The hyperplane obtained by solved Riccati equation is

$$\sigma = Sx_e = [S_1 \quad S_2]x_e \tag{15}$$

For the control law component, the linear component can be obtained by equations

$$\sigma = \dot{\sigma} = S\dot{x}_e = 0 \tag{16}$$

Then, it is easy to obtain

$$u_l = -(SB_e)^{-1}(SA_e x_e + SE_e r) \tag{17}$$

The nonlinear component is defined as

$$u_{nl} = -(SB_e)^{-1}\eta\frac{\sigma}{\|\sigma\|} \tag{18}$$

where η is a small positive constant. For single input in (18), the control law can obtained with η

$$u = u_l + u_{nl} = -(SB_e)^{-1}(SA_e x_e + SE_e r + \eta\frac{\sigma}{\|\sigma\|}) \tag{19}$$

Consider $V = \frac{1}{2}\sigma^2$ as a candidate quadratic Lyapunov function

$$\dot{V} = \sigma S(A_e x_e + B_e u + E_e r) = -\eta\frac{\sigma^2}{\|\sigma\|} = -\eta\|\sigma\| < 0 \tag{20}$$

So the system (11) is quadratically stable. To eliminate chattering phenomenon, the controller is given

$$u = -(SB_e)^{-1}(SA_e x_e + SE_e r + \eta\frac{\sigma}{\|\sigma\| + \varepsilon}) \tag{21}$$

where ε is a constant. The bigger the increase of ε, the less the system chatters and the less robust it is.

D. Sliding mode observer of Walcott-Zak

The observer control strategy is driven by the control input and by the difference between the output of the observer and the output of the plant. So this naturally suggests the exploration of ideas to generate a sliding mode on the subspace in which the output error is zero. Consider the uncertain system described by:

$$\begin{cases} \dot{x} = Ax + Bu + f(t,x,u) \\ y = Cx \end{cases} \tag{22}$$

wher $A \in R^{n\times n}, B \in R^{n\times m}, C \in R^{p\times n}\, p > m$. The function is unknown and represents the system uncertainties and nonlinearities. A natural problem to consider initially is the special case when the uncertainty is matched:

$$f(t,x,u) = B\xi(t,x,u) \tag{23}$$

where the function ξ is unknown, but bounded, so that

$$\|\xi(t,x,u)\| \le r_1\|u\| + \alpha(t,y) \tag{24}$$

where r_1 is a known scalar and α is a known function. The problem to be considered involves estimating the states of the uncertain system given in (22), so that the error system

$$e = \hat{x} - x \tag{25}$$

is quadratically stable despite the presence of the uncertainty. A conceptually appealing approach has been adopted by Walcott-Zak who made the following assumption. There exists a constant gain $G \in R^{n\times p}$ such that $A_0 = A - GC$ has stable eigenvalues and there exists a Lyapunov pair (P,Q) for A_0 such that the structural constraint

$$C^T F^T = PB \tag{26}$$

is satisfied for some $F \in R^{m\times p}$. Utilizing this assumption, a nonlinear sliding-mode observer is proposed whose structure is the following:

$$\dot{\hat{x}} = A\hat{x} + Bu - G(C\hat{x} - y) + Bv \tag{27}$$

where $v = \begin{cases} -\rho(t,y,u)\dfrac{FCe}{\|FCe\|} & if\ FCe \ne 0 \\ 0 & otherwise \end{cases}$, and the scalar function $\rho(\cdot)$ satisfying

$$\rho(t,y,u) \ge r_1\|u\| + \alpha(t,y) + \tau \tag{28}$$

for some positive scalar τ. To prove that this observer guarantees quadratic stability of the error system, consider $V(e) = e^T Pe$ as a candidate Lyapunov function. The error system satisfies

$$\dot{e} = (A - GC)e - B\xi(t,x,u) + Bv \tag{29}$$

And therefore

$$\begin{aligned} \dot{V} &= e^T(PA_0 + A_0 P)e - 2e^T PB\xi + 2e^T PBV \\ &\le -e^T Qe - 2e^T PB\xi - 2\rho(t,y,u)\|FCe\| \end{aligned} \tag{30}$$

Using the structural constraint (26) it follows that

$$\begin{aligned} \dot{V} &\le -e^T Qe - 2e^T PB\xi - 2\rho(t,y,u)\|FCe\| \\ &\le -e^T Qe - 2\|FCe\|(\rho(t,y,u) - \|\xi\|) \\ &\le -e^T Qe - 2\tau\|FCe\| < 0 \end{aligned} \tag{31}$$

So the observer can guarantee quadratic stability. It can be shown that there exists a domain in which sliding motion is induced on the surface in the state error space given by

$$S_{wz} = \{e \in R^n : FCe = 0\} \tag{32}$$

A schematic representation of the sliding-mode observer based FSSMC is shown in Fig. 8

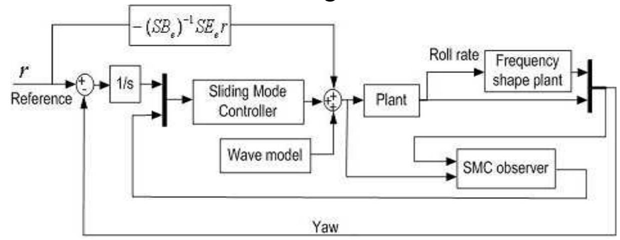

Fig. 8. Block diagram of FSSMC

IV. Numerical Simulation and Experiment

In this section, a numerical simulation and experiment are presented. The wave disturbance used in the simulation is based on the Japan INAGE sea state, where the average wave period is 2.5 s. The wave damping ratio typically is from 0.05 to 0.1. Since our sea trail is carried out at off shore, we choose it 0.1. The wave disturbance is shown in Fig. 9. In order to make the error system apparent, the initial state of the system was chosen to be nonzero. In Fig. 10, the roll rate has a 20 deg/s initial value, and after 0.5s, it becomes zero. And in Fig. 11 the first initial value of yaw is 10 deg. After 0.5 it becomes zero. The switching function is shown in Fig. 12. It can be seen from Fig. 12 that after approximately 2.5 seconds, a sliding motion takes place and the perfect performances are obtained. In addition, the system shows perfect robust performance even if there is a wave disturbance. The yaw and roll rate output error are given in Figs. 13 and 14. In Fig. 15 the observer hyperplane is shown.

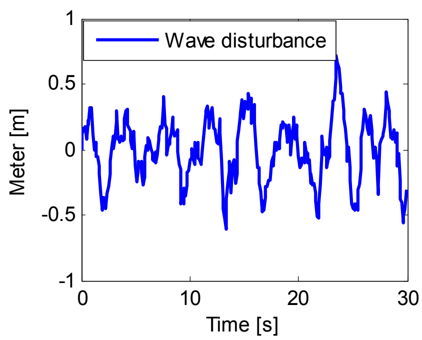

Fig. 9. Wave disturbance

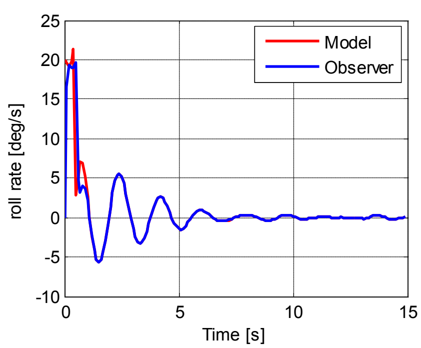

Fig. 10. Roll rate evolution with respect to time

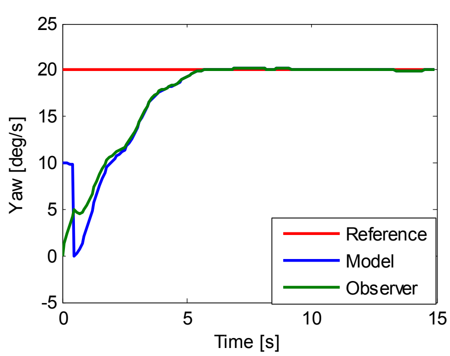

Fig. 11. Yaw evolution via time

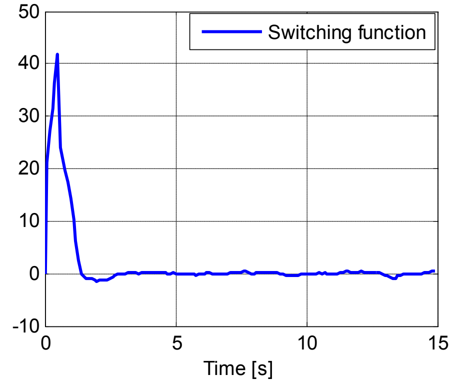

Fig. 12. FSSMC switching function versus time

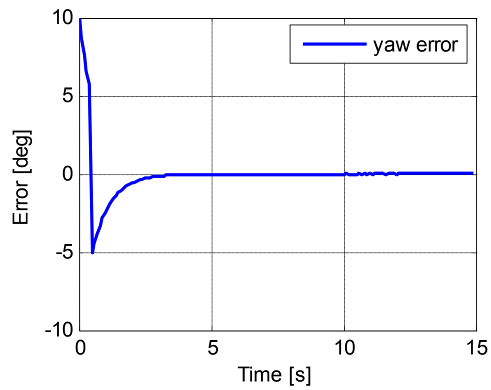

Fig. 13. Evolution of the yaw error

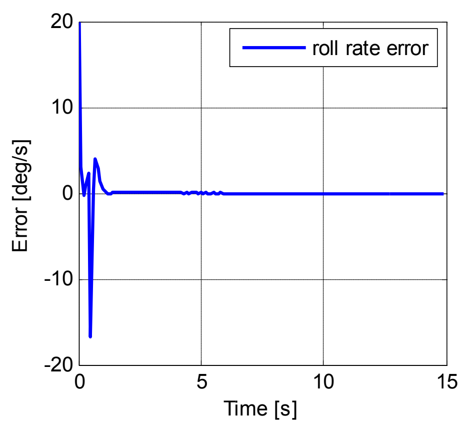

Fig. 14. Evolution of the roll rate error

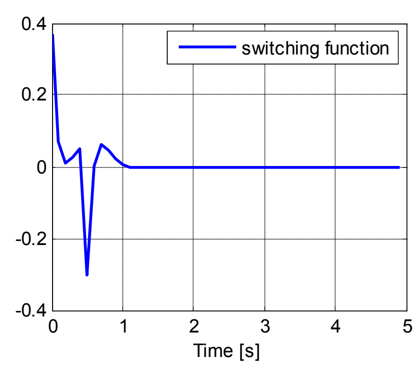

Fig. 15. SMC Observer switching function. It can be seen that a sliding motion occurs after 1 second.

In the sea test the first trial did not employ the controller and the direction was from north to south. And on the boat return trip, the controller was turned on.

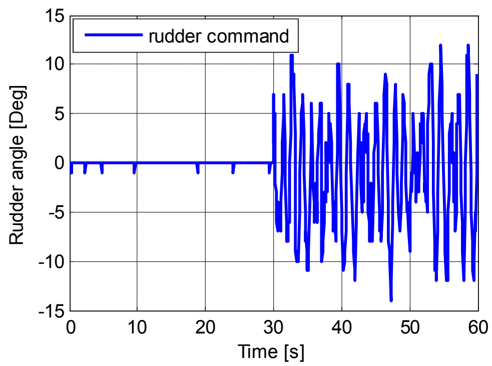

Fig. 16. Rudder command

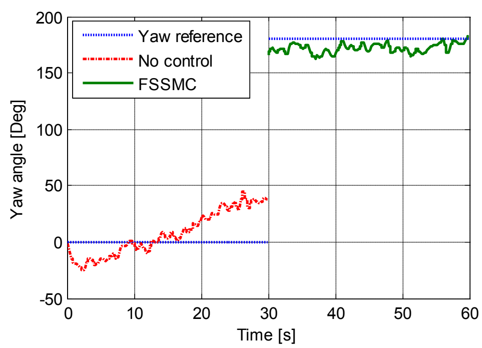

Fig. 17. Yaw motion versus time

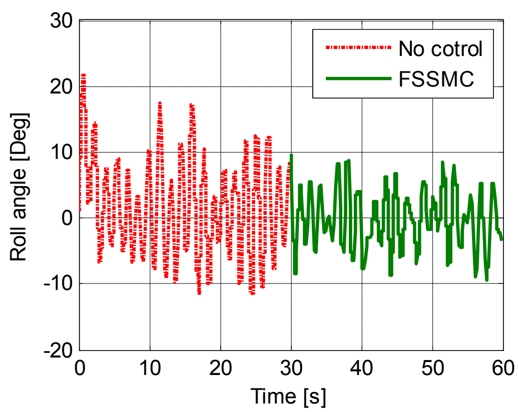

Fig. 18. Roll motion versus time

In Fig. 16, we can see there is no swinging in the rudder on the first trip and on the return trip the controller is turned on. From Figs.17 and 18 we can see heading is increased as time is increased, and the rolling motion also rapid onset without control. The criterion for roll reduction can expressed as follows[12]:

$$100\times\frac{Roll-Roll^{l}}{Roll}\%=40..49\%(RMS)$$

V. Conclusions and Future Research

In this paper, we developed a rudder based roll control system. An FSSMC-based rudder roll damping controller method was been designed with consideration of the terms of wave disturbance rejection. Specifically, using the frequency shaped roll rate and tuning the hyperplane make the controller work better at frequencies close to the roll natural frequency. The sliding mode observer also shows its insensitivity properties and robustness to a wave disturbance in numerical simulations. For the boat-self character such as forward speed and small-sized limitation, the performance is quite good. The topics of our further research include development of a new boat with higher speed, embedded control and obstacle avoidance based video.

The Boat Model Data

In this appendix, the boat parameters of the identification model were obtained by 4SID method. Outputs are yaw, yaw rate and roll rate.

$$A=\begin{bmatrix}0 & 77.042 & 6.2978 & 3.7703\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ 0 & -41.996 & -21.625 & -3.3311\end{bmatrix},$$

$$B=\begin{bmatrix}0 & 0 & 0 & 1\end{bmatrix}^{T},\ C=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 77.042 & 6.2978 & 3.7703\\ 0 & 9.833 & 7.91 & 6.2459\end{bmatrix}$$

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