Identification modeling and Steering Controller Design for Unmanned Surface Vehicles

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***Abstract*— With the continuous advancement of science and technology, many unmanned surface vehicles (USVs) are being developed for many different applications: military, environmental, mapping... So the steering (heading) control is for unmanned surface vehicles important research designed for motion control. It is not only about handling and ship stabilization, but also the basics of trajectory tracking and obstacle avoidance. During the USV research, mathematical models of steering control were critical to explaining vehicle behavior and stability. Therefore, this paper introduces two contents related to USV steering control, namely model identification and steering control design. For this purpose, the Nomoto model is chosen as the recognition model. These defined offline Nomoto models can serve a variety of purposes: simulation purposes or offline control algorithms... First, experiments are performed to collect experimental data (zigzag tests...), then prediction error identification methods are used to identify Nomoto model parameters, such as recursive least squares (RLS). To verify the recognition accuracy and model results, a sliding mode controller (SMC) was designed based on the established model. Finally, the simulation and experimental results show that the sliding mode controller and integrated line-of-sight guidance (ILOS) have good control effects, proving their feasibility and stability. All of this shows the correctness and practical value of the established model, and on this basis, advanced control algorithms, trajectory tracking, obstacle avoidance... are developed for USV.**

Keywords*— *Steering control, Nomoto model, Sliding mode controller, Integral line-of-sight.

I. INTRODUCTION

Currently, unmanned surface vehicles are adapted to civil, environmental and military applications [1], [2]. Along with the growing development and requirements, the development of advanced control algorithms is needed. One aspect of the research focuses on developing methods for performing dangerous tasks. The design of the steering (heading) controller is an important research topic as it concerns not only the stabilization and navigation of the ship, but also the basics of collision avoidance and trajectory tracking [3,5]. In steering control research, the USV mathematical model is important. When it comes to controller design, one of the most important aspects is understanding the dynamic behavior of the vehicle. Thus, determining the parameters of the USV model is a very important task. The design of the controller based on its dynamics can increase both the dynamic performance and the stability of the vehicle. In fact, advanced vehicle controllers are usually based on dynamics structures [6, 7] and [8]. To determine the dynamic model of a system, a method called system identification is often used. The system identification process finds the model that best describes the relationship between input and output data. Generally, the parameters in the system are determined by minimizing the error between the predicted output and the target output given the input. Therefore, this paper proposes a simple identification method to determine the model parameters. The steering dynamics of surface vehicles have been derived by various researchers based on the basic principles using Newton's laws of motion (eg [9, 11]), although complex, the Nomoto model [12] was chosen to describe the USV. It can show the relationship between rudder angle and heading angle. Then, recursive least squares (RLS) were applied to identify the parameters of the Nomoto model [13] offline. Traditional automatic controller systems generally use proportional-integral-derivative (PID) controllers, but when external disturbances change, the quality of PID control will decline. Therefore, there is a need to design a robust adaptive control system that does not degrade the control quality even if some vehicle parameters change. To solve this problem, a sliding mode controller (SMC) has been proposed. Sliding mode control [14,16] has been shown to be a robust and effective control method for nonlinear systems. Numerical simulations and experiments are then performed to collect experimental data [17], and then recursive least squares (RLS) are used to estimate the parameters identified by the Nomoto model. Furthermore, the Integral Line of Sight (ILOS) guidance is proposed and applied to a simple kinematic model of the USV. Finally, the experimental results show that the sliding mode controller and the ILOS guidance [18-20] have good control performance, demonstrating their feasibility and stability in USV. The structure of this paper is as follows: Section II outlines the structure of the USV and introduces the models and identification method. The sliding mode controller is shown in Section III of this research. The proposed Integral Line of Sight (ILOS) method for path tracking is presented in Section IV. Finally, the results are presented in Section V, and the conclusion is in Section VI.

II. USV MODEL AND IDENTIFICATION METHOD

A. Structure of the USV

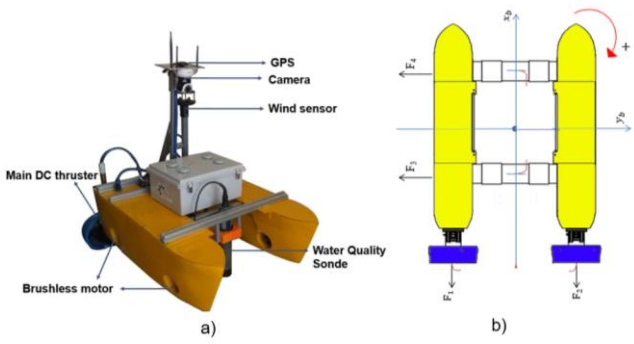


Fig. 1. Unmanned surface vehicle platform and components.

To facilitate the mathematical model estimation and testing experiments, a USV model was designed and built (Figure 1). To increase stability and easily integrate sensors for USV, a catamaran-style ship was designed for various tasks. The vehicle has a length of 1.2 meters and a total width of approx. 0.85 m. This version is a clever platform with built-in lots of sensors including GPS, IMU.... With a unique layout with four thrusters, the USV can without difficulty move in all directions (yaw, sway, and surge motion).

B. USV Model:

To evaluate the overview of the Nomoto model, the full USV model briefly introduces those mentioned in [9], [10]. Since the vehicle only moves on water, only consider the horizontal plane with three degrees of freedom, according to [9], [10] the dynamic model of the vehicle is:

$$\begin{cases} M\dot{\upsilon}+C(\upsilon)\upsilon+D(\upsilon)\upsilon=\tau+\tau_{ext} \\ \dot{\eta}=R(\psi)\upsilon \end{cases} \tag{1}$$

where $R(\psi)$ is the three DOF rotation matrix with:

$$R(\psi)=\begin{pmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{2}$$

$\eta = [x, y, \psi]^T$ are position (x, y) and heading (ψ) of the ship in an earth-fixed inertial frame, $\upsilon = [u, v, r]^T$ contains the linear velocities: surge (u), sway (v) and angular yaw rate (r) in the body-fixed frame. M is the system inertia matrix, $C(\upsilon)$ is a skew-symmetric matrix of Coriolis and centripetal terms, $D(\upsilon)$ is the damping matrix, and $\tau=[\tau_1, \tau_2, \tau_3]^T$ is the control input.

With advanced control algorithms: SMC, Adaptive control, Backstepping... it is necessary to determine all parameters in the matrix M,C,D . It's difficult to determining these parameters due to the complexity and the need for many tools, experimental sensors and measurement time. Some researchers have proposed approximate models, such as the Ross model [12] and the Nomoto model [13], which can help us easily determine the parameters of the model through data collection steps and traditional estimation methods. Therefore, the researchers use linear dynamic models like the Nomoto model [12],[13]. Although the Nomoto model is not as accurate as the model of equation (1), it still guarantees the dynamics of the USV and facilitates the implementation of advanced controllers later. The Nomoto model was obtained by eliminating swaying velocity (1) from a previous model derived from [13]. This results in the second-order model:

$$\frac{r}{\delta}=\frac{K(1+T_3 s)}{(1+T_1 s)(1+T_2 s)} \tag{3}$$

Where, time constants: T_1, T_2, T_3 and K is the gain constant. δ is rubber angle. The first order Nomoto model is obtained by defining the time constant $T = T_1 + T_2 - T_3$, in such a way that the transfer function between r and δ can be simplified:

$$\frac{r}{\delta}=\frac{K}{(1+Ts)} \Rightarrow T\dot{r}+r=K\delta \tag{4}$$

where K and T are the Nomoto time and gain constants, respectively. With $r=\dot{\psi}$, the model can be written in the time domain as:

$$T\ddot{\psi}+\dot{\psi}=K\delta \tag{5}$$

With the Nomoto model (Eq 5), instead of the matrix parameters M,C,D so we only need to estimate two parameters (T,K), the estimation work is easier and there are many methods such as zigzag, square… Evaluation of the recognition model and algorithm is an important step in identifying the system. In [35] several ways to compare models are presented, such as Square Root Mean Square Error (RMSE):

$$J=\sqrt{\frac{1}{N}\sum_{t=1}^{N}\left(r(t)-\tilde{r}(t)\right)^2} \tag{6}$$

C. Ship Maneuvers:

Some vehicle maneuvers (experiments) have been proposed to test the identification of maneuvering characteristics, such as: [16-18]. In this paper, the zig-zag method will be presented and implemented in simulation and experiment. To determine the T and K parameters, we need to change the rudder angle (δ) from side to side over a period of time and the vehicle will move in a zig-zag pattern. All data from the sensor including heading and yaw rates will collect. The speed of the vehicle must correspond to the actual speed, since each model estimate will correspond to a different speed. The test must take place in a wide and provincial environment to avoid noise affecting the estimation results. After zigzagging and collecting all the data, all that remains is to identify the Nomoto model offline using the RLS method..

III. SLIDING MODE CONTROL DESIGN

Heading angle control has many different methods, typically PID, fuzzy, sliding mode, reverse... Consequently, the sliding mode controller is non-linear, very stable, and easy to implement with the Nomoto model. It has been widely used in controlling types of nonlinearity [15]. Select state variable, $x_1=\psi, x_2=\dot{\psi}=r$ and $u=\delta$, so formula Model Nomoto can be simplified as:

$$\begin{cases} \dot{x}_1=x_2 \\ \dot{x}_2=f(x)+b(x)u, \ with \ f(x)=\frac{-1}{T}x_2, \ b(x)=\frac{K}{T}, \ u\in R, \ y\in R \\ y=x_1 \end{cases}$$

(7)

Define tracking error: $e=x_1-x_d$, then the switching function of SMC is defined as :

$$s=c_1 e+\dot{e} \Rightarrow \dot{s}=c_1\dot{e}+\left[f(x)+b(x)u-\ddot{x}_d\right] \text{ ,where } c_1>0 \tag{8}$$

The control law u is designed as:

$$u = -b(x)^{-1}\left[f(x) + c_1 e + \eta \tanh(s) - \ddot{x}_d\right], \eta > 0 \quad (9)$$

In order to verify the stability of the proposed algorithm, the first Lyapunov function is selected:

$$\begin{aligned} &V = \frac{1}{2}s^2, \\ &\dot{V} = s\dot{s} = s\left(c_1\dot{e} + \left(f(x) + b(x)u - \ddot{x}_d\right)\right) = s(-\eta \tanh(s)) = -\eta \tanh(s)s \le 0, \forall s \end{aligned} \quad (10)$$

So far, with $\dot{V} \le 0$ the system is stable. After the controller is designed, in order for the USV to operate and follow the given trajectories, a guidance is needed. For typical tasks the ILOS algorithm is most appropriate.

IV. Guidance System

For small vehicles that only move on water, the guidance law is required to perform various tasks, such as monitoring water quality, rescue, or transporting equipment. The most popular and easiest methods to implement are LOS (Line of Sight), CB (Constant Bearing) and PP (Pure Pursuit). When the vehicle is moving, it will be affected by the current, which will cause it to deviate from the β sideslip angle, which makes the above method unable to solve this problem. Hence the Integral Line of Sight (ILOS) method was proposed to improve the effect of current. It is based on the traditional LOS algorithm, relying on changes in cross-track error (y_e) to predict from that changing the steering angle. Traditional LOS guides are given as follows:

$$\psi_d = \alpha_p + \arctan\left(\frac{-y_e}{\Delta}\right), u_d = u_0, \ \alpha_p = \text{atan2}(y_{k+1} - y_k, x_{k+1} - x_k) \quad (11)$$

$$y_e = -(x - x_k)\sin\alpha_p + (y - y_k)\cos\alpha_p \quad (12)$$

Where: α_p is the path-tangential angle, y_e is the cross-track error, defined as the shortest distance between the Path and the vehicle. Δ>0 is a predefined look-ahead distance, it's selected and adjusted during testing. $P_k(x_k, y_k)$ is the position of the target waypoint that USV will follow and the desired surge speed is predefined as constants u_0 .

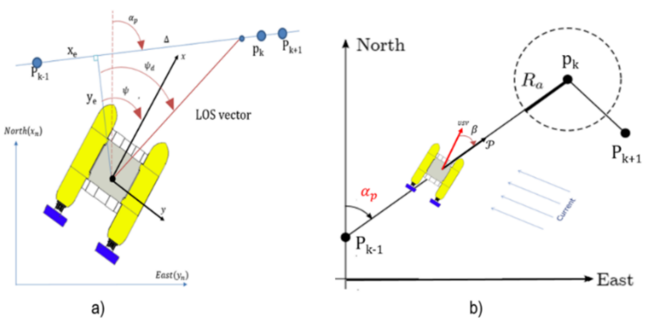


Fig. 2. a) Line-of-sight guidance law for path following. b) The side-slips with a constant angle and follows the path.

Finally, the goal is to converge the cross track to zero:

$$\begin{aligned} &\lim_{t\to\infty} y_e(t) = 0, \lim_{t\to\infty} u(t) = u_0 \\ &\lim_{t\to\infty} \psi(t) = \psi_d, \psi_d = \alpha_p \end{aligned} \quad (13)$$

When affected by external influences such as currents, convergence will not be guaranteed, causing the USV to move at a side-slip angle (β) from the path (Fig. 2b). So we have:

$$\lim_{t\to\infty} \psi(t) = \psi_d, \text{ where: } \psi_d = \alpha_P + \beta, \beta \in \left(\frac{-\pi}{2}; \frac{\pi}{2}\right) \quad (14)$$

To solve this problem, the researchers added integral action in the heading reference (ψ_d) to improve the side-slip β , so the integral LOS guidance is as follows:

$$\begin{aligned} &\psi_d = \alpha_P - \arctan\left(\frac{y_e + \sigma y_{\text{int}}}{\Delta}\right), \\ &\dot{y}_{\text{int}} = \frac{\Delta y_e}{(y_e + \sigma y_{\text{int}})^2 + \Delta^2}, \ 0 < \sigma < u_d - v_{c\max} \end{aligned} \quad (15)$$

The integral effects give nonzero angle, allowing the vehicle to side-slip while staying on the desired path and can counteract the effect of the current. As a result, the vehicle follows the path $\mathcal{P}$ at desired speed u_d (m/s), while avoiding the side-slip angle. The maximum intensity of the unknown current is $v_{c\max}$ (m/s).

V. Experiments and Results

A. Simulation

To evaluate the Nomoto model, the simulation is performed as follows: Collect the data needed for the estimation: the rudder angle change from -50%-50% and collect the values: yaw, yaw rate, velocity. The result is shown in the figure 3. For best results, it is recommended to take multiple samples with the least amount of noise, as the higher the noise, the less accurate the model will be.

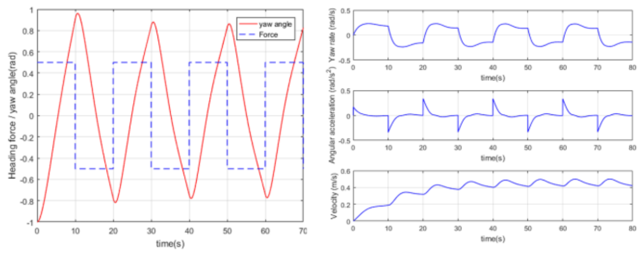
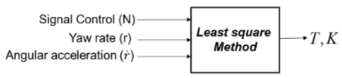


Fig. 3. Rudder, yaw, yaw rate and velocity plot of the 50-50 zig-zag maneuver, u=0.5m/s.

Use the least squares method to estimate the parameters of the model (Fig.4a)



a) A flow chart of system identification

Model	Fit (%)	RMSE(rad/s)
Nomoto	77.2590	0.9449
Ross	96.9983	0.0138

b)

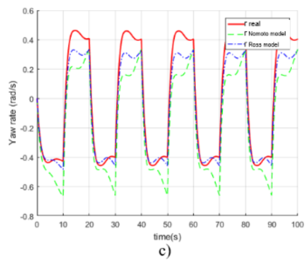


Fig. 4. a) A flow chart of system identification. b) Fit and RMSE of Models. c) The estimated Nomoto (green) and Ross (blue) model compared to real data (red).

The results obtained with the Nomoto model are shown in Figures 4b and 4c. Compared with the real model and the Ross model [12], the simulation results show that the identification of the Nomoto model gives Fit 77% and an RMSE 0.9449, and the estimated Ross model gives Fit 96% and RMSE 0.0138. Of course, the Ross model is the most accurate because we need to estimate more than 20 parameters, while Nomoto has only 2 parameters and is linear. But the Nomoto model can still satisfy the characteristics and accuracy to apply to the SMC controller.

1) Heading Controller Tests: After the Nomoto model parameter is available, the SMC will be performed to evaluate the ability to control the heading angle. We compare the PID and SMC controllers for the Ross model, the results show that the controller works well and the given estimation method is doable. (Fig.5).

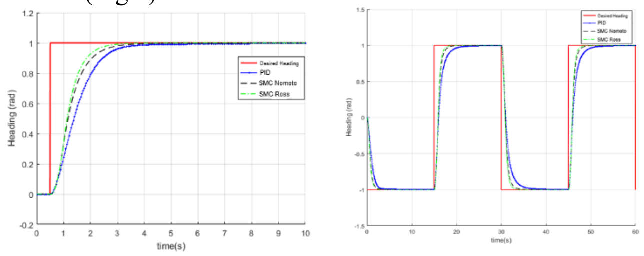


Fig. 5. Results of the SMC controller using the Nomoto model identified zig-zag maneuvers.

2) Waypoint Tracking Tests: With the built-in ILOS guidance, the USV follows a given waypoint (Fig.6a).

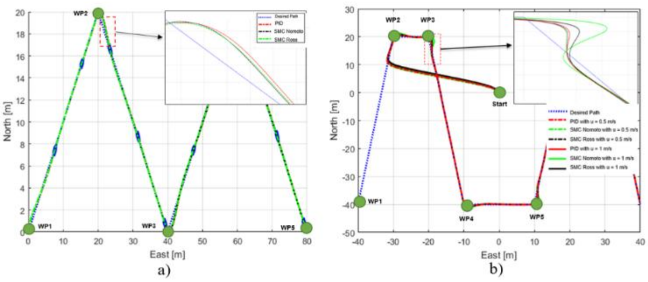


Fig. 6. a) Path following performance comparisons: PID, SMC for Nomoto and Ross Model with velocity u= 0.5m/s. b) Path following performance with velocity u= 0.5m/s and 1m/s.

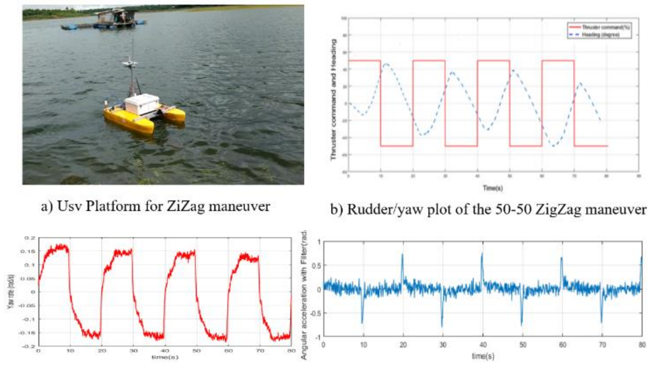
SMC controller performs better at a speed of 0.5 m/s (model estimation at this speed). If increasing it to 1m/s, the model parameters change, so the quality is no longer good. In Fig. 6b, Nomoto's SMC works well at 0.5 m/s, but when it goes up to 1 m/s, it almost deviates from the path, with the PID controller it is still stable, the Ross model itself has less change. Therefore, any model we estimate will correspond to a fixed velocity, and if the velocity increases too much, the quality of control is no longer good. Overall, the simulation results show that the quantitative approach and Nomoto model are executable.

B. Experiments

1) Estimation: To identify the Nomoto coefficient, zigzag maneuvers are performed by alternately reversing the rudder to one rudder angle on either side. The USV has no physical rudder, but is steered by a propeller on top (Figure 1). The power of each propeller is expressed as a percentage and is limited to [-100%, 100%], representing the maximum reverse or forward speed since both propellers can rotate in one direction. To collect data for parameter estimation (T, K) of the Nomoto model:

a) The AHRS sensor collects data: heading angle, angular acceleration, angular velocity and flashing light, and the sampling time is 0.01s.

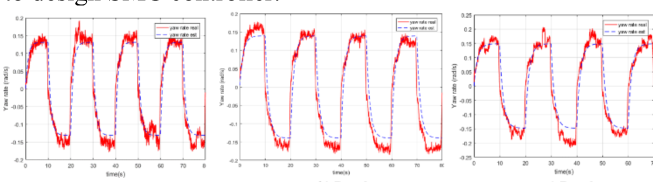
b) Zigzag maneuvers: When the control signal changes -50% - 50% of the thruster, i.e. 2.05kgf (maximum 4.1kgf with 12V motor), we choose the period as 20 because the response is slow (this choice depends on the vehicle, if the model is small, the response fast, we choose a smaller period). Since this model has no speed control, only fixed thrust (50% PWM) should be provided, with a speed of about 0.7-0.8m/s.



c) Yaw rate and Angular acceleration velocity during

Fig. 7. Thruster command/yaw and Yaw rate plot of the zig-zag maneuver

When the vehicle was deployed, it sped up, using 50% of the maximal thrust, meaning $F_1 = F_2 = 50\%$ and after 10 seconds (ensuring a steady speed) the vehicle started its configured number of zigzags with thruster heading (F_4 changes from 50% to - 50%). Data from the Zig-zag maneuver identification of the parameters based on the zig-zag maneuver is presented in Fig.7. And afterwards, the total average of data was taken, in order to identify the Nomoto model. Nomoto model, which results between measured and simulated yaw-rates compared to Fig. 8. With Nomoto's parameters after several times of Zig-zag tests, the model with Fit 70% and RMSE 0.0402 will be selected and proceed to design SMC controller.



a) Run 1 b) Run 2 c) Run 3

Run	Parameter Estimate (T,K)	Fit (%)	RMSE(rad/s)
1	[4.181459081169335 3.128168095090590]	70.3894	0.0402
2	[4.291397449371601 3.814735412773973]	69.1941	0.0425
3	[4.641160476233538 3.371459009826905]	65.9823	0.0923

d) Parameter Estimation Using the Least Square method

Fig. 8. The estimated Nomoto model compared to measured data from zig-zag maneuver

2) Heading Controller Tests: The first type of closed-loop control deployed on USV was the heading control.

Under this test, the speed command is a fixed value. An error between the current heading and commanded heading is calculated using AHRS sensor feedback. In general with the Sliding mode controller, the results show good convergence with the desired heading angles.

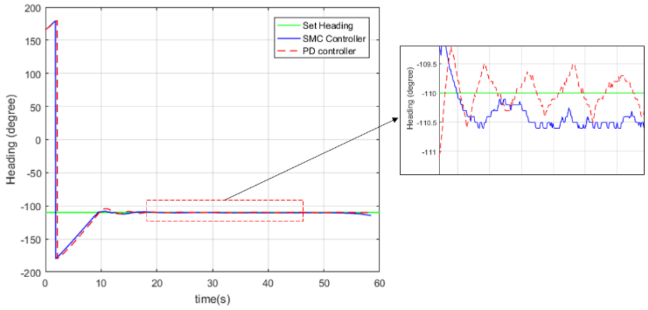
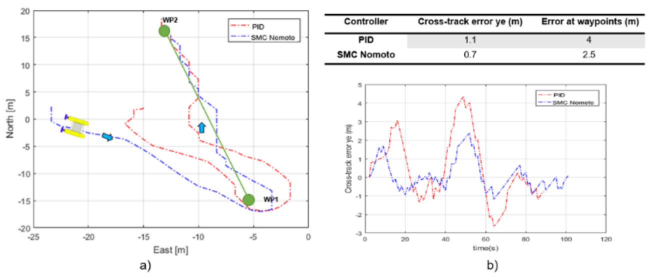


Fig. 9. Heading and step response of PID controller and SMC

3) Waypoint Following Tests: Another reasonable test is to track the desired trajectory. The vehicle was programmed and tracked with a set of predefined waypoints. During operation the current USV position is based on GPS and waypoints are calculated continuously. From there, the set of ILOS algorithms and heading control strategies described in section 3.4 will ensure the USV's correct trajectory. Figure 10a shows the USV trajectory for such an experiment. The USV has followed a given planned route and has little changes in its motion. Furthermore, the test results, as shown in figure 10b, show that the Cross-track error (ye) is in the range of 0.7m when it is in the path. This error is the effect of part of the position, orientation sensor, and they depend on the test environment a lot. Test results have proven all the above suggestions to be reasonable and its practical workability.



Controller	Cross-track error ye (m)	Error at waypoints (m)
PID	1.1	4
SMC Nomoto	0.7	2.5

Fig. 10. a) Trajectory while way point tracking. b) Cross-track error ye.

VI. Conclusion

This paper presents the Nomoto model and sliding mode controller designed for USV, suitable for various tasks. The USV model and identification method are introduced to improve the control quality and stability of it. SMC has been proposed for steering control of USV. Many practical experiments prove that ILOS guidance is not only simple but also effective. The simulation and experimental results prove that the designed guidance and control system has good performance, feasibility and reliability. Ultimately, a fully functional USV will be developed and implemented in the lake, and the platform will be a major step forward in the development of autonomous surface vehicles.

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