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Implementation of an Integrated Navigation, Guidance and Control System for an Unmanned Surface Vehicle

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***Abstract*—In this paper, an integrated navigation, guidance and control system of an unmanned surface vehicle (USV) is implemented. Main contributions are as follows: 1) Aiming to obtain precise heading estimation, Kalman filter technique that can combine predictions from designed model with actual sensor measurements is adopted in navigation system; 2) The line-of-sight (LOS) with a time-varying lookahead distance is employed in guidance system. Remarkably, a novel arc transition strategy is proposed such that the vehicle can turn around smoothly when completing the way-point guidance mission; 3) In addition, strong robustness to dynamic characteristics is enhanced by employing a fuzzy PID controller. Finally, simulation studies and field experiments demonstrate remarkable performance of the integrated USV system.**

Keywords*—Navigation; guidance and control; Kalman filter; line-of-sight; arc transition; fuzzy PID; USV

I. INTRODUCTION

As unmanned systems bring people into the artificial intelligence (AI) era, a great number of attentions have been paid to USV in the maritime. In this case, there have been plenty of advanced theoretical algorithms and even the actual platform design focusing on this subject [1]–[5]. The USV generally is made up of navigation, guidance and control systems that they exchange information and cooperate with each other to realize the autonomous of vessel [6].

The navigation system is very important for the stability and precision control of unmanned surface vehicle. As for an unmanned system, the problem of navigation is to obtain without communication delay and data loss from senor networks in a complex environment [7]. The navigation system of the vessel can provide reliable position, orientation and velocity via global positioning system (GPS) and inertial measurement unit (IMU) [8]. As a consequence, it is highly needed to propose a method of fusion and filter to process sensor data.

In addition to the navigation system, it is significant to develop a guidance scheme that generates a reference path. A well-know and efficient path following algorithm is LOS [9]. It is called a three-point method which consists of start point, end point and virtual tracking point. The method for steering laws has been proposed in [10] with enclosure-based steering. The main drawback of this approach is that limitation of requiring strategy radius greater than cross-track error. Furthermore, tracking the path with straight-line segments was achieved in [11], which could follow the linear path accurately and track error converge to zero. However, in the marine practice ,it suffers from the weakness not considering smooth transition between two segments.

As important as the former two subjects, controller design determines that control forces how to satisfy desired control objectives. A popular and effective control method is PID control whose parameters are constants. In this setting, the control effect may not meet the requirement when the states change. In addition, owing to difficultly establishing precise model, it is a challenge to apply the intelligent control to the vessel. However, fuzzy control doesn't require model information and can enhance the system robustness and improvement the system dynamic characteristics [12], [13]. It should be pointed out that fuzzy control doesn't have the integral, so it is difficult to eliminate the steady-state error. As a consequence, combining PID control with fuzzy control can take advantage of both control and overcome the shortcoming of each other [14], [15].

Motivated by the above observations, we developed an USV named IMV-1 based on the NGC system and its diagram is shown in Fig. 1.

II. NAVIGATION

The primary navigation scheme for IMV-1 consists of global positioning system (GPS) and inertial measurement unit

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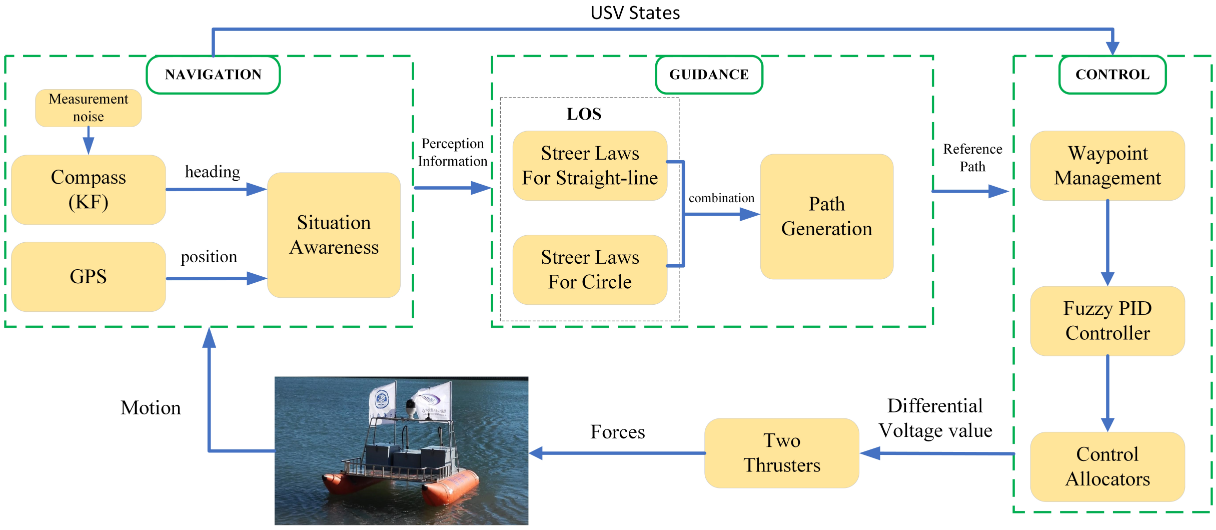

Fig. 1. Structure of USV NGC system

(IMU). This section briefly introduces navigation techniques.

The NEO-M8 GPS updating at $10Hz$ is capable of providing latitude and longitude information. In addition to position information, the vessel real-time velocity is provided by this sensor. The GPS receiver offers a $2.5m$ positional accuracy and $0.05m/s$ velocity accuracy. It series modules include one USART interface, which can be used for communication to the MCU.

The IMU sensor communicating with the MCU through the IIC protocol mainly provides attitude information. For heading estimator, we adopted Kalman filer based navigation filter which can combine predictions from a dynamic model of the compass with actual compass measurements. The state and measurement models for the heading dynamics of IMV-1 may be described by

$$x(k+1) = \boldsymbol{A}x(k) + \boldsymbol{B}u(k) + \omega(k) \tag{1}$$

$$z(k) = \boldsymbol{H}x(k) + \nu(k) \tag{2}$$

where $\omega(k)$ is random vector of the process noise and $\nu(k)$ is random vector of measurement noise. In the IMV-1, the model of the compass is described as

$$\boldsymbol{A} = \begin{bmatrix} 1.002 & 0 \\ 0 & 0.9945 \end{bmatrix}, \boldsymbol{B} = \begin{bmatrix} 6.354 \\ -4.699 \end{bmatrix} \times 10^{-6}$$

$$\boldsymbol{H} = 180 \times \pi \times [34.13 \quad 15.11]$$

In updating state, we compute a state estimate $\hat{x}(k+1|k+1)$ as a linear combination of two parts, one is the priori estimate $\hat{x}(k+1|k+1)$ and the other is the difference between an actual measurement and a measurement prediction, the state estimate is defined by

$$\begin{aligned} \hat{x}(k+1|k+1) = & \hat{x}(k+1|k) + K(k+1)(z(k+1) \\ & - \boldsymbol{H}\hat{x}(k+1|k)) \end{aligned} \tag{3}$$

The form of Kalman filter gain matrix is given by

$$\begin{aligned} K(k+1) = & P(k+1|k)\boldsymbol{H}^T \\ & \times \left[\boldsymbol{H}P(k+1|k)\boldsymbol{H}^T + \boldsymbol{R}\right]^{-1} \end{aligned} \tag{4}$$

with

$$P(k+1|k) = \boldsymbol{A}P(k|k)\boldsymbol{A}^T + \boldsymbol{Q} \tag{5}$$

The $\boldsymbol{Q}$ is the process noise covariance and $\boldsymbol{R}$ is the measurement noise covariance ($\boldsymbol{Q} = cov(\omega), \boldsymbol{R} = cov(\nu)$).

Then the estimate error covariance is updated as follow

$$P(k+1|k+1) = [\boldsymbol{I}_n - K(k+1)\boldsymbol{H}]\, P(k+1|k) \tag{6}$$

The system sampling time has been set as $2.5ms$. The real-time heading of the vessel is input and the compass measurement is output, all in degrees. The Kalman filter algorithm is used to correct the error of the vessel heading angle, which effectively improves the accuracy and stability of the vessel attitude measurement.

III. GUIDANCE

In this section, we briefly illustrated the steering laws for straight lines and circles. In order to complete the waypoint mission, a novel guidance system law with a time-varying lookahead distance is proposed. Furthermore, the reference path is divided into straight lines formed by waypoints and fixed curvature arcs, which more conforming the marine navigation practice.

A. Model

A 3-DOF horizontal dynamics of vessel can be expressed as follows

$$\begin{cases} \dot{x} = u\cos\psi - v\sin\psi \\ \dot{y} = u\sin\psi + v\cos\psi \\ \dot{\psi} = r \end{cases} \tag{7}$$

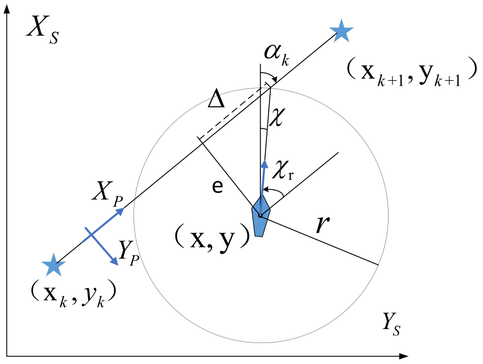

Fig. 2. Guidance laws for straight-line

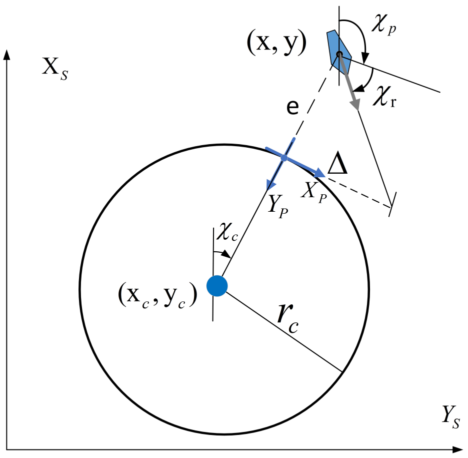

Fig. 3. Guidance laws for circles

here, $(x,\ y)$ represents the position of the vessel in the earth-fixed frame, ψ denotes the heading angle of the vessel; u,v and r denote surge, sway and yaw speeds in body-fixed frame. Normally, they could be simplified as

$$\begin{cases} \dot{x} = U \cos\psi \\ \dot{y} = U \sin\psi \\ \dot{\psi} = r \end{cases} \tag{8}$$

with

$$U = \sqrt{u^2 + v^2} \approx u \tag{9}$$

is known as the speed of the vessel.

B. Straight Line Tracking

There is a straight line formed by two waypoints. As is shown in Fig. 2, let $p_k = [x_k, y_k]^T \in R^2$ presents the waypoint. Define a local reference frame at (x_k, y_k) and christen it the path-tangential reference frame. The angle of the path is given by

$$\alpha_k = \text{atan2}(y_{k+1} - y_k, x_{k+1} - x_k) \tag{10}$$

Suppose the USV is at point (x, y), the error can be computed by

$$\begin{bmatrix} s(t) \\ e(t) \end{bmatrix} = \begin{bmatrix} \cos\alpha_k & -\sin\alpha_k \\ \sin\alpha_k & \cos\alpha_k \end{bmatrix}^T \begin{bmatrix} x(t) - x_k \\ y(t) - y_k \end{bmatrix} \tag{11}$$

where $e(t)$ is the cross-track error. Expanding the equation, the cross-track error becomes

$$\text{e}(t) = -(x(t) - x_k)\sin\alpha_k + (y(t) - y_k)\cos\alpha_k \tag{12}$$

The scheme objective is to achieve $\text{e}(t) \to 0$ as $t \to \infty$, which can be presented as following

$$\lim_{t\to\infty} e(t) = 0 \tag{13}$$

To make sure that the ship converges to geometric path, the desired angle should be computed as

$$\chi(e) = \alpha_k + \chi_r(e) \tag{14}$$

where

$$\chi_r(e) = \arctan(-\frac{e(t)}{\Delta}) \tag{15}$$

It is worthwhile to pay attention to the lookahead distance Δ, which is in front of the vertical projection of $p(t)$ onto the geometric path, is usually a constant. In this paper, we design a time-varying lookahead distance depending on the cross-track error and a circle which the radius satisfies $r > 0$ and centers at $p(t)$.

When the $|e(t)| \geq r$, the lookahead distance $\Delta = 0$ so that the vessel sails to the vertical projection of $p(t)$ onto the path. In addition, when the $|e(t)| < r$, as Fig. 2 shows,

$$e(t)^2 + \Delta(t)^2 = r^2 \tag{16}$$

the lookahead distance is $\Delta(t) = \sqrt{r^2 - e(t)^2}$. Hence, the range of time-varying lookahead distance is from 0 to r.

C. Circles Tracking

Define a circle with radius $r \in R_+$ and centered at $p_c = [x_c, y_c]^T \in R^2$. There is a straight line tangent to the circle, and perpendicular to the line connecting the vessel position with the center of the circle. As is shown in Fig. 3, the angle of straight line is deduced as

$$\chi_p(t) = \chi_c(t) + \frac{\pi}{2} \tag{17}$$

or

$$\chi_p(t) = \chi_c(t) - \frac{\pi}{2} \tag{18}$$

where

$$\chi_c(t) = atan2(y(t) - y_c, x(t) - x_c) \tag{19}$$

Equation (17) and (18) give the opposite orientation, respectively. Compared with the straight lines, the cross-track error is given by

$$e(t) = r - \|p(t) - p_c\|_2 \tag{20}$$

The purpose of accurate tracking to a circle is to satisfy with (13).

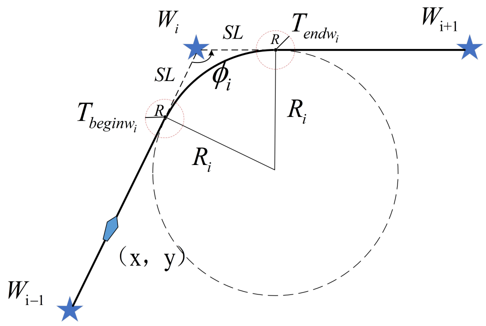

Fig. 4. Waypoints based on marine practice

D. Waypoints

Normally, the navigation system of the vessel connects the adjacent two waypoints through the input to form a straight-line reference path, for further improvement, arc transition is performed on the adjacent path. In Fig. 4, the desired trajectory of vessel is composed of

$$W_{i-1} \rightarrow T_{\mathrm{begin}w_i} \rightarrow T_{\mathrm{end}w_i} \rightarrow W_{i+1} \tag{21}$$

Define a straight-line segment at a positive constant distance SL , where

$$SL = T_{\mathrm{begin}w_i} W_i = W_i T_{\mathrm{end}w_i} \tag{22}$$

The circle is tangent to the straight-line reference path, and the point of tangency are $T_{\mathrm{begin}w_i}$ and $T_{\mathrm{end}w_i}$. ϕ_i is the angle between two straight-line. The radius R_i of circle can be immediately calculated as

$$R_i = SL \tan \frac{\phi_i}{2} \tag{23}$$

In marine practice, the vessel is required to accomplish the path designed above, which is either from straight-line to arc or from arc to straight-line. For the purpose of tracking path continuously and selecting the next path, a switching strategy is needed. The strategy is to judge whether the vessel is beyond the scope of the circle with radius R and centered at $T_{\mathrm{begin}w_i}$ or $T_{\mathrm{end}w_i}$. Once the vessel satisfies the following inequality

$$(x_{T_{\mathrm{begin}w_i}} - x(t))^2 + (y_{T_{\mathrm{begin}w_i}} - y(t))^2 \leq R^2 \tag{24}$$

or

$$(x_{T_{\mathrm{end}w_i}} - x(t))^2 + (y_{T_{\mathrm{end}w_i}} - y(t))^2 \leq R^2 \tag{25}$$

the next path will be selected as the reference path.

IV. CONTROL

In this paper, the method of combining PID control and fuzzy control is employed to take advantage of both control and overcome the shortcoming of each other to achieve precise vessel heading control. The input of the fuzzy controller are angle error E and increment value E_c ; at the same time, the increment parameters ΔK_P , ΔK_I , ΔK_D are chosen as the outputs of the fuzzy control. The final control action for the controller can be calculated according to the increment parameters ΔK_P , ΔK_I ΔK_D as follows

$$\begin{cases} K_P = K_P^* + \Delta K_P \\ K_I = K_I^* + \Delta K_I \\ K_D = K_D^* + \Delta K_D \end{cases} \tag{26}$$

where K_P^* , K_I^* K_D^* are the initial values of PID controller. As is shown in Fig. 5, the schematic diagram of fuzzy PID controller is given to explain the process of the combination system. It is noted that the fuzzy PID controller consists of lots of local PID controllers, which can be selected the parameter on-line. In Fig. 5, five subsets$\{NB, NS, ZE, PS, PB\}$ are selected for each $E, E_c, \Delta K_P, \Delta K_I, \Delta K_D$ for the purpose of fuzzification. And then through introducing quantitative factors to achieve the conversion of input variables from the basic universe to the fuzzy universe.

Normally, the heading control of a surface vehicle is achieved by human experience. However, for the USV, converting the rich experience of human beings into the control strategy is the key to realize fuzzy control. Therefore, the table of fuzzy rules $\Delta K_P, \Delta K_I, \Delta K_D$ is shown in Table 1.

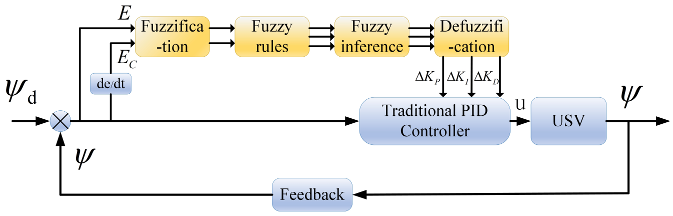

Fig. 5. Fuzzy PID controller

TABLE I. Fuzzy Rules

E/E_c	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	PB NB PS	PB NB ZE	PS NB ZE	PS NB ZE	ZE ZE PS
NS	PB NS NB	PS NS NB	PS NB ZE	ZE PS ZE	NB PS PS
ZE	PS NS NS	PS NS NB	ZE NS NS	NS PS NS	NB ZE PS
PS	ZE NS NB	ZE ZE NS	NS PS NS	NS PB ZE	NB PB PS
PB	ZE ZE PS	NS PS ZE	NS PS ZE	NB PS ZE	NB PB PB

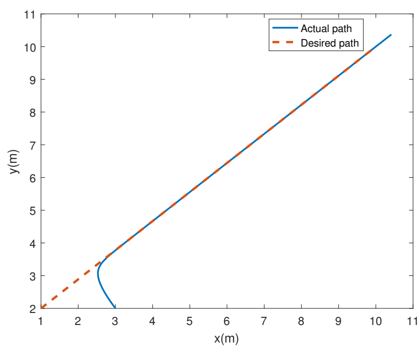

Fig. 6. Tracking straight line

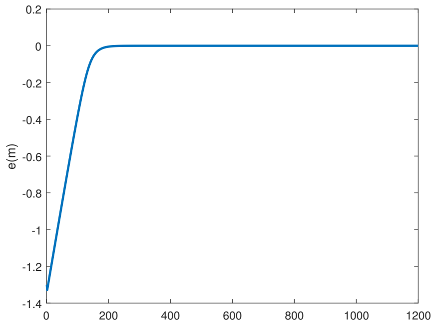

Fig. 7. Cross-track error

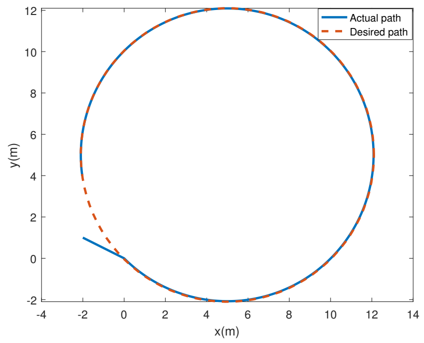

Fig. 8. Tracking circle

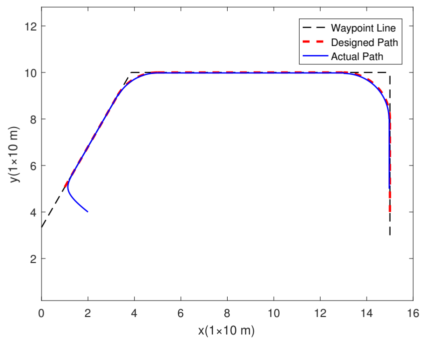

Fig. 9. Wayponits tracking

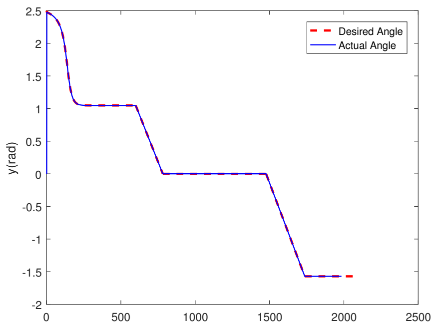

Fig. 10. The desired angle and actual angle

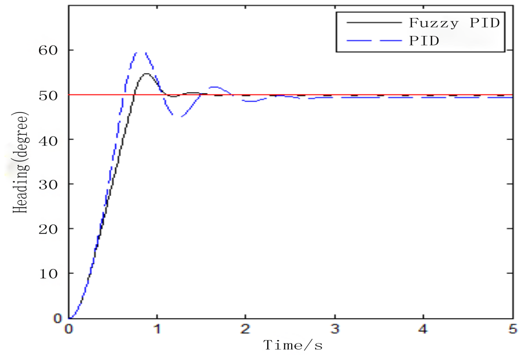

Fig. 11. Heading control of USV

Fig. 12. IMV-1

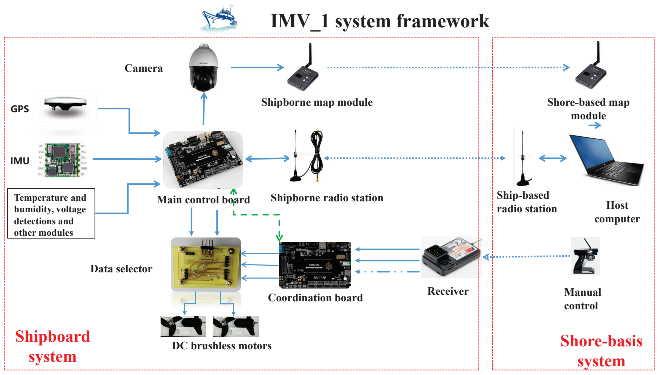

Fig. 13. Fundamental architecture of the USV

Fig. 14. Experimental result without arc transition

Fig. 15. Experimental result with arc transition

V. SIMULATION

In this section, to verify the effectiveness of the designed guidance scheme and control scheme of the vessel, a lot of simulation studies are completed under Matlab environment. Figs. 6−11 fully show our simulation results. Fig. 6 shows the performance of tracking the straight-line path using a time-varying lookahead distance, which achieves the accurate convergence to the desired trajectory. The change of cross-error is shown in Fig. 7, from which we can know that it can converge to zero and remain stable. To batter show the efficiency of the LOS algorithm, steering law for circle is also illustrated in Fig. 8. To complete the waypoint mission, the simulation of arc transition is carried out in Fig. 9, selecting the parameters as follows: $\phi_2 = 2\pi/3$,$\phi_3 = \pi/2, SL = 3L_0, R = L_0$. Note that the USV with arc transition strategy can follow the waypoints one by one smoothly, and as shown in Fig. 10, the system can quickly track desired angle calculated by guidance scheme. In the control simulation comparison analysis, traditional PID and fuzzy PID are provided in Fig. 11. It is obvious that fuzzy PID can converge faster and has little overshoot.

VI. EXPERIMENT

To verify the system navigation, guidance, and control designed in this paper, field experiments were done at the location of a harbor in Dalian Maritime University (DMU). Field experiments were also used to tune algorithm parameters and verify the software program. Our field experiments were done by IMV-1 as shown in Fig. 12, developed by Center of Intelligent Marine Vehicles. The total mass of the vessel is $121.1kg$, the length from the bow to the stern is $2.4m$, the width is $1.9m$, and the maximum output power of two motors is $1500W$. The vessel is underactuated pushed by two DC brushless motors.

The controller of IMV-1 is based on STM32F4xx, which the core has the ability of floating point arithmetic under the frequency of $180MHz$. The perception information is provided by GPS and IMU, and the perception information is sent to the host computer through wireless communication. Fig. 13 represents fundamental architecture of the USV.

For the field experiments, USV completed the way-point guidance mission without arc transition in Fig. 14 . The experimental result in Fig. 15 shows the way-point guidance mission with arc transition, note that the strategy can avoid the overshoot, which is mostly caused by the inertia of the IMV-1. In marine practice, IMV-1 provides the function return home that the vessel can return back along the path sailed before.

VII. CONCLUSION

In this paper, an integrated system composed of navigation, guidance and control have been applied in the IMV-1. Firstly, the navigation system provides heading estimate and positon for the vessel. Secondly, according to perception information, reference path is generated by LOS algorithm. Thirdly, fuzzy PID controller gives two thrusters differential voltage value. Finally, both simulation and field test verify the reliability of system.

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