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Guidance Law Design of Unmanned Robot Boats Based on Vision Navigation

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Keywords： Guidance Law Design, Unmanned Robot Boats, Vision Navigation.

ABSTRACT

A guidance law design is proposed for unmanned robot boats based on the fuzzy control and vision navigation in this investigation. The whole control system contains: 1. a fuzzy based control design, 2. one vision sensing methodology, and 3. a difference design for two propellers, for the purpose of controlling the speed and heading angle of the unmanned robot boats. Images captured by the vision sensing device are used to infer the relative distance between the guided unmanned robot boat and navigation marks. Based on relative distances and light of sight angle error, a fuzzy guidance law is then developed to control the velocity and heading angle of the robot boat via rotating the propellers with different rotation speed, respectively. For demonstrating the control performance of this proposed guidance law, a real robot boat is implemented and evaluated through real experiments. From the practical tests, a promising guidance performance can be obtained.

INTRODUCTION

Robot boats that operate on the surface of the water is one of the useful autonomous surface vessels (ASV) and can automatically explore unknown ocean environments. One important advantage of using unmanned robot boat (URB) is the decrement of the risk for human working in the dangerous and unpredictable ocean environment (Caccia et al, 2005).

Relative technologies of URB have been studied for two decades (Yogang et al., 2018) due to the appealing characters of URB can be widely applying in variety of applications such as collecting data, military, environmental monitoring and so on (Matthew et al., 2009).

For practically investigating the topology and health of river environment with a lower cost, an URB is developed in (Aldegheri et al., 2017) due to the conventional data collection is restricted by the usage of satellite systems, and this developed URB can be adopted for the objective of river environment exploration. Navigation systems play an important role in the guidance law design for guiding robot boats to execute specific tasks. The most famous navigation technique is GPS based navigation and widely used in cases without high accuracy due to GPS naturally possesses a positioning error is of 10 meters. For solving this problem and obtaining pin point accuracy for precise guidance designs of robot boats, the hybrid navigation design via integrating GPS with inertial Measurement Unit (IMU) mostly studied (Hongjie et al., 2018; Alexander et al., 2003). However, this solution may not work well due to the shielding effect of GPS signals. Without the alignment of GPS, awful positioning messages will be delivered from IMU (Ferreira, et al., 2009). Based on these depicted reasons, vision-based navigations is the alternative technique that can perform effectively navigation for robot boats. Recently, artificial vision system can perform really satisfactory navigation performance for various robotic applications in unstructured environments for obstacle avoidance designs (Martins et al., 2009; Terry et al., 2010). There are several vision sensors, and in this investigation, the digital camera is utilized because it can captures a wide range of image messages than others as infra-red (IR) sensor, ultraviolet sensor, and laser, etc. As to the control designs, a fuzzy based control design is proposed for the guidance law of URBs. The main objective of this proposed fuzzy control is to automatically guide the URB sailing along a set of predefined navigation marks without exactly knowing the model of URB.

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URBs are inherently complicated systems which are not capable of easily modeled, let alone design a nonlinear guidance law. Fuzzy controls have been proven as a control methodology which can effectively control highly complex systems without knowing the exact models of controlled systems (Terry, 2007); hence a fuzzy based guidance law with using the vision messages is studied in this paper to guide the URB. Fuzzy control commands trigger the propellers with different rotation speed clockwise or counterclockwise for changing the heading angle and speed of the controlled URB to sail precisely along the predefined navigation marks. This paper is organized as follows: 1. design objective, 2. tracking methodology and guidance law design, 3. Practical tests, and 4. conclusions.

DESIGN OBJECTIVE

The design target of this proposed control method is to guide a robot boat to sail in a course built up with several colored float pairs with adjustable Line of sight Angles (LOS) . The geometry between the controlled URB and the middle point of float pairs is illustrated as Figure. 1.

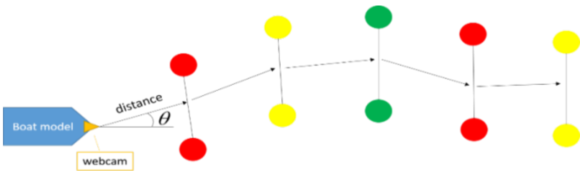


Fig. 1. The geometry between URB and float pairs

Definition of Tracking Errors and Design of Fuzzy Control Algorithm

1. Object Recognition and Relative Distance:

There are three steps including, 1. Shape detection and reconstruction, 2. Roundness identification, and 3. Relative distance calculation, are designed for the object recognition of this research.

1.1. Shape detection and reconstruction

Generally, colors of images can be presented by type of RGB, HSV, and HSL. HSV: Hue, saturation, and value, described in polar coordinate is utilized for presentation of colors of images. The following Figures is a case of separating different color floats by using HSV. In Figure 2, three different color pairs of floats: yellow, green, and red are shown, and one of them will be reserved after the color filtering process based HSV.

Fig. 2. Three pairs of color floats

The target float filtered is the red color. Fig. 2 is the residual image for objects with red color, and red float and extinguisher in the corner are reserved.

Fig. 3. The filtered red color float

1.2. Roundness identification

Objects in Figure 3 are rough in the edge after the above filtered process hence a convex hull method is proposed to modify the uneven shapes of objects, and let them become smoothly. Convex hull method possesses the compensation ability to smooth the uneven shapes of objects via using the minimum surface area in practice; the calculated minimum surface area will cover all points of shapes of objects by doping some new points. For example, the filtered red color floats in Figure. 4 become more smooth and round.

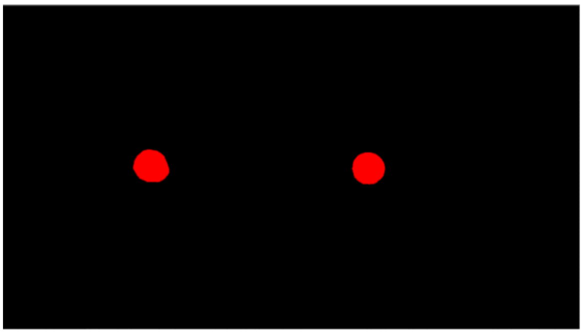


Fig. 4. Compensation image via using convex hull method

In Fig. 3, there are two different shapes of objects. For recognizing the red float, Heywood Circularity Factor which can mathematically assess the roundness of objects is applied to this case.

$$f_{circularity} = \frac{4\pi A}{P^2}, \quad (1)$$

where A is circular area, P is perimeter, and $f_{circularity}$=1 means the assessed object is a circle. Based on Equation (1), the extinguisher in Fig. 3, is successfully removed, and two red floats are reserved finally.

1.3. Relative distance calculation

In this investigation, the relative distance is calculated via using the size of the captured image in real-time. However, due to images enlarge when the relative distance between object and camera is getting closer and closer, a mathematical mapping for the object image and the relative distance is off-line developed. 50 times experiments which range from 100 cm to 350 cm are done for establishing the relationship between captured images and actual relative distance, and this mapping will be adopted to calculate the real-time relative distance when real-time image is obtained. Using curve fitting method, the relationship between captured images and actual relative distance can be approximated by an equation as below

$$y = 10^9 x^{-2.103}, \quad (2)$$

where y is the relative distance, and x is the captured image size.

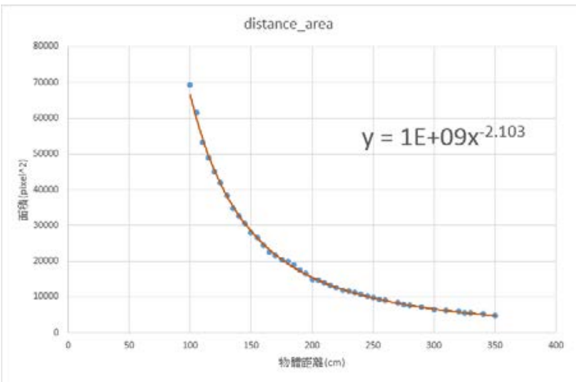


Fig. 5. The relationship between captured images and actual relative distances

In Figure. 5, the blue dots are experiment data, and the red curve shows outputs of Equation (2).

Based on the relative distances, LOS angle can be calculated for turning the heading of the guided URB. In this guidance law design, calculation of angle errors can be obtained by subtracting the LOS angle with the heading angle of URB. As Figure 6, L can be calculated by knowing the relationship of actual relative distance and real-time pixel distances in images.

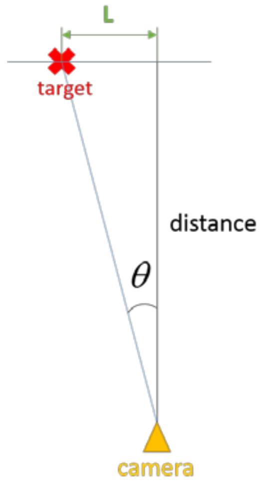


Fig. 6. Geometry between target and camera

Consider the floats are circular after the above filtered and modified process, their area can be expressed as

$$A = \pi r^2, \quad (3)$$

where A is the area of single float, and r is the radius.

By following similar process as finding the relationship between the relative distance and the captured image size, a mathematical representation for the relationship of actual relative distance and real-time pixel distances in images can be obtained via a series of experiments (50 times), and the curve fitting approximation is formulated as follows

$$y = 0.0023x - 0.0221. \quad (4)$$

As Figure7, the blue dot experiment data is approximated precisely via Equation (4), and LOS angle θ can be calculated then.

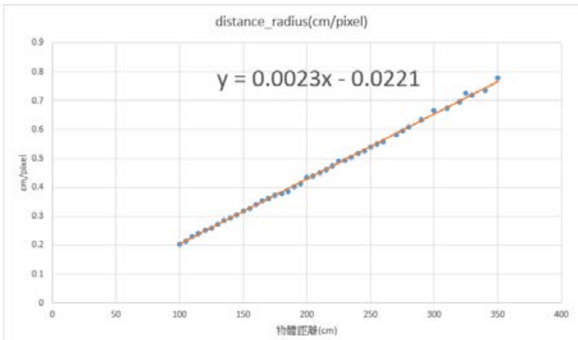


Fig. 7. Approximation equation of the experiments for the relative distance and the captured image size

2. Definition of Tracking Errors:

Two errors are feedback to control the URB, and the tracking errors are defined as Figure 8: 1. the difference δ between LOS angle and heading angle of URB, and 2. the relative distance D.

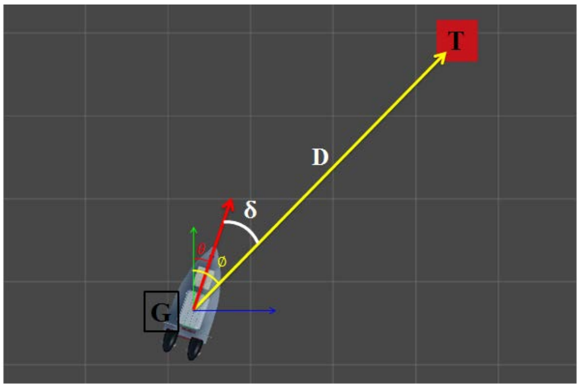


Fig. 8. The geometry between URB (G) and Target (T)

Suppose position of URB is $G=(x_G, y_G)$ and position of middle point of float pairs is $T=(x_T, y_T)$. The relative distance D can be calculated as

$$D=\sqrt{(x_T-x_G)^2+(y_T-y_G)^2}. \tag{5}$$

Based on the geometry between URB and middle point of float pairs, the LOS angle ϕ between heading direction of URB and x axis can be expressed as

$$\phi=\tan^{-1}\frac{(x_T-x_G)}{(y_T-y_G)}. \tag{6}$$

Suppose the real time heading angle θ can be measured by using compass sensor, and from Equation (6), the heading angle δ is presented as

$$\delta=\theta-\phi. \tag{7}$$

3. Fuzzy Controller Design:

In this study, a fuzzy-based controller $C_f(D,\delta)$ is developed to guide the URB to pass through the prearranged float pairs due to the fuzzy control has the property without knowing the actual nonlinear model of the controlled plant and is robust to the modeling uncertainties and environmental distances. Hence, this control design is very suitable for this guidance law design of URB. As mentioned above, error inputs of this guidance law problem of URBs are D and δ. Outputs of the fuzzy controller $C_f(D,\delta)$=[$C_f r$, $C_f l$] are rotation velocities of the propellers of outboard engines. In this investigation, heading rotation of the guided URB is realized via using the output differences of propellers to accurately achieve right or left turns. This rotation structure has the advantage of easy to implement property. In the following, design procedure of the proposed fuzzy controller will be formulated systematically.

Relative distance error D and angle error δ are inputs of this proposed fuzzy guidance law. The angle error δ is named as a linguistic variable and set up with the ranges of [-45°, 45°] due to the sensing limitation of used image sensor, and five membership functions, LL, L, mid, R, and RR are given for the angle error δ as Figure 9.

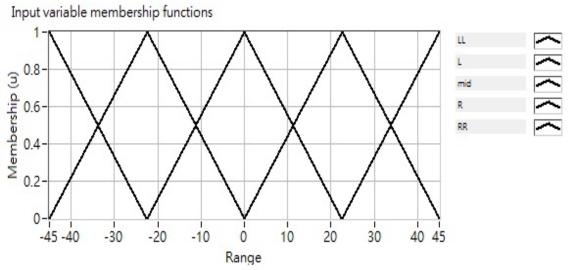


Fig. 9. Membership function of angle error δ (degree)

As to the relative distance error D, it ranges from [0.5(m), 2.5(m)], and five membership functions: very close, close, mid, far, and very far, are set up for D, as Figure 10. Because of the maximum detecting ability of the distance sensor, the maximum relative distance error is specified as 2.5(m).

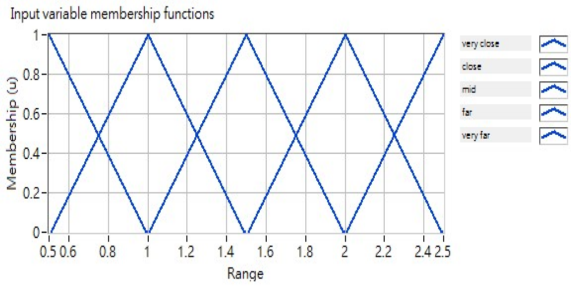


Fig. 10. Membership function of the distance error D(m)

Outputs of this proposed fuzzy guidance law are rotation velocities of propellers of right and left outboard engines. Generally, an 8 bit resolution (2^8) is utilized to present output of each outboard engine, and the minimum and maximum output values of outboard engines are 0 and 255. Based on the specification of the outboard engine, there are five membership functions, stop, slow, mid, fast, and full speed, are arranged for engine motor outputs as Figures 11 and 12.

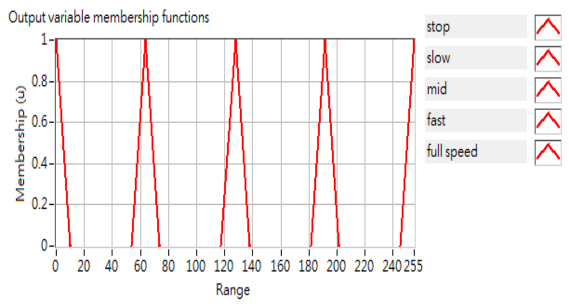


Fig. 11. Membership function of the right engine motor output

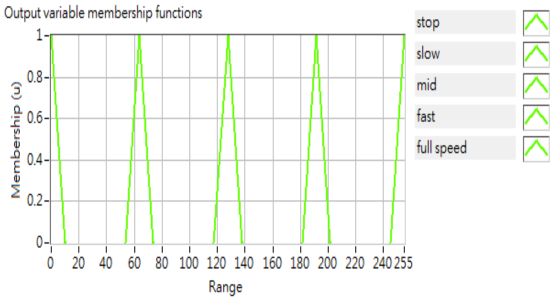


Fig. 12. Membership function of the left engine motor output

Fuzzy rules as follows are made for the guided URB:

Rule *i*: If Relative distance error D is A and angle error δ is B, then $C_f r$ is C and $C_f l$ is D. for $i=1,\ldots,n$.

where i is the rule number and can be calculated as i=membership number of D ×membership number of δ ×membership number of $C_f r$ ×membership number of $C_f l$.

In this fuzzy control design, the total rule number is $i=5\times5\times5\times5=625$. Practically, this is huge burden to the calculator of the URB, and for reducing the computational power of the main board of the guided URB, most of the rules are removed due to they are have similar control property or never been triggered. Finally, there are 25 rules are reserved for the guidance purpose of the URB. Based on the above 2 inputs and 2 outputs arrangement, an fuzzy interference surface can be derived and picturized as Figure 13. From Fig. 13, obviously, two subfigures reveal the tendency of error convergences in two errors. The control outputs of the engine motors are larger if the relative distance D and angle error δ are larger. Control outputs converge to zero when both errors converge to zero. This fuzzy guidance law with 25 rules will be installed in the Labview software platform to output suitable control commands to motors of outboard engines to rotate propellers. Difference between the output control commands will rotate the URB to point to direction of the middle points of float pairs and drive URB to pass through them precisely.

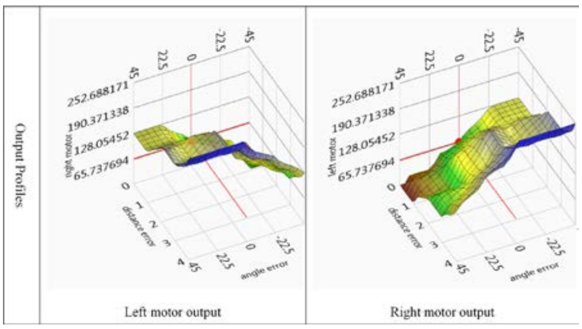
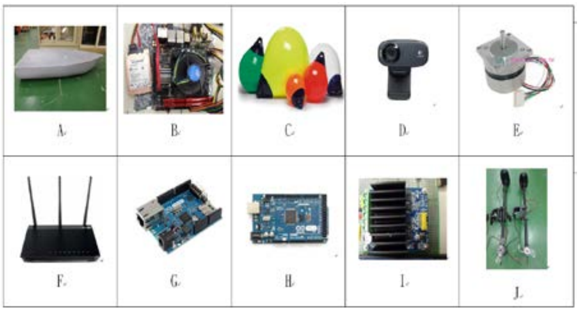


Fig. 13. Control output profiles of the left and right motors

SET UP OF EXPERIEMENTS

Hardware adopted for building up URB are listed in Table 1, including A. a hull, B. main board, C. floats, D. webcams, E. servo motors, F. a router, G. an Arduino Ethernet, H. an Arduino Mega board, I. a motor driver, J. outboard engines with DC motors.

Table 1. Hardware used in the unmanned robot boat



The hull is used for the purpose of loading with necessary devices of the controlled URB, the main board plays the role of collecting sensing data as image data, servo motor data, etc, calculating the fuzzy control commands and triggering surrounding devices as WiFi, Auduino Mega board and so on. Details of listed devices will not described one by one for saving pages.

PRACTICAL TESTS

A sailing course with three pairs of floats which are with different colors: 1. red, 2. green, and 3. yellow, is built up as Figure 14 in the towing tank of department of systems and naval mechatronics engineering, national Cheng Kung University. LOS between centers of float pairs range from 0° to ±45°. In this testing scenario, there are three sub-scenarios: 1. Initial middle point to the center of the first red float pair, 2. The center of the first red float pair to the second green float pair, and 3. The center of the second yellow float pair to the third float pair. For testing the robustness of this scenario, all LOS are set up as three maximum values: -45°, 45°, and 0°, sequentially.

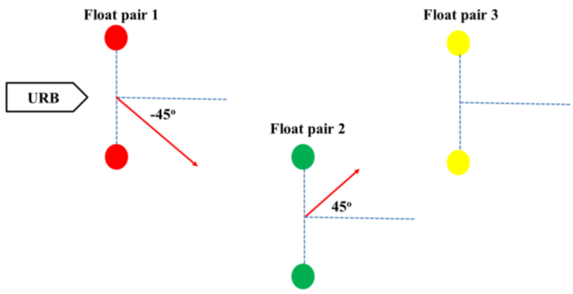


Fig. 14. Testing scenarios in the towing tank

Figures 15 and 16 reveal the testing results of passing through the first red float pair from the initial position. The initial heading of the guided URB direct to the middle point of the first red float pair.

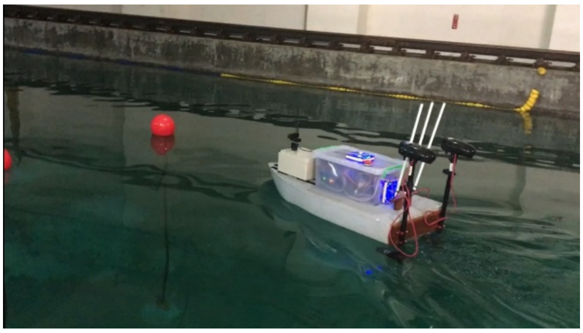


Fig. 15. URB sails to the red float pairs

Figure 16 shows that the controlled URB can be guided precisely to pass through the first red pair float.

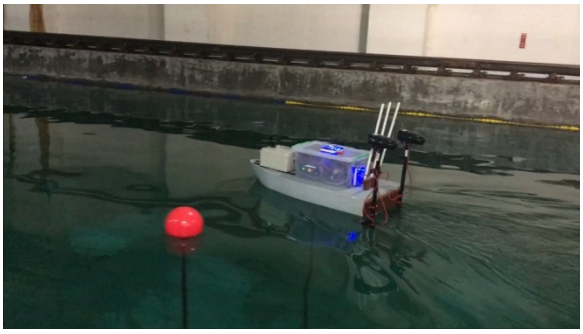


Fig. 16. URB passes through the red float pairs

After passing through the first red float pair, the guided URB sails to the second green float pair as Figure 17 and this mission is achieved from observing Figure 18.

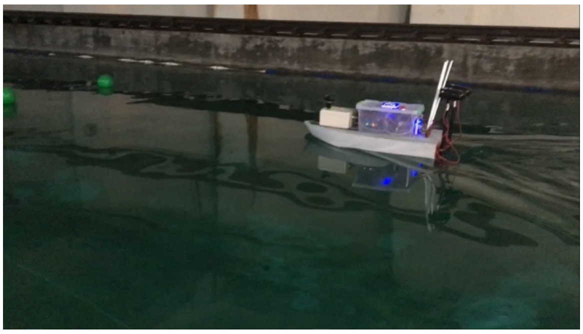


Fig. 17. URB sails to the green float pairs

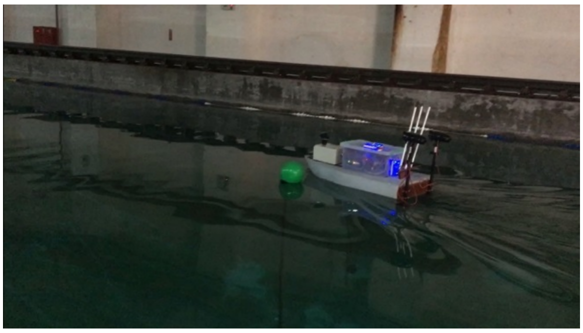


Fig. 18. URB passes through the green float pairs

Similarly, the guided UBM successfully accomplished the third level which is with a yellow float pair as Figures 19 and 20.

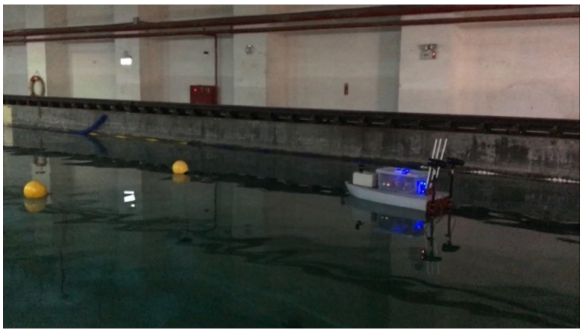


Fig. 19. URB sails to the yellow float pairs

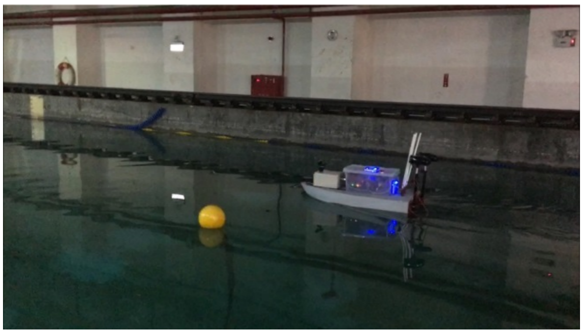


Fig. 20. URB passes through the yellow float pairs

From these real tests, it is obvious that this proposed method possesses the capabilities of the vision navigation and guidance for guiding a well-developed URB to precisely pass through the prearranged course.

CONCLUSIONS

A vision based guidance law is successfully developed for unmanned robot boats in this research. This guidance law integrates a fuzzy-based guidance law, which has two error inputs and two outputs, a vision based sensing technology and a difference control for a pair of propellers, which are actuated separately. For mentioning the guided unmanned robot boat to sail in the middle points of a predefined course, which is set up with several float pairs, the relative distance D and line of sight angle error δ are considered as error inputs of the proposed fuzzy guidance law. Convergences of these two errors guarantee the success of this course tracking design. From practical tests, this proposed guidance law can effectively maintain the sailing course of the guided unmanned robot boat in the middle points of the float pairs, and obviously, this proposed guidance law performs satisfactory guidance performance even under the effect of environmental disturbance as background image noises or random reflection water waves.

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具視覺導航功能之無人船導引律設計

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摘要

此論文提出一具視覺導航與模糊導引之無人船設計，而此無人船經系統性的設計後具備了可自主辨識及穿越色球軌道之功能。為了解決無人船非線性系統模型不易取得完整之數學模型所衍生之控制器無法建構的問題。此研究運用了模糊控制的架構來發展具視覺辨識功能的無人船導引律。運用模糊控制的概念來設計導引律具備以下之優點：1.無須詳知無人船之系統數學模型，2.控制器具備容易實現之特質與 3.極佳之對抗系統模型不確定性及抗環境擾動的能力。經由於台灣成功大學系統系拖行水槽的實際驗證確認後，此視覺無人船導航設計具相當優異之自主導航功能，故未來有極大之機會可運用於大型船舶的進港導引輔助運用。