The Design of a Control System for an Unmanned Surface Vehicle

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Abstract: There is an increasing interest in unmanned surface vehicles as a tool for reconnaissance or other littoral missions. In order to achieve tasks independently and intelligently, an automatic control system is required. Learning from other unmanned vehicles, a control system which is feasible and reliable has been designed by us. An unmanned surface vehicle equipped with this control system has been used to conduct a lake test, and the satisfactory test results show the fine ability of data processing and autonomous navigation.

Keywords: Control system, Lake test, Method of navigational control, Unmanned surface vehicle.

1. INTRODUCTION

Unmanned surface vehicles (USVs) are applied as a small surface platform that has the ability of autonomous path planning and autonomous navigation, and can independently complete tasks such as environmental perception, and target detection. By boarding different sensors or execute equipment, USVs can realize the diversity of missions, but they're mainly used to perform war or non-war missions that are dangerous and unsuited for manned vessels. However, their application is sought later than other unmanned vehicles like unmanned aerial vehicles (UAVs) or unmanned ground vehicles (UGVs). Many countries especially those with vast waters are vigorously developing USVs [1]. Countries such as America and Israel lead the world in the research and application of USVs and are developing USVs in the direction of intelligence, systematization and standardization, while Chinese USV technologies mostly stay in concept design phase. So numerous key fields are still empty.

USVs have a complex system and involve many areas of technology. The key technologies include carriers' overall design and system integration technology, environment perception technology, autonomous decision and control technology, etc. Among them the autonomous decision and control are implemented by the control system whose level reflects the intelligent degree of the USVs. In control system, researchers focus on the aspects of path tracking, path planning, local obstacle avoidance planning and so on, which can improve the autonomous ability of USVs, and certain achievements have been made. Nevertheless, most of the researches still rest on the theory stage in China [2].

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The control system discussed in this paper is consisted of a sensor system, a servo operation system and a main control system. The main control system has a lot of external electrical interfaces, and various measures have been taken to improve its security and reliability. In addition, the control system adopts waypoint guidance and obstacle avoidance through telecontrol. This USV has conducted a lake test, and the test results are satisfying. The USV's main mission is unmanned reconnaissance on the surface of seas or large lakes.

2. THE USV SYSTEM

2.1. Whole USV System

1) The surface platform

The USV was refitted based on a Gas-filled fender aluminum alloy manned boat with one gasoline engine, shown in Fig. (**1**). Table (**1**) lists some specifications of the USV.

Table 1. Specifications of unmanned surface vehicle.

Specification	
Length	6.5m
Width	2.6m
Draft	0.4m
W/payload	Up to 2000lbs
Speed	Up to 25knots
Endurance	24hours
Control	Auto/Teleoperated
Dynamic source	Gasoline Engine

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Fig. (1). The surface vehicle.

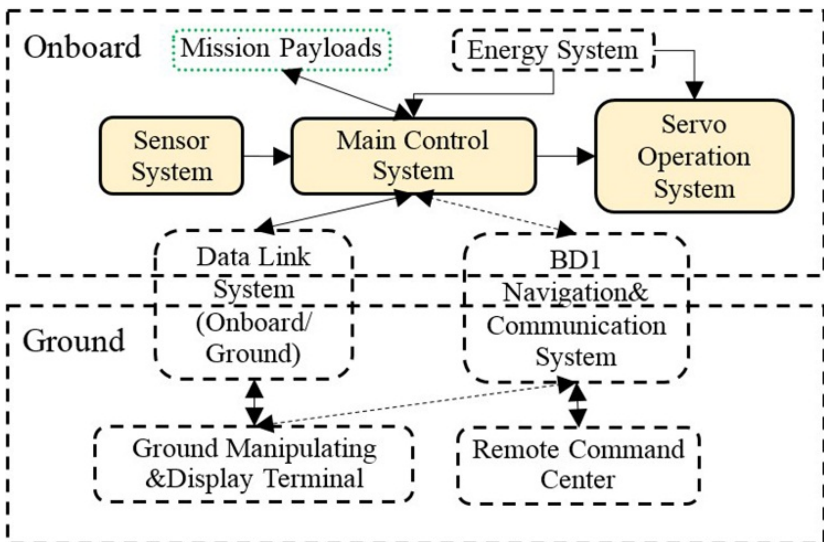

Fig. (2). Schematic diagram of the additional systems.

The USV has a one-body gas-filled fender on three sides, making it not only possess anti-overturning capability but also tolerate larger impact and load. The vehicle's load capacity up to 2000lbs provides possibility for equipping data link, control system, payloads, etc. With the current motor configuration, the shape limits the top speed to 25knots [3].

By equipping with the pipelines of hydraulic steering and the feedback devices of rudder, and reconstructing the lines of the engine, it becomes possible to transform the manned vehicle to a USV. Things such as accumulators, a main control system, and wireless communication equipment are fixed inside the hull. While others like communication antennas, GPS/BD2 satellite receiving antennas, demanded task payloads, etc. are installed outside the hull. The cabin takes sealing treatment to meet the requirement of preventing damp, salt fog and mycete so as to deal with the hostile marine environment.

2) The Additional Systems

In order to transform the manned vehicle into the USV, multiple systems need to be added on the surface platform, as shown in Fig. (**2**). Sensor system mainly includes two parts. One is a marine radar which can achieve surface and underwater target detection, information processing and synchronous output of analog video. The other is a double antenna GPS/BD2/MINS integrated inertial which is not only applied to the navigation control of the USV, but also can offer highly precise attitude references. Servo operation system contains throttle actuators, gear actuators, a hydraulic pump drive and steering mechanism. Data link system undertakes the task of the information interaction between the USV and the ground station. In BD1 navigation communication system, the module of onboard BD1 user receiver works independently and can obtain location and communicate

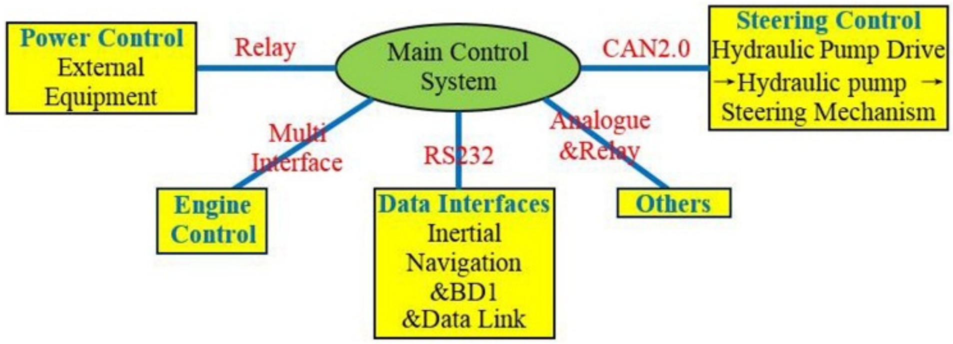

Fig. (3). Electric interfaces of onboard control system.

with other user receivers or the remote command center, so that when the main control system has any fault it can be kept normal. Ground manipulating and display terminal with an externally handheld remote control have many functions such as mission planning, integrated telemetry information display, remote control, condition monitoring of the USV. Remote command center is able to perform remote monitoring. Among the whole USV system, the main control system stands at the core position. Its functions are information collection and processing, control and navigation calculation, management and monitor, control output, etc.

The additional systems bear the responsibilities of navigation control, environment perception, wireless communication, task execution, etc. Each part of these systems performs its own functions but interrelates with each other. The reliability, integrity and perfection of the whole USV system offer the possibility and security to the realization of multi-task. Of all the systems, the sensor system, the servo operation system and the main control system together make up the control system of the USV.

2.2. Control System

The sensor system mainly includes a marine radar and a double antenna GPS/BD2/MINS integrated inertial. The former can realize target detection on the surface or underwater and provides the information of obstacle avoidance, while the later can supply the information of position and attitude. The servo operation system contains throttle actuators, gear actuators, a hydraulic pump drive and a steering mechanism. It serves for the control of rudder angle. The main control system is in a central position linking the other two closely linked together by unscrambling the sensor information and then controlling the servo operation. According to the project requirement, the main control system should have the following functions:

a) Receive telecontrol command and execute;

b) Collect and frame telemetry information;

c) Navigational control and management;

d) Engine control and condition monitoring;

e) Electrical control and condition monitoring;

f) Task payloads control;

g) Emergency safety protection;

h) Data record.

As shown in Fig. (**3**), abundant external electrical interfaces for navigation, task devices, electrical system, power system, etc. have been considered during the design process.

The interface formed between the main control system and the power control, whose function is mainly to control the power supply of task payloads, the marine radar, throttle actuators, and gear actuators, is relay. By installing an angular displacement sensor used for the rudder, a closed loop consisted of a hydraulic pump drive, a hydraulic pump, a steering mechanism and the sensor is formed. On this basis, the main control system and the hydraulic pump drive exchange information such as control commands and rudder angle feedback with each other through CAN2.0. The function of Engine control is to control the gasoline engine which not only has rich control interfaces for its start, stop and trim, but also has signal feedback interfaces for its speed, inclination and the state of electronic control unit (ECU), generator, lubricating oil pressure and overheat. By adding throttle actuators and gear actuators controlled in PWM mode to the original engine, the manipulation of the engine comes true. Data interfaces are used to transmit data between the main control system and the onboard equipment through RS232. Spare RS232 and RS422 interfaces are reserved for other devices. Except for the above, there are some other interfaces for analog collection of the main power voltage and current and for the switching of transferred images between the optoelectronic payload and the marine radar.

Based on the analysis of the functions, interfaces and performance, the main control system was designed according to the concept of universalization and modularization. Adopting double-layer structure, it is divided into an upper-layer CPU module and a lower-layer POWER module, as shown in Figs. (**4** and **5**). The interfaces between the two modules are standardized so that each module can be independently designed, modified and manufactured and can be

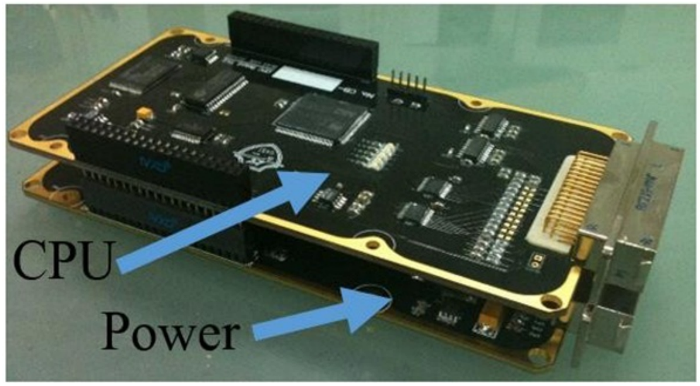

Fig. (4). Real photo of the main control system.

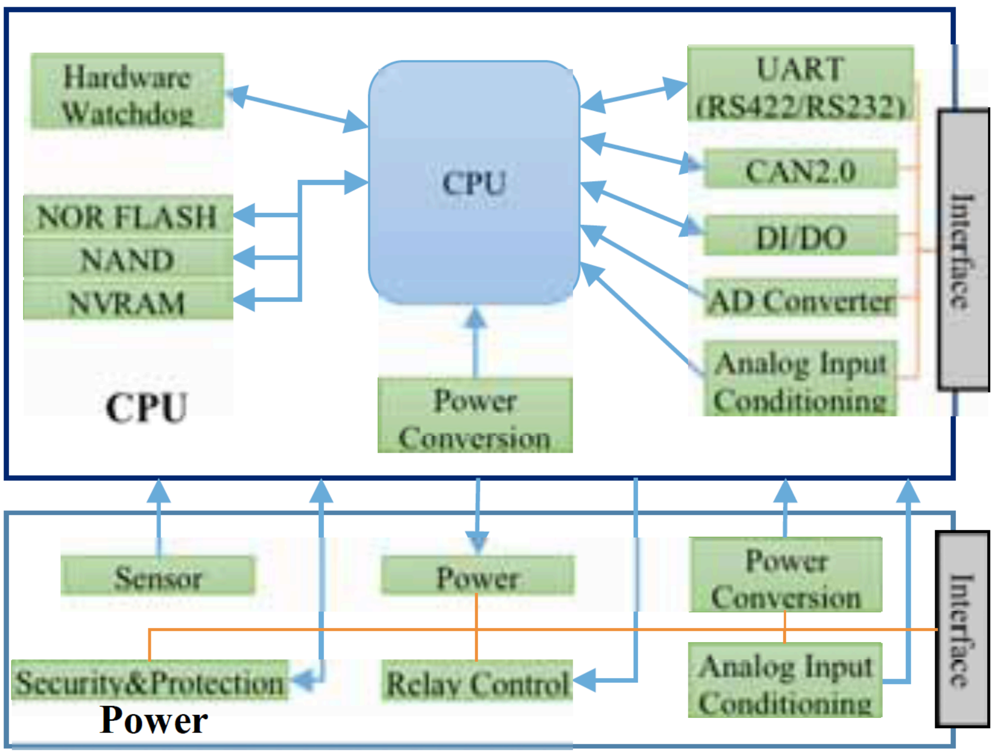

Fig. (5). Structure diagram of main control system.

exchanged with others. Except for the rich electric interfaces described before, the main control system takes some measures to meet the requirements of safety and reliability.

Good methods are to increase some specific chips such as hardware watchdogs, 555 timers, current and temperature sensors. If the CPU doesn't feed the watchdog in about 10 seconds, the system will make a fault reset. The 555 timer serves as a timer for parking after the fault reset. The current and temperature are monitored through the current and temperature sensors, and once any of them becomes transfinite, the system is in protection. In addition, a method combining Nor Flash, Nand Flash and NVRAM is taken to ensure data record and storage. According to the characteristics of the three, we used the high reliable Nor Flash which reads into memory once power is on to store control parameters, factory settings, etc., used the large storage of Nand Flash which writes into memory regularly to store voyage data, and the NVRAM which can autosave when power is off for the data of path planning, control parameters and control output in the process of operation, making it possible for a failure recovery after an accidental reboot. Furthermore, the design of PCB also takes some special treatment. The components are partitioned based on functions and distributed to the nearest. In order to reduce the electromagnetic interference, some filtering, isolation and shielding technology, such as using bypass and decoupling capacitance, single-point grounding with magnetic beads, laying power layer and formation, and packaging PCB with an aluminum shell after surface anodic oxidization are implemented [5].

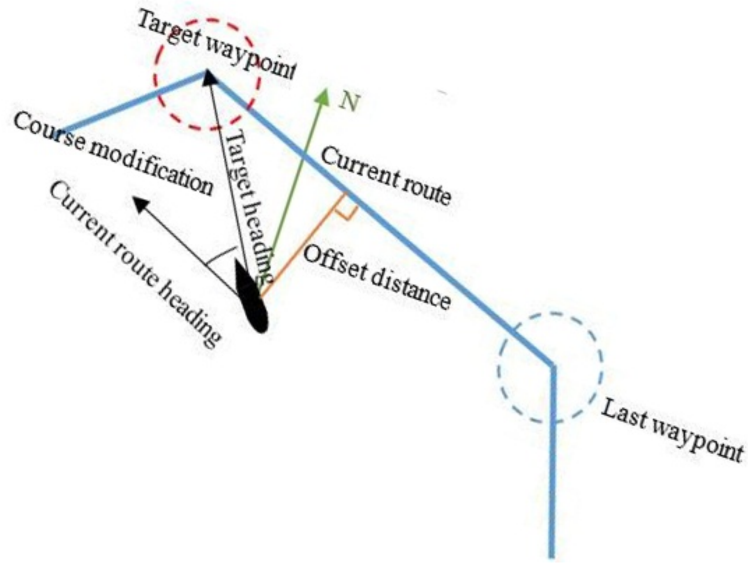

Fig. (6). Definition diagram of offset distance.

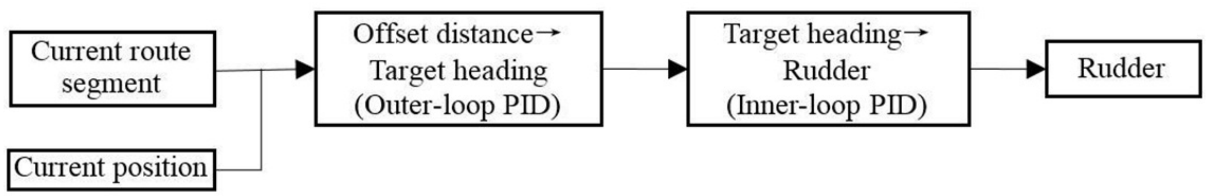

Fig. (7). Guidance based on offset distance.

3. THE METHOD OF NAVIGATIONAL CONTROL

The USV's control channel is divided into one course channel which achieves course control by handling the swing angle of the stern rudder and one speed channel which achieves speed control by regulating the engine throttle.

3.1. Course Channel

Guidance is a key part of autonomous voyage. The simplest of guidance laws is the line-of-sight （LOS） guidance which is at the heart of most guidance laws. In this guidance strategy, the vehicle follows the course between any two given points. Another version of the LOS is the waypoint guidance, where a number of waypoints are defined between the start and destination coordinates. The next waypoint is selected when the vehicle enters within the circle of acceptance (defined as twice the length of the vehicle) of the current waypoint [4-6]. For the sake of patrol and reconnaissance, the USV adopts the waypoint guidance. As seen in Fig. (**6**), current route is the linkage between the last and the target waypoint, and offset distance is the vertical distance between USV and current route.

The course channel took a guidance strategy based on offset distance to ensure the tracking accuracy for planning routes. Course channel consists of an inner loop and an outer loop, as shown in Fig. (**7**). Inner loop keeps control of the stern rudder, and meanwhile outer loop conducts course control.

PID controllers adopted a control law of piecewise PID + integral separated PID in which the proportional coefficients get segmented assignment and the integral coefficients keep zero if beyond the threshold value. In addition, the output is clipped.

3.2. Course Channel

The speed channel mainly contains throttle and gear control. At present, the throttle works by telecontrol of the ground station which has been processed by the onboard control system to prevent flameout caused by throttle's mutation. The gears correlated with the throttle are divided into the gap gear, forward gear and reverse gear. When in manual mode, partition the throttle channel of the handheld remote controller orderly into a shifting threshold and a throttle threshold from the middle to both sides. As such, the middle position means the gap gear, and it becomes the forward gear (push rod) or reverse gear (pull rod) when it surpasses the shifting threshold. Once surpassing the throttle threshold, it can control the throttle. The change of the gear follows the throttle in semi-autonomous mode, and a forward gear will

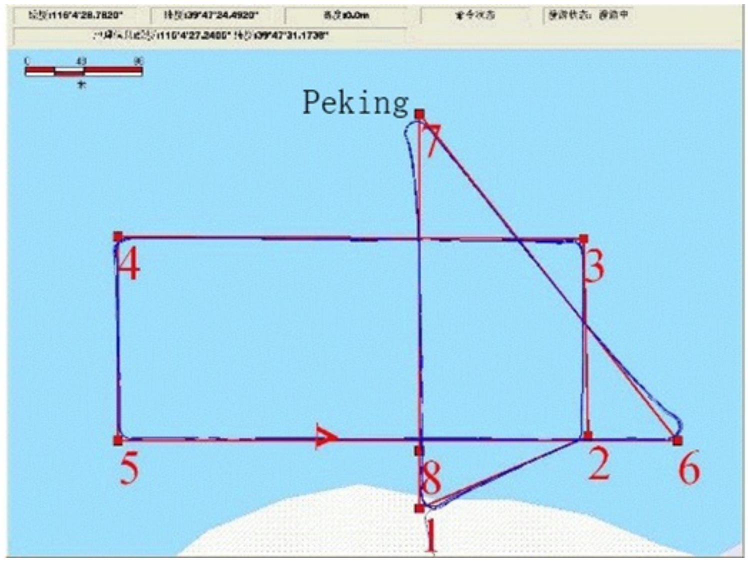

Fig. (8). Track map.

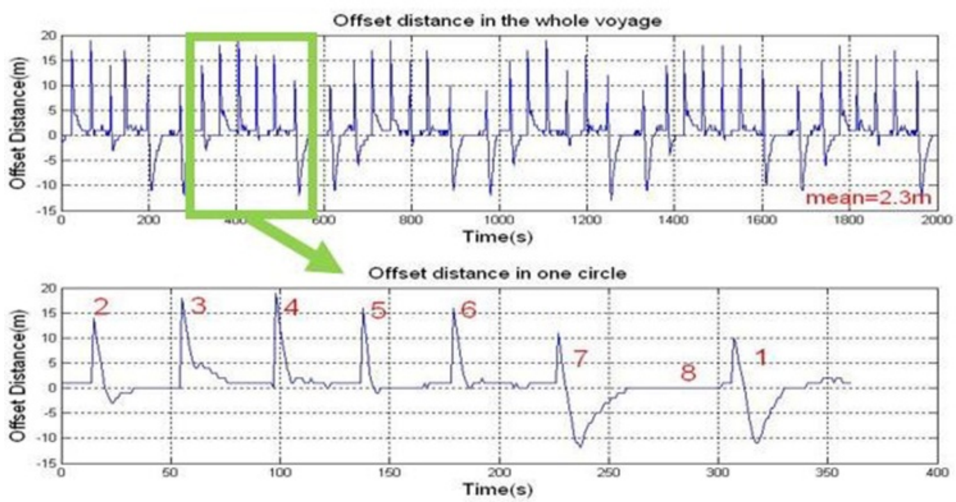

Fig. (9). Offset distance curve.

be automatically engaged if the throttle is greater than zero. When in automatic mode, the gear and the throttle are decided by the uploading waypoint information, whereas a gap gear will be automatically engaged when the engine speed is lower than a certain value.

4. LAKE TEST RESULTS

A lake test has been conducted and the navigation routes are displayed on the display terminal—red lines for the planning 8-point routes and blue lines for the real navigation routes. As seen in Fig. (**8**), the designed USV is able to implement autonomous navigation and its multiple real navigation routes fairly coincide. The average of absolute offset distance in the whole process is 2.3 meters, and large offset distance occurs only at the time of turning, as shown in Fig. (**9**). What makes the track error inevitable in that the vessel cannot sharply turn. However we can find in Fig. (**9**), that the offset distance was less than 20 meters in the whole voyage. A conclusion can be drawn that this control system has higher accuracy and repeatability.

As displayed in Fig. (**8**), the maximum rotation in the whole planning routes occurs at waypoint 7, just like the most unstable attitude. Therefore we take out a part of voyage data containing waypoint 7 and analyze the changes of its offset distance, track direction, rolling angle and pitching angle. From the curves shown in Fig. (**10**), we can find that:

1) Through the selected autonomous voyage process, offset distance has an error of less than 15 meters, and

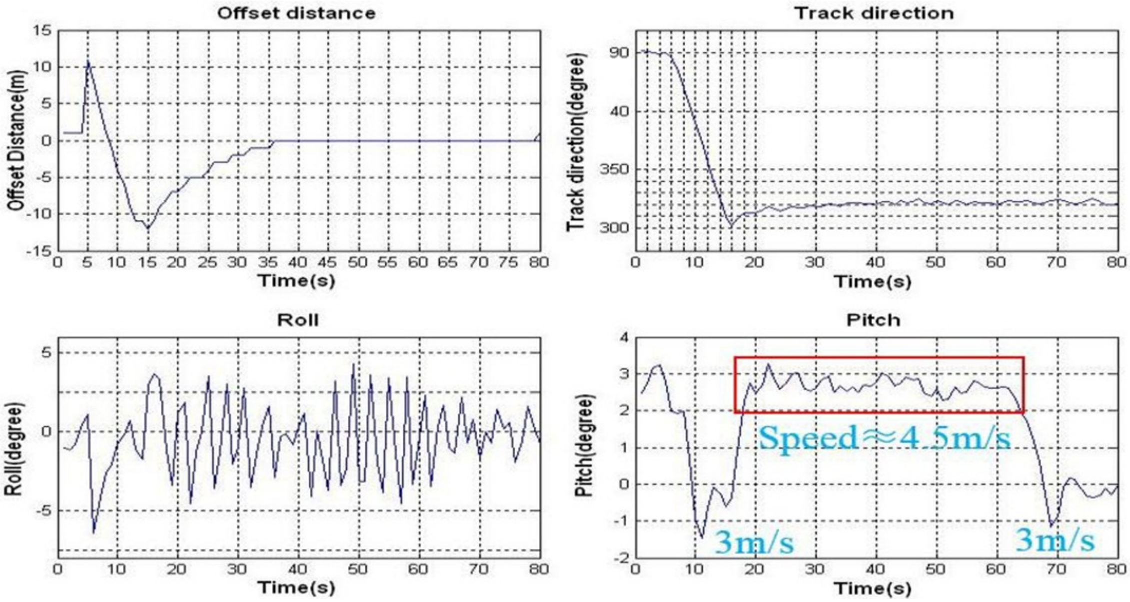

Fig. (10). Offset distance curve & Track direction curve& Rolling curve & Pitching curve.

it takes about 30 seconds to accomplish stable tracking on the corner;

2) Completing a 130-degree turn from 90 degrees to nearly 320 degrees takes 20 seconds. The turning rate is about 6.5º/s;
3) There is a bigger rolling angle, nearly 7 degrees, at the beginning of the turning. After that the USV keeps swing within 5 degrees;
4) The USV gets head down when slows down and head up when speeds up. While it dashes forward at a speed of about 4.5 m/s, its elevation is between 2 degrees to 3 degrees.

CONCLUSION

Via the lake test, we conclude that the USV has realized path planning and autonomous navigation, data transmission and record. The satisfactory results show the fine ability of path tracking, verify the feasibility and reliability of the control system and provide the safeguard for the future work. The USV is going to perform a sea test. As we known, marine environment is more hostile than lake environment. On account of waves, currents and sea wind, the guidance law need to be further optimized. Moreover, adding task payloads will undoubtedly increase the complexity of the USV system. How to ensure the integrity and reliability of the system is also a research focus in the future.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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