Architecture and Design of Unmanned Sailboat Control System with Open Source, Accessibility and Reliability

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2021 IEEE International Conference on Unmanned Systems (ICUS) | 978-1-6654-3885-8/21/$31.00 ©2021 IEEE | DOI: 10.1109/ICUS52573.2021.9641340

Abstract—**This paper analyzes the development status of control technology of unmanned sailboat, and the requirements of control and performance, puts forward a three-layer architecture of open control system of unmanned sailboat for scientific research institutes and R&D companies. after that, all levels of technical route and design ideas were described in detail based on this architecture in this paper; the complete control system of unmanned sailboat is realized based on this system architecture Finally. the system is deployed on the physical sailing ship to complete the function and performance verification. It provides a feasible and reliable system platform and solution for the research and productization of unmanned sailboat related technologies.**

Keywords—Unmanned Sailboat, Control System, Open Source, Autonomous Sailing

I. INTRODUCTION

Unmanned Surface Vessel are developing in the direction of long endurance, intelligence and clustering [1]. Unmanned sailboats can sail autonomously rely on clean energy such as wind energy, wave energy, and solar energy for autonomous navigation. Compared with fixed float monitoring stations and conventional power boats, they have long working hours, high flexibility, large monitoring range, low environmental pollution, low cost of operation and maintenance and other advantages, so it has important application value in marine resource exploration, marine environment monitoring and other fields.

At present, the research work of unmanned sailboats is still in its infancy, and it has not yet formed a relatively stable control system architecture and technical solutions in combination with its own characteristics. Therefore, the construction of an open, reliable, and easily expandable unmanned sailboat control system will accelerate the exploration and implementation of related technologies for long-endurance unmanned surface vehicles, and quickly realize its industrialization.

II. RELATED WORK ON RESEARCH AND DEVELOPMENT OF UNMANNED SAILBOAT CONTROL TECHNOLOGY

The research on unmanned sailboats originated in the 1990s.In order to speed up the research and progress of unmanned sailboats in the world, the World Robot Sailing Championships WRSC and IRSC International Conference have been formed internationally since 2008.The autonomous navigation system of an unmanned sailboat mainly includes three parts: "observation", "decision-making" and "control". The "observation" part means that the unmanned sailboat needs a large number of different types of sensors to perceive the environment; The "decision-making" part involves information processing, multitask execution, and instruction issuing; and the "control" part refers to the control of the unmanned sailboat rudder, sail and other actuators.

The unmanned sailboats are called "unmanned sailboat robots" in academic community because of their autonomy and intelligence conform to the definition of robotics. In the past two decades, many foreign scientific research teams have worked in the research of unmanned sailboat robots, and have made many breakthroughs. They have also designed various unmanned sailboat control systems: Researchers at the University of Plymouth in the United Kingdom used Raspberry Pi and some peripherals to design a simple sailboat control system and provided some open source algorithms [2]; Germany Darmstadt University of Technology (TU Darmstadt) has constructed a 6-DOF dynamic model of an unmanned sailboat[3];The University of Southampton (Soton) provides an open source sailboat autonomous navigation algorithm based on ROS, and proposes an optimal sides changing strategy selection mechanism based on a dynamic weight approximation method [4].Domestically, such as Luo Xiao of Shanghai Jiaotong University and others designed an unmanned sailboat control system based on embedded system PC/104 and ARM microprocessor[5]. Zhejiang University proposed a low-cost, real-time, and robust wind measurement system based on computer vision (CV) [6] .The "Seagull" marine observation unmanned sailboat developed by the Shenyang Institute of Automation, Chinese Academy of Sciences has completed sea trials in Qingdao,etc. [7] In 2018 The first Unmanned Sailboat Crossed the Atlantic Ocean Successfully[8].

Although many unmanned sailboat control systems currently use open source or semi-open source solutions[9], due to the differences in sailboat hulls and their respective scientific research and application requirements, quickly and reliably building their own unmanned sailboat control systems and concentrating more energy on the algorithms

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research of strategies and applications is still difficult for researchers. Therefore, designing a set of general control system architecture and scientific research basic platform according to the control characteristics of unmanned sailboats is particularly important for both scientific researchers and enterprises.

III. OPEN SYSTEM ARCHITECTURE

Similar to unmanned vehicles, unmanned aerial vehicles and other unmanned control systems, considering the convenience of building an unmanned sailboat control system, the computing requirements of autonomous navigation, and the strict working conditions of unmanned sailboats, the control system should have the following Features:.

A. Modularization of hardware components

In order to sail autonomously and perform tasks, unmanned sailboats need to be equipped with a series of navigation sensors, such as positioning sensors, attitude sensors, environmental sensors, etc., as well as various load devices and actuators. In order to improve the efficiency of system construction, the software and hardware interfaces of the above-mentioned sensors and devices must be standardized and normalized design, and by the modular controller to realize access and management.

At the same time, unmanned sailboats usually need to sail all-weather in rivers, lakes, and seas in the open air. Therefore, in order to ensure its long-term stable operation, the control system must meet the requirements of waterproof and anti-corrosion and can work normally in a wide temperature range of -20℃~50℃.

B. Open source software platform

Since unmanned sailboats are currently more used in scientific research, teaching, and various scientific and technological competitions, and their control systems are still being optimized and improved, the control system is required to have good openness and expansibility to support secondary development and multiple programming languages.

C. Flat system architecture

Unmanned sailboat is a typical mobile smart equipment, so it is more suitable to adopt the IoT (Internet of Things) flat architecture of cloud, network, and edge.

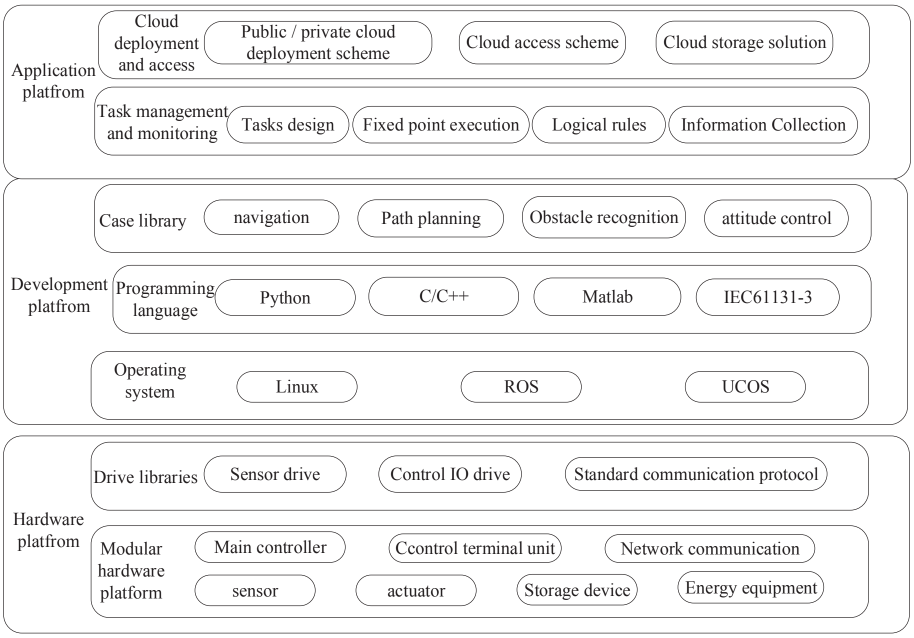

Fig. 1. The Architecture of the Control System

As shown in "Fig. 1", the overall open unmanned sailboat control system can be divided into hardware platform, development platform, and application platform. On the hardware platform, modularization technique is adopted. The hardware interface of variety of sensor networks and actuators are standardized, and general hardware-drivers are also provided in forms of function libraries. The development platform mainly provides a secondary development environment for scientific researchers and software developers. Developers can carry out their own functions and algorithm according to specific requirements. The development platform includes a variety of open source operating systems and supports multiple programming languages. In response to the need for autonomous navigation of unmanned sailboats, a dedicated algorithm case library is provided to support various developers to upgrade and expand. The application platform is mainly for the development and management of specific application functions for end users.

IV. HARDWARE PLATFORM

A. Hardware platform

The hardware platform adopts the master-slave architecture. It consists of the Main Control Unit (MCU) and the Control Terminal Unit (CTU). The MCU is mainly responsible for advanced computing functions of control such as autonomous navigation, environment perception, task decision-making, and motion planning, the signal processing of cameras, lidars and other sensors that require high-speed signal processing; The CTU is mainly responsible for the collection and preprocessing of various medium and low speed sensor signals, as well as the completion of actuator actions according to control instructions; The CTU can also take charge of local control logic and the selection of control modes, such as manual control functions.

The sensor network is mainly composed of environmental perception sensors such as nine-axis Inertial Measurement Unit (IMU), GPS/Beidou module, wind direction and wind speed sensors; The HD multi-angle camera is used to realize machine vision related functions such as obstacle recognition and ranging. In terms of communication, 4G network wireless communication can be used in the internal rivers of the mainland and the coastal waters, and satellite communication is usually used in the deep sea. Considering the long-term operation and detection, the hardware system also needs to be equipped with a local data storage unit so the monitoring data can be record in the boat first on real time. The hardware system architecture is shown in “Fig. 2”:

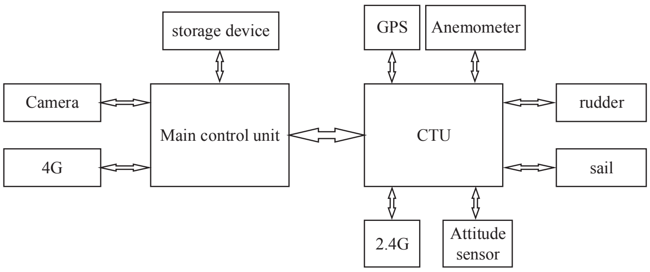

Fig. 2. Hardware System Architecture

1) Main Control Unit(MCU)

The Main Control Unit is powered by high-performance CPU or GPU platforms according to the user requirement. The operating system is based on Linux, so the developers can use the ROS and OpenCV to develop robot systems. Two 100/1000Base-T Ethernet interfaces need to be equipped, so the MCU can be easily debugged and developed through the network. The standardized interfaces for the access of various sensors include USB, UART, RS-485, RS-232, CAN, which can meet the communication.

Navigation control system usually need to process various actuators and load devices. So pulse input, PWM output, analog quantity acquisition and output, configurable digital input and output interfaces are needed.

2) Control Terminal Unit(CTU)

The Control Terminal Unit can be designed with a special PLC control chip with programmable functions [10]. The CTU also integrates various communication interfaces such as Ethernet, serial ports, various industrial buses, and Digital or Analog I/O interface, to deal with external control signal access, servo and other actuators.

In practical applications, if there are many sensors and control devices on the ship, the CTU can be used as an expansion unit of the MCU to achieve system function expansion. The CTU itself has simple logic control functions and supports 2.4G signal access to realize manual control. In some simpler applications that do not require high control functions (machine vision, SLAM, etc.), the CTU can be directly used as the MCU.

3) Sensor network

It is usually necessary to configure a series of positioning navigation and attitude sensors, taking into account the autonomous navigation needs of sailboats, such as GPS, gyroscope, accelerometer, and magnetometer, as well as environmental sensors such as wind direction sensor, wind speed sensor, and temperature sensor; At the same time, in order to achieve various scientific research and monitoring requirements, The cameras, water quality sensors, air sensors, etc. will also need to be equipped and configured. When selecting the above sensors, try to consider the consistency of communication and power interfaces to facilitate system access.

B. *General hardware driver library*

As an autonomous navigation device, it has a wide variety of sensors, peripherals, and loads. This unit mainly provides hardware driver libraries for different devices. The driver library includes various common communication protocols such as CANOpen, Modbus, Ethernet, etc., as well as data preprocessing and calculation algorithms for some special sensors, such as GPS calculation, IMU data conversion, and video data preprocessing.

C. *Reliability and environmental adaptation*

In the past, Researchers usually used Raspberry Pi, Pixhawk, Arduino and other open source hardware to build the automation control system of sailboat [2]. However, this type of platform is not designed for water surface equipment, it is difficult to meet the hardware reliability aspects such as waterproofing, anti-corrosion, and installation and wiring. This design is to further improve the reliability and environmental adaptability of the control system. As unmanned sailboats need to sail autonomously at sea for a long time, there are high requirements for the waterproof and anti-corrosion of the control system. Waterproof shell is adopted in the design, and the IP67 waterproof connector is used for external connection. When the protection performance is required to be high, it can be potted, as shown in “Fig. 3”.

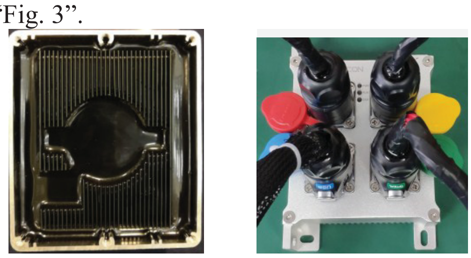

Fig. 3. Hardware Protection Design

V. SOFTWARE DEVELOPMENT PLATFORM

A. *Operating System*

In order to ensure openness as much as possible, the bottom layer of the main controller adopts the Linux operating system, on which the Robot Operating System (ROS) is integrated, and the bottom layer of the CTU adopts the uCOS operating system. Developers can get the rich resources of the open source code. And the control system scale and functions can be flexibly increased or tailored according to user demand. In addition, for the convenience of users, we have open sourced ROS-based algorithms on github, the specific content of the algorithms can be viewed on github and users can also develop their own algorithms on this platform.

B. programming language

In terms of programming language, users can use python, C / C + + and other common programming languages on the MCU, as well as advanced language interfaces such as MATLAB. At the same time, the CTU also supports industrial control special programming languages such as IEC61131-3 and G code.

C. Algorithm Case Library

In order to realize the autonomous sailing we built the Algorithm Case Library which integrated basic control algorithm modules. The architecture of the algorithm is shown in “Fig. 4”. The main function of the data processing module is to collect sensor data and complete the processing, and finally the data information of each sensor for use is released by the basic motion control module.

The Basic motion control model can be divided into two parts: the sailing state of the unmanned sailboat and the target course calculation block (status and target block) and the bottom layer control block. The calculation of the status and target block is performed based on the data received from each sensor module, The Bottom layer control is to convert the result of the navigation state into a control signal output to control the sail and rudder of the unmanned sailboat, and then control the sailboat to move forward.

The path planning module is used to realize global path planning [11]. Normally, you can input the path points directly to specify the target points that the unmanned sailboat needs to reach.

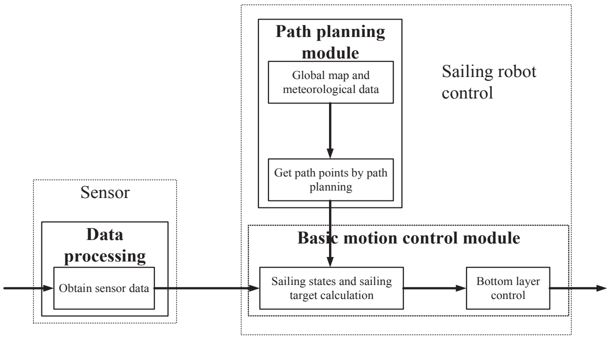

Fig. 4. Architecture of Unmanned Sailboat Algorithm

The algorithm case library provides an open technology reference and accumulation platform for unmanned sailboat developers and researchers. On the one hand, the case library provides basic cases such as positioning and navigation, path planning, Wind Measurement, obstacle recognition, and attitude control [12], developers can quickly realize the basic functions of unmanned sailboats by directly calling algorithm functions. On the other hand, it also supports developers to add their newly developed algorithms to the algorithm case library to share with other developers.

VI. APPLICATION PLATFORM

A. Task management and monitoring

The task management and monitoring platform can provide developers with services such as task design, fixed-point execution, logical rule setting, and real-time information collection.

Developers can design their unique subtasks on the development platform , according to their own job requirements, such as photographing, collecting, anchoring, etc., and number these subtasks. then developers can configure and arrange the subtasks, such as setting the path and coordinate points for task execution, through programmable logic control services on the application platform. Through the monitoring interface, developers can monitor the running status, position, trajectory, and task completion of the unmanned sailboat in real time as shown in “Fig. 5”.

Fig. 5. Task Management and Monitoring Interface

B. Cloud deployment and access

In practical applications, unmanned. sailboats will autonomously sail in rivers, lakes and seas for a long time and generate large amounts of data in real time. Therefore, the control platform must provide remote real-time data transmission solutions and reliable data storage solutions. As a typical IoT node, unmanned sailboats can use the ‘cloud-network-edge’ typical architectures for their monitoring system. The unmanned sailboat can directly use "4G/5G network + public cloud server" solution in onshore waters such as rivers and lakes. If navigating at sea, it can be realized by means of "satellite communication + customized cloud services" solution.

VII. TESTING AND RESULTS

A. Testing system construction

According to unmanned sailboat control system architecture, an unmanned control system for unmanned sailing robots was built, as shown in “Fig. 6” and was applied to a 1.5m sailboat, as shown in “Fig. 7”. The wind direction and speed sensor is installed at the tail of the sailboat, it is used to measure the direction and speed of wind in real time and the wind data is transmitted to MCU by RS485. The camera is installed on the bow of the sailboat, it is used for object recognition.

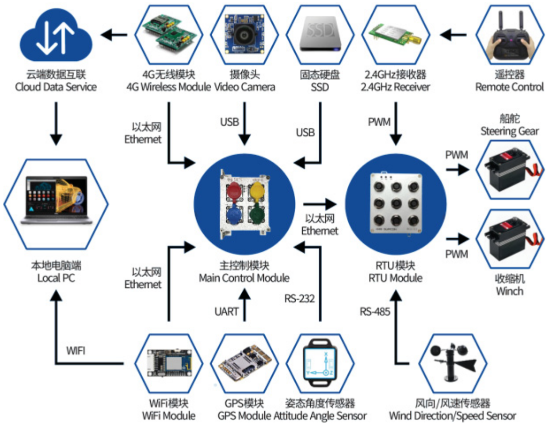

Fig. 6. Unmanned Control System


Fig. 7. Unmanned Sailboat Testing Platform

B. *Algorithm simulation*

A simulation node is established in a ROS project, and the output of each sensor is simulated at the same time, and the relevant data is input into the control algorithm [13]. "Fig. 8" is the simulation result of the three-point racing, which shows that this control algorithm can achieve basic Autonomous navigation control of unmanned sailboat.

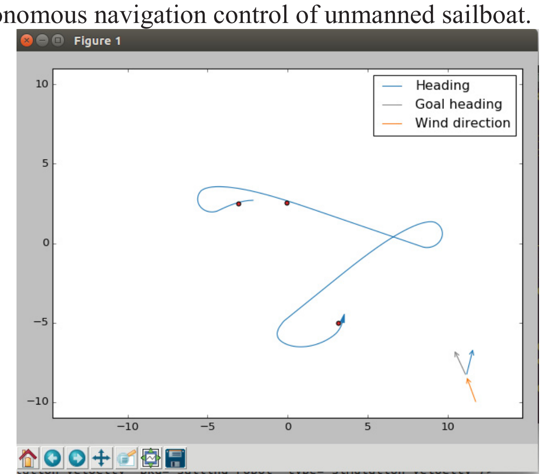

Fig. 8. Three-point Racing Simulation Results

C. *Surface navigation test*

In order to verify the functional performance of the unmanned sailboat system and the reliability of the control algorithms, we tested the sailboat according to the rules of the sailing competition，the experiment was carried out on a Yuehu lake of Ningbo City, on the day of the experiment, the wind speed was about 5m/s and the water flow speed was about 1m/s：

- **Triangle racing:** The unmanned sailboat starts from the starting point and passes through three given GPS coordinate points in turn. Set GPS coordinates and paths through the task management service, and its running condition is shown in "Fig. 9" picture (a) is the actual video picture taken on the scene, and picture (b) is the real trajectory of the unmanned sailboat on site. It can be seen from the picture (b) that the unmanned sailboat can reach the target point more accurately. It is verified that the unmanned sailboat control system can meet the basic requirements of autonomous navigation according to route planning.

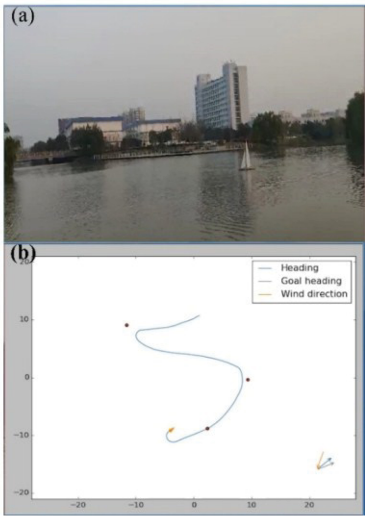

Fig. 9. Triangle Racing Simulation Results

- **Station keeping and avoidance:** Station keeping is derived from some practical situation. Sailboats need to be anchored or cruised in a fixed position to perform operations, which has a great test for the fine control of the sailboat in a small area. Figure10 shows its running condition.

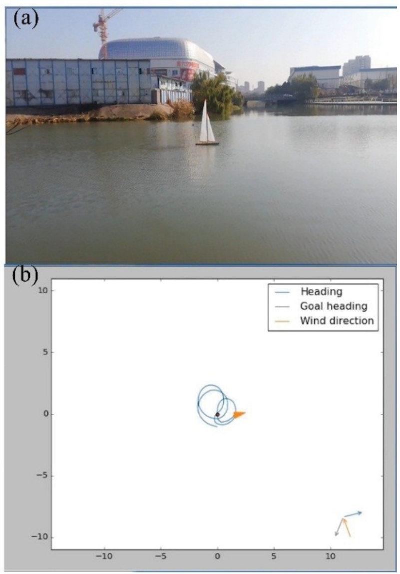

Fig. 10. Station keeping and avoidance running condition

Picture (a) is a video picture taken on site, and picture (b) is a real-time feedback of the real trajectory of an unmanned sailboat. It can be found that the unmanned sailboat can be anchored virtually within a radius of about 3m, indicating that the control system meets the demand for more precise control of unmanned sailboats in a small area.

- **Obstacle recognition and ranging:** The red sphere floating on the water surface is used to simulate obstacles, and the unmanned sailboat is required to recognize the size, direction and distance of the obstacle in real time.

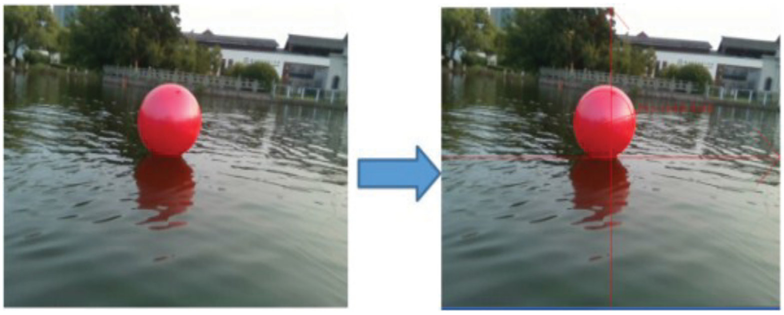

Fig. 11. Obstacle Recognition and Ranging

It can be seen from "Fig. 11" that the recognition and measurement scheme adopts a neural network-based learning algorithm [14], which can more accurately identify the color, shape, distance and relative orientation of the obstacle near the sailboat. In the entire recognition process test, the control system can complete image processing related operations within the specified time.

The velocity of the sailboat is controlled by the angle of the sail, the purpose is to keep the sailboat the best angle of attack during the process, the following control rules of sail are used in this experiment:

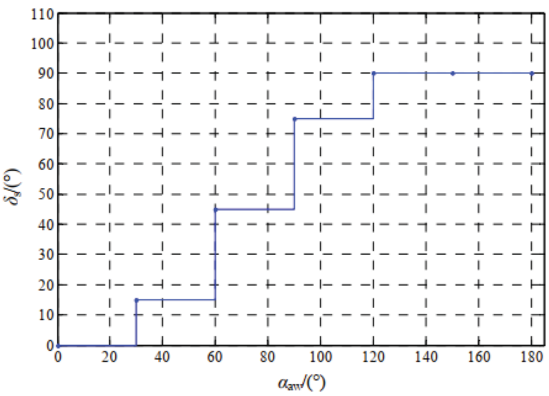

Fig. 12. control rules of sail

αaw is the relative wind and δs is the angle of the sail, According to the "Fig. 12", when the sailing against the (30<αaw <120), the angle of sail is 0, when sailing in crosswind (30 < αaw <120), adjust the angle of sail according to the rules given in the figure to keep the attack angle of the sail at 15, when sailing downwind (120< αaw<180),the angle of sail is 90

Through the tests of four cases, it is verified that the unmanned sailboat system, adopting this system architecture, can meet the basic control requirements of autonomous movement, and can realize fully autonomous navigation.

VIII. Conclusion

With the continuous advancement of smart ocean, long-endurance surface vehicles will gradually play an important role in future marine development. Compared with traditional power driven boats, unmanned sailboats will be widely used due to their low energy consumption, environmental protection, and strong carrying capacity. Combining the technology and application characteristics of unmanned sailboats, this paper proposes an open unmanned sailboat development platform architecture, as well as the technical approaches of functional classification, and finally conducts actual verification. This paper provides relevant scientific researchers and product developers with a quickly built, programmable, customizable, and tailored system architecture and technology accumulation platform of unmanned sailboats and other unmanned surface vehicles.

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