Study of the Control System for an Unmanned Surface Vehicle

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***Abstract*—A control system architecture is designed for an unmanned surface vehicle. The composing and function of the modules of the control system architecture are detailed. A module for the mixing control mode, which alters between manual control and auto control, is implemented based on real-time communication to make the vehicle be steered directly by users with its autonomous capacity retained. Trials on the sea are carried out to validate that this architecture could fulfill the basic functional requirements for travel.**

***Index Terms*—Unmanned surface vehicle, control system, software architecture, manual control, automatic control.**

I. Introduction

The rapid development of robot technology in aerospace, ground and underwater, as well as national attention on security issues of ports and offshore areas, promotes the development of the autonomous unmanned surface vehicle (USV). A variety of USVs have been used in scientific research, military and other fields [1]. The United States holds a leading position in the development of USV, which has developed a few USVs such as the “ghost”, “Piranha” and “Sparta”. Other countries also have substantial progress, such as Israel's “protector”.

Compared with other unmanned underwater vehicles (UUV), USV has many advantages. USV communicates with the console through wireless technology instead of umbilical cable, which makes USV operate far away from the mother ship without limitation and avoids interference on the motion control comparing with remotely operated vehicle (ROV). Compared with autonomous underwater vehicle (AUV), the wireless communication technology used by USV is more reliable and efficient. USV that uses diesel engine as power plant travels faster with good mobility and strong endurance on the water surface, eliminating the need for complex and expensive battery pack. Navigation system and propulsion system can also use more simple and reliable equipment than AUV.

At the early age, the software architecture is rather simple, because the research on unmanned vehicles mainly aims at the validation of basic functions. However, the software architecture becomes much more complex as unmanned vehicles come into use. System structuring gradually becomes inevitably paramount and also is the only practical and effective starting point in the development of an unmanned vehicle [2]. Hence, architectures form the backbone of complete robotic systems [3]. All functions are implemented in the frameworks, such as control laws, errors detection and recovering, tasks planning and so on [4]. The right choice of the architecture will greatly facilitate the specification, implementation and validation of robotic systems [3]. Since Skakey was presented in 1971, a series of architectures have been developed and used in different unmanned vehicles. Most of them can be classified into three categories: the deliberative architecture [5], [6], the reactive architecture [7], and the hybrid architecture [8], [9]. But it is really difficult to evaluate an architecture quantitatively. However, there are still several acknowledged qualitative criteria to conduct us to develop a good architecture [4], [10], [11], namely predictability, reactivity, robustness, modularity, extendibility, generality, and standardization.

Due to the continuous real-time communication with users as USV operates, a control system software architecture is designed, which flexibly switches control mode between operating as users’ instructions and making decisions all by itself with its autonomy at any time.

The rest of this paper is organized as follows. Section II describes the overall framework of the system. Then all the units in the architecture are constructed in detail and discussions are given in section III and section IV respectively. Section V shows the experimental results in the sea. Finally, conclusions are drawn in section VI.

II. Overall Framework

The USV system contains a USV and a user monitoring and control system, as shown in Fig. 1. The USV is the main part of the whole system, which achieves its function in different mission requirements through the devices equipped on it.

The autonomy of the USV is achieved by the computer software program running on the master control system.

This work was supported by the Key Research Program of the Chinese Academy of Sciences Grant KGFZD-125-014, National Natural Science Foundation of China Grant 61273334, and Natural Science Foundation of Liaoning Province of China Grant 2011010025-401.

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Autonomy is built on top of the interaction with the objective environment. The vehicle obtains environmental data and its operational status by the sensors equipped on it and controls its motion through driving devices.

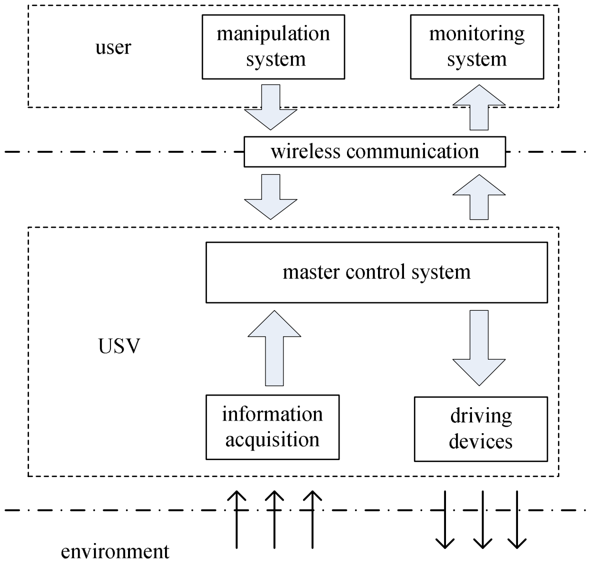

Fig.1. System framework

Users keep a stable real-time data exchange with the USV via wireless technology, who monitor the status of the USV, as well as send manipulation instructions to the USV to interfere with the mission. The USV adapts to tasks with more complex demand by timely human intervention to the autonomous USV.

III. THE CONTROL SYSTEM ARCHITECTURE OF THE USV

The USV control system architecture consists of three parts: data acquisition and processing, intelligent decision-making and control strategy, as shown in Fig. 2.

A. Data Acquisition and Processing

The USV obtains environmental data and its operational status by the sensors equipped on it. Affected by objective environmental uncertainties and sensor measurement errors, the data obtained usually contains noise, which is not available for control system to use. To get more accurate data, the pretreatment measures, such as noise filtering, should be used to remove noise.

The USV obtains its own position and attitude in the three-dimensional geodetic coordinate system by fusing sensor information. Combined with the chart information, USV knows well about the marine environment around it. The sensors provide data related to the ongoing mission for the master control system to make decisions.

Considering the need for fault diagnosis, the master control system monitors the device parameters to detect anomalies and comprehensive information to determine the location of the fault and assess the fault level. And then, the diagnostic information is sent to the intelligent decision -making unit for emergency treatment according to the mission requirements.

B. Intelligent Decision-making

Intelligent decision-making unit is the core part of the USV, which is both the interchange of information of the system and behaviors publisher.

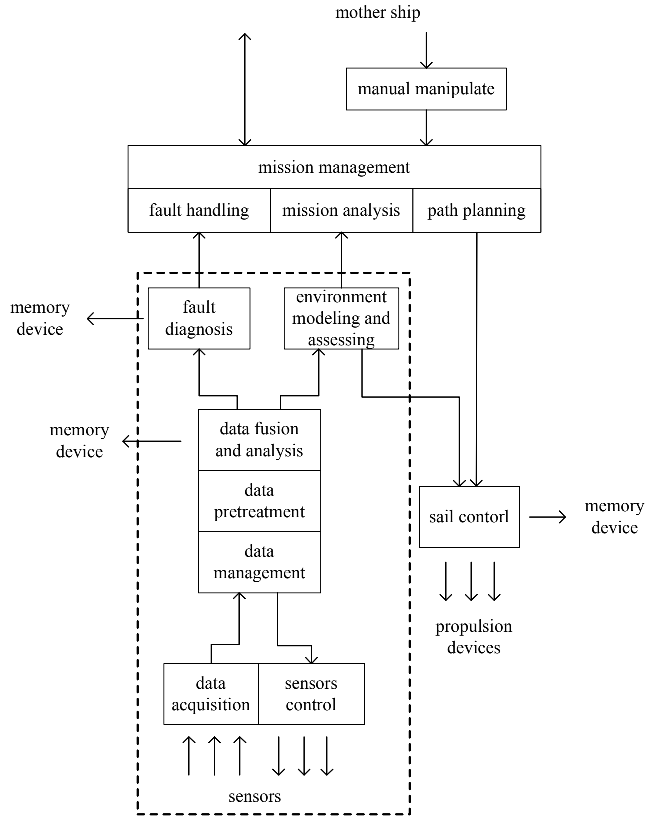

Fig.2. The architecture of the USV

The role of this unit is that the USV autonomously executes tasks without human intervention as well as ensures the safety of the USV when users control it.

The autonomy of the USV is achieved by this unit. The higher the degree of autonomy, the higher the level of intelligence, the less user intervention is required. The USV can complete more complex missions in the same hardware environment.

The intelligent decision-making unit consists of the following modules:

- fault handling

Based on the fault diagnosis information, this module handles the emergency fault. The handling method is related to the ongoing mission requirements, vehicle's operating status and many other factors. The failure of non-critical devices can be ignored. The USV can also disable the failure devices and reuse other devices with the same function to remedy. The failure of critical devices must timely take measures to minimize losses.

- mission analysis

This module lets the USV break complex missions down into a number of simple subtasks, such as travelling to the target position, or making certain devices operate. This module monitors the progress of the implementation of the mission and executes each sub-task based on the mission needs to complete the mission.

- path planning

After determining the destination, combined with the information of operating waters, this module plans a navigation path to reach the target position in accordance with the mission requirements, which can avoid obstacles. When comes to the unknown or unexpected situations, the USV will plan the path again to avoid collision damage.

C. Control strategy

The control strategy model makes the USV travel on the water surface to reach the target position following the planning path with high-speed stably in the external disturbance.

The stability of the USV is related to the motion control algorithm. The USV travels swiftly on the water surface, where there are so much marine environment interferences, such as waves and flow. All these factors make the motion control algorithm more difficult to control the vehicle. In view of the above features, an adaptive PID control algorithm, which adjusts its PID control parameters online, is used to improve the anti-jamming capability of the USV heading control. The depth control algorithm is the same as the one mentioned above.

The adaptive PID controller consists of two parts, as shown in Fig. 3. One part contains a set of PID control parameters obtained from a trial with little interference that make the system travel stably. Another part contains an algorithm which makes an adaptive adjustment of the control parameters. When the control error is prompted by the changes of environment, the latter part makes an online optimization based on the real-time error to adjust control parameters for reducing control errors.

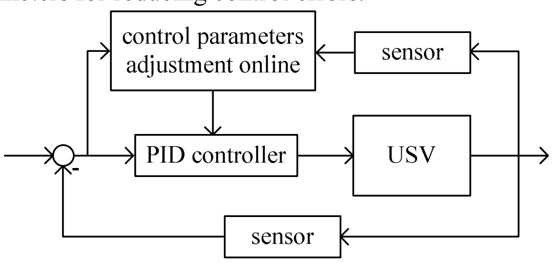

Fig.3. Heading control block diagram

The control strategy including online optimization can be expressed as simplified:

$$\delta_r = (K_P + \frac{d_1}{u^2})\psi + (K_D + \frac{d_2}{u^2})r + K_I \int \psi + \begin{bmatrix} k_{id_1} & k_{id_2} \end{bmatrix} u^2 \psi \xi(\mathbf{x}) \quad (1)$$

where K_P, K_D, K_I are a set of PID control parameters which ensure the USV travel stably. ψ is the heading error in the geodetic coordinate system. r, u are the longitudinal velocity and heading angular velocity in the moving coordinate system respectively. k_{id_1}, k_{id_2} are the parameters related to the executive devices. d_1, d_2 are the experimental data in the trial. $\xi(\mathbf{x})$ is the error promoted by environmental interferences.

IV. MANUAL/AUTO WORK MODE

The USV has two work modes: manual mode and automatic mode which can switch to each other at any time. During the missions, users can directly send instructions to the USV, when the operating environment is complex or the behavior is critical, to compensate for its own lack of autonomy.

The manual mode enhances the flexibility of the USV, but also increases the risk of travelling. In order to ensure the system stable and safe, an intelligent protection mechanism is designed: in manual mode, the intelligent decision-making unit monitors the status of the vehicle to limit dangerous operations and avoid the risk of navigation, as shown in Fig.4.

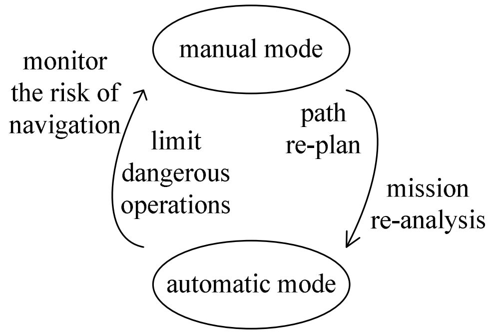

Fig.4. Work mode switch

A. Limitation of Dangerous Operations

Instantaneous substantial adjustments in the course when the USV is in a high speed will make its roll angle increase rapidly and even a rollover may occur. To prevent the adverse effects of such dangerous operations for the stability, intelligent decision-making unit monitors the user's manipulation instructions to assess the security of the instructions, combined with the current state of motion. For the risky manipulation instructions, intelligent decision-making unit will adjust appropriately (such as reducing the speed) to ensure the stability and security of the USV.

B. Monitoring the Risk of Navigation

Because the line-of-sight range of the visual acquisition equipment equipped on the USV is limited and it is difficult to accurately obtain distance information from a two-dimensional image, there is much risk of collision in the manual mode. In order to reduce the risk of colliding obstacles, intelligent decision-making unit monitors the operating waters to make timely forecasts even warning to remind users take evasive measures when obstacles are found on the route. The USV even can make an emergency braking itself in order to ensure its own safety.

Since the user can manually manipulate the USV at any time to interfere missions, intelligent decision-making unit still needs to monitor the implementation of missions, even if the USV is not operated autonomously. When the work mode switches from manual mode to automatic work, the USV automatically removes sub-tasks completed by the user and re-analyze the remaining part of the mission.

V. Experiment

In order to validate the feasibility of the control system software architecture designed, an existing USV is used for sea trials. The dashed lines in Fig.5. is a fixed point mission track. The USV starts from P0 to P1 in manual mode. From P1, the USV switches into automatic mode and travels sequentially through P2, P3, P4, P5, finally back to P1. After a few laps, the USV switches back into manual mode and is manipulated back to P0. In the trial, the USV reaches all points in order and travel the required number of laps in accordance with the mission requirements. The solid lines in Fig. 5 are the actual track of one lap. The experimental results show that the software structure is feasible.

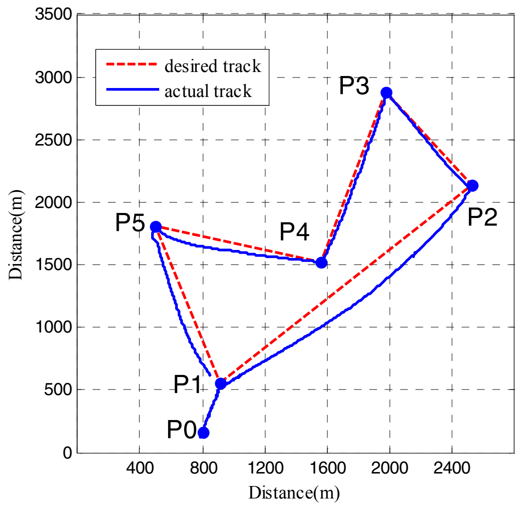

Fig.5. The setting of routes for the sea trial and the track of the first loop

The course of the USV in an experiment is shown in Fig. 6. The desired heading is set from 170 to 50 at the time instant of 70. After a four-minute adjustment, the heading gradually stabilizes, and amplitude of the swing of the nozzle remains less than 5 degrees. The results show that the control system has a good dynamic performance and the actual trajectory follows the desired track. The control system meets the needs of the accuracy for heading control.

VI. Conclusions

In this paper, a USV control system software architecture is designed to achieve a hybrid control function. An existing USV is used to achieve the architecture for sea trials. The results show that the control system operates stably and the work mode switches flexibly, which verify the rationality and feasibility of the software architecture.

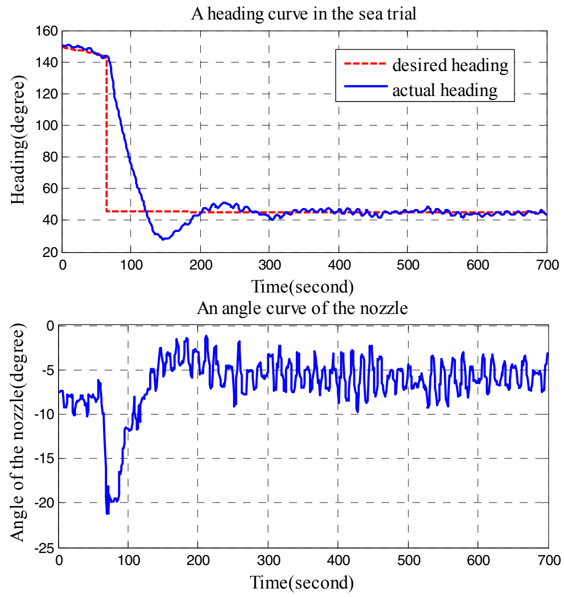

Fig.6. Curves of self-control

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