Research on Redundant Design Technique for USV Autonomous Control System

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Abstract—In the field of USV autonomous control system design, redundant design technology is the important method to improve system reliability. In order to solve the problem of insufficient reliability when USV carrying out long endurance and open sea task, this paper analyzes the critical design elements of autonomous control system redundant configuration, presents a high reliable hybrid redundant structure for USV autonomous control system, and realizes redundant strategy and fault-tolerant control. This paper forms the USV autonomous control system redundant configuration scheme comply with the fault-tolerant capability and redundant rank of USV autonomous control system. Redundancy management strategies and algorithms are used to implement USV autonomous control based on hybrid redundant design. The reliability analysis and computation validate task reliability of the autonomous control system based on hybrid redundant structure.

1. INTRODUCTION
Unmanned surface vehicle has played an increasingly critical role in many areas of marine applications, such as environmental monitoring\cite{1}, harbor survey\cite{2}, coastal surveillance\cite{3}, water quality sampling and maritime search and rescue\cite{4}, etc. The harsh condition of marine environment is a great challenge to navigation and operation of USVs, and its control system needs high reliability to meet these challenges. Redundancy technique uses redundant resources to overcome the effects of system malfunctions, two or more similar components are used to implement the same task synchronously and correctly.

Redundancy technique and fault-tolerant control are widely used by many kinds of USVs, UAVs and UUVs. There are many unmanned vehicles use redundancy configuration for system design\cite{5}\cite{6}\cite{7}.\cite{8} describes a novel scheme for fault tolerant control using a robust optimal control design method.\cite{9} presents a bibliographical review on reconfigurable fault-tolerant control systems, the existing
approaches for fault detection and diagnosis and reconfigurable control are considered with emphasis on the reconfigurable controller design techniques. Literature [10] deals with the reconfiguration of an intelligent autonomous vehicle that utilizes an automatic navigation method and online supervision system. As the operating time and endurance of the USV increase, the reliability requirements of the USV increase, and improving the reliability of the USV is one of the keys[11]. In order to improve the reliability of USV, many researchers have carried out related research. Literature[12] proposes an active fault-tolerant control method to ensure the control performance and stability of the USV under normal and fault conditions. Literature[13] solves the problem of precise tracking of USV under actuator faults, input saturation, and unknown external interference by designing fault-tolerant control of a finite-time fault estimator. The environment with salt spray and moisture on the sea surface can damage sensors, interfaces and cables and cause sensor failures. In response to this problem, [14] and [15] proposes and verifies a federated Kalman filter based on fuzzy logic adaptive technology for different sensor types. for estimating the true state of the USV. Judging from existing research, researchers have carried out research on sensor faults and fault-tolerant algorithms to improve the reliability of USV, which will greatly increase the complexity of the algorithm. Therefore, this article will design the USV from the level of redundant system design. Literature[16] focuses on the network-based fault estimation and fault-tolerant controller designing for an unmanned surface vehicle submit to actuator faults.

In this paper, we used the hybrid redundant design technique as an effective mean to improve the reliability and fault-tolerant ability of USV’s autonomous control system. We also use fault detect or fault diagnosis technique to locate the system failure, and use redundancy management technique to bypass the fault channel, keep the system operate correctly. We will analysis the control system from three aspects: hardware architecture and system configuration, software and algorithm, reliability analysis.

2. HARDWARE ARCHITECTURE AND SYSTEM CONFIGURATION
The autonomous control system is the critical system used to implement USV’s intelligent and autonomous capability. As USV’s nerve center, its main function is to implement three-tier functionalities: target recognition, planning and decision making, motion and servo control. Target recognition implements the function of sensor data fusion, marine target detection and recognition etc. Planning and decision making implements the function of global and local route planning, obstacle avoidance etc. Motion and servo control is mainly used to control USV heading, speed, and to control movement of the actuators. USV autonomous control system consists of navigation sensors, perception computers, network switches, control computers, servo controllers etc. The hardware architecture has great impact on task reliability of USV autonomous control system. The hardware architecture diagram is shown in Figure. 1.
2.1. Hybrid redundant structure configuration

In order to balance the system complexity and the task reliability, USV autonomous control system adopts the hybrid redundant structure that combined dual-redundancy and triple-redundancy into the same system. Heading sensors, speed sensors and position sensors adopts non-similarity redundancy scheme. If gyro compass is in fault, INS can provide heading information. If GPS is in fault, INS can provide speed and position information. If INS is in fault, gyro compass and GPS can provide heading, speed and position information. Perception computers, network switches, servo controllers and the communication channels all adopt similarity redundancy. For the sake of ensuring the core components of the system have the FO/FS fault-tolerant capability, control computer adopts the triple-redundancy scheme. The redundant control computers implement the procedure of channel self-monitoring, cross-checking and voting, etc. USV actuators adopt dual-redundancy scheme, when one actuator fails, another actuator can produce enough force and moments for safe navigation. The diagram of hybrid redundant structure configuration for USV’s control system is shown in Fig. 2.

![Hybrid redundant structure configuration](image)

Figure. 2. Hybrid redundant structure configuration

2.2. Triplex Redundant Control Computer

Control computer is the most important component of USV’s autonomous control system. It undertakes the task of data processing and control calculation for autonomous control system, such as data fusion, route planning, decision making, motion control, servo control. In order to improve the reliability of the control channel of the system, the autonomous control system’s kernel is made up of triplex OpenVPX based computers. OpenVPX is a high reliable, high performance computer standard, and widely accepted by aerospace and nation defense industry. OpenVPX computer is composed of task planning module, data processing module, vision processing module, photoelectric control module, main control module, data exchange module, switch module, power module etc.

Task planning module is a single board computer used to run task planning application, which implements the function of global route planning and local route planning based on electronic chart data and navigation data. Data process module is a single board computer used to run data processing application, which implements the function of radar data processing and forms information for future data fusion and situation awareness. Perception module is a single board computer coupled with GPU used to run vision processing application, which implements the function of vision target recognition based on deep learning algorithm. Main control module is the kernel of OpenVPX computer system, it is also a single board computer used to run main control application, which implements the function of decision making, obstacle avoidance, motion control etc. Data transfer module is the single board computer used to run data exchange application, which implements the function of receiving data from navigation sensors and sending data to actuators. Switch module is used to interconnect the single board computers through 1G/10G ethernet. Dual redundant power modules transform AC input power and provide DC power for each functional module in the ruggedized computer. The diagram of OpenVPX ruggedized computer is shown in Figure. 3.
3. SOFTWARE AND ALGORITHM

Autonomous control software realizes the critical functionality of marine object recognition, planning and decision making, fault detection and redundant management, etc. In this paper, we use Radar and AIS data to create the navigation situation. Radar and AIS targets can be used to guide the optical device to further identify the classification of the object through optical image processing and deep learning algorithm. Meteorological data, electronic chart data and steering performance of USV is used to generate global route automatically. Furthermore, Route data, target data, motion data is used for USV guidance and obstacle avoidance. Motion control and servo control use heading, speed, position and actuator data to control USV to navigate automatically. The closed loop data flow diagram of USV control software is shown in Figure. 4.
3.1. Environment perception and target recognition
When USV carries out its tasks at sea, the images produced by the optical sensors include many complex objects on the background. It’s a difficult task to extract the desired objects from the background in the image[17][18][19]. Gaussian filtering is used to reduce the noise, histogram equalization is used to increase the contrast of image, thus facilitates subsequent image processing. Perception software uses deep learning algorithms to detect and recognize the typical marine target.

3.2. Path planning and decision making
Global path planning, local path planning and automatic obstacle/collision avoidance are critical aspects of USV’s autonomous planning and decision making capability. In the sailing process, USV control software uses modeling algorithm to convert electronic chart into useful environment model which describes the global environment information. A star algorithm[20][21][22] is used to generate global route. In order to find the best route for USV sailing. RRT algorithm is used as local planning algorithm to adjust the global route according to the information provided by radar or other navigation sensors.

3.3. Redundancy management strategy and algorithm
Redundancy management is based on the redundant structure of the system. In this paper, the critical component of USV autonomous control system is the triplex control computers. Redundancy management strategy is used by triplex redundant control computers to make sure the autonomous control system work normally. Synchronization and voting are the critical process of redundancy management for the autonomous control system. As a mean to coordinate different redundant channels to work properly, clock synchronization, loose synchronization, or task synchronization can be used. In this paper, we use loose synchronization to synchronize the triplex control channels periodically to make sure the system operate properly, time delay and some degree of asynchronization if allowed. Loose synchronization can eliminate the effect of transient fault in the system, and has high degree of capability to suppress the common mode failure. Synchronization make sure the signal of redundant sensors can be sampled, processed, equalized, and voted nearly at the same time. Synchronization set the base for voting algorithm, such as arithmetic mean value voting, median value voting, majority value voting etc. In this paper, majority voting algorithm is adopted to generate the proper output command for USV autonomous control. The diagram of redundancy management process can be shown in Figure. 5.
4. RELIABILITY ANALYSIS

In order to analyze the reliability of USV autonomous control system precisely, we need to setup the system reliability module. The typical reliability model includes cascade model, parallel model, voter model, etc. Cascade model is used to analyze the cascade system, this type of system is the non-redundant system, failure of any component in the system will affect the whole system. Parallel model is used to analyze the parallel system, this type of system is a kind of redundant system, only failure of the whole components in the system will affect the operation of the system. The diagram of reliability model for the hybrid redundancy structure of USV autonomous control system can be shown as Figure 6.

\[ R(t) + F(t) = 1 \]  

Failure probability density function \( f(t) \) is the derivative of unreliability function, the expression can be described as:
\[ f(t) = \frac{dF(t)}{dt} \]  

(2)

We chose exponential distribution to describe the reliability of electronic product. Hence, failure probability density function and reliability function can be expressed as:

\[ f(t) = \lambda e^{-\lambda t} \]  

(3)

\[ R(t) = e^{-\lambda t} \]  

(4)

MTBF is often used to describe the mean operation time before product failure, the mathematical expression of MTBF can be described as below:

\[ M_{\text{MTBF}} = \int_0^\infty R(t)dt = \frac{1}{\lambda} \]  

(5)

We use the following expression to describe the reliability function of the cascade system with n units:

\[ R_i(t) = \prod_{i=1}^{n} e^{-\lambda_i t} = e^{-\sum_{i=1}^{n} \lambda_i t} = e^{-\lambda t} \]  

(6)

The mathematical expression of reliability function for the parallel system with n units is described as follows:

\[ R_s(t) = 1 - F(t) = 1 - \prod_{i=1}^{n} F_i(t) = 1 - \prod_{i=1}^{n} (1 - e^{-\lambda_i t}) \]  

(7)

We use basic data from the reference [23], with the consideration of actual condition of the autonomous control system for unmanned marine vehicles, the assumed MTBF of each critical module in the USV control system is presented in TABLE. I.

| Module No. | Module Name          | MTBF/h |
|------------|----------------------|--------|
| 1          | 1# control computer  | 5000   |
| 2          | 2# control computer  | 5000   |
| 3          | 3# control computer  | 5000   |
| 4          | 1# servo controller  | 8000   |
| 5          | 2# servo controller  | 8000   |

Control computers of USV autonomous control system adopt cascaded triple redundancy structure, we suppose its failure rate is \( \lambda_{nc} \). Servo controller adopt cascaded dual redundancy structure, we suppose its failure rate is \( \lambda_{rc} \). the reliability of control computer and servo controller can described respectively as below:

\[ R_{nc}(t) = 1 - (1 - e^{-\lambda_{nc} t})^3 \]  

(8)

\[ R_{rc}(t) = 1 - (1 - e^{-\lambda_{rc} t})^2 \]  

(9)

In USV autonomous control system, control computers and servo controllers are cascaded firstly, then the triplex control computers and duplex servo controllers are paralleled together. Use the mathematical expressions described above, MTBF of the autonomous control system can be presented as follows:

\[ MTBF = \int_0^\infty R_{nc}(t) \cdot R_{rc}(t)dt = \frac{1}{\lambda_{nc} + \lambda_{rc} - \frac{2\lambda_{nc} + \lambda_{rc}}{3\lambda_{nc} + \lambda_{rc}} + \frac{3\lambda_{nc} + \lambda_{rc}}{3\lambda_{nc} + 2\lambda_{rc}}} \]  

(10)
If control computer and servo controller of the autonomous system are cascaded without redundancy, it becomes a single channel cascaded system, therefore, the expression of MTBF of the legendary USV autonomous control system without redundancy is presented as follows:

\[
MTBF = \int_0^{\infty} R_{nc}(t) \cdot R_{rc}(t) \, dt
\]

\[
= \frac{1}{\lambda_{nc} + \lambda_{rc}} = 3077
\]

(11)

According to the analysis presented above, the system reliability is improved by 113.3% compared to the legendary system without redundant design. We can say that by using the hybrid redundant structure, the reliability of USV autonomous control system improves dramatically, and fault-tolerant capability of the system is also improved.

5. CONCLUSION

The redundancy design is the most important method to increase the task reliability and fault-tolerant capability of USV autonomous control system. This paper presents hardware architecture and software realization of USV’s autonomous control system based on hybrid redundant structure. This paper discusses the critical stage of redundant design for autonomous control system in details. This paper compares the computation result of the task reliability of the USV autonomous control system with and without hybrid redundancy. In this paper, we use the reliability analysis to prove that by using the hybrid redundancy structure, the system reliability and fault-tolerant capability improve dramatically. It is an interesting topic to extend the reliability analysis and to consider the fault-tolerant capability of USV autonomous control system incorporate more sensors and actuators.

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