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Research on the Electronic and Electrical Architecture of Multi-Functional Intelligent Inspection Unmanned Surface Vehicle for Inland Waterways

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To address the issues of low efficiency and insufficient safety in traditional inland waterway inspections, this paper proposes a domain-controlled electronic/electrical architecture featuring "centralized decision-making and distributed execution." By coordinating perception-execution, network transmission, and decision-making layers, this architecture resolves the coupling between resources, information, and control in multi-functional units, thereby enhancing system reliability, scalability, and autonomous efficiency. Experiments demonstrate that this architecture achieves significantly lower latency than distributed architectures in perception and navigation tasks while exhibiting superior stability, providing effective support for high-real-time missions of the USV in complex inland waterway environments.

Keywords: Multifunctional, USV, Domain Controller, E/E Architecture, Inland waterway operations.

1. INTRODUCTION

To address the challenges of low efficiency and poor safety in traditional inland waterway inspections, the development of intelligent inspection technologies is urgently needed. This paper proposes a domain controller system architecture featuring "centralized decision-making and distributed execution" for multi-functional intelligent inspection unmanned surface vehicle (USV), enabling integrated, autonomous, and highly reliable waterway patrols.

This architecture establishes a three-tier collaborative framework encompassing perception and execution, networking and transmission, and decision-making layers. Through centralized coordination management, it resolves coupling issues in resource allocation, information exchange, and control among multifunctional units. Consequently, it enhances the mission reliability, functional scalability, and autonomous operation efficiency of the unmanned vessel, providing core hardware support for modern waterway management and maintenance.

1.1. *Intelligent detection USV*

USV are intelligent unmanned systems capable of autonomous navigation and mission execution on water surfaces. In recent years, numerous countries worldwide have actively advanced the USV research and development: the US has achieved high autonomous navigation coverage; Japan has proposed phased unmanned operation goals and conducted multiple tests; South Korea has deployed numerous intelligent systems and plans to implement remote control operation; and

Europe has also introduced fully electric USV into experimental operations. Although China started later, it has made significant progress in recent years, including cross-continental remote control, test site construction, and the operational deployment of multiple intelligent vessel types. With continued investment and technological accumulation worldwide, intelligent vessels are gradually advancing toward demonstration application stages. The representative intelligent vessels developed by domestic and foreign research institutions are shown in Fig 1.

Fig. 1. Intelligent vessels developed through domestic and international research.

Intelligent unmanned inspection vessels, as a new type of aquatic inspection platform, are gradually replacing traditional manned operations due to their safety, efficiency, flexibility, and cost-effectiveness. Since the 1990s, the United States, Europe, and other regions have successively developed multiple types of the USV for surveying, monitoring, and hydrographic mapping. Although China started later, since the deployment of the “Tianxiang-1” for water quality monitoring in 2008, multiple product series have emerged from companies like Yun zhou, Lao lei, Shanghai University, and Wuhan University of Technology. These have formed preliminary application systems in areas such as inland waterway scanning and maritime patrols, demonstrating promising development prospects.

Thombre et al. (2022) have reviewed the sensors and AI techniques applied for situational awareness in autonomous ships, providing core technical references for the design of environmental perception systems for the USV; Wang et al. (2024) have conducted research and application on panoramic visual perception-assisted navigation technology for ships, further enriching the technical pathways for navigation perception of the USV; while Blindheim & Johansen (2022) have developed electronic navigational charts to support the visualization, simulation, and autonomous control of ships, offering critical support for the practical implementation of autonomous navigation for the USV.

1.2. *Integrated technology for multifunctional transport vehicle*

As the USV increasingly diversify in functionality, dedicated vessel designs face high development costs and low utilization rates. Consequently, multifunctional integration technology based on modular design has emerged as a trend, with innovation in electronic and electrical architecture at its core. Drawing from automotive and aviation experiences, architectures are evolving from traditional distributed designs toward functional domains and hybrid approaches. By merging functions and decoupling hardware from software, this approach significantly enhances system flexibility, scalability, and maintainability. It supports rapid software iteration while reducing integration complexity.

Research on electronic/electrical architectures for vessel control system platforms began relatively late, primarily focusing on distributed architecture designs0. However, with the advancement of smart ships and intelligent navigation technologies, frequent data and information exchange occurs between multiple functional domains such as ship perception, decision-making, and control. Additionally, frequent maintenance and upgrades of intelligent system modules, along with the need for rapid switching between various navigation and operational functions, make traditional distributed architecture designs inadequate for meeting the demands of smart ship development.

Liu et al. (2023) have designed a distributed drive electric vehicle control architecture based on module division principles, offering a cross-domain reference for the optimization of distributed architectures for marine vessels; Alaviani et al. (2023) have proposed a new decentralized architecture and a fully parallel distributed algorithm for the charge scheduling of plug-in electric vehicles, whose design concept of a decentralized architecture provides technical inspiration for the research and development of domain control architectures for vessels; while Li et al. (2024) have carried out research on service-oriented data consistency for in-vehicle Ethernet, laying a protocol foundation for the network transmission layer design of vessel electronic and electrical architectures.

2. PROPOSED ELECTRONIC AND ELECTRICAL ARCHITECTURE

The shipboard network architecture, as an intelligent system integrating all electronic and electrical equipment onboard, achieves core functions such as status monitoring, fault early warning, autonomous navigation, and central coordination through unified protocols. It also possesses potential for remote monitoring and intelligent development. Unlike traditional architectures, this paper proposes a three-layer network framework: the perception, execution, and mission layers form the “ship's body,” the network and transmission layers serve as the “nervous system,” and the decision-making layer acts as the “brain,” collectively realizing highly integrated intelligent ship control. The overall network architecture of the designed shipborne system is depicted in Fig 2 for a more intuitive understanding.

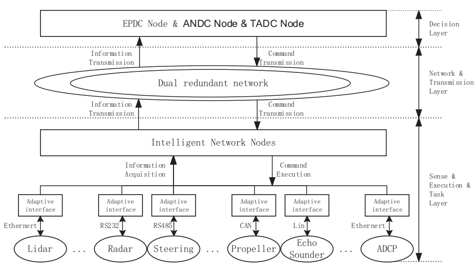

Fig. 2. Network architecture of shipborne network.

2.1. *Perception and execution layer (“hull”)*

The perception and execution layer forms the foundational nodes of the intelligent ship network. Each node possesses a unique IP identifier and performs dual functions of information acquisition and command execution. Unlike the perception layer in IoT systems, which solely handles data collection, this layer not only gathers real-time status and fault information from electronic and electrical equipment but also receives and executes coordination and control commands from higher layers. It serves as the critical foundation for realizing onboard intelligent communication and control.

Wang et al. (2022) have proposed a real-time ship collision risk perception model based on domain-based approach parameters, providing model support for hazardous information perception and processing at the perception-execution layer; Zhu et al. (2023) have realized vessel detection through multi-order saliency-based fuzzy fusion of spaceborne and airborne SAR images, whose multi-source data fusion method offers a reference for the processing of heterogeneous data at the perception layer.

2.2 *Network and transport layer (“nervous system”)*

The network and transport layer ensures reliable transmission of vessel-wide status information and control commands. This layer employs industrial Ethernet technology based on Time-Sensitive Networking (TSN), utilizing a unified protocol for standardized data encapsulation to guarantee low-latency, deterministic transmission under mixed traffic conditions. Combined with dual physical and logical redundancy design, it enables seamless failover during primary network failures, providing highly reliable and real-time communication assurance for the unmanned vessel detection system.

Saez-Perez et al. (2023) have designed, implemented, and empirically validated a framework for remote car driving utilizing commercial mobile networks, whose remote communication framework design offers insights for the optimization of remote transmission in shipborne networks; while Li et al. (2024) have carried out research on service-oriented data consistency for in-vehicle Ethernet, providing core technical references for the design of protocol consistency at the network transmission layer.

2.3 *Decision-making layer (“brain”)*

The decision-making layer comprises three domain controllers: environmental perception, autonomous navigation, and mission operations. The environmental perception domain serves as the “perception hub,” responsible for integrating, fusing, and processing multi-source heterogeneous data. It provides a unified data foundation for 3D reconstruction and obstacle recognition, supporting the vessel's comprehensive awareness of complex waters. The Autonomous Navigation Domain serves as the “control hub.” Through standardized interfaces and unified timing scheduling mechanisms, it achieves precise control and coordinated operation of actuators such as thrusters and rudders, ensuring fully autonomous navigation and intelligent obstacle avoidance. The Mission Operations Domain serves as the “mission hub,” integrating proprietary equipment without open APIs. Leveraging remote desktop protocols and a structured mission database, it enables full-cycle management of multiple tasks and processing of multi-channel heterogeneous data, ensuring centralized control and reliable execution of complex operations.

Qian et al. (2022) have designed an adaptive neural network-based tracking control strategy for underactuated offshore ship-to-ship crane systems affected by unknown wave motion disturbances, whose adaptive control algorithm offers a technical reference for actuator control in the autonomous navigation domain; while Lee et al. (2024) have constructed a synthetic maritime traffic generation system for verifying the performance of maritime autonomous surface ships, providing platform support for mission planning and simulation validation at the decision-making layer.

3 PERCEPTION & EXECUTION AND MISSION LAYER DESIGN FOR SHIPBORNE NETWORK ARCHITECTURE

In the shipboard network proposed in this paper, a large number of electronic and electrical devices are connected via intelligent network nodes. Based on their functions and the domain controllers to which they belong, they are categorized into three types.

3.1 *Intelligent network nodes*

3.1.1. *Intelligent sensor network node*

As the fundamental unit of the perception system, this node integrates multimodal sensors to establish a comprehensive environmental data acquisition chain. Compatible with various sensors, it features industrial interfaces including RS485/232, CAN, and Ethernet. Through modular design, it enables unified access and standardized transmission of heterogeneous data, providing a flexible hardware configuration foundation for diverse operational scenarios. The specific composition, functions and interface parameters of the intelligent sensor network node are detailed in Table 1.

Table 1. Intelligent sensor network node device

Device Name	Primary Function	Communication Method	Physical Interface
INS	Position Velocity Heading and Time	NMEA0183 NMEA2000 Serial	Multi-core terminal RJ45
Gyrocompass	True North Heading and Rate of Turn	NMEA0183 NMEA 2000	Gyrocompass
Radar	Distance and Bearing	Ethernet Serial	RJ45 Fiber Optic Multi-core terminal
AIS	Vessel and Other Vessel Information	NMEA0183 NMEA2000	Multi-core terminal
Lidar	3D Point Cloud	Ethernet (UDP/TCP)	RJ45, M12
Camera	Image perception	Ethernet USB	RJ45, USB-B
Anemometer	Wind Speed and Wind Direction	NMEA0183 NMEA2000 4-20mA	Multi-core terminal

3.1.2. *Intelligent network node for actuators*

As the core execution unit of the vessel control system, this node drives propulsion units, steering gear, and various operational devices to establish a comprehensive motion control and operational chain. Compatible with industrial interfaces such as Ethernet and CAN, it precisely parses and outputs commands. Leveraging a modular and distributed architecture, it provides the precise and reliable hardware foundation for vessel control across diverse operational conditions. The relevant device information and communication configuration of the actuator intelligent network node are summarized in Table 2.

Table 2. Actuator intelligent network node device

Device Name	Primary Function	Communication Method	Physical Interface
Thruster	Provide propulsion and steering for vessels	CAN bus Modbus	Multi-core terminal
Rudder actuator	Drive rudder blade rotation to alter course	CAN bus, Modbus	Multi-core terminal
Rudder angle indicator	Actual rotation angle	Modbus CAN bus	Multi-core terminal
Anchor winch	Control anchor chain deployment and retrieval	Modbus hardwired signals	Multi-core terminal, Relay
Specialized work equipment	Integrate equipment	Ethernet Modbus CAN bus	RJ45 Multi-core terminal

3.1.3. *Intelligent network node for task equipment*

As the core unit for unmanned vessel mission functions, this node integrates specialized payloads including water quality samplers, hydrological sensors, and side-scan sonar to establish a complete operational chain. Compatible with Ethernet, CAN, and 4G/5G interfaces, it enables precise command transmission and real-time data feedback. Its modular design provides rapid deployment and flexible hardware adaptation for diverse waterway inspection and maintenance tasks. The specific parameters and interface types of the task device intelligent network node are presented in Table 3.

Yuan et al. (2023) have explored the present applications and future prospects of unmanned vehicle platforms in marine environmental monitoring, providing application guidance for the payload selection and functional design of intelligent network nodes for mission equipment.

Table 3. Task device intelligent network node

Device Name	Primary Function	Communication Method	Physical Interface
Multibeam echo sounder	Underwater topography 3D point cloud data	Ethernet (TCP/IP)	RJ45
Single-beam echo sounder	Water depth data	RS232 RS485	DB9, Terminal Block
Side-scan sonar	Acoustic imaging of underwater topography	Ethernet (TCP/IP) RS232	RJ45, DB9
ADCP	Vertical current velocity profiles	RS232 RS485 Ethernet (TCP/IP)	DB9, Terminal Block, RJ45
Water sampler	Collection of water quality parameters.	Modbus RS485 RS232 SDI-12	Terminal Block, DB9

3.2 *Modular design of intelligent network nodes*

As functional units directly connected to equipment, intelligent network nodes undertake three core tasks: status acquisition, drive control, and fault diagnosis. They collect equipment status in real time via dedicated modules, enhance data reliability through fusion before uploading, receive control commands to drive precise equipment execution, and simultaneously monitor operational data to achieve autonomous identification and localization of equipment-level faults. The detailed functional decomposition of the intelligent network node is illustrated in Fig 3.

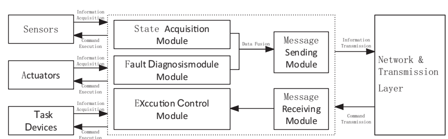

Fig. 3. Deconstruction the intelligent network node's functionality.

3.2.1. *Status acquisition*

In the state acquisition of intelligent ship network nodes, the hardware layer integrates TSN interfaces and multi-protocol adaptation modules. Through interface normalization and global clock synchronization, it provides a unified time reference for heterogeneous sensors, enabling precise alignment of multi-source data. At the data layer, a complete processing chain is constructed based on time alignment, encompassing acquisition, cleansing, parsing, and storage. This delivers accurate, reliable, and spatiotemporally consistent state information to upper-level control systems.

3.2.2. *Execution control*

In the design of execution control functions for intelligent ship network nodes, the hardware integrates TSN interfaces with physical interface adaptation modules, supporting multiple actuator standards while enabling signal conversion and control signal generation. Transmission priorities are assigned based on mission-criticality through TSN, ensuring deterministic delivery of control commands. Global clock synchronization facilitates multi-motor coordinated control, thereby establishing a highly reliable, real-time execution control system with multi-device collaboration capabilities.

3.2.3. *Fault diagnosis*

In the design of fault diagnosis functions for intelligent ship network nodes, the nodes simultaneously monitor both equipment operating parameters and communication link quality, establishing a multi-dimensional health assessment and early warning mechanism. By dynamically tracking characteristic parameters and performing multi-level threshold analysis, the system enables early identification and precise localization of equipment anomalies and communication failures, thereby significantly enhancing the maintainability and overall operational reliability of the ship's network.

Kim et al. (2022) have discussed the safety challenges faced by autonomous ships in mixed navigational environments, providing directional guidance for the design of risk warning and safety protection in the fault diagnosis process.

4 NETWORK & TRANSPORT LAYER DESIGN FOR SHIPBORNE NETWORK ARCHITECTURE

The network and transport layer serves as the data channel for the shipboard network, connecting devices at higher and lower layers. It encapsulates and forwards perception data and control commands via specified protocols, enabling reliable data transmission between the decision layer and all intelligent nodes. The specific data transmission process and schematic of the shipborne network transport layer are shown in Fig 4.

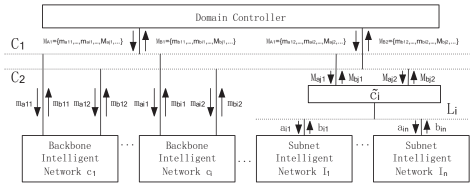

Fig. 4. Schematic diagram of data transmission.

Data transmission is categorized into two types: electronic and electrical equipment information (including operational status and fault diagnosis data) and control commands (motion control and task control instructions). The data transmission process is as follows:

The backbone network intelligent network node c_i synchronously transmits information data to the primary backbone network C_1 and the backup backbone network C_2. The subnetwork intelligent network node In transmits information data to the subnetwork. The gateway $\tilde{c}_i$ encapsulates all data information for this subnetwork Li, generating information packets M_{bj1} and M_{bj2}, which are sent to the primary backbone network C_1 and the backup backbone network C_2 respectively. Information from all intelligent network nodes in the primary backbone C_1 and backup backbone C_2 is encapsulated into information packets M_{B1} and M_{B2}, respectively, and transmitted to the decision layer deploying different functional domain controllers; The decision layer performs fusion processing and comprehensive coordination on the information, generating command packets M_{A1} and M_{A2} and sending them to the primary backbone C_1 and backup backbone C_2; The intelligent network node c_i on the backbone network obtains its corresponding command packets M_{Ai1} and M_{Ai2}, while the gateway acquires command packets M_{Aj1} and M_{Aj2} for subnetwork Li and distributes them to specific intelligent network nodes.

Through this design, each intelligent network node communicates exclusively with management nodes, achieving decoupling between nodes for orderly network management and coordination. Simultaneously, it significantly simplifies the functional logic of individual nodes, enhances design and development efficiency, and markedly reduces the impact scope of a single node failure. Building upon this, the dual-redundant network architecture of trunk networks C_1 and C_2 further elevates the system's fault tolerance and survivability. This dual-redundancy architecture ensures that if either backbone network fails, the other network can immediately assume all communication tasks, enabling seamless switching. This effectively prevents system-level paralysis caused by single points of failure, providing dual assurance for the continuous and reliable operation of the entire network.

5 DESIGN OF THE DECISION LAYER IN SHIPBORNE NETWORK ARCHITECTURE

5.1 *Central coordination and management mechanism*

The central coordination management mechanism utilizes the status and self-diagnostic information of all onboard electronic and electrical equipment as input. By analyzing logical relationships between devices, it establishes subsystem correlation models, state combination functions, and state machines, while setting equipment priorities. Based on this mechanism, it achieves unified coordination control over data bandwidth, energy, and resources among multi-domain controllers, while simultaneously performing comprehensive diagnostics of correlated faults and generating command outputs. The operational mechanism of the central coordination management system for the intelligent ship is visualized in Fig 5.

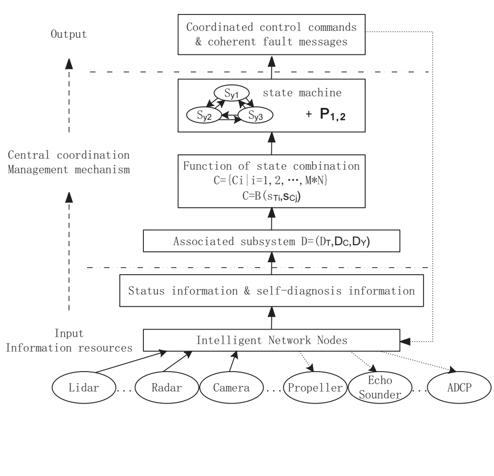

Fig. 5. Intelligent ship system coordination mechanism.

5.2 *Design of the central coordination management mechanism*

5.2.1. *Associated subsystems*

The subsystem architecture of intelligent vessels characterizes logical constraints between domain controllers through typical operational states (e.g., low-power, normal-power, high-power) and critical functions (e.g., central processor computation and real-time image processing). The system establishes a multidimensional resource coordination mechanism that dynamically allocates energy supply, flexibly adjusts communication bandwidth, and centrally schedules heterogeneous computing power. This enables adaptive coordination and state management capabilities among functionally complementary or mutually exclusive devices. The structural composition and logical relationship of the associated subsystem are shown in Fig 6.

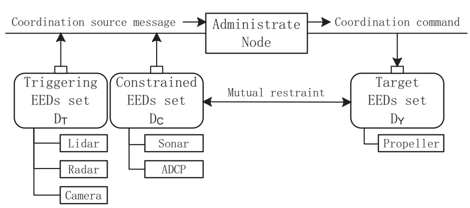

Fig. 6. Correlative subsystem

The associated subsystem consists of triggering E/E equipment, restraining E/E equipment, and target E/E equipment, expressed as follows:

$$D = (D_T, D_C, D_Y) \quad (1)$$

Among these, D represents the associated subsystem; D_T denotes the triggering E/E device set, capable of initiating actions in target E/E devices (primarily sensing devices and HMI operation screens); D_C signifies the constraining E/E device set, capable of restricting actions in target E/E devices (primarily mission-critical equipment); D_Y indicates the target E/E device set, serving as the control object for the associated subsystem and typically comprising actuators (thrusters, motors, etc.).

As shown in Figure 6, the management node acquires the status information and self-diagnostic information of D_T and D_C, generating coordination commands for D_Y. Triggering electronic/electrical equipment and constraining electronic/electrical equipment are collectively referred to as the associated equipment of the target electronic/electrical equipment.

5.2.2. *Conflict monitoring*

For smart vessels, the electronic and electrical system architecture encompasses internal system interconnections, device access system interconnections, and original equipment manufacturer (OEM) interconnection services. In these three interconnection scenarios, command conflicts may easily arise. Therefore, devices within the system are prioritized based on their criticality, while parameters P_1 and P_2 are designed with the following definitions:

$$P_{1,2} = \begin{cases} 1\ X_{e1} \neq 0\ and\ X_{e2} = 0;\ X_{e1} \neq 0\ and\ X_{e2} \neq 0; \\ 0\ X_{e1} = 0\ and\ X_{e2} \neq 0; \end{cases} \quad (2)$$

Among these, X_{e1} represents instructions generated based on the central coordination mechanism, while X_{e2} denotes instructions generated based on the interconnection approach. Evidently, when the two sets of instructions conflict, the vessel will execute the instructions generated by the onboard network (due to its higher credibility), which is also the core reason for introducing this parameter.

6 EXPERIMENTAL RESULTS AND ANALYSIS

6.1 *Topology of the shipborne network architecture for the USV mechanism*

The system architecture proposed in this paper has been successfully applied to a certain type of inland river survey intelligent unmanned vessel. This inland river survey unmanned vessel features an aluminum alloy catamaran structure with an overall length of 4.96 meters. It is equipped with four fully reversible motors and a high-capacity battery pack, achieving a maximum speed of 3 m/s and an endurance of 8 hours. Integrated with LiDAR, visual, and navigation equipment, it can stably perform complex tasks such as engineering surveying and water quality monitoring under Sea State 2–3 conditions, demonstrating high reliability and intelligent operational capabilities. The physical prototype of the inland river survey intelligent unmanned vessel applied with this architecture is shown in Fig 7.

Li et al. (2023) have conducted a comprehensive survey on maritime unmanned search systems, including their theoretical foundations, practical applications, and future development directions, providing a theoretical reference for the functional design and mission planning of the USV.

Fig. 7. Unmanned vessel prototype

The electronic and electrical architecture designed in this paper is shown in the figure. The overall design of the shipwide electronic and electrical architecture for the prototype vessel is presented in Fig 8. The environmental perception and autonomous navigation domain controller utilizes the EAORA07 device, integrating dual ORIN chips and a TC397 chip, running the Linux operating system. The mission management domain controller operates on the Windows operating system, equipped with an Intel i7 processor and a RAID1 storage array. The three controllers respectively handle environmental perception, autonomous navigation, ansd mission management functions. Specific tests are as follows.

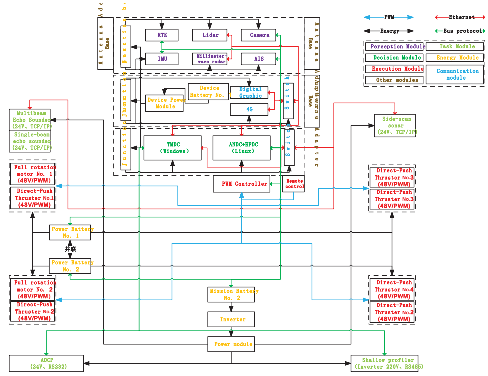

Fig. 8. Shipwide Electronic and Electrical Architecture

6.2 *Functional experiment of unmanned vessel system architecture*

Functional testing of the unmanned vessel system architecture aims to comprehensively validate the collaborative performance of its core systems. Key focuses include: - The environmental perception system's capability to fuse multi-source sensor data for real-time construction of the surrounding environmental situation; - The reliability of the autonomous navigation system in performing global path planning, dynamic obstacle avoidance decisions, and precise track following based on perceived information; - The control accuracy and mission execution efficiency of the task operation system for specialized payloads. This ensures the entire architecture can safely, intelligently, and efficiently accomplish its designated missions within complex inland waterway channels. The test results of the key functional modules of the unmanned vessel system architecture are shown in Fig 9.

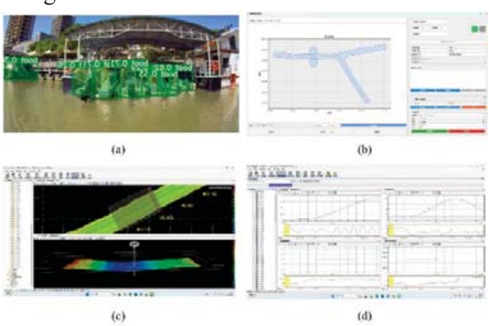

Fig. 9. Architecture functional test results

(a) Environmental Perception Test(b) Navigation Control Test(c)(d) Task Execution Test

6.3 *Performance experiment of unmanned vessel system architecture*

The core of the EAORA07 device employs a symmetric architecture centered on the ORIN-A and ORIN-B main processors. Both processors are directly interconnected via a PCIe bus to the built-in Gigabit Ethernet switch, forming the backbone network for on-board data exchange. This board-to-board interconnection eliminates the need for external physical ports and cables found in traditional architectures, significantly reducing signal attenuation and external interference. Consequently, inter-board communication achieves both higher stability and greater bandwidth compared to external wired transmission. For critical control links, the two ORIN processors communicate directly with the core MCU (TC397) responsible for navigation control via an SPI bus. The direct hardware interconnection and protocol simplicity of SPI effectively bypasses the protocol encapsulation and parsing overhead associated with traditional methods like CAN bus. This reduces system command transmission latency from milliseconds to microseconds, delivering ultra-real-time control capabilities for the unmanned vessel. The latency comparison results of the domain control architecture and traditional distributed architecture in key tasks are depicted in Figure 10. The specific quantitative performance comparison data of the two architectures are statistically summarized in Table 4.

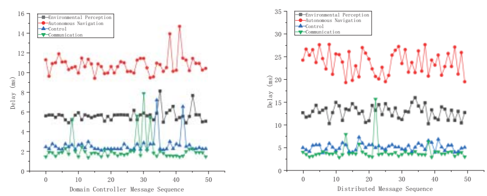

Fig. 10. Comparison of domain controller latency across different system architectures

Table 4. Performance comparison data across different architectures

Architecture	Domain	Mean /ms	Min /ms	Max /ms
Domain Control	Environmental Perception	4.90	2.38	6.85
Distributed	Environmental Perception	8.04	4.16	13.44
Domain Control	Autonomous Navigation	10.10	5.14	15.78
Distributed	Autonomous Navigation	15.32	8.63	21.57

This study demonstrates through latency testing that the domain-controlled architecture outperforms distributed architectures in both environmental perception and autonomous navigation domains, achieving latency reductions of 35.1% and 34.1%, respectively. Furthermore, the latency curve of the domain-controlled architecture exhibits greater stability, with significantly reduced fluctuations as message sequences increase. Consequently, its comprehensive advantages in reducing latency and enhancing stability make it an ideal choice for high-real-time applications.

7 CONCLUSIONS

This paper addresses the pain points of low efficiency and insufficient safety in traditional inland waterway inspections by innovatively proposing and implementing a domain-controlled electronic/electrical architecture featuring "centralized decision-making and distributed execution." This architecture provides core hardware and system support for the multi-functional intelligent inspection USV. Through a three-layer collaborative design encompassing perception-execution, network transmission, and decision-making, this architecture effectively resolves coupling issues in resource allocation, information exchange, and control logic among multifunctional units. It significantly enhances the vessel's mission reliability, functional scalability, and autonomous operation efficiency. Performance testing demonstrates that the domain-controlled architecture achieves significantly lower latency than traditional distributed architectures in environmental perception and autonomous navigation, while offering superior stability. This provides critical assurance for executing high-real-time tasks (such as dynamic obstacle avoidance and precise track following) in complex inland waterway environments. Beyond delivering a viable system solution for inland river intelligent inspection USV, this research's architectural design philosophy and collaborative management mechanisms offer valuable reference for evolving the electronic/electrical architectures of other complex mobile intelligent equipment. In the future, this architecture can be further integrated with technologies like ship-shore coordination and swarm intelligence, expanding into broader application scenarios such as regional vessel scheduling and multi-vessel collaborative operations, thereby advancing the development of an intelligent inland waterway transportation system.

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