

Construction of Intelligent Sensing Network for Wetland Ecological Protection and Multi-Scenario Practical Applications

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Abstract: Aiming at the prominent problems in wetland ecosystem monitoring such as insufficient real-time performance, limited coverage, and single data dimension, this paper designs an intelligent multi-parameter sensing network based on the edge-cloud collaboration architecture. The system integrates heterogeneous sensing nodes, 4G/Beidou dual-mode communication links, and intelligent energy management modules to construct an integrated air-space-ground wetland ecological perception system. It elaborates on the network hierarchical model based on the digital twin concept, the adaptive selection method of key sensors, and the intelligent data preprocessing process. The innovative applications of the network in three typical wetland scenarios, including carbon flux monitoring of alpine wetlands in the Three-River-Source Region, ecological restoration effect evaluation of salt marshes in the Yellow River Delta, and water quality safety early warning of constructed wetlands in Taihu Lake, Suzhou, are verified. Practice shows that the system realizes high-precision and long-time series monitoring of key parameters such as water level and salinity, provides scientific support for ecological protection decision-making, and significantly improves the intelligent level of wetland management.

Keywords: Intelligent perception network; Wetland ecosystem; Edge computing; Digital twin; Internet of Things; Ecological big data

1. Introduction

Wetlands, as ecosystems rich in biodiversity and crucial for ecological services, serve as important indicators of regional and even global environmental changes^[1]. Under the dual impact of global climate change and human activities, wetlands face severe challenges such as area reduction and functional degradation^[2]. Traditional monitoring methods, such as manual patrols and periodic sampling, can no longer meet the modern wetland protection needs for real-time, continuous, and multi-dimensional data^[3]. With the development of the Internet of Things (IoT) and artificial intelligence technologies, constructing intelligent and networked ecological perception systems has become an inevitable trend in environmental monitoring^[4]. Current research faces limitations such as single node functions, weak data fusion capabilities, and poor environmental adaptability^[5]. This paper proposes an integrated solution that combines intelligent perception, reliable transmission, edge computing, and cloud platform analysis, and verifies its application potential in wetland scientific protection and precision management through case studies. The goal is to provide a reusable technological paradigm for "smart environmental protection."

2. Technical Challenges in Wetland Ecological Monitoring and the New Paradigm of Intelligent Perception

Wetland environments are characterized by a mix of water and land, complex terrain, and variable climate, posing high requirements for monitoring technology. The main challenges are:

Wide monitoring dimensions, requiring simultaneous acquisition of multi-dimensional parameters such as hydrology, soil, meteorology, and biology;

Difficult deployment and energy supply, requiring devices to have high protection levels and ultra-low power consumption, with reliance on renewable energy in remote areas;

High communication reliability requirements, with backup communication links needed in public network blind spots;

Shallow data value mining, where massive data needs to be transformed into decision-making information^[6].

To address these challenges, this study proposes a new intelligent perception paradigm. The core of this paradigm is to construct a wetland monitoring network with a "nervous system," which is not just a data "collector" but also an environmental "perception brain." Based on the concept of digital twins, this paradigm enables real-time interaction between physical sensor networks and virtual cloud platforms, achieving dynamic mapping and simulation prediction of wetland ecological processes.

3. Intelligent Perception Network System Architecture Design and Key Technologies

3.1 System Overall Architecture

Based on the edge-cloud collaborative layered model, the system adopts a four-layer architecture to achieve efficient collaboration between edge computing and cloud computing:

Intelligent Perception Layer: Composed of multi-functional sensing units deployed at key wetland nodes, integrating various sensors to monitor environmental factors such as water, soil, and air;

Reliable Transmission Layer: Uses a 4G/Beidou dual-mode heterogeneous network as the communication backbone. When public network signals are available, 4G is prioritized for transmitting large data volumes, and in signal-free areas, it automatically switches to Beidou short message communication to ensure zero data loss^[7];

Edge Computing Layer: Lightweight AI algorithms are embedded in data collectors (e.g., Campbell CR1000X) to provide capabilities for data cleaning, anomaly detection, and local modeling. These algorithms reduce raw data to effective information, easing transmission pressure and enabling rapid local response;

Cloud Platform Application Layer: A digital twin platform is built using cloud-native technology to handle data aggregation, storage, deep analysis, and visualization. Machine learning algorithms are used to uncover data patterns and provide early warning reports and decision-making suggestions to managers.

3.2 Key Hardware and Intelligent Selection Strategy

The hardware selection follows the principles of "high precision, low power consumption, and environmental adaptability." For hydrological monitoring, the AP7000 multi-parameter water quality instrument is chosen, which features self-cleaning and anti-pollution capabilities. For soil monitoring, the CS650 three-parameter probe is used, which simultaneously captures data on water content, temperature, and electrical conductivity profiles. For meteorological monitoring, the HMP155A temperature and humidity sensor and ultrasonic wind speed and direction instruments are used to ensure data accuracy and comparability.

3.3 Energy Management and Intelligent Communication Protocol

The energy system combines solar-lithium battery hybrid power supply with dynamic energy consumption management (DEM) strategies. The DEM strategy dynamically adjusts the sensor sampling frequency and communication module wake-up cycle based on battery power and weather conditions to achieve optimal energy configuration. In terms of communication protocol, an adaptive heartbeat mechanism and data retransmission strategy are designed to ensure the stability of the communication link.

3.4 Key Technological Breakthroughs

3.4.1 Intelligent Energy Consumption Management Technology

Dynamic voltage-frequency scaling (DVFS) technology is used to dynamically adjust the processor's operating state based on computational load, reducing system power consumption by 30%. Coupled with an energy scheduling algorithm based on reinforcement learning, energy expenditure is

predicted using weather forecasts, allowing intelligent adjustment of monitoring strategies. In continuous rainy conditions, the system can guarantee ≥ 180 days of continuous operation. The solar-lithium battery hybrid power supply system uses maximum power point tracking (MPPT) technology to maximize energy collection efficiency. This energy consumption optimization solution draws from the application experience of multi-agent deep reinforcement learning in extreme environmental sensor networks, further improving energy efficiency through collaborative optimization of sensing and communication strategies^[8].

3.4.2 Multi-source Data Fusion Technology

A multi-modal data fusion method based on an attention mechanism is proposed. LSTM networks are used to explore the spatial and temporal correlations between hydrological, soil, and meteorological parameters, addressing the issue of insufficient use of multi-source data features in traditional methods. Applications in the Yellow River Delta indicate that this method improves water level prediction accuracy by more than 25%^[6]. A hybrid model combining LSTM and CNN is built to further improve the accuracy of data fusion.

3.4.3 Adaptive Monitoring Technology

An intelligent sampling mechanism based on the Q-learning algorithm is developed. The system autonomously decides the sensor sampling frequency and transmission priority by analyzing historical data features and environmental change trends, reducing 40% of ineffective data transmission while ensuring data integrity^[9]. The adaptive sampling method based on reinforcement learning optimizes monitoring frequency and transmission strategies according to environmental changes and energy conditions, thereby reducing system energy consumption.

4. Wetland Ecological Multi-Scenario Applications and Effectiveness Verification

4.1 Carbon Flux Monitoring and Model Assimilation in Alpine Wetlands

Twelve intelligent monitoring nodes were deployed in the alpine wetlands of the Three-River-Source region to establish an elevation gradient monitoring network. Each node integrated a CO₂ flux monitoring system (LI-7500DS), soil three-parameter sensor (CS650), and a meteorological station (HMP155A), with edge computing modules enabling real-time data quality control and feature extraction.

Monitoring data shows that the system successfully captured the daily variation of CO₂ flux during the growing season (0.2-1.5 $\mu\text{mol}/\text{m}^2/\text{s}$), with measurement accuracy verified by standard instruments to be within $\pm 5\%$. The correlation coefficient with manual sampling data was 0.97 ($p < 0.01$). The high-frequency monitoring data supported the optimization of carbon sink models, improving the simulation accuracy of net ecosystem exchange (NEE) from $R^2 = 0.76$ to $R^2 = 0.89$. In ecological applications, the system accurately identified the carbon source/sink conversion threshold for alpine wetlands for the first time: when soil temperature exceeds 8°C and water level falls below 15 cm, the wetland shifts from a carbon sink to a carbon source, providing scientific evidence for revising ecological protection plans and optimizing seasonal grazing management in the Three-River-Source region^[10].

4.2 Precision Control of Ecological Restoration in Coastal Salt Marsh Wetlands

In the Yellow River Delta, 32 groundwater level monitoring points (HOBO U20-001-01), 16 soil salinity sensors (5TE), and 8 surface water salinity monitors (AP7000) were deployed to establish a three-dimensional monitoring system. The system adopted an adaptive sampling strategy, automatically increasing the sampling frequency to once every 15 minutes during the spring ecological irrigation period to capture the dynamic changes in soil salinity during freshwater infiltration.

Monitoring data shows that the optimized irrigation plan based on real-time salinity data reduced the soil surface salinity from 15.6‰ to 3.2‰ in 30 days, with the restoration rate of salt marsh vegetation (reed, seepweed) improving by 37%, significantly outperforming the traditional fixed irrigation scheme (salinity reduced to 5.8‰ and vegetation restoration rate improved by 21%)^[11]. The system's integrated "rainfall-water level" response model, optimized by machine learning algorithms, improved the accuracy of flood warning to 92%, increased pump station efficiency by 35%, and reduced annual maintenance costs by 220,000 yuan, providing a replicable technological model for

coastal wetland ecological restoration^[12].

4.3 Artificial Wetland Water Quality Safety Early Warning and Smart Operation and Maintenance

In the Taihu Lake artificial wetland in Suzhou, a water quality monitoring IoT system was deployed, combining traditional sensors and spectral analysis technology. An online UV-visible spectrometer (s::can moni) was used to monitor parameters such as COD and TOC in real-time, with data from conventional multi-parameter water quality meters (AP7000) integrated to build a deep learning-based water quality anomaly warning model.

Operational data shows that the system achieved an 89% accuracy rate in identifying COD mutations (change rate > 15%), with a warning response time of ≤ 30 minutes, six times more efficient than traditional manual inspections. In terms of smart operation and maintenance, by analyzing the correlation between incoming water quality and operational parameters, the system dynamically optimized aeration intensity and hydraulic retention time, reducing energy consumption by 18% and improving purification efficiency by 23%. During high-temperature seasons, by predicting algal proliferation risks, the system initiated preventive measures in advance, effectively avoiding biofilm blockages.^[13]

4.4 Comprehensive Comparative Analysis and Discussion

The intelligent perception network demonstrated significant advantages across different types of wetlands but faced unique challenges:

Alpine wetlands required solutions to communication and energy supply issues, which were effectively addressed by combining Beidou satellite communication and low-temperature battery technology;

In coastal wetlands, sensor corrosion resistance was crucial;

In urban artificial wetlands, higher demands were placed on monitoring accuracy and response speed.

The innovation of this study lies in the use of multi-source data fusion analysis to extract ecological significance, such as revealing the impact mechanisms of temperature and precipitation on the carbon sink function of alpine wetlands and determining the salt tolerance thresholds of different plants. Based on case studies, standardized deployment plans were derived:

For natural wetlands (e.g., Three-River-Source), the focus is on solving energy and communication problems;

For disturbed wetlands (e.g., Yellow River Delta), the emphasis is on quantifying ecological restoration effects;

For artificial wetlands (e.g., Taihu Lake), the focus is on upgrading operation and maintenance management with intelligent technologies.

5. Research Progress and Outlook

Current research on intelligent sensing networks shows three major trends:

The architecture is shifting from centralized to edge-cloud collaboration to enhance response speed and reliability.

Algorithms are integrating machine learning with physical models to strengthen data analysis capabilities.

Platforms are integrating digital twin technology to enable dynamic simulation and optimization of monitoring processes.

Future key research directions include:

Miniaturization and low-power design of intelligent sensors to enhance adaptability and endurance in complex wetland environments.

Development of multi-scale data assimilation algorithms to improve the ability to fuse and analyze

multi-source heterogeneous data.

Establishing standardized interfaces and interoperability protocols to promote the interconnection of different monitoring systems and data sharing.

6. Conclusion

The intelligent sensing network constructed in this study uses an edge-cloud collaborative four-layer architecture, integrating various advanced technologies, effectively addressing many issues of traditional wetland monitoring. Multi-scenario applications demonstrate that the system has significant effects in carbon flux monitoring in alpine wetlands, precision control of ecological restoration in coastal salt marshes, and water quality safety early warning in artificial wetlands, providing strong support for wetland protection and management decision-making. With the development of sensors, communication, and artificial intelligence technologies, intelligent sensing networks will play an increasingly important role in wetland ecological protection, contributing "Chinese wisdom" to global ecological security.

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