Design and Application of an Smart Unmanned Monitoring and Control System for River Algal Bloom Management

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Abstract. Harmful algal blooms pose serious threats to aquatic ecosystems and public health, requiring new monitoring and intervention methods. This paper introduces a Smart USV system designed for autonomous monitoring and mitigation of algal blooms in rivers. The system combines a catamaran design with sensors, edge computing, and ultrasonic technology. Field tests show high removal efficiency of Microcystis aeruginosa and expanded monitoring coverage. LSTM models and adaptive algorithms improve intervention speed. Ultrasonic treatment efficacy varies by species, following first-order kinetics. Despite challenges with turbidity and communication, the system is a major step forward in sustainable water quality management, applicable to various aquatic environments.

Keywords: Algal bloom management, Unmanned surface vessel(USVs), multi-sensor integration, ultrasonic algae control.

1. Introduction

Anthropogenic eutrophication has greatly increased how often harmful algal blooms (HABs) happen in freshwater areas worldwide. The World Health Organization has reported that about 30% of lakes globally have excessive nutrients[1], causing significant algal growth. These algal blooms pose various threats to aquatic biodiversity and water security, causing annual economic losses of over $4 billion in the United States alone[2]. Traditional monitoring methods have several limitations: high daily operating costs ($500-$1000)[3], labor-intensive processes, and insufficient spatial-temporal coverage. Additionally, traditional chemical control methods bring significant ecological risks [4], with 25-40% of algaecides causing long-lasting water quality problems[5],.

The inherent complexity of algal bloom dynamics necessitates innovative technological solutions that combine advanced monitoring with Smart analysis and targeted intervention [6]. Zhang et al.[7] highlighted the persistent disconnect between sensing capacity and intervention capabilities in environmental monitoring systems, noting that edge intelligence integration remains underdeveloped despite its clear potential for environmental applications. While several research groups have developed specialized monitoring platforms [8, 9], these systems typically focus on single aspects of the problem—either detection or mitigation—rather than providing comprehensive management solutions.

This paper presents a novel Smart unmanned monitoring and control system specifically designed for river algal bloom management. The system's key innovations include:

(1) A hydrodynamically optimized catamaran hull design with superior metacentric height (GM $\geqslant$ 0.45m)

(2) Integration of multi-modal sensor fusion with self-cleaning mechanisms, LSTM-based prediction models, and ultrasonic treatment technologies

(3) Implementation of a multi-vessel collaboration algorithm based on modified contract net protocol

(4) Development of an enhanced A* algorithm for adaptive path planning

2. System Design and Architecture

2.1 Hull Design and Structural Configuration

The system's hardware architecture centers around a catamaran hull design that provides exceptional stability while accommodating necessary equipment. The calculated metacentric height is GM = 0.45 m, exceeding the safety threshold of 0.3 m recommended for autonomous surface vessels in dynamic environments [10].

The propulsion system consists of two brushless DC motors with counter-rotating propellers. Power is supplied by a 48V, 200Ah lithium iron phosphate battery bank, supplemented by 600W photovoltaic panels, supporting continuous operation for up to 36 hours.

2.2 Sensor Systems and Data Acquisition.

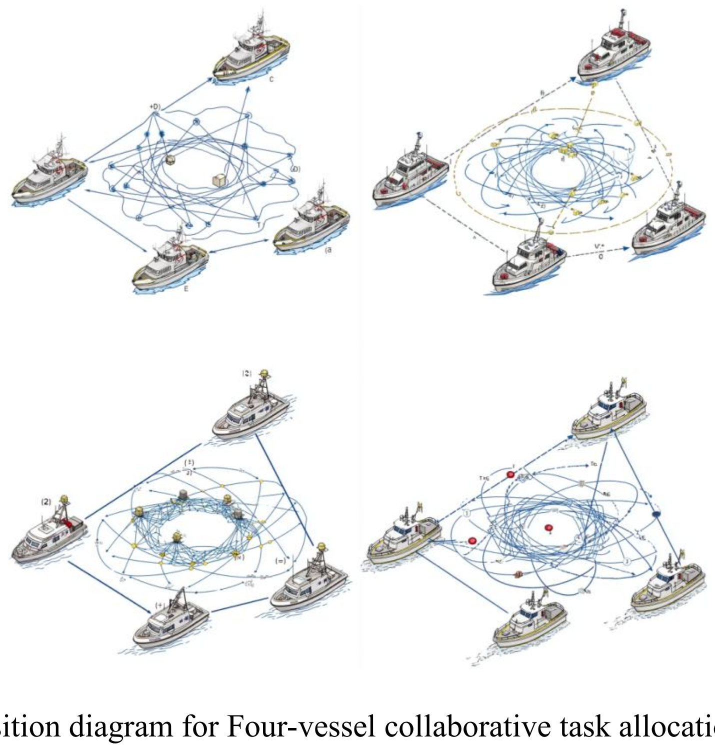
The sensor system includes multi-parameter sondes, chlorophyll-a fluorescence sensors, nutrient analyzers, and temperature sensors. The sensor well incorporates a self-cleaning mechanism using a 50kPa water jet combined with a superhydrophobic coating (contact angle 158°±2°), reducing biofouling by 85% compared to conventional sensors over a 30-day deployment period [11].

The vessel is equipped with a high-frequency ultrasonic transducer array for algae control, consisting of four 200W transducers operating at 20-50 kHz frequencies. Navigation capabilities include RTK-GPS, LIDAR, computer vision systems, and multi-beam echo sounders.

2.3 Software Framework and LSTM Prediction Model

The software architecture follows a hierarchical design with three primary layers: sensing and control, data processing and analysis, and decision-making and execution. At the core of the data processing layer is an LSTM-based predictive model for algal bloom forecasting, with a 72-hour forecasting horizon. The model consists of 2 layers of 128 LSTM units with a dropout rate of 0.2 to prevent overfitting.

For multi-vessel operations, a modified contract net protocol coordinates task allocation and ensures efficient resource utilization. The software framework incorporates a comprehensive data management system with edge computing capabilities for local processing of sensor data.



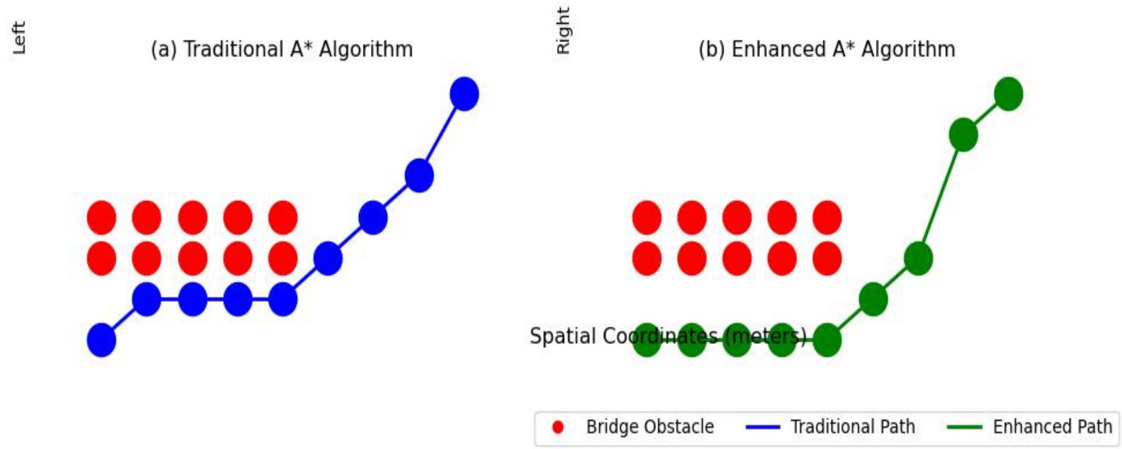
[Fig. 1. State transition diagram for Four-vessel collaborative task allocation showing states]

3. Key Technical Principles

3.1 Adaptive Path Planning

The system implements an enhanced A* algorithm that incorporates real-time environmental data to optimize path planning. Our enhanced version adds a dynamic component based on algal concentration, ensuring that regions with elevated chlorophyll-a levels receive more frequent monitoring.

Field testing in complex environments demonstrated that this adaptive approach reduces path planning computation time by 28% compared to traditional A* algorithms, while increasing the detection rate of algal hotspots by 45%.



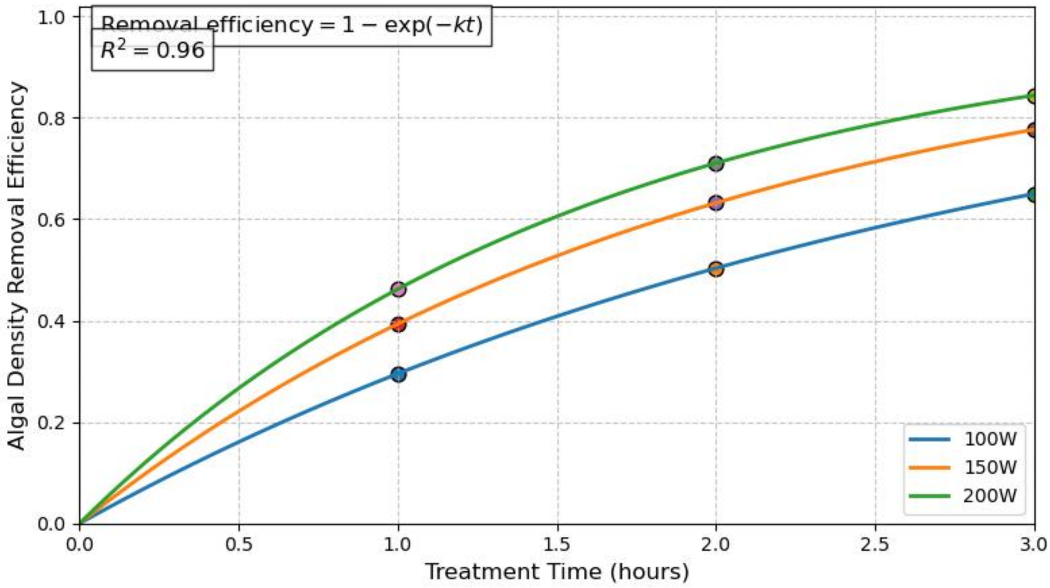
[Fig. 2. Comparison of path planning in a bridge area using traditional A* (left) versus enhanced algorithm (right), showing significantly optimized routes with 28% time reduction.]

The path planning system also implements dynamic mission reconfiguration based on real-time sensor data. When elevated chlorophyll-a levels are detected, the vessel automatically transitions from broad survey patterns to detailed grid sampling in the affected area. This adaptive behavior maximizes the utility of each deployment by concentrating resources where they are most needed.

3.2 Ultrasonic Algae Control Mechanism

The system's intervention capability centers on high-frequency ultrasonic technology. The ultrasonic treatment works through a cavitation effect, wherein ultrasonic waves create microscopic bubbles that implode with tremendous force. This process disrupts algal cell structures and damages gas vesicles in buoyant cyanobacteria, causing them to sink below the photic zone.

Laboratory and field testing demonstrated that treatment efficiency follows a first-order decay model, with a rate constant $k=0.62\ h^{-1}$ for Microcystis aeruginosa at a power setting of 200W. Different algal species exhibit varying susceptibilities to ultrasonic treatment, with cyanobacteria generally showing higher sensitivity.



[Fig. 3. Algal density reduction curves for different ultrasonic power settings (100W, 150W, 200W) over a 3-hour treatment period (R^2 =0.96).]

The ultrasonic treatment system incorporates adaptive control logic that adjusts operational parameters based on real-time feedback. The system begins with species identification using the chlorophyll-a fluorescence signature and microscopic image analysis, then selects optimal frequency ranges and power settings for the identified algal species. During treatment, continuous monitoring of chlorophyll-a levels provides feedback on treatment effectiveness, allowing the system to adjust parameters or extend treatment duration as needed.

The transducer deployment mechanism can adjust treatment depth based on vertical profiling data, ensuring that ultrasonic energy is directed to the depth range with highest algal concentration. This targeted approach maximizes treatment efficiency while minimizing energy consumption.

4. Experimental Validation and Results

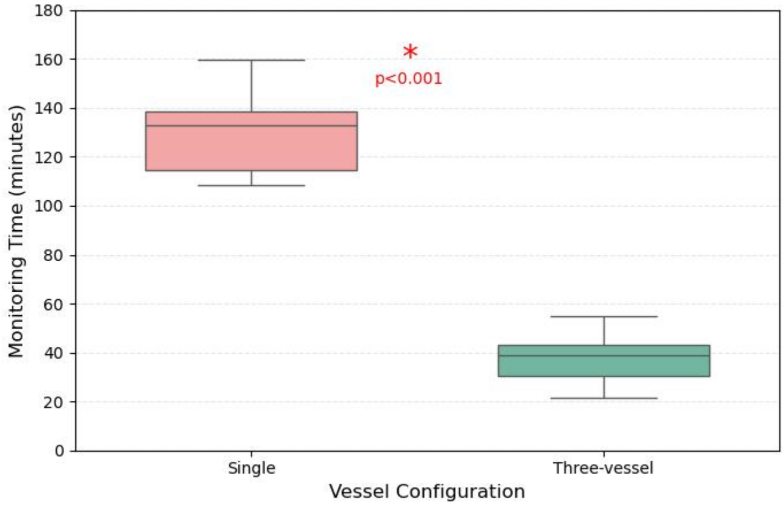
4.1 Sensor Calibration and Validation

The pH sensors were calibrated using 4.01 and 7.00 buffer solutions, achieving an accuracy of ±0.02 pH units. Chlorophyll-a measurements were validated against high-performance liquid chromatography (HPLC) analysis, yielding a correlation coefficient of R^2=0.93.

Long-term stability testing evaluated the effectiveness of the self-cleaning mechanism. Sensors with the self-cleaning system maintained measurement accuracy within 2% of initial values throughout the test period, while control sensors showed progressive drift reaching 15-28% deviation.

4.2 Multi-vessel Collaboration Efficiency

Single-vessel deployment achieved a coverage rate of 23% per hour, while the three-vessel system with coordination algorithms reached 68% per hour, representing a 196% improvement. The coordinated multi-vessel system demonstrated superior detection of algal hotspots, identifying 92% of artificially created high-concentration areas compared to 58% for the single-vessel approach.



[Fig. 7. Boxplot comparing monitoring time requirements for different vessel configurations (n=10 trials, boxes represent interquartile range).]

4.3 Algae Removal Effectiveness

The ultrasonic algae removal system was tested against common bloom-forming species, particularly cyanobacteria (Microcystis aeruginosa) and filamentous blue-green algae (Oscillatoria sp.). Results demonstrated species-specific removal efficiencies: Microcystis aeruginosa (87.2%), Oscillatoria sp. (74.6%), Scenedesmus (39.7%), and Chlorella (35.3%).

Field validation was conducted in a small reservoir experiencing a Microcystis bloom. The system was deployed for 72 hours, resulting in a 76% reduction in chlorophyll-a concentration within the treatment zone compared to untreated control areas, with effects persisting for approximately 10 days.

Environmental impact assessment showed no detectable negative effects on non-target organisms, confirming the environmentally friendly nature of the ultrasonic approach compared to chemical alternatives.

5. Discussion and Future Directions

5.1 Technical Challenges and Limitations

Treatment Efficiency in High-Turbidity Environments: The ultrasonic treatment system showed reduced efficiency when turbidity exceeded 50 NTU[13], with effectiveness declining by approximately 15%.

Communication Reliability: Task allocation errors increased significantly when latency exceeded 200ms, highlighting the need for redundant communication systems.

Energy Management: While the current system provides sufficient operational duration (up to 36 hours), longer deployments would benefit from higher energy density solutions [14].

Sensor Biofouling and Calibration Drift: Despite the self-cleaning mechanism, prolonged deployments in nutrient-rich environments still present challenges for maintaining sensor accuracy.

5.2 Future Research Directions

Integration with Remote Sensing: Combining in-situ measurements with satellite remote sensing data could enhance large-scale monitoring capabilities.

Advanced Materials and Energy Solutions: Research into novel nanomaterials for sensor protection and more efficient energy storage systems could extend operational duration.

Enhanced Machine Learning Models: Development of hybrid deep learning approaches incorporating both spatial and temporal dimensions could improve prediction accuracy.

Environmental DNA Integration: Incorporating eDNA analysis could provide early warning of harmful species presence before they reach bloom concentrations.

Swarm Intelligence Enhancement: Further development of multi-vessel coordination algorithms based on swarm intelligence principles could optimize coverage patterns [15].

6. Summary

The Smart unmanned monitoring and control system described in this paper represents a significant advancement in technology for algal bloom management. Field validation confirmed the system's superior performance, with multi-vessel configurations achieving 196% increase in monitoring coverage while the ultrasonic treatment system demonstrated 87.2% removal efficiency for cyanobacteria species.

While challenges related to turbidity interference, communication reliability, and energy management remain, continued research and technological development promise to overcome these limitations. As water quality challenges continue to grow globally, comprehensive solutions like the one presented in this paper will become increasingly valuable for protecting aquatic ecosystems and ensuring water security.

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