Artificial Intelligence and Machine Learning Applications in Aquaculture Engineering: A Review

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ABSTRACT

In order to meet the demand for seafood around the world, aquaculture is growing quickly. However, it confronts several obstacles, such as environmental unpredictability, effective feed use, disease outbreaks and sustainable production. Aquaculture engineering can benefit from data-driven solutions that improve monitoring, automation, decision support and predictive analytics by integrating Artificial Intelligence (AI) and Machine Learning (ML). With an emphasis on water quality management, feeding optimization, disease detection, biomass estimate and intelligent control systems, this study examines recent advancements in AI/ML technologies used to aquaculture. The development of reliable, scalable and sustainable smart aquaculture systems is guided by challenges and future research directions.

KEYWORDS

Artificial Intelligence (AI), Machine Learning (ML), Aquaculture Engineering, Monitoring.

1. INTRODUCTION

Aquaculture plays a crucial role in global food security and economic development yet faces challenges due to intricate environmental factors, workforce restrictions and sustainability demands. Conventional management methods frequently fall short in terms of real-time adaptability and forecasting ability. Improvements in sensor technology, data analysis and computational capabilities have driven the integration of AI and ML methods in aquaculture engineering, facilitating smart, self-sufficient and effective operations. AI denotes systems that can make decisions similar to humans, whereas ML, a branch of AI, emphasizes algorithms that enhance performance by learning from data. Deep learning (DL), reinforcement learning (RL), and hybrid intelligence systems serve as effective tools in this scenario.

Recent review studies indicate that AI and ML are revolutionizing aquaculture, shifting it from conventional methods to data-informed intelligent operations, facilitating advancements in environmental management, fish well-being and production efficiency.

2. DATA ACQUISITION AND SYSTEM ARCHITECTURE

2.1 Sensors and IoT Integration

Contemporary aquaculture systems utilize sensor arrays to monitor water quality factors including pH, Temperature, Dissolved oxygen (DO), Turbidity, Free CO_2 and Ammonia concentrations etc. Connection with the Internet of Things (IoT) enables instant data transfer

to centralized systems for AI evaluation. IoT sensors are the foundation of intelligent aquaculture, facilitating automated data gathering, storage and remote accessibility for ML models.

2.2 AIoT System Architecture

AIoT (Artificial Intelligence + IoT) frameworks generally feature edge devices for gathering data, cloud servers for storage, processing, ML models for analysis and decision-making assistance. For instance, intelligent cage systems combine underwater cameras, environmental sensors and communication networks to provide extensive data streams that AI algorithms analyze for feed management and health tracking.

3. AI AND ML APPLICATIONS IN AQUACULTURE

3.1 Water Quality Monitoring and Prediction

The quality of water is essential for the health and productivity of fish. ML models such as regression trees, support vector machines and deep recurrent architectures like CNN-LSTM have been utilized to forecast water quality parameters from time series sensor data with a high degree of accuracy. Hybrid approaches integrating CNN for feature extraction with LSTM/GRU for temporal dependencies have exceeded the performance of independent models in multi-site assessments.

3.2 Smart Feeding and Optimization

Feeding constitutes a significant operational expense in aquaculture. Excessive feeding results in waste and damage to the environment, whereas insufficient feeding hinders growth. AI-driven feeding systems utilize vision and behavioural analysis to customize feed distribution.

3.2.1 Vision and Behavioural Models

Computer vision systems assess fish behaviour while feeding, employing neural networks to evaluate satiation and adjust feed quantities. Models integrating CNN with GRU networks have been created to forecast feed rations according to fish size and environmental factors, resulting in accurate control and reduced waste.

3.2.2 Reinforcement Learning

Adaptive feeding strategies have been designed using reinforcement learning frameworks, which learn the best feeding rates by interacting with real or simulated surroundings. These RL approaches seek to enhance growth while reducing feed expenses and environmental effects.

3.3 Fish Health and Disease Detection

Timely identification of diseases is vital for lowering death rates and promoting well-being. Conventional approaches depend on manual evaluation, which is labour-intensive and biased.

AI and ML models especially deep learning architectures such as CNNs currently automate the detection of diseases using images and behavioural information.

Diagnosis via Images- Deep learning algorithms trained on annotated datasets of both healthy and infected fish are capable of accurately classifying disease conditions. Certain methods integrate CNN with feature enhancement and attention mechanisms to boost performance, facilitating real-time diagnosis even in environments with limited resources.

Predictive Analytics- Machine learning models utilize environmental sensor information and past disease data to anticipate outbreak risks, providing practical insights for preventive measures.

3.4 Biomass Estimation and Growth Prediction

Accurate estimation of fish biomass aids in planning for harvests and making stocking choices. Conventional sampling techniques require significant labour and cause disruptions. ML models employing imaging and object detection techniques like YOLO and Mask-RCNN have attained high accuracy in real-time estimation of fish counts, size and weight causing minimal disruption to fish.

3.5 Automation and Robotics

Autonomous systems, such as underwater robots and UAVs (drones), are utilized for inspection, maintenance and monitoring activities. Reinforcement learning improves adaptive control functions, allowing robotic systems to react to changing environmental signals and carry out tasks like cage inspection or net cleaning with minimal human oversight.

4. Methodologies and Algorithms

AI in aquaculture includes a wide range of techniques:

Supervised Learning

SVM, Random Forest, KNN and neural networks for classification and regression tasks (for example- categories of water quality, states of disease).

Deep Learning

CNNs, RNNs (LSTM/GRU) for analyzing images and predicting time-series data.

Reinforcement Learning

Q-learning and policy gradient methods for optimal control challenges like feeding approaches.

Hybrid Models

CNN-LSTM and multimodal fusion networks integrating visual and sensor information to improve feature representation and decision precision.

5. CHALLENGES AND LIMITATIONS

Despite the promise of AI and ML, several challenges persist:

5.1 Data Quality and Availability

AI systems rely on extensive amounts of high-quality annotated data. Limited data, fragmented sensor data and unreliable environmental readings hinder model effectiveness, particularly in small-scale farming.

5.2 Model Interpretability and Adoption

Numerous sophisticated models function as "black boxes," hindering understandability and acceptance by professionals. Methods of Explainable AI (XAI) are essential for establishing trust and transparency.

5.3 Infrastructure and Cost

Implementing AIoT systems incurs expenses for sensors, connectivity, and computing resources. Significant capital costs may restrict adoption in developing areas, although affordable, modular solutions are starting to appear.

6. FUTURE DIRECTIONS

Future studies should concentrate on:

- Merging AIoT and edge computing for immediate analytics with minimized latency and bandwidth requirements.
- Multimodal data integration combining environmental, visual and acoustic information for comprehensive decision assistance.
- Digital replicas for modeling and enhancing aquaculture systems.
- Models focused on sustainability that enhances economic performance while considering environmental impact indicators.

7. CONCLUSION

Artificial intelligence (AI) and machine learning (ML) are swiftly reshaping aquaculture engineering by facilitating precise monitoring, smart automation and data-informed decision-making throughout production systems. Sophisticated applications like intelligent feeding optimization, immediate water quality forecasting, automated illness detection, behavior assessment and biomass evaluation have shown notable enhancements in feed efficiency, survival rates, environmental sustainability and general economic performance. The combination of AIoT platforms, computer vision, deep learning and reinforcement learning boosts system agility and scalability, promoting accurate aquaculture methods.

Even with these encouraging developments, various obstacles impede wide-scale implementation, such as the scarcity of well-characterized and annotated datasets, substantial upfront deployment and upkeep expenses, infrastructure limitations in rural aquaculture environments and issues surrounding model interpretability, transparency and dependability. Moreover, the ability of AI models to generalize across different species, cultural systems and geographic areas is still a significant research gap.

Advancements in intelligent aquaculture will rely on robust interdisciplinary cooperation among aquaculture engineers, data scientists, biologists and policymakers. Focusing on explainable AI, affordable sensor development, edge computing and uniform data frameworks will be crucial for effective implementation. Through ongoing innovation and careful implementation, AI and machine learning technologies can create robust, efficient and environmentally sustainable aquaculture systems that meet the increasing worldwide need for aquatic food sources.

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