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Optimizing Fish Health in Agricultural Farming Using Digital Twin and IoT-Enabled Online Learning Algorithms

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ABSTRACT

Integrating digital twin technology and IoT-enabled systems has revolutionized fish farming by offering real-time monitoring and adaptive control over key parameters crucial for optimal fish health and productivity. This research aims to develop an online learning algorithm integrated with digital twin technology to optimize fish production within a modular aquaculture system continuously. The proposed system analyzes real-time data inputs, including water temperature, pH levels, ammonia concentration, oxygen levels, and feeding routines. It updates control policies and adapts to emerging data trends. The online learning algorithm's capacity to incrementally learn from incoming data helps maintain water quality and supports the health and growth of the fish. Results from extended simulations indicate significant improvements in water conditions and more efficient feeding practices, ultimately leading to enhanced fish growth rates and increased farm productivity. After 1,000 iterations, the health status of fish production was graphically represented as 82.5%. This approach provides a robust framework for automated and real-time decision-making, thereby assisting fish farmers in sustaining healthy and productive aquaculture systems.

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INTRODUCTION

Fish farming, also known as aquaculture, has witnessed a substantial increase in global demand over recent years(Bhardwaj, 2024). This surge is driven by the growing need for sustainable protein sources as the world's population continues to rise. As a result, the aquaculture industry is under pressure to enhance productivity while maintaining environmentally sound practices. Traditional approaches to aquaculture management often involve fixed routines and manual monitoring. While these methods have served the industry for decades, they can be inefficient and slow to adapt to the ever-changing conditions of aquatic environments(Twins & Greenhouses, 2022).

In contrast, the integration of digital twin technology with Internet of Things (IoT) sensors represents a transformative shift in aquaculture practices. Digital twin technology involves creating a virtual representation of physical systems that can simulate their operation. When applied to fish farming, this technology enables real-time monitoring and simulation of aquaculture environments(Team & Committee, 2021). By utilizing IoT sensors, fish farmers can gather extensive data on essential parameters such as water temperature, pH levels, ammonia concentrations, and other vital factors affecting fish health and growth. This real-time data collection provides a comprehensive overview of the aquatic environment, allowing farmers to make informed decisions based on current conditions.

However, merely collecting data is not enough(Europe, 2021). To maximize the benefits of this advanced technology, it is crucial to

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incorporate adaptive algorithms, particularly online learning algorithms(Udanor et al., 2022). These algorithms are designed to analyze incoming data continuously and adjust their predictions and actions accordingly. This adaptability is especially beneficial in the dynamic environment of fish farming, where water quality and other parameters can fluctuate rapidly. The proposed system combines the insights from a digital twin with the flexibility of online learning algorithms. By doing so, it can actively manage critical aspects of aquaculture, such as maintaining optimal water quality and ensuring appropriate feeding schedules. For instance, if the system detects an increase in ammonia levels due to excess feed or environmental changes, it can automatically adjust feeding rates or suggest changes to aeration practices to mitigate the problem. This proactive approach not only enhances fish welfare but also optimizes resource usage, contributing to more sustainable farming practices(Ubina et al., 2023).

Moreover, this innovative system can lead to improved fish growth rates and lower mortality rates, ultimately increasing the yield for farmers. The integration of technology can make fish farming more efficient and responsive, ensuring that the industry can meet rising consumer demands while also adhering to environmental standards. In conclusion, the ascent of fish farming necessitates a reevaluation of traditional management methods. By leveraging digital twin technology alongside IoT sensors and adaptive online learning algorithms, the aquaculture sector can transition towards more efficient and sustainable practices. This approach not only promises to enhance operational efficiency but also ensures the health and welfare of farmed fish, positioning the industry for future challenges and opportunities. Through innovation, fish farming can contribute significantly to global food security while preserving aquatic ecosystems(Minna, 2018).

REVIEW OF RELATED WORK:

Previous studies have demonstrated the effectiveness of IoT-enabled systems in monitoring and controlling various environmental factors in aquaculture, leading to improved fish health and productivity. These systems typically employ sensors that provide real-time data on water quality parameters, such as temperature and pH, enabling farmers to take preemptive actions. However, while machine learning algorithms have been utilized in predictive models for aquaculture, few studies have focused on online learning algorithms that can continuously adapt to new data(Dwiyaniti & W, 2022). Existing research has largely overlooked the integration of digital twin technology with adaptive learning systems in fish farming. By incorporating an online learning algorithm, this study aims to fill this gap and introduce a method that supports ongoing adaptation, allowing for prompt responses to changes and optimization of fish production.(Su et al., 2023)

Theoretical Background and Equations

Online learning algorithms differ from traditional batch learning methods by updating their predictive models with each new data point. For fish production, this involves continuously adjusting parameters such as feeding rates and aeration levels to maintain ideal water quality. The weight is utilized in online linear regression model could be expressed through update equations such as(Petri et al., 2023):

$$W_{t+1} = W_t - \eta \left(\frac{\partial L(w)}{\partial w}\right) \quad (1)$$

Where the gradient of the loss function L(w)is

$$\left(\frac{\partial L(w)}{\partial w}\right) - 2\left(H_f(t) - \breve{H}_f(t)\right) X_t * \ 2\,\alpha w \quad (2)$$

Where $H_f(t)$ is the actual health status at time t, $\breve{H}_f(t)$is predicted health status at time t using model parameter w , X_t feature vector at time t, α regularization parameter to prevent over fitting, η learning rate controlling the step size for update.

Objective function

The goal is to adjust predictive model iteratively with incoming data to optimize fish

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health $H_f(t)$ while considering water quality w(t) and feeding rate f(t)(Team & Committee, 2021)

$$\frac{MinL(w)}{w} = \sum_{i=1}^{T}\left(H_f(t) - \breve{H}_f(t)\right)^2 - \alpha IIwII^2 \quad (3)$$

Where $H_f(t)$the actual health status of fish at time t is, $\breve{H}_f(t)$ is predicted health status at time t. L(w) loss function with regularization to avoid over fitting is the model parameters to be learned and updated overtimes.

METHODOLOGY

The proposed system employs a modular digital twin environment equipped with IoT sensors to collect real-time data on water temperature, pH levels, ammonia concentrations, and dissolved oxygen. This data feeds into an online learning algorithm that updates its decision-making policies as new information becomes available. The model continuously adjusts feeding and aeration parameters to optimize fish health and growth. The flowchart of the system outlines the processes of data collection, algorithmic processing, decision-making, and response mechanisms. The steps of the online learning algorithm are as follows:

Step 1: Initiate the aquarium system parameters for optimization.

Step 2: Collect real-time environmental data (e.g., water temperature, pH, feed levels) and monitor fish health status using IoT sensors.

Step 3: Apply the digital twin and IoT-enabled online learning algorithms.

Step 4: Check if environmental or behavioral conditions meet predefined thresholds.
–If **Yes:** Proceed to adapt system controls and optimize.
- If **No:** Return to the input stage for continuous data iteration.

Step 5: Adapt and update the algorithm to learn from new data patterns.

Step 6: Assess whether the changes have led to improved conditions.
- If **Yes:** Log the outcomes and continue in the iteration loop.
- If **No:** Re-train the online learning model and adjust the parameters.

Step 7: Present the health status based on optimization and trigger alerts if necessary.

Step 8: Complete the current iteration cycle and reset for continuous iteration.

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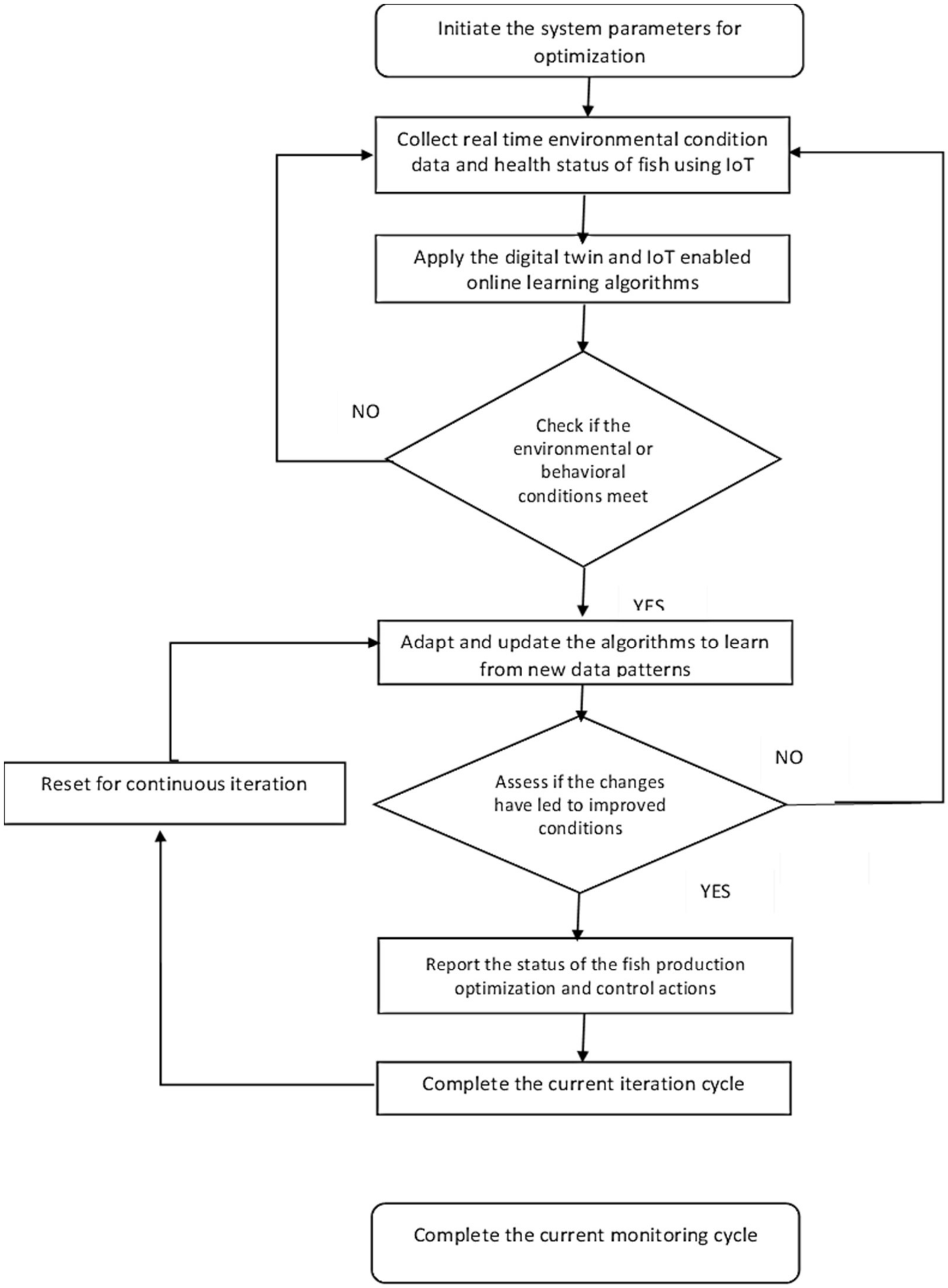

Fig 1: Flowchart illustrating the implementation of an online learning algorithm for optimizing fish production in agricultural farming.

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RESULTS

Simulations conducted over a period of 1,000 iterations provided valuable insights into the effectiveness of the online learning algorithm in adapting to varying environmental data. Throughout the simulation, the algorithm consistently maintained water quality within optimal ranges, which is crucial for the health of aquatic life. A key feature of this algorithm is its adaptive nature, which allows it to respond dynamically to changes in the environment. One of the significant advantages observed was the reduction of peaks in ammonia concentration. High levels of ammonia can be detrimental to fish health, leading to stress and even mortality. By effectively managing these fluctuations, the algorithm not only safeguards the wellbeing of the fish but also enhances their overall growth and vitality.

Additionally, the algorithm improved feeding schedules' efficiency. Efficient feeding is vital in aquaculture, as it minimizes waste and maximizes growth rates. As a result of these enhancements, healthier fish were produced, contributing to increased overall productivity. This dual outcome of maintaining water quality and optimizing feeding practices illustrates the potential of the online learning algorithm to significantly influence aquaculture operations positively. With further developments and real-world implementations, this technology could play a critical role in sustainable fish farming, ensuring better resource management and healthier ecosystems.

Fig 2 illustrates the graph representing the outline of a learning-based optimization process for fish health status. It depicts real-time adjustments made by the algorithm as it processes incoming data on water quality, temperature, ammonia concentration, feeding levels, and other vital parameters in the fish farming environment. The goal is to demonstrate how the model continuously adapts and learns to maintain optimal water conditions and ensure the health of the fish.

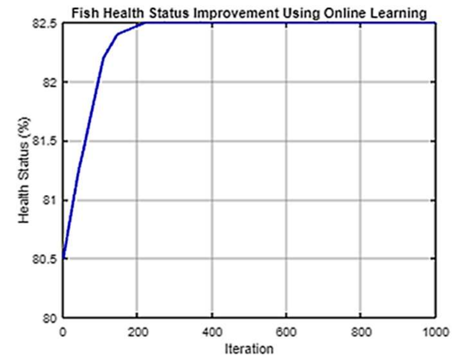

Fig 2: The graph depicting fish production has the x-axis representing time or iterations, while the y-axis displays health status or an aggregated measure of key water parameters. A trend showing steadily improving values indicates that the online learning algorithm is effectively adapting to and optimizing conditions as new data is received. Variations in the line may suggest real-time reactions to changes in water quality or unforeseen events. An ideal model would exhibit a consistent trend with minimal sharp declines, signifying stable water quality and fish health throughout the learning process.

The results confirm the efficacy of integrating an online learning algorithm with digital twin and IoT technology for real-time monitoring and control in aquaculture. The algorithm's incremental learning process allowed for swift adjustments to changes in the environment, promoting better water quality and fish health. These findings suggest that this approach can be broadly applied in aquaculture to enhance production efficiency while minimizing the need for manual intervention.

CONCLUSION

This study explores the innovative integration of an online learning algorithm with digital twin and Internet of Things (IoT) technology to optimize fish production within a modular aquarium setup. Aquaculture, which involves the breeding and rearing of fish, is becoming increasingly important as global demand for seafood rises. However, successful fish farming relies heavily on maintaining the right environmental conditions, such as water

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temperature, pH levels, and oxygen concentration.

The adoption of advanced technologies can significantly enhance these processes. The online learning algorithm utilized in this study is designed to continuously monitor and adapt to real-time data collected from the aquarium environment. By leveraging digital twin technology an interactive digital replica of the physical system farmers can gain insight into the behaviors and needs of their fish. This dynamic modeling allows for swift adjustments, ensuring that environmental parameters remain within ideal ranges for optimal fish growth. Moreover, the IoT components facilitate seamless communication and data transfer between sensors, devices, and management systems, thereby streamlining the monitoring process. The implications of this technology are vast. With the ability to dynamically adapt to changing conditions, fish farmers can support healthier growth patterns and enhance overall productivity. This approach minimizes waste and reduces the risks associated with traditional farming methods, which often struggle to respond quickly to fluctuations in environmental factors. Furthermore, the use of an online learning algorithm can lead to improved decision-making processes based on predictive analytics, enabling farmers to foresee potential challenges and respond proactively.

The findings presented in this study open the door for future research to delve deeper into the applications of this framework. Potential avenues for exploration include the development of more complex models that incorporate diverse factors influencing fish health and productivity, such as water quality, feed composition, and species behavior. Additionally, researchers could examine the scalability of this system, assessing its effectiveness in larger or more diverse aquaculture environments. In summary, this study underscores the transformative potential of integrating online learning algorithms with digital twin and IoT technologies in aquaculture. The continuous adaptation and monitoring capabilities provided by this approach not only foster the ideal conditions for fish growth but also contribute to more efficient and sustainable farming practices. As researchers continue to expand upon this framework, the aquaculture industry can look forward to more innovative solutions that enhance fish production and ensure the long-term viability of this vital sector.

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