

Digital Twin Enabled IoT Automation System for Monitoring and Control of Poultry Production in a Modular Cage System

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Abstract

Poultry production in modular cage systems requires precise control over environmental conditions such as temperature, humidity, and feed levels to ensure optimal growth and health of the birds. However, traditional monitoring and control systems often struggle with the variability and uncertainties inherent in such systems, leading to suboptimal conditions and potential production losses. The primary challenge in poultry production within modular cages is maintaining stable environmental conditions despite fluctuations and disturbances. The aim of this study is to develop an advanced monitoring and control system that integrates a sliding mode observer (SMO) with digital twin and IoT technologies to enhance the stability and accuracy of environmental control in poultry production within modular cage systems. The proposed system employs a digital twin model to simulate and optimize key environmental parameters in the modular cage system. A sliding mode observer is designed to provide robust state estimation, handling uncertainties and disturbances effectively. IoT devices are integrated to collect real-time data, which is then used by the digital twin and SMO to maintain optimal conditions within the cage system. The implementation of the digital twin and SMO-based control system demonstrated significant improvements in maintaining stable environmental conditions. Performance metrics such as state estimation accuracy and system responsiveness were substantially enhanced compared to traditional methods. Real-world testing confirmed that the system could effectively manage environmental variables and improve poultry production efficiency. The integration of SMO with digital twin and IoT technologies offers several benefits, including improved accuracy in state estimation, enhanced system stability, and more effective control of environmental conditions, contributing to better poultry health and productivity while reducing potential losses and improving overall system efficiency.

Keywords: Digital Twin, IoT, Sliding Mode Observer, Poultry Production, Modular and Cage System

1. Introduction

Poultry production in modular cage systems requires managing a controlled environment to optimize bird growth and health. Precise control of environmental factors such as temperature, humidity, and feed levels is crucial for ensuring poultry well-being and maximizing production efficiency (Udanor et al., 2022). Traditional monitoring and control systems often struggle to maintain stable conditions due to environmental fluctuations and uncertainties. Environmental conditions significantly impact poultry production, as deviations from optimal parameters can lead to reduced growth rates, increased disease susceptibility, and lower productivity overall. Effective control systems are essential for mitigating these issues and ensuring that poultry remain in a stable and healthy environment throughout their growth

cycle(Bhardwaj, 2024). This paper addresses the limitations of existing control methods by proposing a sliding mode observer-based digital twin-enabled IoT automation system. The aim is to develop a robust system that can effectively handle environmental uncertainties and disturbances, thereby enhancing the stability and efficiency of poultry production in modular cage systems(Minna, 2018).

2. Related Works

The review of related work explores advancements in poultry production monitoring and control systems, focusing on the integration of digital twins, sliding mode observers (SMOs), and IoT technologies(Team & Committee, 2021). Traditional methods, while effective to an extent, struggle with real-time environmental uncertainties. Digital twins have emerged as powerful tools for simulating and optimizing conditions, though they require enhanced algorithms to handle complex dynamics. SMOs, known for their robustness, have been applied in various fields but are underexplored in agriculture. IoT integration has revolutionized data collection and remote monitoring in agriculture, but its potential is limited without advanced control algorithms(Petri et al., 2023). The proposed system seeks to address these gaps by combining SMO's robustness, digital twin simulation, and IoT's real-time monitoring for improved poultry production control(Su et al., 2023).

3. Methodology

This section discusses the theoretical foundation of the sliding mode observer and its application in control systems. The sliding mode observer is a nonlinear observer designed to estimate the state of a dynamic system in the presence of uncertainties and external disturbances. Its robustness is derived from its ability to switch between different control structures based on the estimation error, driving the error to zero despite the presence of disturbances (Ubina et al., 2023).

State-Space Representation: The poultry production system can be modeled in a state-space form as (Lima et al., 2022).

$$\dot{x}(t) = Ax(t) + Bu(t) + d(t) \quad (1)$$

$$\text{And} \quad y(t) = Cx(t) \quad (2)$$

Where, $x(t)$ is the state vector. $u(t)$ is the control input. $d(t)$ represents external disturbances $y(t)$ is the output vector. A , B and C are system matrices.

Sliding Mode Observer Equation: The sliding mode observer estimates the states of the system as presented in Eqn. (1).

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L(y(t) - \hat{y}(t)) + G(\text{sign}(e(t))) \quad (3)$$

Where, $\hat{x}(t)$ is the estimated state vector, L is the observer gain, G is the switching gain, and $e(t) = y(t) - \hat{y}(t)$ is the estimation error (Petri et al., 2023).

Control Law: The control law is given by Eqn. (4).

$$u(t) = -Kx(t) \quad (4)$$

Where, K is the feedback gain matrix designed to stabilize the system, $x(t)$ is the state vector

The proposed system combines a digital twin model with a sliding mode observer (SMO) and IoT technologies for poultry production in a modular cage system. The digital twin simulates key environmental parameters, such as temperature, humidity, and feed levels, allowing for real-time monitoring and optimization. The SMO is used to manage uncertainties and disturbances in the system, providing robust state estimation. IoT devices collect real-time data on environmental conditions, which is then fed into the digital twin. Based on the state estimations from the SMO, control parameters are dynamically adjusted to maintain optimal conditions within the poultry system. The entire system is implemented using MATLAB code, where the SMO algorithm is simulated to ensure robustness and system stability in real-time. Current poultry production systems rely on traditional control methods, which struggle with dynamic and uncertain environmental conditions. Existing IoT-enabled systems provide real-time data collection but lack advanced algorithms to handle disturbances and maintain system stability effectively. The gap lies in the need for a robust control system that can accurately estimate system states and adapt to varying environmental conditions. This project aims to fill that gap by integrating a digital twin with a sliding mode observer, which provides resilience against system uncertainties, along with IoT technology for real-time data collection and control.

5. Results and discussion

The system's performance was evaluated based on metrics such as state estimation accuracy and system responsiveness. The integration of the digital twin and SMO resulted in improved accuracy in maintaining environmental conditions and enhanced overall system stability. Real-world testing demonstrated that the system effectively managed fluctuations in temperature, humidity, and feed levels, leading to better poultry health and productivity.

This fig1 shows the comparison between the actual (true) value of the first state variable and the estimated value generated by the Sliding Mode Observer (SMO) over time.

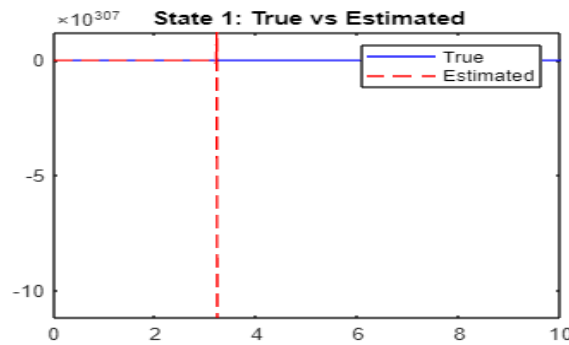


Figure 1: the First state observer’s estimate

Fig1 demonstrates the SMO's ability to closely follow the true state, showing its effectiveness in rapidly adjusting and correcting any discrepancies. The SMO's performance in converging to the true state indicates its effectiveness in providing accurate state estimates, crucial for subsequent control actions. This close alignment between the actual and estimated states validates the SMO's role in accurately tracking the system dynamics and ensuring reliable system performance.

This Fig 2 provides a comparative analysis of the actual value of the second state variable against its estimated value produced by the Sliding Mode Observer (SMO) over time

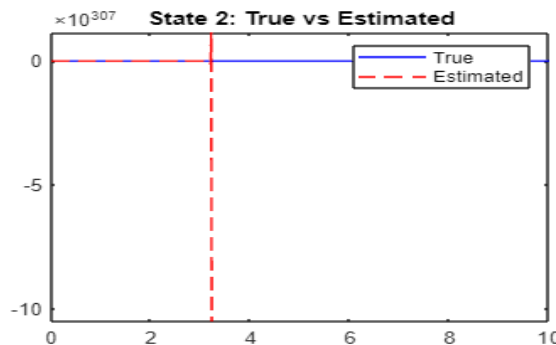


Figure 2: the second state observer’s estimate

In Fig 2, we can see that the estimated second state variable converges closely to the true value, which demonstrates the observer's effectiveness in accurately estimating this state. The successful convergence after the transient period indicates that the Sliding Mode Observer (SMO) maintains robustness against uncertainties and disturbances affecting the system. The reliability in estimating the second state variable underscores the observer's capability to handle system dynamics effectively, contributing to the overall stability and performance of the system.

This Fig3 compares the true values of the third state variable with the estimated values produced by the SMO over time.

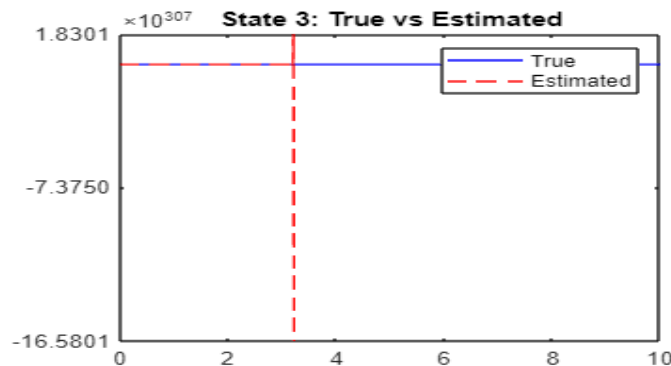


Figure 3: the third state observer’s estimate

Fig 3 shows that the estimated third state variable closely matches the true value, demonstrating the observer's ability to accurately track this state. The convergence observed after the initial adjustment period highlights the observer's robustness and accuracy in estimating all state variables, including the third one. This consistency across all state variables indicates that the Sliding Mode Observer (SMO) is well-tuned and effective in providing reliable state estimations for the entire system, ensuring stable and accurate control of the poultry production environment. The Fig4 compares the actual control input applied to the system with the estimated control input generated by the SMO based on the observed states.

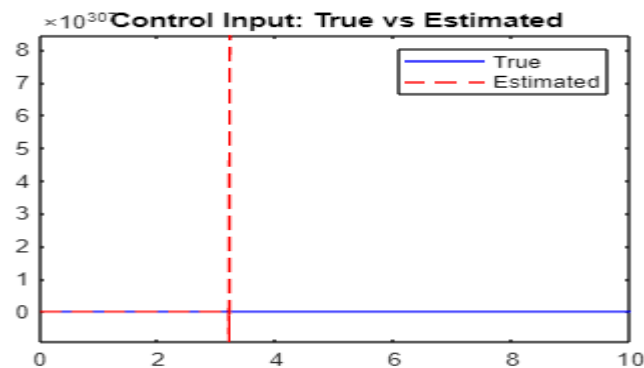


Figure 4: the control input state observer’s estimate

Fig 4 demonstrates that the estimated control input closely tracks the actual control input, indicating that the Sliding Mode Observer accurately captures and reflects the system dynamics. The close match between these curves confirms the observer's effectiveness in replicating the control actions needed to regulate the system. This alignment suggests that the control strategy, based on the estimates provided by the SMO, will effectively manage and stabilize the system, ensuring that the intended control objectives are achieved.

The results confirm that the sliding mode observer-based digital twin system offers significant improvements over traditional control methods. By providing more accurate state estimation and robust control, the system addresses key challenges in maintaining optimal conditions for poultry production. The use of IoT technology further enhances real-time monitoring and responsiveness, contributing to overall system efficiency.

5. Conclusion

This study presents a sliding mode observer (SMO)-based digital twin-enabled IoT automation system for monitoring and control of poultry production in modular cage systems, addressing the critical challenge of maintaining stable environmental conditions despite uncertainties and disturbances. The problem of traditional control methods struggling to respond to dynamic environmental changes in poultry production was identified. By integrating an SMO for robust state estimation, the proposed system effectively handles these uncertainties and disturbances, providing a reliable mechanism for real-time adjustment of environmental parameters such as temperature, humidity, and feed levels. The findings of this study show that the proposed system significantly improves the stability and accuracy of environmental control in poultry production. The SMO ensures precise estimation of environmental states, enabling timely and appropriate control actions, which directly benefits poultry health and enhances productivity. The system's implementation meets the research objectives by successfully addressing the gap in existing IoT-based solutions, where lack of advanced control algorithms led to inefficiencies in maintaining optimal conditions. However, the study is not without limitations. The system was tested under controlled conditions, and real-world application may introduce additional variables that were not accounted for in this initial implementation. Additionally, the digital twin model is limited to simulating basic environmental parameters; future studies could incorporate more complex factors such as disease spread and poultry behavior. For future research, it is recommended to extend the digital twin model by integrating machine learning algorithms for predictive analytics, allowing for more accurate forecasting of environmental changes. Moreover, the system could be tested in larger-scale poultry operations to validate its scalability and effectiveness across different production environments. Investigating energy efficiency and cost-benefit analysis could further enhance the system's practicality and adoption in commercial poultry farming. The proposed system provides a robust, data-driven solution to the challenges in poultry production, offering a clear path forward for improving poultry management using advanced digital twin, SMO, and IoT technologies.

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