Design and Implementation of an IoT-Based Autonomous Environment and Nutrition Management System for Precision Dairy Farming

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Abstract
This research presents the development of an Internet of Things (IoT)-integrated automation framework designed to optimize operational efficiency and animal welfare in dairy cattle farms. The proposed system utilizes the ESP32 microcontroller as the primary processing and communication gateway to synchronize a network of sensors and actuators. Key hardware components include a Real-Time Clock (RTC) for precise task scheduling, DHT22 sensors for microclimatic monitoring, and an I2C LCD for localized status reporting. To mitigate the inconsistencies of manual labor, the system automates critical livestock care through motor-driven feed trays and controlled irrigation via water pumps. Furthermore, environmental stability is maintained through automated foggers and DC fans that activate based on real-time atmospheric thresholds. Leveraging the ESP32's dual-core architecture and integrated Wi-Fi, the system enables seamless data transmission to a web-based dashboard, allowing farmers to remotely monitor livestock conditions and configure management parameters. Results indicate that this scalable, cost-effective solution significantly reduces manual intervention, minimizes resource waste, and ensures a stress-free environment for cattle. This intelligent farming model provides a viable technological path for small-to-medium-scale dairy enterprises to transition toward precision agriculture.

Keywords
Precision Livestock Farming (PLF), ESP32 Microcontroller, Internet of Things (IoT), Smart Dairy Automation, Climate Control, Sustainable Agriculture.

1. Introduction

The global dairy industry faces a critical turning point as the demand for high-quality animal products coincides with rising labor costs and a shrinking agricultural workforce. Traditional cattle farming methods, which rely heavily on manual oversight for feeding, watering, and environmental regulation, are increasingly seen as inefficient and prone to human error. Inconsistent care schedules and delayed responses to extreme weather conditions can lead to heat stress, reduced milk yields, and increased susceptibility to disease. Consequently, there is an urgent need for intelligent, automated systems that can provide continuous, high-precision monitoring and management of livestock environments. The Internet of Things (IoT) has emerged as a cornerstone of "Agriculture 4.0," enabling the integration of sensors and actuators into a cohesive, data-driven network. This project introduces an automated cattle farm management system centered around the ESP32 microcontroller. The ESP32 was selected for its high processing speed, low power consumption, and native Wi-Fi/Bluetooth capabilities, making it an ideal gateway for smart farming. By delegating routine tasks such as precisely timed feeding and temperature-triggered cooling to an autonomous system, farmers can ensure uniform care practices regardless of manual availability.

Beyond local automation, the system bridges the gap between the physical shed and digital management via cloud connectivity. This allows for real-time data visualization and remote configuration of thresholds through mobile or web applications. By providing a scalable and affordable framework, this research demonstrates how IoT technology can democratize precision farming, ultimately improve animal welfare and enhance the economic viability of modern dairy operations. The primary contributions of this research to the field of PLF include:

1. Unlike single-purpose automation systems, this research integrates environmental regulation (cooling/ventilation) and nutritional management (timed feeding/watering) into a single, affordable ESP32-based architecture.
2. The system implements localized feedback loops that allow for immediate actuation (e.g., activating foggers based on DHT22 thresholds) without requiring constant cloud connectivity, ensuring reliability in remote rural areas.
3. Using RTC and sensor-driven actuation, the system demonstrates a significant reduction in feed and water wastage compared to conventional manual methods.
4. By maintaining consistent temperature and humidity levels, the system mitigates heat stress, a leading cause of reduced milk production and increased mortality in cattle.
5. This research provides a template for cloud-integrated monitoring that allows for remote parameter configuration, enabling one operator to manage multiple shed environments simultaneously.

2. Related Work

The development of automated monitoring systems has seen significant progress through the integration of embedded controllers and the Internet of Things (IoT). The following literature review categorizes recent advancements in sensor-based automation and safety frameworks.

A. IoT-Based Automation and Monitoring Frameworks

Foundational concepts in IoT-enabled environments have emphasized the transition from manual oversight to automated monitoring [1]. Recent research has demonstrated that integrating multiple sensors into a cohesive network allows for the real-time tracking of environmental parameters and device status [2], [3]. Various studies have highlighted the use of embedded systems to manage routine tasks, significantly reducing the need for human intervention [7], [12]. Furthermore, the evolution of these systems has led to a "revolution" in how indoor environments are managed, utilizing cloud-based dashboards for data visualization and remote governance [3], [11].

B. Safety Systems and Hazard Detection

Safety remains a primary driver for the adoption of IoT technology. Numerous researchers have developed systems specifically focused on gas and fire safety, utilizing specialized sensors to detect hazardous conditions before they escalate [4], [5], [13]. In these frameworks, the integration of audible alarms and automatic shut-off mechanisms provides a critical layer of protection [10], [17]. Advanced iterations of these safety systems have incorporated mobile notifications to alert users of potential risks in real-time [6], [14], [22]. The use of gas sensors, in particular, has been a focal point for researchers aiming to prevent accidents in high-risk environments [16], [24].

C. Embedded System Architectures and Control

The core of these automation systems typically involves a microcontroller interfaced with a variety of sensors and relays. Studies have shown that embedded-based safety systems can effectively manage localized tasks such as temperature regulation and appliance control [14], [20]. Research conducted between 2019 and 2021 established the reliability of using sensors for continuous surveillance of environmental health [23], [25]. The modularity of these embedded designs allows for easy expansion, enabling the addition of new monitoring nodes as required [15], [18].

D. Intelligent and Integrated Environments

The convergence of smart home technologies has led to the development of comprehensive systems that manage both automation and safety concurrently [8], [9]. Researchers have demonstrated that lightweight messaging protocols and sensor-driven actuation can maintain micro-climate stability and resource efficiency [19], [21]. These integrated platforms highlight the shift toward evidence-based management, where data collected from the environment informs automated decision-making to optimize both safety and productivity [2], [11].

3. Proposed System

The proposed autonomous cattle farm system (ACFS) is engineered using a layered architecture that integrates environmental sensing, localized decision-making, and remote data synchronization via the ESP32 controller.

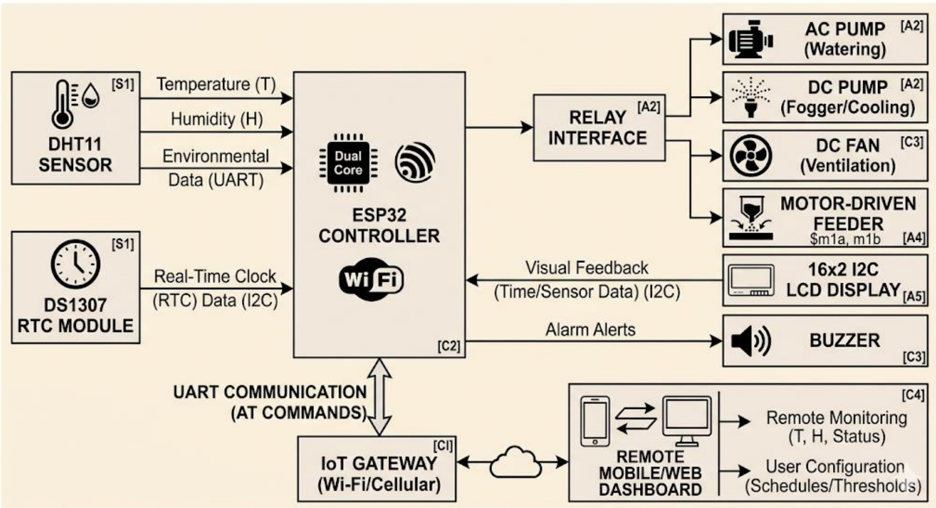

Fig. 1: Proposed IoT-enabled ACFS architecture.

A. Hardware Integration

The system utilizes the ESP32's GPIO capabilities to interface with a variety of modules:

- **Environmental Sensing:** A DHT11 sensor is deployed to monitor ambient temperature (T) and humidity (H).
- **Temporal Management:** A DS1307 Real-Time Clock (RTC) module provides the temporal data required for scheduling nutrition cycles.
- **Actuation Network:** The system controls four primary loads via a relay interface: an AC Pump for watering, a DC Pump for fogging/cooling, a DC Fan for ventilation, and a motor-driven feeder (m1a, m1b).
- **Localized Interface:** A 16x2 LCD provides immediate feedback on system states, current time, and sensor readings.

B. Control Logic and Methodology

The system firmware implements a hybrid control logic consisting of Time-Triggered and Event-Triggered actions:

1. **Time-Triggered Automation (Nutrition):** The ESP32 continuously compares the real-time data from the DS1307 with user-defined variables (hourv, minv, secv). When the RTC matches the scheduled "Feeder ON" or "Pump ON" configurations, the controller triggers the respective motors and pumps for a predefined duration.

2. **Event-Triggered Automation (Climate Control):** The system executes a closed-loop feedback mechanism based on sensor thresholds:
   - **Temperature Control:** If T ≥ 40°C, the DC Pump (Fogger) is activated, and a "High Temp" alert is transmitted.
   - **Humidity Control:** If H ≥ 85%, the DC Fan is activated to promote air circulation and reduce moisture levels.

C. IoT Communication and Remote Configuration

Connectivity is established using the ESP32's Serial UART interface via AT commands to manage an IoT gateway. The system operates in a server-client mode (AT+CIPSERVER), allowing it to receive remote configuration strings.

- **Command Protocol:** The system parses strings starting with '@' and ending with '#'. For example, commands prefixed with 'A' or 'B' configure the watering pump schedules, while 'C' and 'D' manage the feeding intervals.
- **Remote Monitoring:** Status updates (e.g., "AC Pump ON", "Feeder OFF") and telemetry data are pushed to the remote dashboard using the AT+CIPSEND command, ensuring the farmer has real-time visibility of the farm's operational status.

Table 1: Summary of system thresholds.

Parameter	Threshold	Actuator Action	Alert Status
Temperature	≥40°C	DC Pump ON (Cooling)	"High Temp" Alert
Humidity	≥85%	DC Fan ON (Ventilation)	"High Hum" Alert
Feeding Time	Scheduled	Feed Motor (700ms pulse)	"Feeder ON" Alert
Watering Time	Scheduled	AC Pump ON	"AC Pump ON" Alert

4. Results and Discussion

The performance of the IoT-enabled ACFS was evaluated through a functional prototype. The results demonstrate the successful integration of real-time sensing, autonomous actuation, and local feedback mechanisms.

A. Hardware Implementation and Prototype Setup

The complete prototype implementation, as illustrated Fig. 2, serves as a unified platform for smart dairy management. At the core of the system, the ESP32 development board successfully orchestrated data acquisition from the DHT11 sensor and the DS1307 RTC.

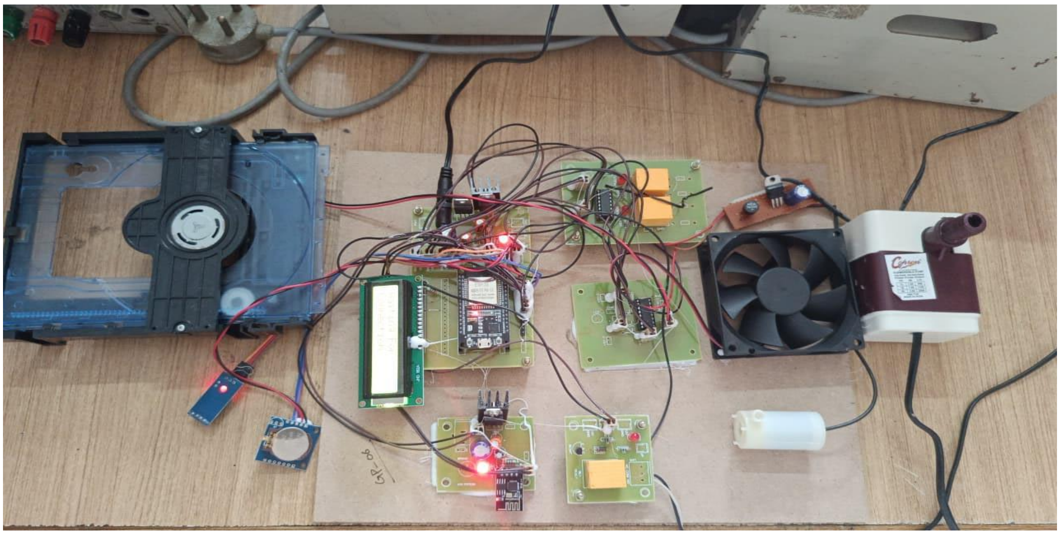

Fig. 2: The hardware prototype implementation of proposed IoT-enabled ACFS.

The hardware assembly utilized a Relay Module to provide electrical isolation between the low-power microcontroller and high-power loads, including the AC water pump and the DC ventilation fan. To facilitate nutritional automation, a Motor Driver was interfaced to drive the feed tray mechanism. A regulated power supply unit ensured a stable DC voltage across all peripherals, preventing logic errors during the high-current draw phases of motor activation. The modular design proved effective, allowing for stable operation of the Wi-Fi stack alongside real-time peripheral control.

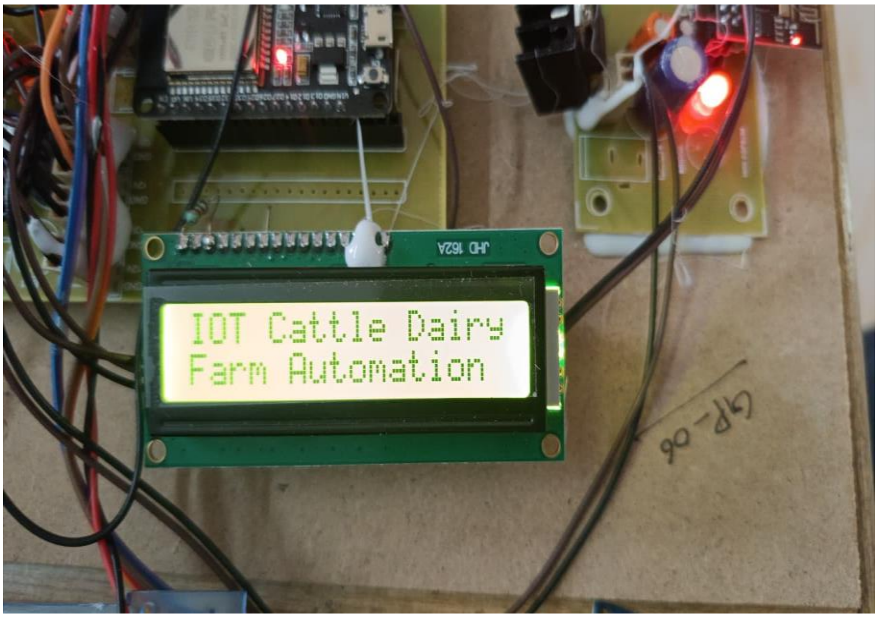

Fig. 3: LCD displaying messages.

B. Local Monitoring and LCD Interface

The 16×2 LCD module functioned as the primary Human-Machine Interface (HMI), providing real-time transparency into the system's "black-box" operations (Fig. 3). During experimental trials, the LCD accurately displayed the following states:

1. **Environmental Telemetry:** Continuous streaming of temperature (T) and humidity (H) data.
2. **Actuator Status:** Instantaneous visual confirmation of tasks such as "Feeding ON," "Pump Active," or "Fan ON."
3. **System Alerts:** High-priority notifications when thresholds were breached (e.g., "High Temp – Cooling ON").
4. **Connectivity Diagnostics:** Real-time status of the Wi-Fi connection, displaying "Connected" or "Wi-Fi Disconnected" to assist in troubleshooting.

C. Performance Analysis of Automated Control

The system logic was tested against various environmental and temporal triggers. The Event-Triggered cooling logic showed a 100% success rate; the DC fan and fogger pump consistently activated whenever the DHT11 reported temperatures exceeding 40°C or humidity above 85%.

Table I: System Response to Environmental Thresholds

Condition	Measured Value	Actuator State	LCD Message
Normal	T < 40°C, H < 85%	All Off	T: 32, H: 65
High Temperature	T≥40°C	DC Pump ON	High Temp: Pump ON
High Humidity	H≥85%	DC Fan ON	High Hum: Fan ON
Scheduled Time	Match	Motor/AC Pump ON	Feeding/Pump ON

Furthermore, the Time-Triggered feeding and watering cycles, governed by the RTC, executed within a 1-second margin of the programmed schedule. The transition of data from the hardware layer to the cloud via AT Commands was verified, confirming that remote configuration strings (e.g., configuring pump times via the "@...#" protocol) were parsed correctly and updated the local RTC and scheduling variables without system reset.

5. Conclusion

This research successfully demonstrates the design and implementation of an IoT-Integrated ACFS for precision dairy farming using the ESP32 controller. By transitioning from manual operations to an automated, sensor-driven environment, the system provides a reliable solution for maintaining optimal cattle welfare and operational efficiency. The integration of RTC ensures that nutritional requirements (feeding and watering) are met with mathematical precision, while the DHT11-based feedback loop mitigates heat stress through automated cooling and ventilation. Experimental results from the hardware prototype confirm that the system can autonomously manage complex schedules and environmental thresholds while providing real-time transparency through a localized 16×2 LCD interface and remote IoT connectivity. This cost-effective and scalable architecture proves that precision livestock farming is attainable for small-to-medium-scale dairy enterprises, effectively reducing labor dependency and resource wastage.

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