International Journal on Smart Material and Mechatronics
IJSMM Vol. 11 No.1 2025 DOI. 10.20342/IJSMM.11.1.491

p-ISSN: 2356-5314
e-ISSN: 2460-075X

Design a Temperature Control System in a Fuzzy Logic-Based Baby Incubator

Rafiuddin Syam, Churnia Sari, Rivaldy Fazri
Automation Engineering Technology Study Program, Faculty of Engineering, State University of Jakarta, Indonesia
rafiuddin_syam@unj.ac.id, churnia.sari@unj.ac.id, rivaldy.fazri7@gmail.com

***Abstract*—Premature infants require a stable temperature of 33–35°C and a humidity of 60–80% RH, but conventional manual incubators have low accuracy (±2–5°C) and are less adaptive to environmental changes. This study designed a temperature and humidity control system for a baby incubator based on an IoT-integrated Adaptive Neuro-Fuzzy Inference System (ANFIS), using an ESP32 microcontroller, DHT22 sensor, as well as a PTC heater actuator, Peltier module, and ultrasonic humidifier. Two ANFIS Sugeno order-1 models are designed for heating and cooling control, each with 2 inputs, 3 Gaussian membership functions, and 9 fuzzy rules of hybrid learning training. The system features manual mode as well as a Firebase-based web dashboard for real-time monitoring. The test results showed the accuracy of the DHT22 sensor with an average error of 2.39%, as well as a first-order thermal incubator model with a dead time of 80 seconds and a time constant of 473.4 seconds. In setpoint tests of 33–35°C, the ANFIS mode is more responsive to the target temperature than the manual mode which tends to be stable below the setpoint, although it results in greater temperature and humidity oscillations. The system is also able to recover the temperature after being given an external interference. These results show that ANFIS improves control responsiveness compared to manual control, but still requires refinement of training data and actuation strategies to suppress oscillations.**

***Index Terms*—ANFIS, baby incubator, ESP32, DHT22, fuzzy logic, IoT.**

I. Introduction

Premature babies, that is, babies born before the 37th week of pregnancy, require a tightly controlled microclimatic environment to maintain their vital functions. Based on Basic Health Research data in 2018, the prevalence of premature births in Indonesia reached 29.5 per 1,000 live births with around 657,700-675,700 cases per year, placing Indonesia in the fifth highest position in the world (Ministry of Health of the Republic of Indonesia, 2018). Globally, the WHO recorded 13.4 million babies born prematurely in 2020, or more than 1 in every 10 births (Ohuma et al., 2023).

Baby incubators are a crucial medical device to provide an environment with a temperature of 32-37°C and a humidity of 50-80% RH according to the SNI IEC 60601-2-19:2014 standard (National Standardization Agency, 2009). Manual incubator systems in regional general hospitals generally have low accuracy (±2-5°C), whereas current medical needs demand accuracy of up to ±0.5°C, considering that effective thermoregulation plays an important role in the safety of neonates (Knobel, 2014). The fuzzy logic-based intelligent control approach has been proven to be able to improve the accuracy of incubator temperature control, for example through a fuzzy logic and independent energy-based system reported by Setiawan et al. (2025), as well as an automatic humidity control system based on the ATMega328 microcontroller developed by Panjaitan et al. (2021).

However, most previous studies still have limitations, which are that they generally only control one environmental variable (temperature or humidity) separately, only provide heating actuators with no active cooling capabilities so that they are susceptible to overshoot, and use fuzzy parameters that are determined based on expert knowledge (expert-tuned) and not automatically optimized through learning algorithms. It is this gap that underlies this research, which offers novelty in the form of: (1) simultaneous dual control of temperature and humidity in one integrated architecture; (2) actuation of active heating (PTC heater) and active cooling (Peltier module) at the same time; (3) control parameters that are automatically optimized through ANFIS with hybrid learning algorithms (Least Square Estimation and gradient descent); (4) two independent order-1 ANFIS Sugeno models for each actuator; and (5) direct quantitative validation between ANFIS mode and manual control on identical hardware prototypes.

The design of IoT systems for simple incubators based on microcontrollers and DHT22 sensors has shown that this combination is commonly used for real-time temperature and humidity monitoring through web-based platforms (Fauzi, 2020). Based on this, this research aims to: (1) build a sensor-based temperature and humidity control system as a basis for decision-making; (2) implement the fuzzy logic method (ANFIS) to regulate the performance of PTC heaters, Peltier modules, and ultrasonic atomizer humidifiers; and (3) evaluate the performance of the system in maintaining the condition of the incubator room in a stable and responsive manner compared to threshold-based manual control.

II. Research Methods

A. Time and Place of Research

The research was carried out in the even semester of the 2025/2026 academic year within the Automation Engineering Technology Study Program, Faculty of Engineering, State University of Jakarta, covering the design stage, hardware assembly, software development, and comprehensive system testing.

B. Research Tools and Materials

The main hardware used includes an ESP32 DEV Kit V1 microcontroller as the main processing unit, a DHT22 sensor

p-ISSN: 2356-5314
e-ISSN: 2460-075X

for temperature and humidity readings, a 20x4 I2C LCD as a display interface, an 8V 8-channel relay as an actuator switch, two Peltier TEC1-12706 modules as a cooler, two 12V 50W PTC modules as a heater, an ultrasonic atomizer humidifier as a humidifier, and a 12V 15A power supply as the main power source. The software used includes Arduino IDE for ESP32 programming, MATLAB for ANFIS model training, EasyEDA for PCB design, as well as Firebase Realtime Database and JavaScript-based web dashboards for remote monitoring.

C. Control System Design

The system works cyclically: the DHT22 sensor reads the actual temperature and humidity, the temperature value is compared to the setpoint to generate errors and delta errors. If the error is positive (temperature below the setpoint), the ANFIS heater model is activated to determine the heating level through the PTC element drive relay; on the other hand, if the error is negative, the ANFIS cooler model regulates the activation of the Peltier module. The two models were trained separately because the heating and cooling plants have asymmetrical thermal dynamics. Humidity is controlled independently through a simple threshold, i.e. the humidifier turns on when RH is below 60% and off when it reaches 75%. The control decision results are sent to the Firebase Realtime Database and used to drive the actuator through an 8-channel relay. The sensors, ESP32 microcontroller, 8-channel relay, and all actuators are assembled into one prototype of an acrylic-based baby incubator.

D. Model ANFIS

The control model was designed using the Adaptive Neuro-Fuzzy Inference System (ANFIS) of the order-1 Sugeno structure. Two independent models were compiled, namely the Heater Model and the Cooler Model, each with two inputs (error and delta error), three Gaussian membership functions per input (Negative, Zero, Positive), and nine fuzzy rules resulting from the combination of the two inputs. The premise parameters (membership function) and consequent parameters were trained using a hybrid learning algorithm, which is a combination of Least Square Estimation (forward pass) for the consequential parameter and gradient descent (backward pass) for the premise parameter, so that both parameters are obtained automatically from the training data without manual determination by experts.

E. Data Analysis Techniques

The evaluation of system performance was carried out through: (1) analysis of the accuracy of the DHT22 sensor against the HTC-2 digital hygrometer as a comparison instrument; (2) analysis of transient response (rise time and time to stability) at three setpoints (33°C, 34°C, and 35°C); (3) steady-state error analysis between ANFIS mode and manual mode; and (4) testing the system's resilience to external disturbances in the form of sudden changes in environmental temperature.

III. Results and Discussion

A. DHT22 Sensor Accuracy

Accuracy testing was performed 13 times over one hour with a recording interval of 5 minutes, comparing the readings of the DHT22 sensor with that of the HTC-2 hygrometer. A summary of the test results is presented in Table I.

TABLE I. SNIPPET OF COMPARISON RESULTS OF DHT22 SENSOR WITH HTC-2 HYGROMETER

Testing to-	Time (minutes)	DHT22 (°C)	HTC-2 (°C)	Error (%)
1	0	24,5	25,2	2,85
4	15	34,2	35,2	3,07
7	30	34,7	35,9	3,45
10	45	34,4	34,9	1,45
13	60	34,5	34,2	0,86
Rat-rat error				**2,39%**

Source: personal test data

Based on 13 tests, the average error percentage was obtained at 2.39%. This value indicates that the DHT22 sensor readings have a small range of differences with the reference instruments, so this sensor is considered adequate to be used as a feedback element in the incubator monitoring system.

B. Comparison of ANFIS Mode Performance and Manual Mode at 34°C Setpoint

Testing was conducted at a temperature setpoint of 34°C to compare the performance of ANFIS mode and threshold-based manual mode. The recording results showed that the ANFIS mode was able to reach and maintain temperatures closer to the setpoint with a regular up-and-down oscillation pattern in the range of 33.6-34.7°C, while the manual mode tended to be stable at a value slightly below the setpoint, which was around 33°C, without significant oscillations. This indicates that the ANFIS mode has a more aggressive response in pursuit of setpoint values than the manual mode which is more conservative in nature.

In humidity parameters, the ANFIS mode experienced much greater fluctuations, even increasing to close to 70% RH, compared to the manual mode which tended to decrease gradually towards the range of 37-40% RH. This difference suggests that humidifier activation in ANFIS mode occurs more frequently, likely as a consequence of the longer duration of activation of the heating element due to temperature oscillation patterns.

C. Consistency at 33°C and 35°C Setpoints and Interference Test

Testing at setpoints of 33°C and 35°C showed a pattern consistent with the results at the 34°C setpoint, i.e. ANFIS mode was consistently more responsive in approaching and even penetrating setpoint values, while manual mode always left a steady-state offset below the target. In tests with external interference in the form of a sudden drop in room temperature, the system was shown to be able to restore the incubator temperature back to the setpoint within a reasonable time span, demonstrating the robustness of ANFIS's control against environmental disturbances.

D. Discussion of System Limitations

The temperature oscillation in ANFIS mode is strongly thought to be derived from the "Zero" membership function at the input error that is too narrow ($\sigma = 0.063$), resulting in extreme consequential coefficients in some rules, especially the "Up" error delta condition. Coupled with the disproportionate actuation properties of the ON/OFF relay, the temperature and humidity oscillations in ANFIS mode are greater than in manual mode, even though the average temperature is closer to the target.

IV. CONCLUSIONS AND SUGGESTIONS

A. Conclusion

The ANFIS-based baby incubator temperature and humidity control system on the ESP32 microcontroller was successfully designed, implemented, and evaluated as a closed-loop control system. The DHT22 sensor is proven to have adequate accuracy with an average error of 2.39% compared to the HTC-2 hygrometer. The fuzzy logic method was successfully implemented through two ANFIS Sugeno order-1 models (Model Heater and Model Cooler) which were trained using a hybrid learning algorithm. Performance evaluations showed that ANFIS mode was more responsive in pursuing setpoints than manual mode in 33°C, 34°C, and 35°C tests, although it was accompanied by greater temperature and humidity oscillations due to the actuation nature of the ON/OFF relay and the inequality of the training data around near-zero error conditions.

B. Suggestions

Further research is recommended to: (1) enrich ANFIS training data around near-zero error conditions or apply consequential coefficient regularization so that the transition between rules is smoother; (2) apply PWM control to the PTC heater and Peltier actuator in place of pure ON/OFF relay control to suppress oscillation; (3) addressing the imbalance of training data classes, for example through oversampling techniques such as SMOTE; (4) extend the duration of continuous testing (e.g. 24-48 hours) to evaluate long-term stability; and (5) optimize humidity control hysteresis so that RH fluctuations in ANFIS mode can be further suppressed.

ACKNOWLEDGMENTS

The author expressed his gratitude to the Automation Engineering Technology Study Program, Faculty of Engineering, State University of Jakarta, for the support of facilities and academic guidance during the implementation of this research.

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