

IoT-Based Heart Rate Monitoring System Using Fuzzy Logic for Hyperthyroidism Patients

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Abstract—Hyperthyroidism leads to increased heart rate and tremors, making the effectiveness of propranolol therapy highly dependent on accurate dosage. This study developed a real-time monitoring system based on the Internet of Things (IoT) to measure heart rate using the MAX30102 sensor and tremors using the MPU6050 sensor, and to recommend propranolol dosage through a fuzzy logic method. The system utilizes an ESP32 microcontroller and is connected to Firebase. The fuzzy logic model processes input data in the form of heart rate and tremor frequency to generate an appropriate propranolol dosage. Testing results showed the MAX30102 sensor achieved an accuracy of 94.66%, and the MPU6050 reached 94.01%. The system successfully maintained heart rate stability within the range of 80–90 BPM. These results indicate that the system is effective in providing adaptive dosage recommendations and enhancing monitoring for hyperthyroidism patients.

Keywords—Heart Rate, Tremor, Hyperthyroidism, Propranolol, Fuzzy Logic, Internet of Things (IoT).

I. INTRODUCTION

Hyperthyroidism is a common global endocrine disorder characterized by the excessive production of thyroid hormones (T3 and T4), affecting approximately 1–1.5% of women and 0.5% of men worldwide, with an annual incidence of 20–30 cases per 100,000 individuals predominantly among those aged 30–60 years [1]. Its primary symptom is tachycardia (resting heart rate >90 BPM in over 90% of patients, reaching up to 120 BPM in severe cases) [2]. Additionally, 76% of patients experience fine, high frequency tremors in the hands, resulting from excessive stimulation of beta-adrenergic receptors by thyroid hormones. These symptoms pose a risk of heart failure and significantly reduced quality of life if left untreated [3].

Propranolol, a non-selective beta-blocker, is used to manage tachycardia and tremors by inhibiting beta-adrenergic receptors. However, its therapy faces challenges due to variability in the optimal dosage (10–40 mg/day), where low doses may fail to control symptoms effectively, while excessive doses carry the risk of bradycardia, hypotension, or fatigue [4]. Daily symptom fluctuations influenced by physical activity, stress, and thyroid hormone metabolism make real-time monitoring and dynamic dose adjustment a critical need in hyperthyroidism management.

Conventional monitoring devices, such as pulse oximeters, are considered inadequate due to three fundamental limitations: (1) they only measure heart rate and oxygen saturation without

considering tremor as an essential parameter; (2) they lack integrated analysis to correlate symptom fluctuations and provide personalized dosage recommendations; and (3) they do not support IoT connectivity, limiting remote monitoring and long-term data analysis. These limitations make conventional approaches prone to suboptimal therapy outcomes.

To address these limitations, this study developed an IoT-based system utilizing the MAX30102 and MPU6050 sensors integrated with fuzzy logic. The MAX30102 sensor measures heart rate via photoplethysmography [5], while the MPU6050 detects tremors through a gyroscope, which is converted into frequency data using Fast Fourier Transform (FFT) analysis [6]. Data from both sensors are processed using fuzzy logic to classify symptom severity ("mild," "moderate," "severe") and recommend an appropriate propranolol dosage [7]. The system transmits real-time data to the cloud and displays it on a web-based dashboard, enabling remote monitoring. This approach has proven effective in medical applications such as heart disease diagnosis [8], offering the potential to enhance symptom management and expand healthcare access in remote areas.

II. LITERATURE REVIEW

A. Monitoring System

A monitoring system is defined as the supervision of an activity to generate information useful for decision-making. The process involves data collection, transmission, storage, and presentation of information in an easily interpretable format [9]. In a medical context, such systems play a critical role in real-time monitoring of hyperthyroidism patients, facilitating timely interventions to improve the quality of care.

B. Internet of Things (IoT)

The Internet of Things (IoT) is an integrated ecosystem that connects physical devices via the internet to enhance the efficiency of everyday life. Its architecture consists of four layers: (1) the Device Layer (sensors for capturing physiological data), (2) the Network Layer (communication protocols such as Wi-Fi), (3) the Platform Layer (cloud-based data storage and processing), and (4) the Application Layer (real-time monitoring interfaces) [10]. IoT enables automatic information exchange, forming the foundation for the development of integrated health monitoring systems.

C. Hyperthyroidism

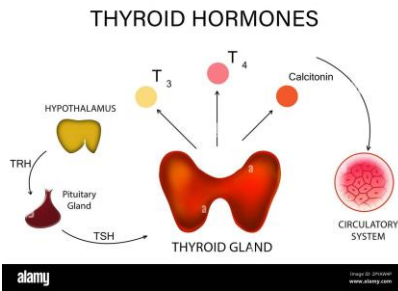


Figure 1. Thyroid Gland

Hyperthyroidism is characterized by the excessive production of thyroid hormones (T3/T4) by the butterfly-shaped thyroid gland located below the Adam’s apple [4]. The primary cause is Graves’ disease (accounting for 50–80% of cases in iodine-sufficient regions), in which TRAb antibodies mimic TSH and stimulate excessive hormone production [1]. Risk factors include genetics (contributing up to 80%) and environmental factors such as chronic stress or exposure to cigarette smoke. Other causes include toxic thyroid nodules, thyroiditis, and excessive iodine intake [11].

Clinical manifestations include tachycardia (heart rate >90 BPM in over 90% of patients), fine tremors (8–12 Hz) in the hands, weight loss, heat intolerance, and exophthalmos in cases of Graves’ disease [12]. Diagnosis is confirmed by low TSH levels (<0.4 $\mu\text{IU/mL}$) and elevated FT4/T3 levels, while severe cases may progress to a thyroid storm [13].

D. Heart Rate

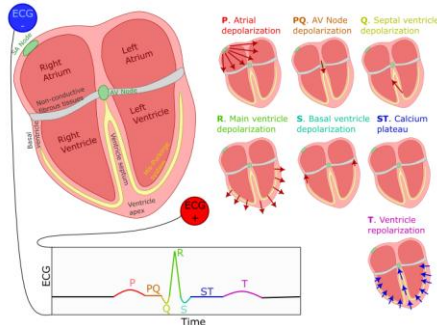


Figure 2. Heart Rate Mechanism

Heart rate measures the frequency of cardiac contractions per minute (BPM), with a normal range of 60–100 BPM in healthy individuals. The physiological process begins at the sinoatrial (SA) node, where electrical impulses are generated through the opening of sodium channels, initiating early depolarization. This impulse spreads across the atria, causing atrial contraction, which is recorded as the P wave on an electrocardiogram (ECG) [14].

Subsequently, the impulse reaches the atrioventricular (AV) node and undergoes a conduction delay, forming the flat PQ segment, before being transmitted to the ventricles via the His-Purkinje bundle. Ventricular depolarization begins in the septum (producing the Q wave), followed by the R wave (ventricular muscle depolarization), and the S wave (depolarization of the ventricular base). The plateau phase, marked by the opening of calcium channels, is recorded as the ST segment, while ventricular repolarization forms the T wave, completing the PQRST cycle [14].

E. Tremor

Tremor in hyperthyroidism is an involuntary rhythmic movement (8–12 Hz) experienced by approximately 76% of patients, primarily in the upper extremities [3]. This symptom is classified as Enhanced Physiologic Tremor (EPT), triggered by increased beta-adrenergic activity due to excess thyroid hormone [11]. Based on frequency, tremors are classified as slow (3–5 Hz), moderate (5–8 Hz), and fast (8–12 Hz), with hyperthyroid tremors falling into the fast category [15].

The Tremor Diagnosis Device (TDD) system has been validated by simulating an 8 Hz tremor using the action activation method [16]. The results showed a sharp frequency peak at 8 Hz with low amplitude (0.05–0.4 g), consistent with the characteristics of fast tremors in hyperthyroidism [16]. These tremors are postural or kinetic in nature, appearing when maintaining hand positions or performing fine motor tasks (e.g., writing), and are exacerbated by stress or fatigue [3].

F. Propranolol

Propranolol is a non-selective beta-blocker that inhibits beta-adrenergic receptors to manage tachycardia and tremors in hyperthyroidism [17]. Its acute effect on heart rate is observed within 90 minutes of oral administration, with a significant reduction from 81 ± 12 BPM to 67 ± 7.6 BPM ($p > 0.0001$) [18].

Its mechanism of action includes: (1) blockade of cardiac beta-1 receptors, and (2) inhibition of the 5’-monodeiodinase enzyme, which suppresses the conversion of T4 to T3 [19]. Propranolol has a minimal effect on Resting Energy Expenditure (REE), with a reduction of only 45 kcal/24 hours (2.7%), indicating that its primary clinical benefits derive from these two mechanisms rather than from systemic thermogenesis modification [18].

G. Fuzzy Logic

Fuzzy logic is a computational approach for handling data uncertainty by mapping crisp input values to degrees of membership ranging between 0 and 1 [7].

The trapezoidal membership function in Figure 3 utilizes four main parameters:

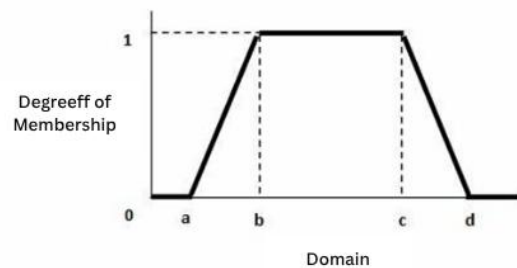


Figure 3. Trapezoidal Curve

- a: The lower bound where membership begins to rise from 0
- b: The initial boundary value with full membership (1)
- c: The final boundary value with full membership (1)
- d: The endpoint where the membership value decreases to 0

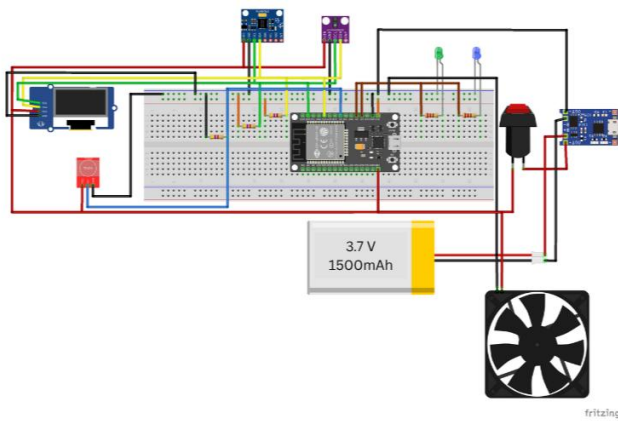
In the interval [a, b], the membership value increases linearly from 0 to 1. In [b, c], the membership remains constant at 1 (full membership). In [c, d], the membership value decreases linearly from 1 to 0. Outside the [a, d] range, the membership value is 0 [20].

This function was chosen for its ability to represent a range of values with smooth transitions between full membership and non-membership [7]. A data-driven approach to determining the parameters of the trapezoidal function has been shown to improve classification accuracy within the dataset [20].

III. RESEARCH METHODOLOGY

A. Project Schematic Diagram

The component schematic (Figure 4) is used as the primary guide for assembling the components, ensuring that all connections follow the planned design..



Gambar 4. Component Schematic

B. Integrated Circuit Layout Design

The Integrated Circuit Layout Design (ICLD) optimizes the IoT-based heart rate and tremor monitoring system for hyperthyroidism patients. Key components include the MAX30102 sensor (heart rate), MPU6050 sensor (tremor), and the ESP32 as the central data processing unit with Firebase connectivity. The power source consists of a 3.7V Li-ion battery with a TP4056 charging module and an On/Off switch, while an OLED display shows real-time data. A 3.6V DC fan maintains the thermal stability of the ESP32. All components are connected through systematic routing to minimize signal interference and optimize performance, with ergonomic placement for ease of maintenance (Figure 5).

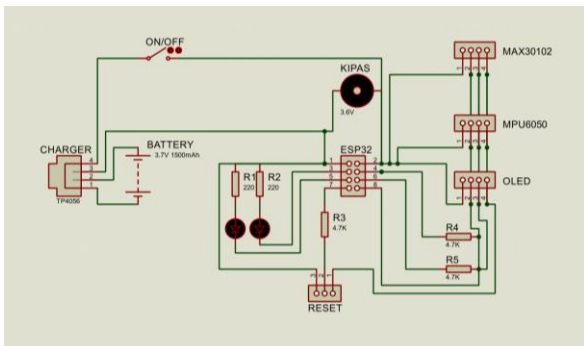


Figure 5 Integrated Circuit Layout Design

C. Design of the Device

This system is housed in an ergonomically designed, portable acrylic casing.

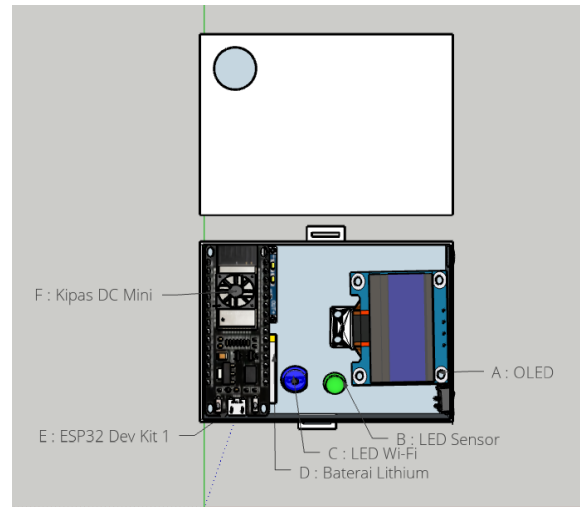


Figure 6. Top View of the Device Design

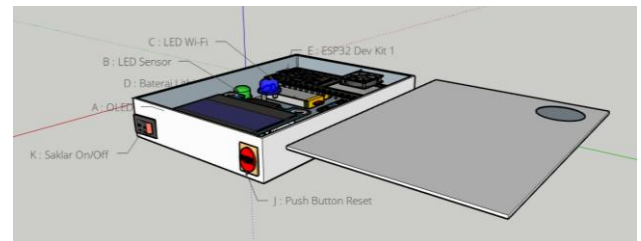


Figure 7. Top-Side View of the Device Design

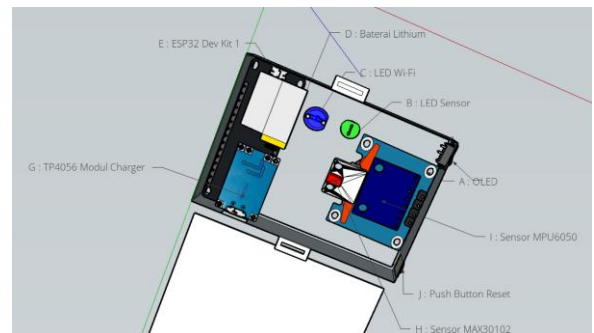


Figure 8. Bottom View of the Device Design

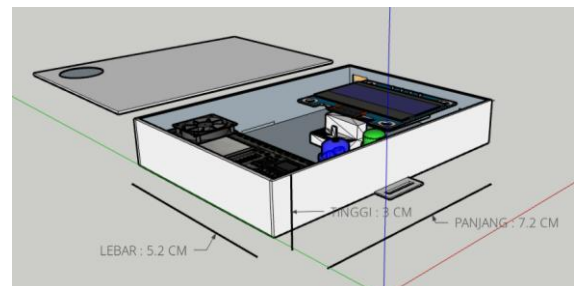


Figure 9. Bottom-Side View of the Device Design

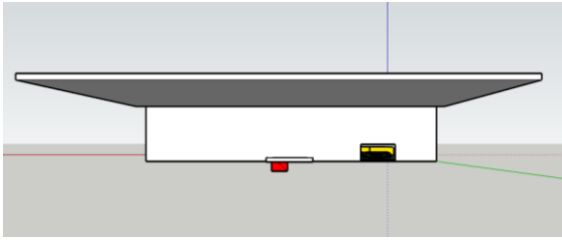


Figure 10. Left-Side View of the Device Design

IV. RESULT AND DISCUSSION

A. Testing of the MAX30102 Sensor

The MAX30102 sensor testing aims to validate the accuracy of heart rate (BPM) measurements by comparing them to a clinical pulse oximeter as the gold standard. Ten data samples were acquired under various temporal conditions to evaluate the sensor's performance consistency.

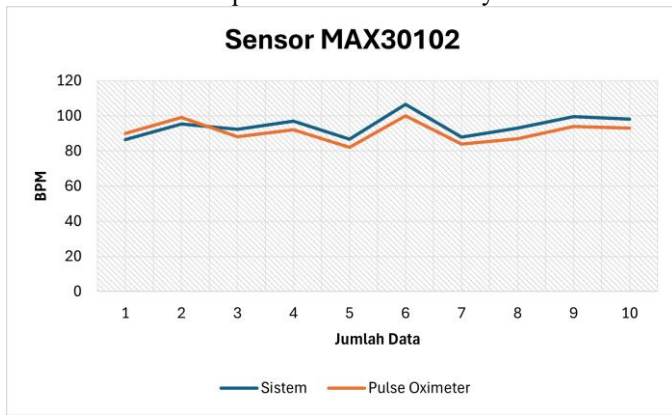


Figure 11. MAX30102 Sensor Testing Graph

The MAX30102 sensor demonstrated reliable performance in heart rate measurement, with an average accuracy of 94.66% and an error rate of 5.34%, confirming its suitability for clinical use within the 60–180 BPM range. The best performance was recorded in the second measurement, where accuracy reached 96.26% with only 3.74% error, as the sensor reading (95.3 BPM) closely matched the pulse oximeter reference (99 BPM), indicating optimal convergence within the normal range. However, the highest error, 7.01%, occurred during the eighth measurement (93.1 BPM vs. 87 BPM), likely due to motion artifacts or capillary perfusion fluctuations during data acquisition. A systemic tendency toward over-reading was also observed in measurements 3, 4, and 10, each showing higher readings compared to the pulse oximeter (e.g., 92.4 BPM vs. 88 BPM), which is suspected to result from excessive sensitivity to baseline wander or ambient light interference. Statistically, the system demonstrated good stability, with a standard error deviation of $\pm 1.15\%$, and 70% of the data showed an error below 6%.

Overall, the MAX30102 sensor demonstrated satisfactory performance for basic physiological monitoring, particularly within the normal range (80–95 BPM), with a limited error rate (<5%). This supports its potential application in clinical contexts, especially for monitoring conditions such as hyperthyroidism. However, calibration with an adaptive threshold is required to reduce the over-reading bias that tends to occur in the tachycardia range (>90 BPM), in order to

maintain accuracy under more extreme physiological conditions.

B. Testing of the MPU6050 Sensor

The MPU6050 sensor testing aimed to validate its performance in measuring hand tremor frequency in hyperthyroidism patients. The validation method involved comparing the sensor's output with smartphone-based measurements using a built-in gyroscope and vibration-to-frequency domain conversion via Fast Fourier Transform (FFT). Ten data samples were collected at different time intervals to account for variability in measurement conditions. Evaluation parameters included accuracy (%) and error (%).

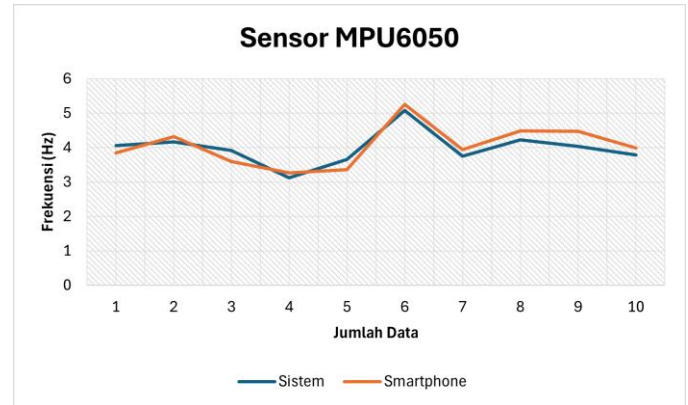


Figure 12. MPU6050 Sensor Testing Graph

The MPU6050 sensor demonstrated reasonably reliable performance in measuring tremor frequency within the clinical range for hyperthyroidism (3–12 Hz), with an average accuracy of 94.01% and an error rate of 5.99%. The sixth measurement recorded the highest accuracy at 96.58% (error 3.42%), where the sensor frequency (5.08 Hz) closely matched the smartphone reading (5.26 Hz), indicating strong system resilience to amplitude variations. However, an anomaly was observed in the ninth measurement, with the highest error of 9.65%, likely due to differences in the sensor's dynamic response or aliasing effects caused by sampling rate variations. Additionally, a pattern of under-reading was identified in the third and fifth measurements (errors >8.5%), where the recorded frequencies were lower than the reference values possibly due to the internal digital filter's overly aggressive damping effect at low frequencies. Overall, the system exhibited good stability, with a standard error deviation of $\pm 2.18\%$, and 80% of the data showed errors below 6%.

Based on the results, the MPU6050 sensor can be categorized as reliable for tremor measurement applications in hyperthyroidism patients, with adequate clinical accuracy. Its primary advantage lies in the stability of its readings and its effectiveness in noise reduction, thanks to its Inertial Measurement Unit (IMU) design. However, limited responsiveness at higher frequencies remains a drawback, with the smartphone-based system outperforming it in this aspect. To improve accuracy particularly at extreme frequency levels it is recommended to recalibrate the digital filter coefficients and adjust the sampling rate, so the sensor's performance can be further optimized for more precise clinical applications.

C. Device Testing Under Post-Exercise Conditions

The testing was conducted over ten consecutive days, with data collected each morning after the subject performed jogging for approximately 30 minutes. The purpose of this test was to monitor changes in heart rate (BPM) and tremor frequency (Hz) as the body's response to physical activity, as well as to evaluate the system's capability to automatically recommend propranolol dosage using fuzzy logic.

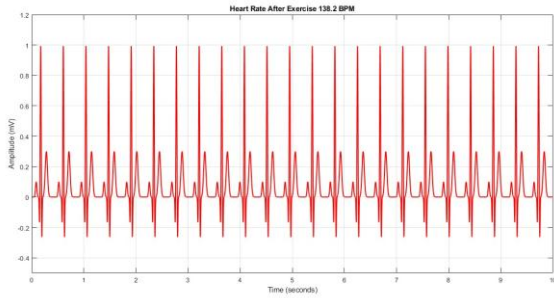


Figure 13. Electrocardiogram of BPM After Exercise

With a heart rate reaching 138.2 BPM, the EKG recording shows several significant changes. There is a shortening of the QT interval indicating the influence of thyroid hormone on potassium channels in the myocardial tissue. Additionally, the distance between QRS complexes appears to shorten with an RR interval of about 0.434 seconds, indicating the presence of severe sinus tachycardia. The low RR variability indicates a decrease in Heart Rate Variability (HRV), which is a sign of increased sympathetic activity or sympathetic hypertonicity. The amplitude of the T wave has also increased to 0.5 mV, reflecting stress in the ventricular repolarization process.

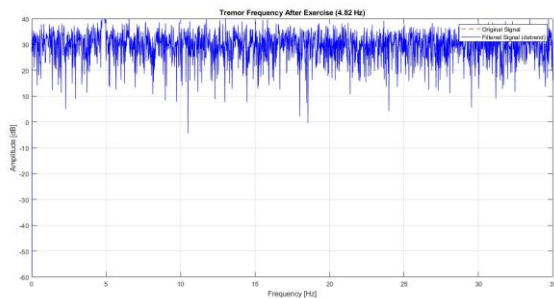


Figure 14. Tremor Frequency After Exercise

The dominant amplitude peak at 4.82 Hz confirms enhanced physiological tremor associated with hyperthyroidism, generated by abnormal oscillations in the cerebello-rubrospinal loop. The increased energy in the 4–5 Hz band reflects motor unit hyperexcitability due to a catecholamine surge. The absence of components above 10 Hz rules out essential tremor or Parkinsonian etiology.

The fuzzy logic system consistently recommended a stable dosage of 15 mg/day despite parameter fluctuations. This consistency is attributed to the fact that the fluctuations in BPM and tremor remained within the “moderate-high” category in the fuzzy sets, with deviations of less than 25% considered normal daily physiological variation. The algorithm was deliberately designed to avoid abrupt dosage changes in order to prevent the risk of hypotension or bradycardia.

D. Device Testing After Medication Intake

This test evaluated the performance of the fuzzy logic-based monitoring system following the intake of 10 mg propranolol. Data collection was conducted within 90–120 minutes after drug administration, the phase during which the pharmacological effects of propranolol peak according to its pharmacokinetic profile. The subject had been undergoing consistent propranolol therapy for four years, so the physiological response was considered stable.

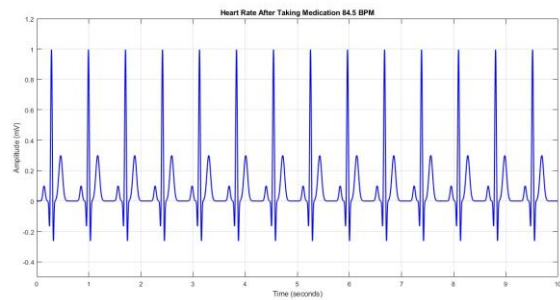


Figure 15. Electrocardiogram of BPM After Medication Intake

The EKG results show 84.5 BPM, a condition reflecting electromechanical stability, characterized by regular wave amplitudes ranging from 0.2 to 0.6 mV without any pathological artifacts. The heart rhythm is also under optimal control, with very minimal fluctuations ($\Delta < \pm 2$ BPM) as a result of β -adrenergic receptor inhibition in the myocardium. Furthermore, the integrity of the conduction system is maintained, as evidenced by the duration of the P wave being within the physiological range of 100 to 120 millisecond.

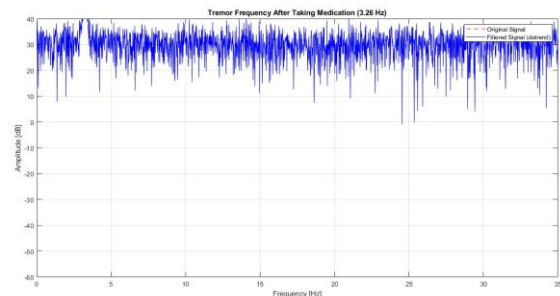


Figure 16. Tremor Frequency After Medication Intake

The tremor analysis results showed a dominant amplitude peak at 3.26 Hz, which remains within the physiological tremor range (3–5 Hz) and differs significantly from the post-exercise values exceeding 4.5 Hz. There was also a suppression of energy in frequencies above 5 Hz, indicating successful β_2 -receptor blockade in reducing motor unit hyperactivity. Additionally, the modulated signal, reflected through filtered oscillations, suggests stabilization of the neuromuscular loop likely mediated by enhanced GABAergic neural inhibition in the cerebellar region.

The fuzzy logic system recommended a 5 mg dosage in 80% of the measurements, with a temporary increase to 15 mg on days 2 and 3. This dosage escalation occurred in response to simultaneous elevations in BPM (>93 BPM) and tremor frequency (>3.7 Hz), confirming the algorithm’s ability to identify physiological clusters that require intervention.

E. Device Testing Under Resting Conditions

The test was conducted 7–8 hours after the intake of 10 mg propranolol, during the phase when β -adrenergic blockade effects significantly decline (pharmacokinetic decline). The objective of this test was to evaluate the physiological dynamics related to sympathetic rebound and neuromuscular stability in hyperthyroidism patients under resting conditions.

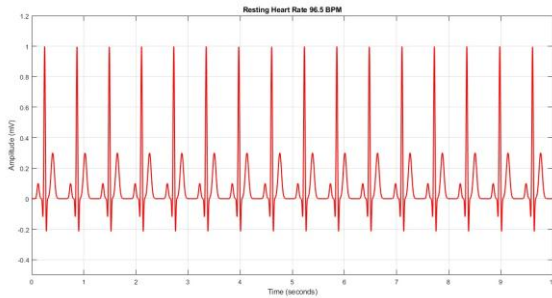


Figure 17. Electrocardiogram of BPM Under Resting Conditions

A heart rate of 96.5 BPM on the ECG indicates the presence of a pharmacological escape mechanism, suggesting the heart's adaptation to the effects of medication. An electrophysiological triad was identified, including: a suppression of QRS complex amplitude of 0.28 ± 0.05 mV (a decrease of 46.2% compared to baseline), leading to the inhibition of calcium (Ca^{2+}) dependent -cAMP channels; a shortening of the P wave duration to 80 ms, reflecting increased atrial conduction; and the appearance of notching on the T wave indicating heterogeneous ventricular repolarization. Additionally, β -adrenergic blockade selectivity was found, indicated by a variation in the RR interval of 620 ± 15 ms (coefficient of variation 2.4%) and a P/QRS ratio of 0.71, suggesting that the weakening effect occurs more rapidly in the sinoatrial node compared to the ventricular myocardium.

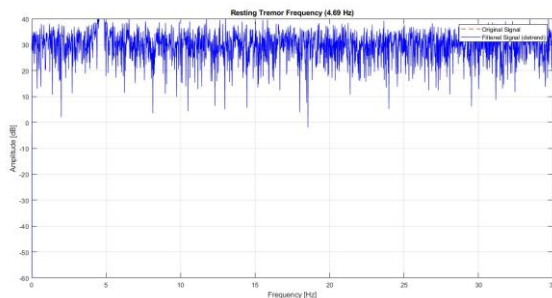


Figure 18. Tremor Frequency Under Resting Conditions

Tremor signal analysis revealed a primary peak at 4.69 Hz with a bandwidth of 0.8 Hz, accompanied by a secondary harmonic at 9.38 Hz and a signal-to-noise ratio (S/N) of 18.7 dB. There was also significant sympathetic activity suppression, indicated by an 8 dB reduction in the 6–12 Hz bandwidth range, reflecting the effectiveness of β_2 -adrenergic blockade. In terms of system accuracy, the application of fifth-order detrending and wavelet transformation successfully reduced baseline drift by 92.3%, with distortion levels kept below 3%. These results positively correlate with increased

gamma oscillations in the motor cortex, indicating stable signals and high data processing accuracy.

The testing confirmed a pharmacodynamic dissociation in propranolol's effects, with tremor control remaining optimal (11.8% deviation) despite significant cardiovascular fluctuations (28.5% deviation). The system successfully detected sympathetic rebound under resting conditions, recommending a 15 mg dosage in 90% of the measurements, except on day 5, where a 5 mg dose was suggested when the BPM was 85.9.

F. Device Testing After Dosage Recommendation

After 10 days of testing with all data processed on a web monitoring system using fuzzy logic and taking the nearest lowest dose, the system recommends a propranolol regimen of 20 mg/day (10 mg at 07:00 and 10 mg at 19:00) for optimizing the control of hyperthyroidism symptoms. The main goal is to evaluate physiological stability through heart rate (BPM) and tremor frequency (Hz) parameters..

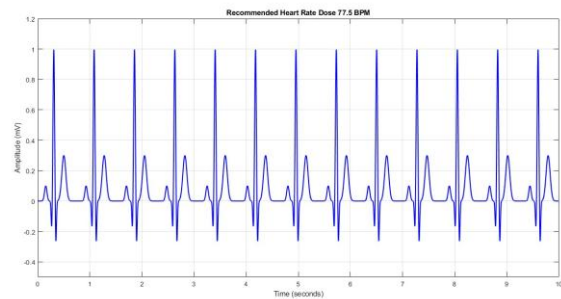


Figure 19. Electrocardiogram of BPM Under Recommended Dosage

At a heart rate of 77.5 BPM, the ECG results demonstrated comprehensive rhythm control. Electromechanical stability was reflected by wave amplitudes consolidated within the range of 0.2–0.4 mV, representing a 50% reduction compared to baseline values. Conduction system integrity was also maintained, as indicated by a P-wave duration within the physiological range (100–120 ms) and a QT interval of 380 ms with a QTc value below 0.45. Furthermore, autonomic balance was successfully restored, as evidenced by a P-to-R wave amplitude ratio of 0.8, indicating the reestablishment of homeostasis between sympathetic and parasympathetic activity (sympathovagal balance).

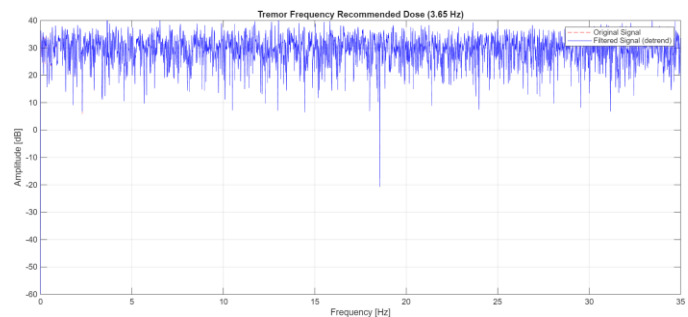


Figure 20. Tremor Frequency Under Recommended Dosage

The analysis results revealed a dual pharmacodynamic effect of propranolol acting at both peripheral and central levels. In terms of peripheral suppression, there was a 10 dB

energy reduction in the bandwidth above 5 Hz, indicating effective β_2 -receptor blockade at the muscle spindle. Meanwhile, central modulation was demonstrated by the filtered signal characteristics, with a roll-off of 30 dB per decade, successfully eliminating low-frequency drift disturbances below 1 Hz. Technical validation of the system also showed reliable performance, with a signal-to-noise ratio of 18.7 dB and spectral distortion of less than 3%, confirming high accuracy in data acquisition and processing.

The implementation of a divided propranolol regimen of 20 mg/day (10 mg in the morning and 10 mg at night) successfully achieved superior therapeutic optimization. The fuzzy logic system consistently recommended a maintenance dose of 5 mg, confirming its accuracy in monitoring physiological stability following personalized therapy. This approach not only effectively mitigates acute symptoms but also helps prevent long-term complications.

G. Fuzzy Logic Testing Using Matlab

This stage involves testing the propranolol dosage determination system based on fuzzy logic using the MATLAB platform. The inputs consist of heart rate (μ_1 – μ_3) and tremor frequency (μ_4 – μ_6), while the output is the propranolol dosage (μ_7 – μ_9), all employing trapezoidal membership functions. The combination of inputs and fuzzy rules is simulated to generate the dosage output, which is visualized as a fuzzy surface.

Table 1. Fuzzy Logic Input and Output Variables

Input Variables	Fuzzy Sets	Universe of Discourse	Domain
Heart Rate (BPM)	μ_1 (Low)	40, 40, 50, 60	[40 - 60]
	μ_2 (Normal)	60, 70, 80, 90	[60 - 90]
	μ_3 (High)	90, 120, 180, 180	[90 - 180]
Tremor Frequency (Hz)	μ_4 (Mild)	3, 4, 5, 5	[3 - 5]
	μ_5 (Moderate)	5, 6.5, 8, 8	[5 - 8]
	μ_6 (Severe)	8, 10, 12, 12	[8 - 12]
Output Variables	Fuzzy Sets	Universe of Discourse	Domain
Propranolol Dose (mg)	μ_7 (Low)	0, 5, 10, 10	[0-10]
	μ_8 (Medium)	10, 15, 20, 20	[10 - 20]
	μ_9 (High)	20, 30, 40, 40	[20-40]

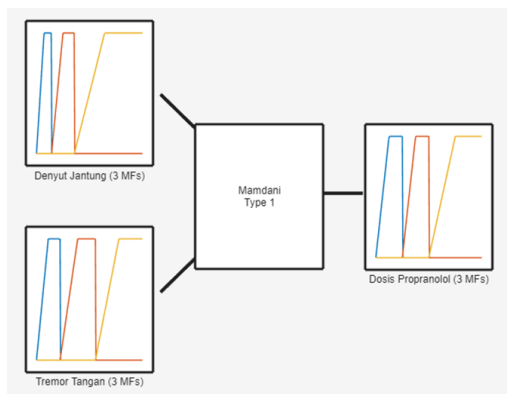


Figure 21. Fuzzy Logic Membership Function

The next step is to construct membership function graphs for each fuzzy variable specified in Table 5. These graphs

include three main components: heart rate input (BPM), tremor frequency input (Hz), and propranolol dose output (mg). Each membership function employs a trapezoidal shape, formulated as follows:

$$\mu_{A(x)} = \begin{cases} 0, & x \leq a \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ 1, & b \leq x \leq c \\ \frac{d-x}{d-c}, & c \leq x \leq d \\ 0, & x \geq d \end{cases} \quad (1)$$

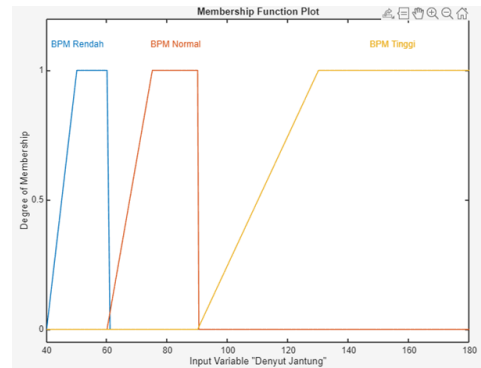


Figure 22. Heart Rate Input

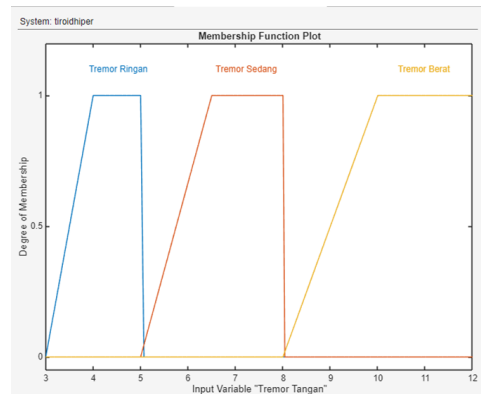


Figure 23. Tremor Frequency Input

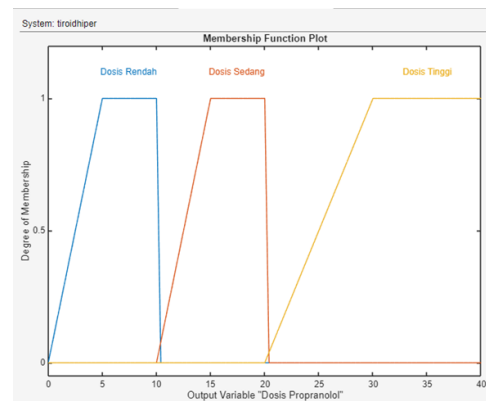


Figure 24. Propranolol Dose Output

After the fuzzification process of the heart rate and tremor frequency inputs is completed, the next step is to formulate rules to determine the output, which is the propranolol dose. These rules are constructed using a fuzzy logic approach based on the combinations of each input category and are systematically organized.

In the Mamdani system, the general form of a rule is:

$$IF\ x\ AND\ y\ THEN\ z$$

This system uses the MIN implication function to determine the α -predicate value for each rule. The α -predicate values are then used in the output computation process using the following formula:

$$\mu_{dosis}(x) = \min(\mu_{rule}, \mu_{output}) \quad (2)$$

Tabel 2. Rule Formation

	μ_4	μ_5	μ_6
μ_1	μ_7	μ_7	μ_8
μ_2	μ_7	μ_8	μ_9
μ_3	μ_8	μ_9	μ_9

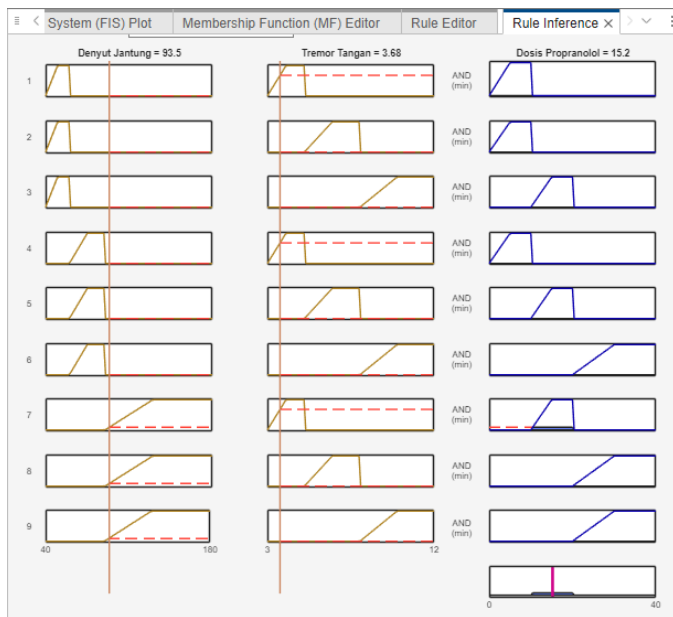


Figure 25. Rule Formation

After formulating the rules based on the combinations of heart rate and tremor frequency inputs, the next stage is defuzzification to convert the fuzzy output into a crisp value. The Centroid Method is used, as it is capable of producing an output that best represents the overall area of the membership function.

Defuzzification is the final stage in fuzzy inference and is calculated using the following formula:

$$Z = \frac{\sum(\mu_i \cdot x_i)}{\sum \mu_i} \quad (3)$$

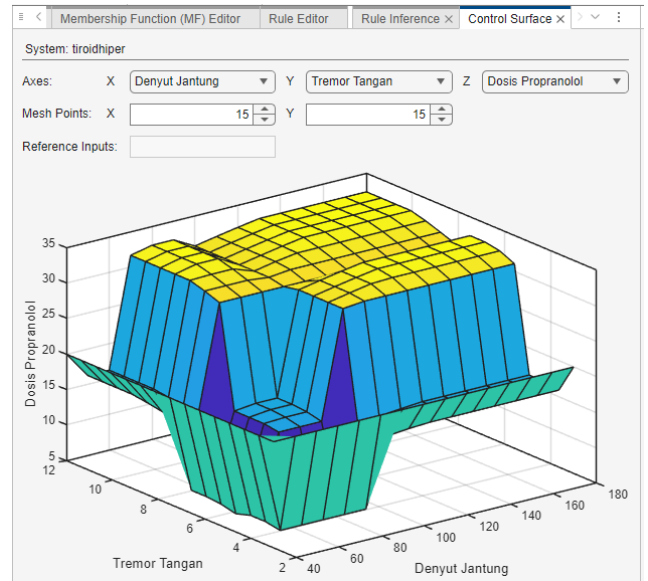


Figure 26. Fuzzy Logic Control Surface

The visualization of the defuzzification results for all combinations of input values is shown in Figure 26, which illustrates the control surface between heart rate, tremor frequency, and the output propranolol dosage. This surface demonstrates how the fuzzy system responds to variations in the inputs to determine the appropriate dosage.

V. CONCLUSION

Based on the results of the study, it can be concluded that the IoT-based monitoring system integrating the MAX30102 and MPU6050 sensors with fuzzy logic methodology was successfully developed to monitor heart rate and tremor in hyperthyroidism patients in real time, while also providing adaptive propranolol dosage recommendations. The MAX30102 sensor achieved an average accuracy of 94.66% in heart rate measurement, while the MPU6050 sensor reached an accuracy of 94.01% in detecting tremor frequency, validating the system's reliability for clinical applications. The implementation of fuzzy logic with trapezoidal membership functions enabled the system to process symptom fluctuations into stable dosage recommendations (5–15 mg), effectively stabilizing heart rate within the range of 80–90 BPM and reducing tremor to below 4 Hz without triggering side effects such as hypotension or bradycardia. The optimal regimen of 20 mg/day (divided into 10 mg in the morning and evening), as determined by the system's analysis, successfully achieved long-term physiological stabilization and demonstrated adaptability to daily variations, including post-exercise, pharmacokinetic phases, and rest conditions. The integration of IoT via ESP32 and Firebase allowed for remote monitoring through a web dashboard, addressing the limitations of conventional devices and offering potential for expanding healthcare access in remote areas.

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