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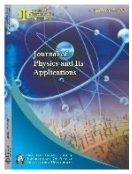

Characterization and Performance Evaluation of the TCRT5000 Reflective Optical Sensor for Early Detection of Flow Disturbances in an IoT-Based Peristaltic Infusion System

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ABSTRACT

Flow disturbances in peristaltic infusion systems, including reduced drip rates, unstable dripping, and occlusion, may compromise infusion therapy and increase patient safety risks. This study aimed to characterize the performance of a TCRT5000 reflective optical sensor integrated into an Internet of Things (IoT)-based peristaltic infusion monitoring system for early detection of infusion flow disturbances. The proposed prototype consisted of a TCRT5000 reflective optical sensor for drip detection, a NodeMCU ESP32 for data acquisition and processing, Firebase for cloud-based data storage, and an MIT App Inventor mobile application for real-time monitoring. Experiments were conducted at infusion flow rates of 20, 50, 80, 100, 150, 200, 250, 300, 350, and 400 drops/min. Sensor performance was evaluated through sensitivity, linearity, and repeatability analyses. The results showed that the sensor exhibited a sensitivity ranging from 0.78 to 1.25 ADC/(drops/min) and a highly linear response described by the regression equation y = 1.0082x + 3.2590, with a coefficient of determination R^2 = 0.9992 and a correlation coefficient r = 0.9996. Repeatability analysis produced coefficients of variation below 5% for most measurements, indicating consistent sensor performance, although slightly higher variations were observed at lower flow rates. These findings demonstrate that the TCRT5000 reflective optical sensor provides reliable sensitivity, linearity, and repeatability, supporting its application as a sensing element in IoT-based infusion monitoring and the development of early infusion flow disturbance detection systems.

1. Introduction

Infusion therapy is an essential clinical procedure widely performed in healthcare settings to maintain fluid and electrolyte homeostasis in patients. Ensuring an appropriate infusion flow rate is critical, as abnormalities such as reduced drip rates, flow interruption, or occlusion may compromise treatment effectiveness and increase the likelihood of adverse clinical outcomes [1], [2]. Consequently, an infusion monitoring system capable of continuously tracking flow-rate variations and delivering real-time information to healthcare providers is of considerable importance.

Recent advances in Internet of Things (IoT) technology have facilitated the development of intelligent infusion monitoring systems that enable continuous acquisition and wireless transmission of sensor data. Through IoT connectivity, infusion parameters can be monitored remotely in real time, thereby improving the efficiency of patient supervision and reducing the workload of healthcare personnel [3], [4]. Among the sensing devices commonly employed in such applications, the TCRT5000 reflective optical sensor has attracted considerable attention due to its compact design, low manufacturing cost, low power consumption, and straightforward integration with microcontroller-based platforms [5].

Previous studies have demonstrated the applicability of the TCRT5000 sensor for infusion drip monitoring and IoT-based healthcare applications. Firdaus et al. [6], [15] utilized the TCRT5000 sensor to detect infusion droplets, primarily focusing on the measurement accuracy and overall performance of the monitoring system. Similarly, Afrianda et al. [13] developed an IoT-enabled infusion monitoring prototype employing an optical sensing approach to support remote patient observation. Nevertheless, the majority of these studies have concentrated on system implementation and monitoring functionality, whereas comprehensive characterization of the sensor itself, including its fundamental performance characteristics, has received comparatively limited attention. As a result, the scientific basis for assessing the suitability of the TCRT5000 sensor as a sensing element in IoT-based infusion monitoring systems remains insufficiently explored.

The review of previous studies indicates that the performance of the TCRT5000 reflective optical sensor has not yet been comprehensively investigated in terms of its fundamental metrological characteristics, particularly sensitivity, linearity, and repeatability. Although the sensor has been successfully implemented in several IoT-based infusion monitoring systems, a systematic evaluation of these performance parameters remains limited. Such characterization is essential for determining the intrinsic capability of the sensor before it is employed as a sensing element in infusion monitoring and early flow disturbance detection applications. Therefore, further investigation is required to quantitatively characterize the sensor under different infusion drip-rate conditions.

Table 1: Comparison of Previous Studies with the Present Study

Authors	Research Focus	Limitation	Contribution of the Present Study
Firdaus et al. [6][15]	Infusion monitoring using the TCRT5000 sensor	Focused on drop-rate measurement accuracy and did not comprehensively characterize the sensor	Characterizes the TCRT5000 sensor through sensitivity, linearity, and repeatability analyses
Afrianda dkk. [13]	IoT-based infusion monitoring system	Focused on system implementation and did not evaluate sensor metrological characteristics	Evaluates the basic sensor characteristics as a basis for application in an IoT-based infusion monitoring system
Shukla et al. [7]	IoT-based infusion management system	Did not quantitatively examine optical sensor performance	Presents a quantitative evaluation of TCRT5000 reflective optical sensor performance
Present study	Characterization of the TCRT5000 sensor for an IoT-based infusion system		Provides comprehensive characterization through sensitivity, linearity, and repeatability as a basis for sensor feasibility in early flow disturbance detection

The primary contribution of this study is the comprehensive performance characterization of the TCRT5000 reflective optical sensor by analyzing its sensitivity, linearity, and repeatability over an infusion flow-rate range of 20–400 drops/min. In contrast to earlier studies, which mainly emphasized system implementation and drip-counting accuracy [6], [13], [15], the present work focuses on evaluating the fundamental performance characteristics of the sensor itself. This approach provides a stronger scientific basis for determining the feasibility of the TCRT5000 sensor as a sensing component in the development of IoT-based early infusion flow disturbance detection systems.

Accordingly, this study aims to investigate the performance characteristics of the TCRT5000 reflective optical sensor integrated into an IoT-based peristaltic infusion system through sensitivity, linearity, and repeatability analyses. The results are expected to contribute to the scientific understanding of the sensor's operational characteristics and to support the development of more reliable infusion monitoring and early flow disturbance detection technologies.

2. Methods

This study adopted an experimental approach to characterize the performance of the TCRT5000 reflective optical sensor integrated into an Internet of Things (IoT)-based peristaltic infusion system. The research consisted of four main stages: hardware development, software implementation, prototype integration, and quantitative performance evaluation. The hardware stage involved the design of the sensing and processing units, whereas the software stage focused on developing the data acquisition, communication, and monitoring functions. Subsequently, the complete prototype was assembled and experimentally evaluated using sensitivity, linearity, and repeatability analyses to assess the performance characteristics of the proposed sensor system. The methodology adopted in each stage is presented in the following subsections.

2.1. Block Diagram Design

The block diagram illustrates the operational workflow of the IoT-based early flow disturbance detection system for peristaltic infusion. The system consists of three main stages: input, processing, and output. The input stage provides data to the microcontroller, the processing stage is responsible for reading and analyzing sensor signals, and the output stage presents the processed results through local alarms and remote monitoring.

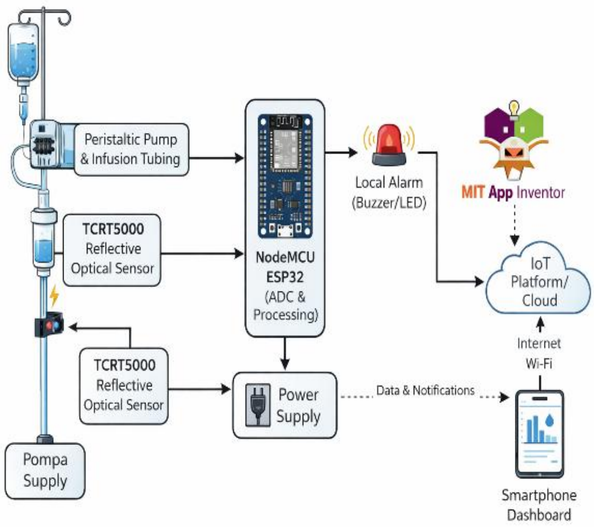

Fig. 1: Block Diagram of the Developed System

In this study, Internet of Things (IoT) technology served as a data communication medium between the sensor, NodeMCU ESP32 microcontroller, Firebase database, and MIT App Inventor application so that sensor readings could be monitored in real time by users. The primary focus of this study was the performance characterization of the TCRT5000 reflective optical sensor through sensitivity, linearity, and repeatability analyses, while the IoT infrastructure was used as a means of data acquisition, transmission, and visualization.

Therefore, this study did not quantitatively evaluate IoT network performance, such as communication latency, data transmission reliability, connection stability, system scalability, or alarm performance. Evaluation of these parameters requires network and communication testing scenarios that differ from the scope of this study. Nevertheless, during testing, the IoT system was able to transmit sensor-reading data continuously to the monitoring application, thereby supporting the sensor characterization process.

The TCRT5000 reflective optical sensor was used to detect changes in optical response related to flow conditions in the peristaltic infusion system. The sensor output signal was transmitted to the NodeMCU ESP32 as the main processing unit. At this stage, the ESP32 reads the sensor signal through an analog-to-digital converter (ADC) and analyzes the signal pattern to identify whether the system is operating normally or experiencing flow disturbances. The output stage includes a sound alarm and an IoT-based monitoring application developed using MIT App Inventor, which displays sensor data and real-time disturbance notifications on a smartphone.

2.2. Hardware Design

The hardware design in this study aimed to develop an IoT-based early detection system for flow disturbances in a peristaltic infusion system. The main components consisted of the TCRT5000 reflective optical sensor as the sensing element, NodeMCU ESP32 as the data acquisition and processing unit, a peristaltic pump as the fluid-flow actuator, a local alarm in the form of a buzzer or LED, and a smartphone as the monitoring platform. The TCRT5000 sensor was positioned in the detection area along the flow path to capture variations in optical response associated with flow conditions. The sensor output was then transmitted to the ESP32 for further processing, and the detection results were displayed through an alarm and sent to the IoT-based monitoring application. Fig. 2 illustrates the hardware design of the developed system.

2.3. Software Design

This section presents the software design of the Internet of Things (IoT)-based early detection system for flow disturbances in the peristaltic infusion system. The discussion focuses on program development using the Arduino IDE. The program was designed to acquire data from the TCRT5000 reflective optical sensor, process sensor readings through the NodeMCU ESP32, and determine whether the infusion flow was in a normal or disturbed condition. The processed data were then transmitted to Firebase as a database and displayed through an application developed using MIT App Inventor, with real-time notifications delivered to the smartphone. Fig. 3 illustrates the flowchart of the developed system.

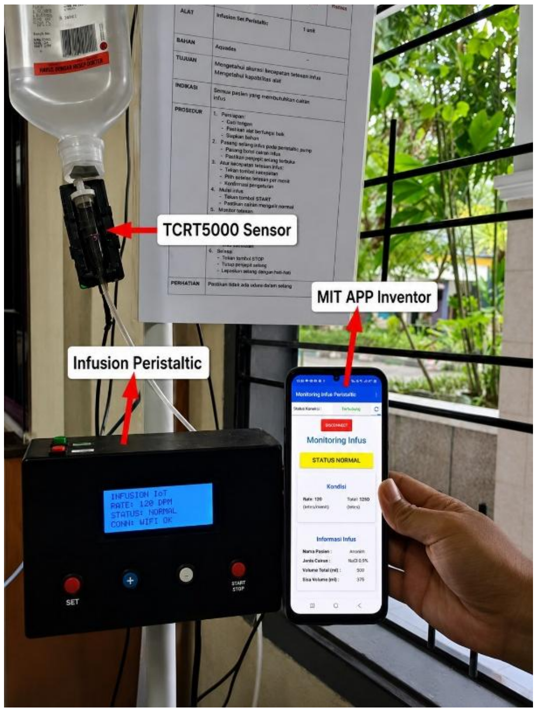

Fig. 2: Peristaltic Infusion System Using the TCRT5000 Sensor

2.4. Software Design

This section presents the software design of the Internet of Things (IoT)-based early detection system for flow disturbances in the peristaltic infusion system. The discussion focuses on program development using the Arduino IDE. The program was designed to acquire data from the TCRT5000 reflective optical sensor, process sensor readings through the NodeMCU ESP32, and determine whether the infusion flow was in a normal or disturbed condition. The processed data were then transmitted to Firebase as a database and displayed through an application developed using MIT App Inventor, with real-time notifications delivered to the smartphone. Fig. 3 illustrates the flowchart of the developed system.

2.5. Experimental Design

Experimental testing was conducted to evaluate the ability of the system to detect infusion flow conditions under normal and disturbed states. All tests used a peristaltic infusion system prototype consisting of a TCRT5000 reflective optical sensor, an ESP32 microcontroller, Firebase Realtime Database, and a smartphone-based monitoring application. The normal condition was defined as a condition in which infusion fluid flowed continuously without obstruction, no blood backflow occurred, and the infusion fluid volume remained above the minimum threshold.

Under this condition, the sensor detected drops periodically according to the specified flow rate, so the system displayed the Normal status and the alarm remained OFF. Conversely, the disturbed condition was defined as a condition that caused a change or interruption in infusion flow and therefore required corrective action. In this study, disturbance conditions were simulated using three scenarios:

1. Bent tubing (occlusion), simulated by bending the infusion tube until the flow decreased or stopped.

2. Blood backflow, simulated using a red-colored medium in the infusion tube to change the optical characteristics detected by the sensor.
3. Empty infusion, simulated by emptying the infusion bag until the fluid volume reached the minimum threshold so that drops were no longer formed.

Each scenario was tested repeatedly to evaluate sensor response, disturbance detection accuracy, alarm response time, and successful data transmission to the IoT-based monitoring application.

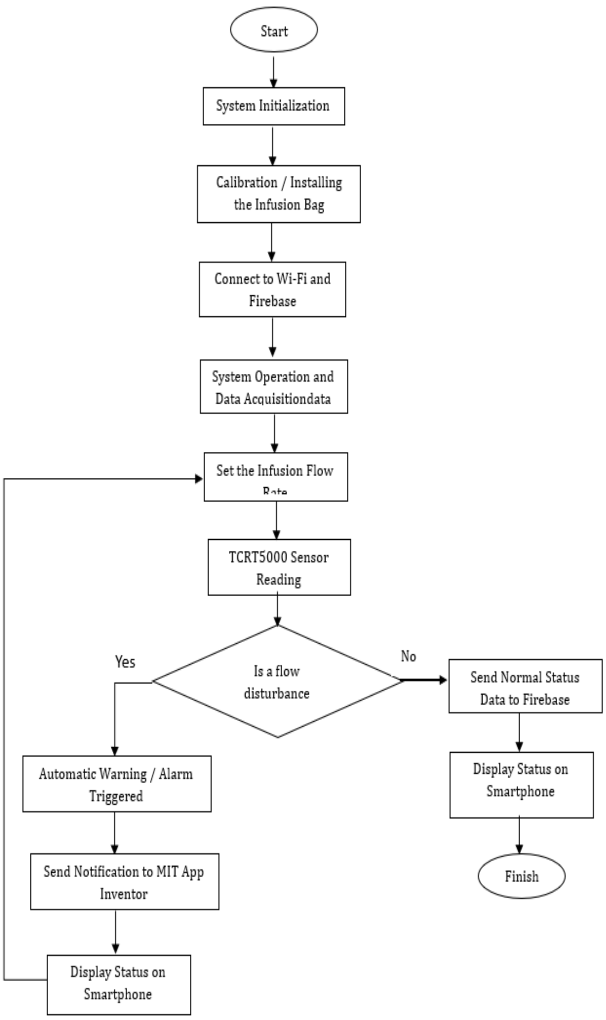

Fig. 3: System Flowchart

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2.6. Data Analysis Method

Data analysis was performed to evaluate the characteristics of the TCRT5000 reflective optical sensor in response to changes in infusion drip rate. The TCRT5000 is a reflective sensor that integrates an infrared emitter and a phototransistor and can produce output signal variations according to changes in the detected object condition [7]. The evaluation consisted of three stages: sensitivity analysis, linearity analysis, and repeatability analysis.

Sensitivity was operationally defined as the ratio between the change in the average sensor output and the change in input between two consecutive measurement points, as expressed in the following equation:

$$S = \frac{\Delta y}{\Delta x} \quad (1)$$

where S is the sensor sensitivity, Δy is the difference in the average sensor output, and Δx is the difference in flow-rate value.$\Delta S \Delta y \Delta x$

Linearity was analyzed using simple linear regression:

$$y = ax + b \quad (2)$$

where y is the average sensor output, x is the flow-rate setting, a is the slope, and b is the intercept. The degree of linearity was evaluated using the coefficient of determination and the correlation coefficient, where values approaching 1 indicate a highly linear input-output relationship.

Repeatability was analyzed based on repeated measurement data obtained under the same conditions using standard deviation and coefficient of variation. The standard deviation was calculated as follows:

$$SD = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}} \quad (3)$$

and the coefficient of variation was calculated as follows:

$$CV = \frac{SD}{\bar{x}} \times 100\% \quad (4)$$

where SD denotes the standard deviation, $\bar{x}$ denotes the mean value, and CV denotes the coefficient of variation. Repeatability reflects the closeness of measurement results obtained under identical conditions [20], whereas the coefficient of variation is used to evaluate the relative variability of the measurement results.

3. Results and Discussion

3.1. Results

3.1.1. TCRT5000 Sensor Characterization

The characterization of the TCRT5000 reflective optical sensor was conducted at infusion drip-rate variations of 20, 50, 80, 100, 150, 200, 250, 300, 350, and 400 drops/min. The evaluated parameters included sensitivity, linearity, and repeatability. Sensor output data were obtained from ADC/voltage readings at each drip-rate setting and subsequently analyzed to determine the sensor response to changes in infusion drip rate.

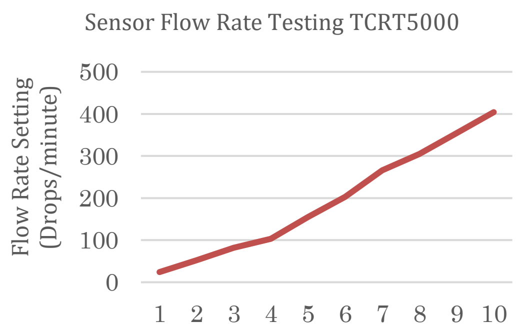

Fig. 4: Flow-Rate Testing of the TCRT5000 Sensor

As shown in the graph above, the TCRT5000 sensor output varied with changes in the number of drops per minute. This result indicates that the sensor was able to respond to variations in the infusion drip rate. The average sensor output at each test point was used as the basis for sensitivity and linearity analyses, while repeated measurement data were used for repeatability analysis.

3.1.2. Sensitivity Analysis

Sensitivity analysis was conducted to evaluate the sensor response to variations in the number of infusion drops. The sensitivity value was determined based on the change in average sensor output relative to the change in input at each flow-rate interval.

Table 2: Sensitivity Analysis Results

No	Drip-rate interval (drops/min)	(drops/min)	Δ*y* (ADC)	Sensitivity (Δy/Δx)
1	20–50	24.2	28.2	0,94
2	50–80	52.4	29.4	0,98
3	80–100	81.8	21.4	1.07
4	100–150	103.2	51.6	1.03
5	150–200	154,8	48.4	0,97
6	200–250	203.2	62.6	1,25
7	250–300	265,8	38.8	0,78
8	300–350	304.6	49.4	0,99
9	350–400	354.0	50.2	1.00

Based on the test results in Table 2, the sensitivity of the TCRT5000 reflective optical sensor ranged from 0.78 to 1.25 ADC/(drops/min). The highest sensitivity was obtained in the 200-250 drops/min interval, at 1.25 ADC/(drops/min), whereas the lowest sensitivity was obtained in the 250-300 drops/min interval, at 0.78 ADC/(drops/min). The increase in sensitivity in the 200-250 drops/min interval was presumably due to the sensor operating in an optimum response region, where the drop-formation pattern was relatively stable so that changes in infrared light reflected toward the phototransistor could be read more clearly.

The decrease in sensitivity in the 250-300 drops/min interval was presumably caused by the increasing frequency of drops passing through the sensor detection area. Under this condition, the time between drops became shorter, causing changes in reflected light intensity received by the phototransistor to be less clearly separated. Consequently, the change in ADC output for each increase in drip rate became smaller than in the previous interval. In addition, at higher flow rates, the sensor response may begin to approach the boundary of its linear response region, so that an increase in the number of drops does not always produce a proportional increase in sensor output.

Thus, sensitivity variations in the 200-250 and 250-300 drops/min intervals indicate that the response of the TCRT5000 sensor was influenced by the drop-formation pattern, drop frequency, optical conditions in the detection chamber, and sensor response limitations to changes in infrared light intensity at higher flow rates.

Physically, fluctuations in the sensitivity of the TCRT5000 sensor were affected by the interaction mechanism between infrared light and fluid drops passing through the detection area. The TCRT5000 sensor operates based on the principle of infrared light reflection; therefore, changes in drop shape, drop size, distance between drops, and the time a drop remains in the sensing region influence the intensity of reflected light received by the phototransistor.

At moderate drip rates, the drop-formation pattern tends to be more uniform, so changes in reflected light intensity can be detected more clearly. This condition causes the ADC output change to become larger for each change in drip rate, thereby increasing sensor sensitivity. Conversely, when the drip rate increases, the distance between drops becomes shorter and the reflected-light changes received by the sensor occur within a very short time interval. This condition causes the output signal change to become smaller because the phototransistor response begins to approach a steady-state condition, resulting in a decrease in sensor sensitivity.

In addition to drop characteristics, sensitivity fluctuations were also affected by the optical characteristics of the TCRT5000 sensor, such as the distribution of infrared light intensity, the acceptance angle of the phototransistor, and variations in the reflectance of the infusion drop surface. Therefore, the sensitivity changes obtained in this study are a consequence of the interaction between the optical characteristics of the sensor and the dynamics of drops in the peristaltic infusion system.

In this study, the minimum detection limit of the sensor for flow-rate changes was not formally determined as a limit of detection (LOD), because the test did not include baseline noise measurements or blank-signal standard deviation required for LOD calculation. However, based on the experimental design, the smallest flow-rate change evaluated was 20 drops/min, namely in the 80-100 drops/min interval. At this interval, the sensor was still able to show a measurable output change with a sensitivity of 1.07 ADC/(drops/min). Thus, based on the available experimental data, the TCRT5000 sensor was able to respond to the minimum tested flow-rate change of 20 drops/min. A more precise determination of the minimum detection limit requires additional testing with smaller flow-rate intervals and signal-noise analysis.

The performance of the TCRT5000 reflective optical sensor was influenced by the interaction between infrared light emitted by the LED and infusion fluid drops passing through the detection area. When a drop passed through the detection area, part of the light was reflected toward the phototransistor, while another part was absorbed and scattered by the drop surface. The intensity of the reflected light was influenced by drop size, drop shape, sensor-to-drop distance, and the optical characteristics of the infusion fluid. Changes in reflected light intensity caused changes in the phototransistor current, which were then converted into changes in ADC values by the NodeMCU ESP32. Therefore, the variation in sensor sensitivity obtained in this study was influenced not only by changes in drip rate but also by the optical characteristics of the drops during infrared light reflection.

3.1.3. Repeatability Analysis

Repeatability was analyzed to evaluate the consistency of the TCRT5000 sensor output when measurements were repeated under identical input conditions. This parameter is important because it indicates the sensor's ability to produce a stable and reproducible response, thereby supporting its feasibility for integration into an infusion flow monitoring system. Repeatability data were analyzed using mean value, standard deviation (SD), and coefficient of variation (CV).

Table 3: Repeatability Analysis Results

No	Drop-rate interval (drops/min)	Δx (drops/min)	Δy (ADC)	Sensitivity (Δy / Δx)
1	20–50	24.2	28.2	0.94
2	50–80	52.4	29.4	0.98
3	80–100	81.8	21.4	1.07
4	100–150	103.2	51.6	1.03
5	150–200	154.8	48.4	0.97
6	200–250	203.2	62.6	1.25
7	250–300	265.8	38.8	0.78
8	300–350	304.6	49.4	0.99
9	350–400	354.0	50.2	1.00

Based on the calculation results, most data showed low coefficient of variation (CV) values, mostly below 5%. This finding indicates that the sensor showed good repeatability at almost all flow-rate settings. The lowest CV value was obtained at a flow rate of 300 drops/min, at 0.29%, reflecting a very high level of measurement stability and consistency under this condition. Similarly low CV values were observed at flow rates of 200, 350, and 400 drops/min, with values of 0.81%, 0.82%, and 0.81%, respectively, indicating that the sensor performed very well within this operating range.

At flow rates of 80, 100, and 150 drops/min, the CV values ranged from 2.01% to 2.21%, which still indicates good repeatability. Likewise, the CV value of 3.96% at a flow rate of 50 drops/min remains acceptable, although data variation was slightly greater than that observed at several other points. Two measurement points require special attention: 20 and 250 drops/min. At a flow rate of 20 drops/min, the CV value of 9.87% indicates relatively larger variation in measurement results, which may be caused by increased signal fluctuation at low flow rates. At a flow rate of 250 drops/min, the CV value of 7.21% also indicates lower repeatability than other points. This was most likely caused by one deviating measurement, namely 300, which was substantially higher than the other four measurements recorded at the same point. This deviating data point significantly increased the standard deviation and consequently produced a larger CV value.

In general, these findings indicate that the TCRT5000 sensor demonstrated good repeatability across most of the tested range. Although larger variations were observed at specific points, particularly at low flow rates and at points containing an indication of an outlier, the overall sensor performance still showed sufficient consistency for flow monitoring applications.

The relatively low coefficient of variation (CV) values indicate that the sensor was able to produce consistent outputs in repeated measurements. The increased CV at several test points was presumably influenced by fluctuations in drop formation, variations in drop position when passing through the detection area, and optical disturbances during infrared light reflection. These factors caused small variations in sensor output, although overall sensor repeatability remained in a good category.

3.1.4. IoT Latency Evaluation

To evaluate the ability of the IoT system to perform real-time monitoring, delay (latency) testing was conducted between sensor reading by the ESP32 and data reception on the MIT App Inventor application through Firebase. The test was conducted five times on the same Wi-Fi network.

Table 4: Latency Evaluation

No	Delay (ms)
1	560
2	920
3	790
4	860
5	950
Average	816

Table 4 presents the latency measurements obtained from five consecutive tests conducted under the same Wi-Fi network conditions. The recorded communication delays ranged from 560 ms to 950 ms, with an average latency of 816 ms. The observed variations are primarily attributed to fluctuations in wireless network conditions, including signal strength, bandwidth availability, and temporary transmission delays between the ESP32, Firebase Realtime Database, and the MIT App Inventor application. Despite these variations, all measured latency values remained below 1 s, indicating that the proposed IoT-based monitoring system is capable of delivering near real-time data updates. Furthermore, the communication performance was sufficiently responsive to support continuous monitoring of infusion parameters and timely alarm notifications under both normal and fault conditions, demonstrating the suitability of the proposed system for real-time peristaltic infusion monitoring.

3.1.5. Alarm Function Test

The alarm function test aimed to provide an automatic warning when a condition that could potentially interfere with infusion fluid administration was detected. The ON alarm status indicates that the system successfully detected a disturbance and activated the warning mechanism for the user. The tested conditions included:

Table 5: Alarm Function Test

Disturbance	Alarm Status
Bent Tubing	On
Blood Backflow	On
Empty Infusion	On

The results showed that the system was able to activate the alarm under all tested disturbance conditions, namely bent tubing, blood backflow, and empty infusion. This indicates that the detection and notification mechanism in the IoT system functioned according to the design and could support real-time infusion condition monitoring.

3.1.6. Real-Time Monitoring

The real-time monitoring system was developed to display infusion conditions directly through an Internet of Things (IoT)-based application. Data obtained from the TCRT5000 optical sensor were processed by the ESP32 microcontroller and sent to the Firebase platform via a Wi-Fi network. Furthermore, information such as infusion volume, drop count, flow status, blood condition, and alarm status was displayed automatically on the smartphone application.

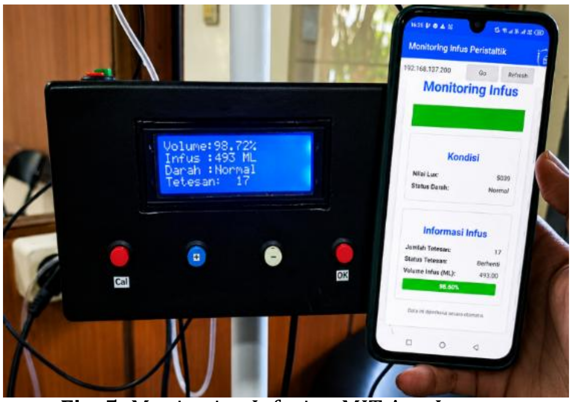

Fig. 5: Monitoring Infusion MIT App Inventor

Fig. 5 shows that the test data were updated continuously with an average latency of 0.816 seconds, allowing users to monitor infusion conditions quickly and receive early warnings when disturbances occurred, such as bent tubing, blood backflow, or empty infusion. This indicates that the system can support real-time, accurate, and reliable infusion monitoring.

3.2. Discussion

Linearity analysis produced the regression equation y = 1.0082x + 3.2590, with R^2 = 0.9992 and r = 0.9996. This finding indicates a highly linear input-output relationship and a very strong positive correlation. Therefore, variations in drip rate can be accurately converted into corresponding changes in the sensor signal. In the repeatability analysis, most CV values were below 5%, indicating good measurement consistency. Nevertheless, the relatively high CV values at 20 and 250 drops/min indicate that sensor performance at low flow rates and at certain points still requires further optimization, particularly to improve the reliability of IoT-based systems under real operating conditions.

This study did not directly evaluate the sensor response time when sudden flow changes occurred. The testing focused on characterizing sensor output against variations in drip rate through sensitivity, linearity, and repeatability parameters. Therefore, the sensor response time to sudden flow disturbances cannot be quantitatively stated based on the present data. Response time testing requires sudden-flow-change scenarios, such as partial occlusion simulation, flow interruption, or abrupt changes in pump speed, as well as time-based sensor signal recording. This aspect is a limitation of the study and is recommended for future investigation.

Table 6: Comparison of Results with Previous Studies

Study	Analyzed Parameter	Results	Comparison with the Present Study
Firdaus et al. [6]	Drop-rate measurement accuracy	Low average error (<5%)	This study not only evaluates system accuracy but also characterizes sensor sensitivity, linearity, and repeatability.
Firdaus et al. [15]	Infusion monitoring using TCRT5000	The sensor was able to detect infusion drops	This study complements previous work by evaluating sensitivity of 0.78-1.25 ADC/(drops/min), linearity of R^2 = 0.9992 and r = 0.9996, and repeatability with CV = 0.29-9.87%.
Present study	Sensor characterization	Sensitivity of 0.78-1.25 ADC/(drops/min); R^2 = 0.9992; r = 0.9996; CV = 0.29-9.87%	Provides more comprehensive quantitative characterization as a basis for evaluating sensor feasibility.

Based on Table 5, this study not only evaluated the ability of the TCRT5000 sensor to detect infusion drops as reported in previous studies, but also presented a quantitative characterization of sensor performance through sensitivity, linearity, and repeatability analyses. The results showed that the sensor had a sensitivity of 0.78-1.25 ADC/(drops/min), a very strong linear relationship with the regression equation (y = 1.0082x + 3.2590), coefficient of determination (R^2 = 0.9992), correlation coefficient (r = 0.9996), and coefficient of variation (CV) of 0.29-9.87%.

Compared with the study by Firdaus et al. [6][15], which primarily emphasized the evaluation of infusion monitoring system accuracy, this study provides quantitative information on the intrinsic characteristics of the TCRT5000 sensor. Thus, this study contributes additional sensor-characterization evidence that can be used as a basis for developing IoT-based infusion monitoring and early flow disturbance detection systems.

3.2.1. Comparison of the Proposed Approach with Other Sensing Technologies

The TCRT5000 reflective optical sensor is one of the sensors widely used in infusion monitoring systems because it has a simple structure, relatively low cost, low power consumption, and easy integration with microcontrollers such as the NodeMCU ESP32. Compared with load cell sensors, ultrasonic sensors, and camera-based sensors (computer vision), the TCRT5000 sensor has advantages in implementation simplicity, compact size, and the ability to provide direct output without complex computational processing. These characteristics make this sensor suitable for IoT-based infusion monitoring applications that require low-cost and easily implemented devices.

However, the proposed approach also has several limitations. TCRT5000 sensor performance is strongly affected by optical conditions in the drip chamber, such as sensor position, installation distance, fluid drop characteristics, and possible interference from ambient light if the system is not properly designed. In addition, this sensor only detects drop changes in the infusion chamber and therefore cannot directly provide information on flow pressure, remaining fluid volume, or occlusion conditions quantitatively, as can be achieved by several other sensing technologies.

Thus, the proposed approach has advantages in simplicity, implementation cost, and ease of integration into an IoT system, whereas its limitations lie in its dependence on optical conditions and inability to directly provide hydrodynamic flow information. Therefore, future research may develop a multisensor system by combining the TCRT5000 optical sensor with pressure or weight sensors to improve the capability of detecting flow disturbances more comprehensively.

3.2.2. Research Limitations

This study has several limitations that should be considered when interpreting the results. First, testing focused on the characterization of the TCRT5000 reflective optical sensor using sensitivity, linearity, and repeatability parameters, and therefore did not include a comprehensive evaluation of the system under actual flow disturbance conditions, such as partial occlusion, total occlusion, air bubbles, or blockage in the infusion line.

Second, this study did not evaluate several system performance parameters, such as response time, detection accuracy, detection error percentage, or formal limit of detection. Therefore, the results of this study place greater emphasis on sensor performance characterization as a basis for developing an early flow disturbance detection system rather than on a comprehensive system-performance evaluation.

Third, testing was conducted under laboratory conditions using a flow-rate range of 20-400 drops/min; therefore, the obtained results do not fully represent the variability of conditions that may occur in clinical use. Factors such as variations in infusion fluid type, changes in environmental conditions, and variations in drip-chamber characteristics were not evaluated in this study.

Fourth, this study used only the TCRT5000 reflective optical sensor as the sensing element and did not conduct an experimental comparison with other sensing technologies, such as pressure sensors, weight sensors (load cells), ultrasonic sensors, or computer-vision-based systems. Therefore, further research is needed to evaluate the relative advantages of each technology through testing under the same operating conditions.

Despite these limitations, this study provides quantitative information on the sensitivity, linearity, and repeatability characteristics of the TCRT5000 sensor, which can serve as a basis for developing IoT-based infusion monitoring and early flow disturbance detection systems.

4. Conclusion

Based on the characterization results, the TCRT5000 reflective optical sensor demonstrated good performance in detecting changes in infusion drip rate over the range of 20-400 drops/min. The sensor showed adequate sensitivity with a relatively stable response, very good linearity as indicated by the regression equation y = 1.0082x + 3.2590, R^2 = 0.9992, and r = 0.9996, as well as good repeatability at most test points, with most CV values below 5%. Although fluctuations were observed under low-flow-rate conditions and an indication of an outlier was found at a specific measurement point, the TCRT5000 sensor overall demonstrated its feasibility for implementation in an IoT-based early detection system for flow disturbances in peristaltic infusion systems. $y = 1.0082x + 3.2590R^2 = 0.9992r = 0.9996CV$

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