IoT-driven Real-Time Glucose Monitoring: Empowering Diabetes Care and Prevention*

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Abstract. The widespread use of Internet of Things (IoT) devices has revolutionized monitoring systems, driving advancements in various societal domains. This study presents a cutting-edge IoT-based architecture for real-time glucose monitoring in the context of Internet of Medical Things, emphasizing its ability to enable timely and accurate sample collection. The primary objective of this system is to continuously monitor glucose levels using the Freestyle Libre 3 sensor, making a significant impact on the health management of patients affected by diabetes and proactively preventing the disease's onset. To ensure the system's effectiveness, a comprehensive quantitative evaluation is conducted, focusing on both battery life and the seamless collection of real-time samples. This meticulous assessment guarantees the system's reliability, efficiency, and ability to deliver vital health data promptly. Additionally, the contribution includes an evaluation of the system's alignment with the Sustainable Development Goals (SDGs), demonstrating its potential contributions to broader social, economic, and environmental objectives. This research showcases the transformative potential of IoT technology in healthcare, offering unprecedented opportunities for continuous health monitoring and proactive intervention.

Keywords: Internet of Medical Things · Real-time glucose monitoring · Monitoring System · Diabetes · Healthcare technology · Freestyle Libre 3 sensor

1 Introduction

Nowadays, the Internet of Things (IoT) is widely employed across various domains. IoT, as a technology enabling communication among diverse Internet-connected devices, has transformed the provision of numerous services, leading to enhanced quality.

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The prevalence of IoT is evident in numerous fields, including home [14], city [11], agriculture [3], and notably, healthcare [2][6]. For instance, in home settings, such systems can be utilized to ensure real-time location tracking [10] of patients, preventing undesirable incidents like falls.

IoT technology serves as the foundation for monitoring systems, aiming to control specific characteristics through smart devices and/or sensors. These systems collect data, perform data cleansing, store it persistently, and even employ intelligent processing to extract valuable insights. In the realm of healthcare, this knowledge extraction supports diagnostics and disease monitoring by healthcare professionals.

While these systems facilitate various societal aspects, there is a growing need to analyze their alignment with Sustainable Development Goals (SDGs), which some studies have overlooked, as indicated by Espinosa et al. [19].

Presently, diabetes is becoming increasingly prevalent worldwide. According to the World Health Organization (WHO), diabetes is a chronic disease [22] caused by either insufficient insulin production by the pancreas or ineffective utilization of insulin by the body. Consequently, patients with diabetes experience hyperglycemia, an uncontrolled increase in blood sugar levels that can lead to severe complications if left untreated.

In 2021, the International Diabetes Federation [8] reported that 537 million adults (aged 20-79) were living with diabetes (1 in 10 patients). This number is projected to increase to 643 million by 2030 and 783 million by 2045. Europe alone accounts for 61 million adults with diabetes (1 in 11), of which 36% remain undiagnosed. Healthcare costs related to diabetes amounted to USD 189 billion in 2021, with 1.1 million diabetes-related deaths reported.

Diabetes is commonly classified into three types. The first type is gestational diabetes, where patients experience hyperglycemia with blood sugar levels above normal but below those diagnosed for diabetes. The second type is type 2 diabetes mellitus, which can cause high blood sugar levels due to the body's ineffective use of insulin. In these cases, treatment through pills or even insulin injections is often required. Lastly, type 1 diabetes mellitus involves deficient insulin production in the body, necessitating daily insulin administration.

Monitoring systems, combined with IoT, can be a valuable tool to enhance the quality of life for patients with diabetes, aid in diagnosing the condition, and even prevent its onset. This leads to reduced mortality and healthcare costs associated with diabetes. Thus, this paper introduces a real-time monitoring system based on IoT devices, designed to control glucose levels for patients using the Freestyle Libre 3 sensor [1]. In addition, it includes a web application to access the latest glucose data received and any historical data of the patient. Compared to other applications such as Nightscout, it allows the data of any patient who wants to use the system to be sent and consulted. Also, the robustness of the system is evaluated in relation to battery life and samples collected, a crucial feature for patients with diabetes.

Finally, evaluating this proposed system against the Sustainable Development Goals (SDGs) is of utmost importance as it allows us to assess its potential positive impact on broader social, economic, and environmental aspects. Additionally, this evaluation presents the alignment of the proposed system with specific SDGs, enabling us to understand how it addresses key sustainability issues and contributes to achieving the global agenda for a more sustainable and inclusive future.

The following are the sections comprising the document. Firstly, Section 2 provides a brief literature review of related works. Next, in Section 3, the proposed glucose monitoring system is presented. Subsequently, in Section 4, a quantitative evaluation of the system is conducted concerning battery life and collected samples. Finally, in Section 5, an assessment of the system's alignment with the SDGs is performed, and in Section 6, the conclusions and the future works of the contribution are presented.

2 Related works

In the healthcare field, numerous works [2] aim to monitor and address various health issues with the ultimate goal of improving people's quality of life. Within this domain, IoT is often referred to as the Internet of Medical Things (IoMT). One such research by Bhardwaj et al. [6] presents a system designed to identify COVID-19 patients through the monitoring of blood pressure, heart rate, oxygen level, and temperature.

Regarding the topic addressed in this research, some works focus on diabetes [16]. On one hand, some opt for non-invasive technologies using sensors based on split ring microwave resonators [5] or smartphone photoplethysmogram (PPG) [23]. However, these experimental technologies may not provide reliable samples and lack a real-world applicable architecture and sampling method.

On the other hand, literature includes works using invasive sensors. In these cases, the research focuses on the methodology for intelligent processing but does not address the continuous real-time data acquisition. For example, the study by Whelan et al. [21] evaluates the experience of diabetes patients with the Freestyle Libre 2 sensor, but this version of the sensor does not provide continuous data and requires patient interaction. Moreover, Nasser et al. [12] propose a prototype for continuous glucose monitoring, which does not include a real system.

These models are based on machine learning [12][20] or deep learning [12] and are primarily used for two different types of predictions. The first type predicts glucose levels in the future to anticipate harmful hyperglycemia and hypoglycemia. Glucose prediction is usually performed in a relatively short future period (between 30 and 60 minutes). For example, Nasser et al. [12] provide a prediction for the next 30 minutes using a deep learning model.

The second type detects whether a person has diabetes or not [15][20]. Other characteristics are often used in addition to glucose levels to determine whether a person is diabetic. In the work of Padhy et al.[15] a total of 14 characteristics are used, such as age, gender, family history, physical activity, blood pressure, among others.

Finally, all these research works lack evaluation from a sustainable perspective. While some of the mentioned works contribute to sustainability in energy, industry, economic growth, and even healthcare, none of them explicitly address the SDGs.

3 Proposed real-time glucose monitoring system

In this section, we propose an IoT-based monitoring system for real-time glucose control.

First and foremost, it is essential to define what glucose is and how it is measured. Blood glucose refers to the sugar present in the blood at a given moment and is measured in milligrams of sugar per deciliter (mg/dL).

Currently, patients with diabetes, especially those with type 1 and type 2 diabetes mellitus, use a glucometer to measure their blood sugar levels. A glucometer is a device that measures capillary blood glucose using a drop of blood obtained from a finger. This process involves two elements: the lancet and the test strip. The lancet is used to prick the finger and extract a small drop of blood, while the test strip reacts with the blood to determine the glucose level. Finally, the glucometer analyzes the test strip to provide the blood glucose reading in mg/dL. All these elements are illustrated in Figure 1.

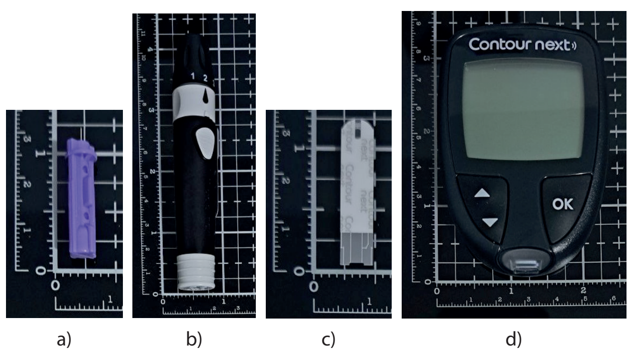

Fig. 1: Devices needed to measure blood glucose: a) needle, b) lancet, c) test strip and d) glucometer (own image).

Blood glucose measurement is a painful process, especially for patients with type 1 diabetes mellitus, which may need to be repeated up to 10 times a day. Additionally, it incurs a significant expense in non-reusable materials, such as lancets and test strips. Therefore, this process could benefit from a more sustainable perspective.

3.1 Proposed glucose sensor

Currently, there are commercial sensors available that allow us to measure glucose at regular intervals. Unlike traditional glucometers that measure capillary glucose, these devices use glucose from interstitial fluid, which originates from exchanges between cells in the tissue and blood.

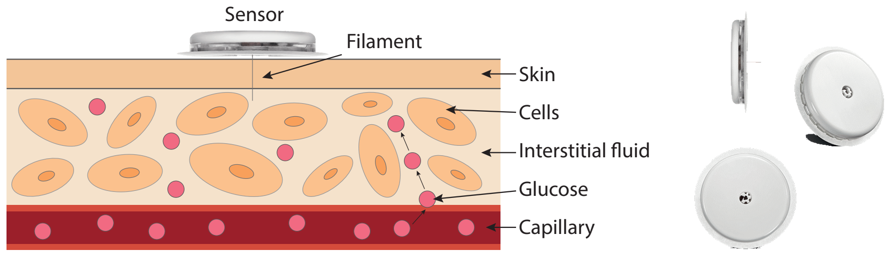

Fig. 2: Example of sensor placement on a person's skin (own image).

The main difference is that it has a delay of 5 to 10 minutes compared to capillary glucose readings, and both measurements are only coincident during stable moments. For instance, when a user consumes a meal, the values will not coincide and will exhibit a slight delay.

These types of sensors are composed of an electrode or filament. This element is placed subcutaneously using an applicator and measures interstitial glucose values through an enzymatic reaction, providing readings at regular intervals. An example of the sensor applied to a person's skin can be observed in Figure 2.

In this research work, the commercial sensor Freestyle Libre 3 [1] is utilized, and its characteristics are outlined in Table 1.

Table 1: Characteristics of the glucose sensor.

Size (diameter x depth)	21 x 2, 9 mm
Battery life	14 days
Reusable	No
Frequency of data transmission	5 minutes
Type of connectivity	Bluetooth Low Energy (BLE)
Approximate cost	59.91€

3.2 Architecture of the proposed system

To monitor the user wearing the sensor, it is necessary to establish an architecture for sending and persistently storing the data. The system's architecture consists of two layers: the fog layer and the cloud layer, as illustrated in Figure 3.

In the fog layer, the glucose sensor is attached to the user's body, along with a fog node. It is recommended to place the glucose sensor on the upper arm, in an area with minimal muscle activity to avoid any discomfort during movements. This sensor sends a glucose sample every 5 minutes.

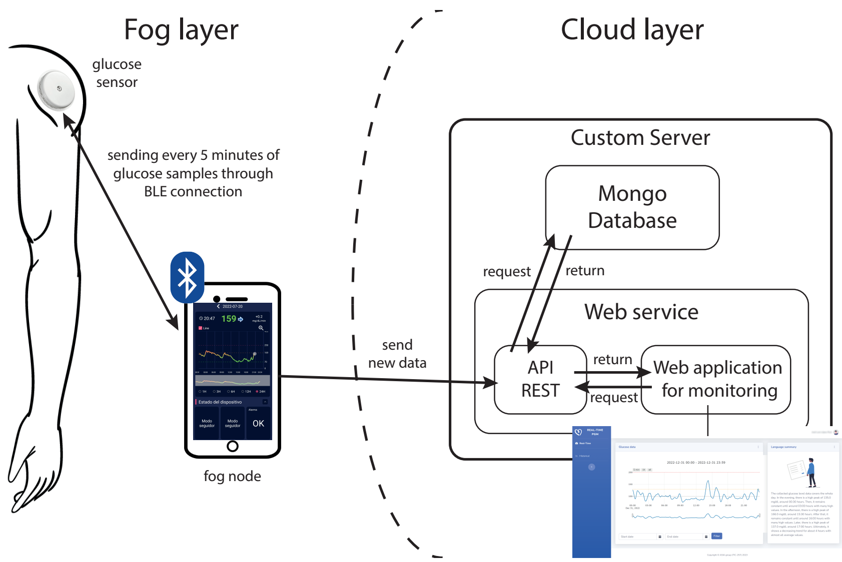

Fig. 3: Proposed Architecture for the Monitoring System Communication (own image).

On the other hand, there is the fog node, which is a smartphone equipped with Near-Field Communication (NFC) and Bluetooth Low Energy (BLE) capabilities. The first step is to initiate communication with the sensor using NFC technology by placing the smartphone close to the sensor. Once this connection is established, the sensor will continuously send glucose data without requiring any further action. All the data is received, processed, and sent to a RESTful service through the Diabox application [7], which is exclusively available for Android devices.

To establish communication with the RESTful service deployed in the cloud, it is necessary to follow the same request schema as Nightscout [13]. This service collects the data sent by the fog node and persistently stores it in a MongoDB database.

Each glucose sample is stored in the MongoDB database as a JSON format document. An example of such a document is shown in Figure 4. For each sample, the most relevant fields include:

- **sgv**: indicates the glucose value in mg/dL.
- **dateString**: indicates the time instant at which the sample was collected.
- **utcOffset**: offset in minutes to be applied to the date. In this case the actual date would be: "2022-12-24T16:41:17".


```
{
    date : 1671896477434
    dateString : 2022-12-24T15:41:17.434Z
    sgv : 115
    delta : 8.007
    direction : FortyFiveUp
    type : sgv
    filtered : 127000
    unfiltered : 127000
    rssi : 100
    noise : 1
    sysTime : 2022-12-24T15:41:17.434Z
    utcOffset : 60
}
```


Fig. 4: Example of a document in MongoDB for each sample collected (own image).

Additionally, a web application has been developed to display glucose data for patients. Unlike the Nightscout service, this application allows centralized remote access to glucose data for anyone who wishes to send their glucose data through our platform. To identify the patient, the security code requested in the Nightscout tool is used. In our case this 12-character alphanumeric code (e.g. wyQ9e9jFY5rt) is to identify the patient. This code is provided when the user registers and is unique. Although the system can support a large number of patients, the prototype has been tested with a small group of people, as the system has limited resources.

This web application offers two types of monitoring: real-time glucose and historical data for the user. The real-time monitoring provides an immediate view of the data from the last hour, along with the date of the last sent sample and the smartphone battery status used for data transmission. The real-time graph also includes a slider to view data from the past 24 hours, and it automatically updates with new glucose data. This type of monitoring is illustrated in Figure 5.

The second type of monitoring allows users to query historical glucose data. These queries enable filtering time ranges between two dates. If the start and end days are the same, it will display the historical data for that particular day only. Additionally, a linguistic summary of the most relevant events within that time span is included. This second type of monitoring is illustrated in Figure 6.

In both cases, glucose data is visualized through line graphs, which users can interact with using various actions: scrolling on the X-axis, zooming, a slider to narrow down the time range with different step options (5 minutes, 1 hour, or no limit), reset to the initial state, and exporting the graph as a PNG image. Moreover, three horizontal lines are included to represent the glucose levels defined by the American Diabetes Association (ADA) [4]: normal (grey), medium (orange), and high (red).

Fig. 5: Web application interface for the first type of monitoring: a) Current time, b) Time instant when the last sample was received, c) Remaining smartphone battery and d) Vertical bar showing the current minute (own image).

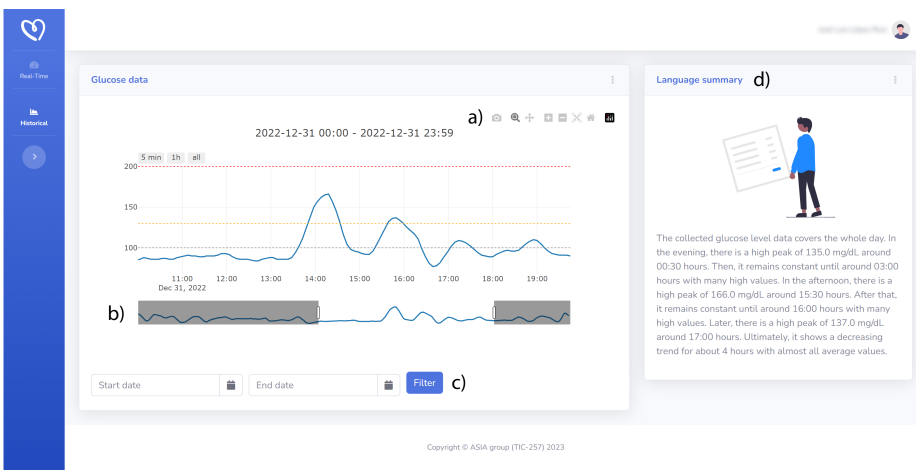

Fig. 6: Web application interface for the second type of monitoring: a) Available actions, b) Slider to modify the time range, c) Query form between two dates and d) Linguistic summary of the filtered time span (own image).

4 Quantitative evaluation of the effectiveness of the proposed real-time glucose monitoring system

In this section, a quanti-tative evaluation of the effectiveness of the proposed real-time glucose monitoring system will be conducted. This evaluation will take into account several factors such as the number of missed samples, the actual sensor battery duration, and the overall system performance. To test the architecture, a sensor was used on a user, and samples were collected until the sensor's battery was depleted (continuously for 14 days).

The data collection period spans from December 24, 2022 (15:36h) to January 7, 2023 (13:21h), defined based on the first and last received samples. Overall, the sensor has operated for 99.33% of the time set by the manufacturer (14 days).

Regarding the samples, considering a sampling frequency of 5 minutes, 4005 samples were expected within that time frame. The system has successfully collected a total of 91.3% of the expected samples. Out of the 8.7% of missed samples, 7.1% were intentionally omitted to test whether the sensor could store data temporarily until reconnecting with the fog node. Thus, the system effectively captured 98.4% of the total samples. Additionally, it was observed that at times, the sensor readings experienced slight delays, leading to a partial loss of expected samples.

Based on the results, it can be concluded that the sensor performed as expected according to the manufacturer's specifications (99.33%). Furthermore, the connection and sample transmission have been robust and reliable (98.4%), which is crucial for type 1 diabetic patients, as they require a dependable system at all times. One limitation is that the sensor cannot store samples when the fog node is unavailable.

These findings are summarized in Figure 7 and the data used for the evaluation is presented in Table 2.

Table 2: Data used for evaluation.

Time period of data collection			
Start	2022-12-24 15:36	*End*	2023-01-07 13:21
Number of estimated samples		4005	
Number of samples collected		3656	

Testing time periods	
Start	*End*
2023-1-3 00:50	2023-1-3 07:48
2023-1-4 22:35	2023-1-5 07:29
2023-1-5 23:32	2023-1-6 07:23
Number of samples lost	284

Example of samples with altered frequency		
Timestamp 1	*Timestamp 2*	*Time between samples (min)*
2022-12-25 17:17	2022-12-25 17:24	7
2022-12-25 18:05	2022-12-25 18:13	8
2022-12-25 22:58	2022-12-25 23:04	6

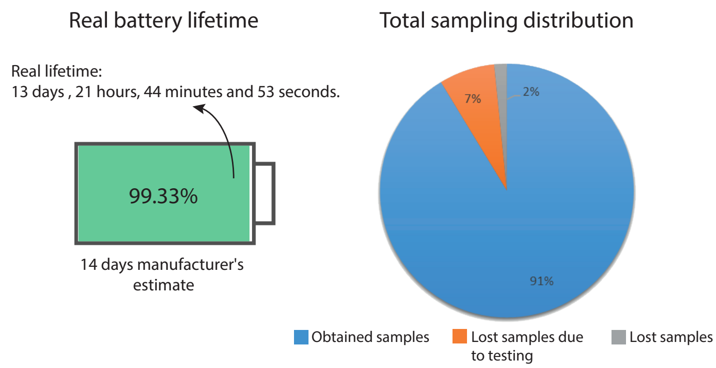

Fig. 7: Summary of the results obtained in the quantitative assessment (own image).

5 Alignment with Sustainable Development Goals

In 2015, the United Nations (UN) established the 2030 Agenda as an urgent call for action by all countries. This agenda includes 17 SDGs, 169 targets, and 232 indicators. Therefore, it is essential to evaluate this work from a sustainable perspective [17].

This type of evaluation is crucial for the implementation of the system in the real world, because it allows us to know how it affects our society and the environment. It also provides another type of metric to compare related systems. In the literature, there are studies [18][9] that propose methodologies to evaluate this type of system in a comprehensive way. In contrast, this paper makes a generalist evaluation of this system by listing the main SDGs with which we consider the monitoring system to be aligned.

Firstly, we consider the system proposed in this document aims to replace the traditional method of glucose measurement using a glucometer. On one hand, we believe that the presented proposal establishes a new service in the healthcare domain to assist patients and provide a means for disease management by healthcare professionals. Hence, we consider that it aligns with *SDG 3: Good Health and Well-being*.

On the other hand, an patientes with type 1 diabetes is estimated to use the glucometer 10 times a day. By substituting this method with the proposed system, they would avoid using 140 needles and test strips over a 14-day period. Therefore, we also consider that the system aligns with *SDG 12: Responsible Consumption and Production*.

6 Conclusions and futures works

This document presents a real-time glucose monitoring system for patients with diabetes. The proposed system utilizes an invasive glucose sensor that reads glucose levels from the interstitial fluid. By enabling real-time sample collection, this innovative system empowers healthcare professionals and patients alike to make informed decisions, leading to better health outcomes and improved quality of life. To do so, the sensor is connected to a smartphone via NFC and BLE, and it continuously sends glucose readings without requiring any action from the user. Additionally, the glucose values are persistently stored in a MongoDB database. These data are retrieved and displayed in a web application, enabling real-time visualization of glucose levels, historical data with temporal filtering capabilities, and linguistic summaries of the selected time frames. The system underwent a 14-day evaluation and achieved a capture rate of 98.4% of the expected samples. Furthermore, the sensor's battery lasted 99.33% of the manufacturer-specified duration. Therefore, we believe that the system meets the expected requirements and needs. Finally, by considering the SDGs, we can better gauge the significance of this system in promoting health and well-being (SDG 3) and supporting responsible production and consumption practices (SDG 12), and thus guiding future developments towards a more sustainable world.

Our future work in this area will focus on providing real-time descriptive summaries of blood glucose levels to raise awareness among patients about the impact of their dietary choices and exercise habits on their health. By integrating data from the monitoring system with nutrition and activity logs, the proposed system aims to offer personalized feedback and insights to patients, empowering them to make informed decisions and adopt healthier lifestyle choices. The descriptive summaries will not only facilitate self-monitoring but also foster a deeper understanding of the relationship between glucose levels and daily habits, encouraging patients to take a proactive approach to managing their condition and ultimately improving their overall well-being. This aspect of the system holds immense potential for promoting patient engagement and adherence to treatment plans, leading to more effective diabetes management and enhanced health outcomes.

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