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IoT-based intelligent monitoring system for biological sample management

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***Abstract* — In biomedical research, biobanks are essential tools for collecting and storing biological samples, providing researchers with valuable data such as medical history or genetic profiles, essential for personalized medicine. Managing and monitoring these biobanks is a major challenge, especially in developing countries like Senegal, where resources and infrastructure are often limited. This paper proposes to design an intelligent monitoring system controlling the temperature of biological samples in the biobank. We used sensors connected to a microcontroller to continuously measure temperature and transmit the data to a local or cloud-based server via Wi-Fi and the MQTT protocol. Data is also saved locally to an SD card to prevent loss in the event of a network failure. Data visualization is provided by the Node-RED platform, which displays the most recent measured temperatures. A real-time alert system has been set up to automatically send emails to the administrator if the temperature exceeds critical thresholds. With these combined technologies and tools, our system enables remote monitoring of our various thermal chambers by viewing temperature data in real-time and recording this data in an electronic file.**

***Keywords* — biobank, IoT, remote monitoring, biological samples.**

I. INTRODUCTION

Biobanks play a crucial role in facilitating the collection, storage and management of biological samples for various studies, particularly in the context of biomedical research and public health. They store various repositories for a wide range of biological samples and associated data [1]. The first initiatives for the preservation of biological samples date back to the 1970s, around 1990, with work on cryopreservation and human tissue banks [2], [3]. These early biobanks, often specialized in infectious disease or cancer research, provided conceptual and technical bases for the long-term preservation of biological samples. Over the years, the importance of biobanks has increased exponentially, driven by technological advances and the emergence of precision medicine initiatives.

However, effective management and monitoring of their samples remain a challenge, especially in developing countries such as Senegal. Storage equipment is installed in environments marked by power outages, causing temperature drops. Although these temperature fluctuations can alter biological samples. The lack of connected IoT solutions or real-time analytics platforms also compromises the reliability of the monitoring process. This underlines the importance of an appropriate monitoring system and proactive management of biological resources.

This article aims to design an intelligent monitoring system for the management of biological samples in our biobank, based on IoT technologies. This system enables real-time monitoring through interconnected sensors, which continuously measure critical parameters such as temperature. This connectivity ensures instant visualization of equipment status and early detection of anomalies, reducing the risk of sample deterioration. This approach strengthens the management capacity of biobanks but also contributes to the development of biomedical research in West Africa.

The rest of the article is structured as follows: the first section presents the state of the art by reviewing some previous work. The second section describes the methodology used to design and implement this system.

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The third section deals with the results obtained. Finally, the last section offers a conclusion and opens up perspectives.

II. RELATED WORKS

A. *Biobanks in Africa*

Biobanks are essential to biomedical research in Africa, as they store and manage biological samples. Many studies have focused on this area, including the H3Africa consortium, which has also invested significant resources in the creation of high-quality biobanks in Africa [4]. These biobanking systems are essential for studying various disorders and improving public health; they not only contribute to research on infectious diseases such as malaria, tuberculosis and HIV/AIDS, but are also increasingly in demand for studies on chronic and genetic diseases affecting local populations [5]. Institutions such as the Institut Pasteur in Dakar have biobanks that contribute significantly to epidemiological and clinical research [6]. The Institut Pasteur also houses a reference center for the storage of samples used in surveillance and research on infectious diseases, such as dengue fever and yellow fever, which are major concerns in West Africa [7]. These studies, which are often prospective, require significant clinical and biological retrospection to allow retrospective analyses. It is in this context that the IRESSEF (Institute for Health Research, Epidemiological Surveillance and Training) is in the process of setting up a modern biobank capable of generating quality biological samples (serum, plasma, PBMC, whole blood, buffy diaper) in collaboration with health structures and various partners [8]. The ambition of this structure is to become a modern sub-regional biobank, equipped with infrastructure and equipment to collect, conserve and make available to researchers a variety of quality biological resources.

These projects not only contribute to the development of more effective treatments for the local population but also contribute to global science by offering an African perspective on public health issues.

B. *Traditional biobanking monitoring systems*

The operation of biobanking systems is based on conventional monitoring systems with significant constraints. Local control and spot checking of the thermal chambers is carried out by thermometers. Their primary function is to provide accurate reading and manual tracking in the event of a failure of the main device [9]. The measurements made are usually recorded on local media, most often in the form of paper logs or monitoring sheets, and then manually recorded by technical staff for archiving and in-depth analysis. Regular visits are carried out to check that the equipment is working properly and to carry out the necessary maintenance operations. This method, although operational, relies entirely on human intervention for reading, transcribing and archiving data. Such an approach illustrates the traditional model of surveillance that is still widely used in many biobanks, especially in resource-constrained settings.

III. METHODOLOGY

At this stage, after analyzing the existing biobank system, identifying and proposing a framework for the acquisition of temperature data, we chose the ESP biobank as a case study. We have set up a new system based on sensors, connected to microcontrollers, deployed in our biobank. These sensors continuously measure the temperature and transmit the data via Wi-Fi and the MQTT protocol to a central server. Moreover, this data is stored locally on an SD card to prevent loss in the event of a network failure. We used the Node-red platform to visualize data on its dashboard in real-time, generating alerts when critical thresholds were exceeded.

Fig. 1 Architecture of the proposed system

Our proposed model aims to establish communication between the nodes and the server. An ESP 32 microcontroller, which acts as an IoT gateway, sends the temperature measurements to the server, which in our case is a Raspberry Pi 5. The latter is responsible for processing requests and providing the acquired sensor data.

IV. RESULTS AND DISCUSSION

A. *Data visualization*

Temperature data visualization facilitates real-time monitoring, providing intuitive visual access to the thermal environment of biobanks. In Node-Red, we display the most recent measured temperatures, allowing us to quickly read the current status of all our freezers, as shown in the figure below. A real-time alerting system has been set up, automatically sending emails to the administrator in the event of a critical thermal deviation (see figure below).

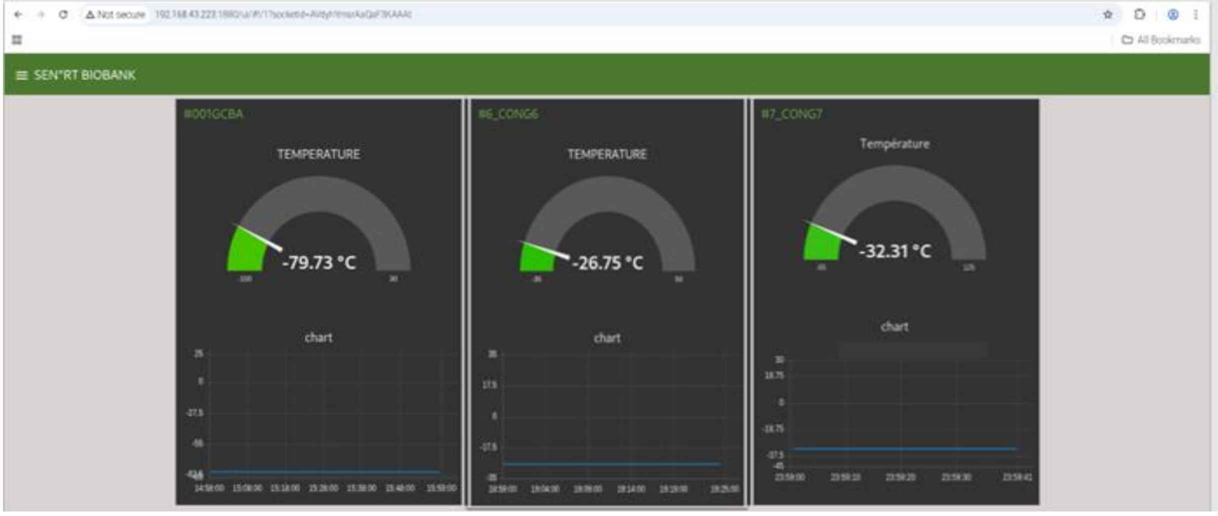

Fig. 2 Temperature visualization

B. *Descriptive analysis*

The data from freezer #07_CONG7 show very good thermal stability around -25°C, which corresponds to the usual requirements for the preservation of bioresources, especially wastewater samples. This stability shows that the control system keeps the temperature within an optimal range, ensuring sample viability and reliable measurements. Compliance with the storage standard demonstrates that the control system is correctly dimensioned. (See Figure 3).

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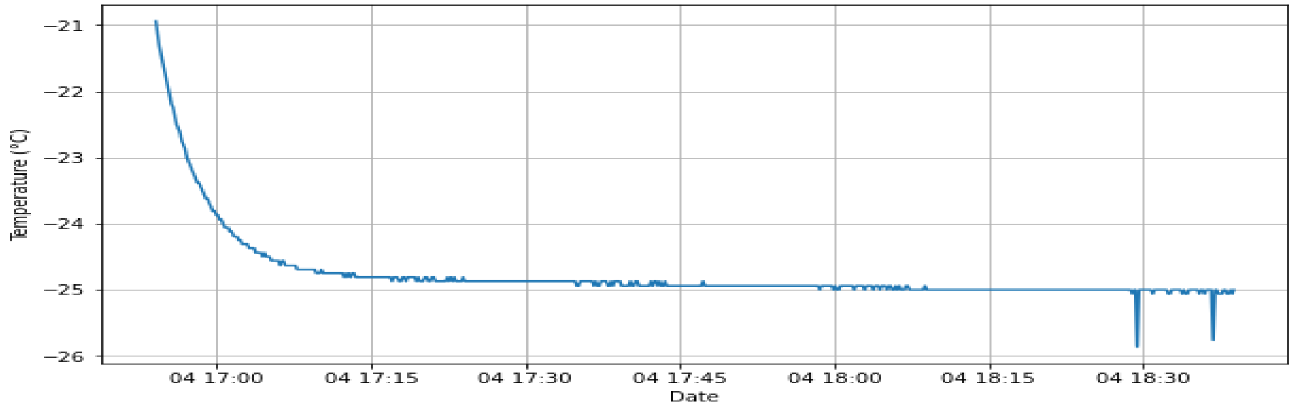

Fig.3 Temperature change over time of #07_CONG7

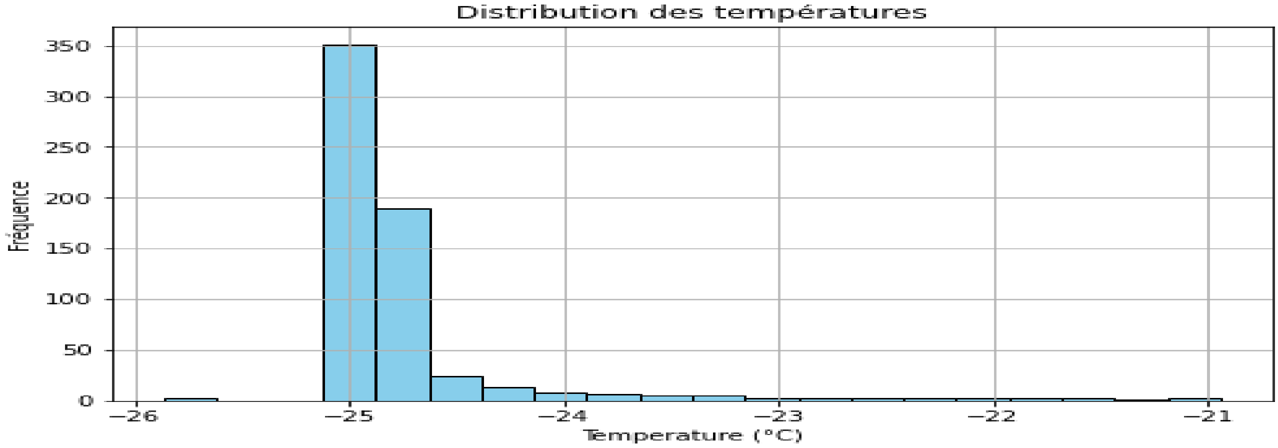

Fig.4 Temperature distribution for #07_CONG7

The maximum temperature, -20.9°C, seems to be a one-off anomaly, but does not represent a real temperature increase. This is due to the response time of the sensor when immersed in a new cryogenic environment. In addition, the histogram shows an asymmetric graphical distribution on the right side (Figure 4). Of the 624 temperature measurements, almost all are concentrated between -25 and -24.5°C, confirming the thermal stability observed in Figure 3. A few higher values can be seen between -21 and -20°C, but they are rare and isolated due to the response time of the sensor. These isolated deviations reinforce the idea of structural stability of the system.

For freezer #06_CONG6, out of 525 temperature readings, almost all values are between --29.7°C and -29.8°C (see Figure 5). This range perfectly matches the recommended conditions for long-term storage of biological resources, thus ensuring their structural and molecular integrity [10]. This stability illustrates the efficient design of the cooling system and its precise regulation.

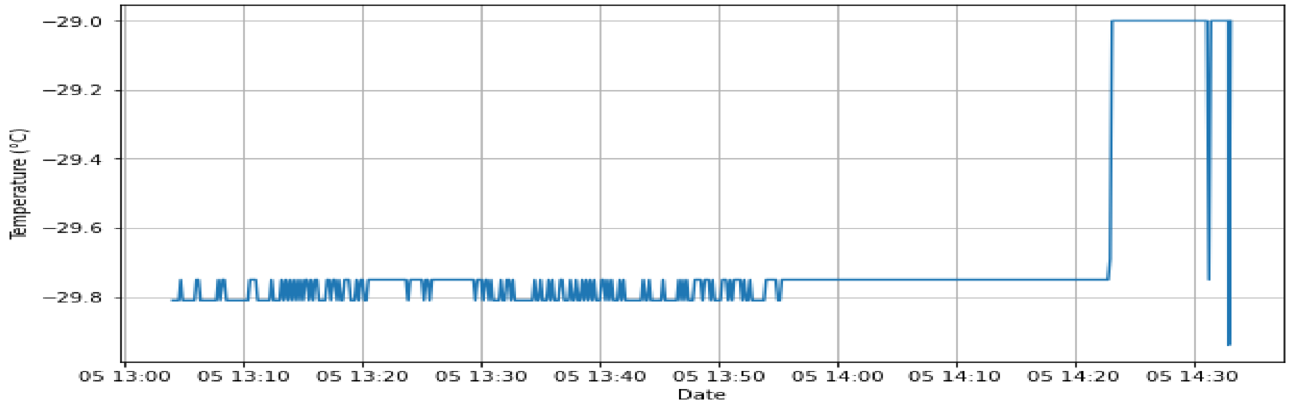

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Fig.5 Temperature evolution over time of #06_CONG6

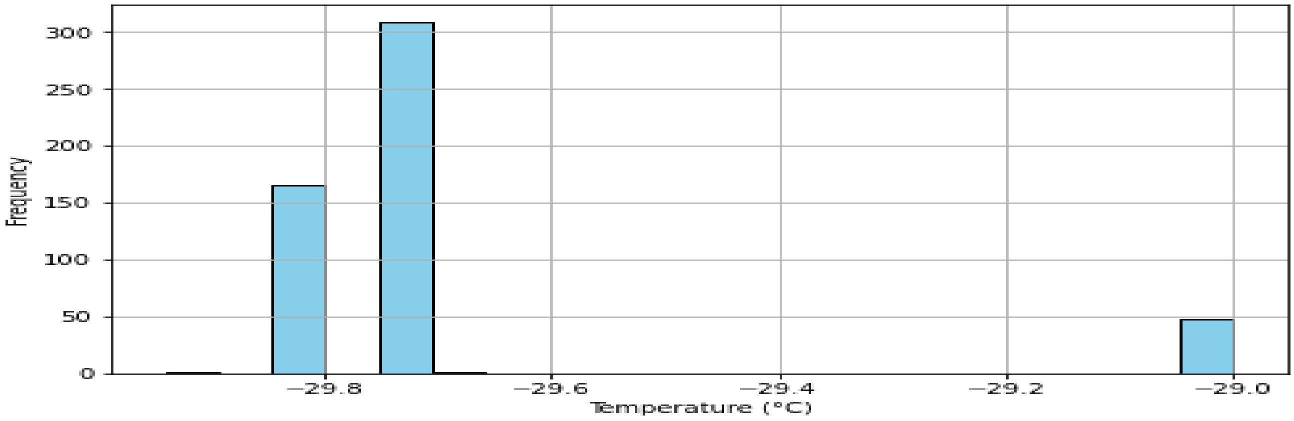

Fig.6 Temperature distribution for #6CONG6

The maximum value is -29°C, with a very low frequency. The data indicate excellent overall temperature control, with occasional slight drifts with no immediate impact on sample integrity.

In this freezer, #01_GCBA, three distinct phases are recorded (see Figure 7): before 5 p.m., the temperature is very stable, fluctuating around -80.5°C, which corresponds to the normal operation of the ultra-low freezer (ULT) [11]. This phase illustrates the system's ability to maintain optimal conditions for blood and plasma samples. A rapid rise in temperature was then observed between 5:20 p.m. and 5:25 p.m., reaching -78.3°C. The visible fluctuations around this value indicate active but unstable regulation. Finally, a gradual return to normal is observed around 5:50 p.m. at -80.0°C. This 2°C increase may be due to frost forming or the opening of the door to calibrate the sensor.

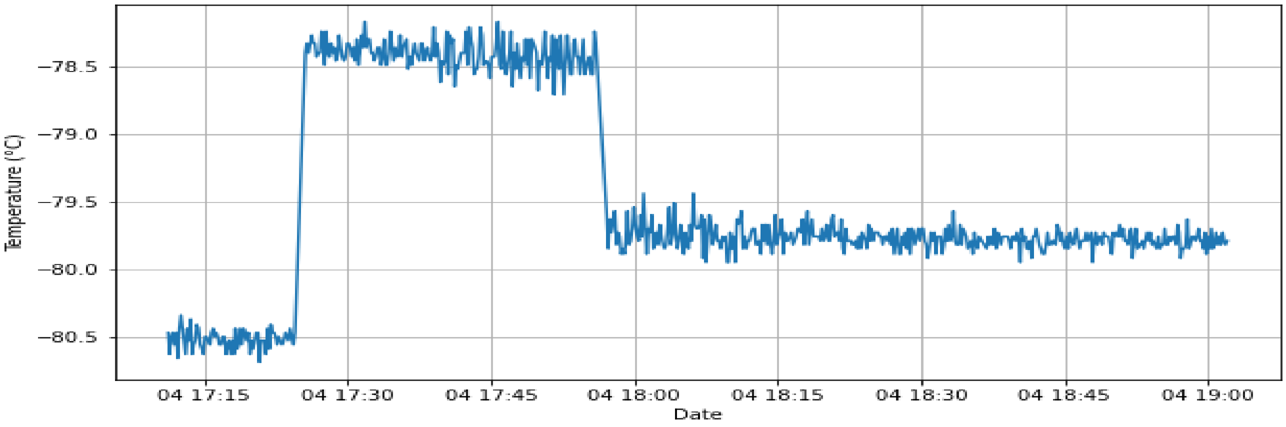

Fig.7 Temperature change over time of #001_GCBA

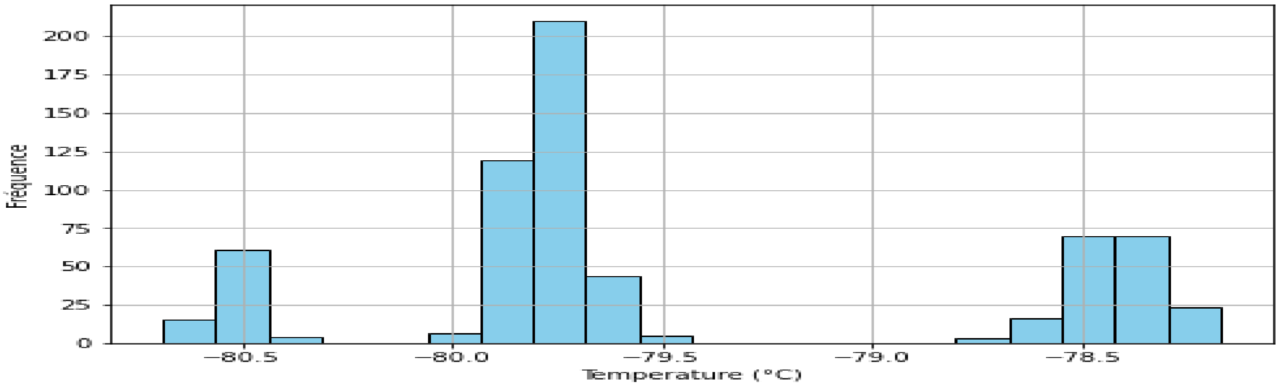

Fig.8 Temperature distribution for #001_GCBA

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Although the temperature is above -78°C, this drop must be considered because, beyond this value, heat-sensitive samples, especially those stored near the door, can be modified. However, the critical threshold has not been reached, and the frequency of these measurements is low, about 100 measurements out of the 646 values taken (see Fig.8). Thus, the samples maintain their integrity according to the criteria for long-term storage [12].

TABLE I
TABLE 1. SUMMARY OF TEMPERATURES MEASURED IN STORAGE UNITS.

ID	**Count**	**Villain**	**Year**	**Min**	**Max**
#07_CONG7	624	-24,7631	0,5668	-25,8600	-20,9400
#06_CONG6	525	-29.7006	0.2242	-29.9400	-29.0000
#001_GCBA	646	-79.4781	0.7180	-80.6900	-78.1700

The overall results obtained from the three storage units analyzed highlight the reliability of the IoT monitoring system deployed. The recorded measurements show remarkable thermal stability, with limited variations and a standard deviation of less than 0.5°C, attesting to the performance of the refrigerator and the accuracy of the sensor system.

V. CONCLUSIONS

In this article, we have designed and implemented an IoT-based smart monitoring system for the management of biological samples in our biobank. This system has demonstrated the effectiveness of a technological approach to ensure the quality and integrity of biological resources, in the face of the challenges posed by traditional monitoring methods. The results of the study confirmed the thermal stability of the equipment and the effectiveness of the refrigeration system in maintaining the required storage conditions. This modern surveillance system represents a major step forward in protecting valuable samples and ensuring their quality for future studies, marking an important step towards modernizing Senegal's health research infrastructure.

Our future work will focus on the integration of artificial intelligence to better revolutionize biobank management through the analysis of temperature data. This approach will enable the implementation of predictive anomaly detection mechanisms to analyze thermal trends and predict potential failures before they occur.

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