Design and implementation of a mechatronic system for monitoring worker exposure in cold storage facilities

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Abstract. In response to the increasing need for enhanced occupational safety in cold storage facilities, this study presents the design and validation of a mechatronic time control device specifically developed for monitoring the exposure times of warehouse operators in a multinational company. Over the past two decades, Ecuador has significantly increased regulations to safeguard worker health and safety. This research addresses operators' challenges when exposed to sub-zero temperatures during work shifts. The proposed system integrates mechanical, electronic, and control components to track and manage operators' time in cold rooms, ensuring compliance with predefined safety thresholds. The device's core comprises a NodeMCU microcontroller, digital temperature sensors, and a robust communication interface. This device records entry and exit times, monitors ambient conditions, and triggers alerts when exposure limits are approached. Extensive validation was conducted using a 3D-printed resin prototype, demonstrating the device's capability to function effectively in harsh environments. The system's efficacy was evaluated through real-world testing, where operators used the prototype during their shifts. Data collected confirmed the device's reliability in tracking exposure times and enhancing worker safety. The results suggest that implementing this mechatronic device can significantly improve monitoring, ensuring regulatory compliance and protecting worker health. This study contributes to advancing occupational safety technologies, offering a practical solution for industries reliant on cold storage operations.

Keywords: Mechatronic System, Occupational Safety, Cold Storage Monitoring, Time Control Device.

1. INTRODUCTION

In recent years, the emphasis on occupational safety has intensified, particularly in industries where employees are exposed to harsh working environments (Chen, 2023; Walters, 2024; BSIGroup, 2024). The cold storage sector, integral to food production and pharmaceutical industries, exemplifies this challenge due to the prolonged exposure of workers to sub-zero temperatures. This exposure poses significant health risks, including hypothermia and frostbite, necessitating stringent monitoring and safety measures (Romo, 2014).

In alignment with global trends, Ecuador has progressively enhanced its legislative framework to protect worker health and safety (Toro, 2020). The Ministry of Labor and other regulatory bodies have mandated specific guidelines to ensure safe working conditions in cold storage facilities (Vasco, 2018). Despite these regulations, the practical implementation of monitoring systems remains inconsistent, often relying on manual records prone to errors and inefficiencies (Son, 2021; Pistolesi, 2024). Figure 1 shows the historical evolution of occupational accidents in Ecuador from 1992 to 2020.

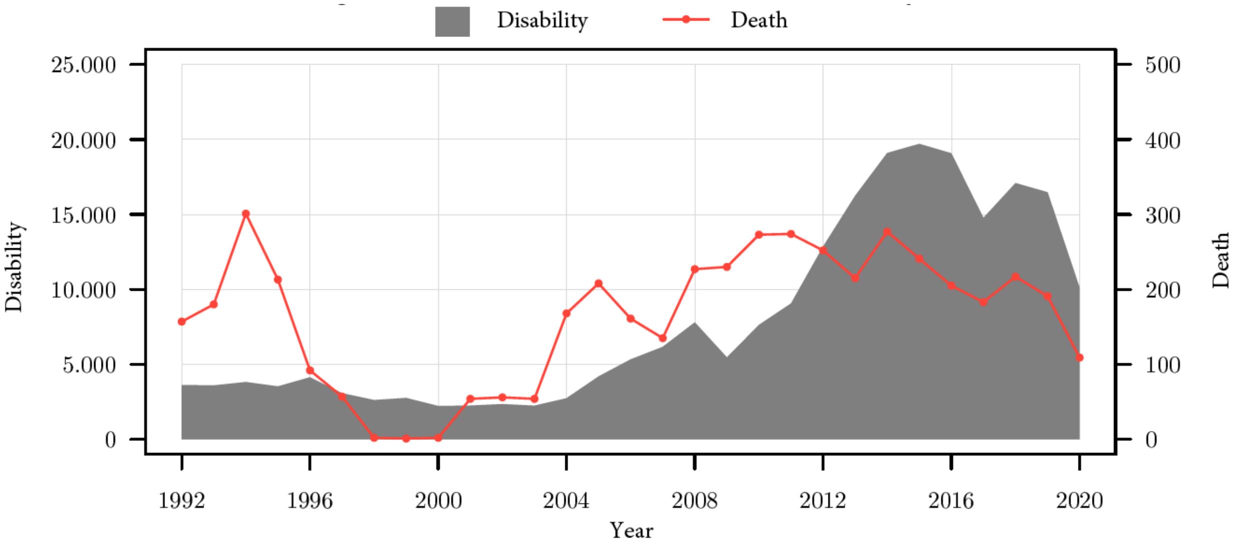

Figure 1. Historical evolution of workplace accidents (IESS, 2020)

The need for a reliable, automated solution is evident. This study addresses this gap by designing and validating a mechatronic time control device tailored for cold room environments. By integrating modern mechatronic principles with robust data monitoring capabilities, the proposed system aims to enhance the accuracy and reliability of exposure tracking.

Previous studies have explored various aspects of occupational safety in cold environments. Diez (2020) demonstrated the effectiveness of wearable sensors in monitoring physiological responses to cold. However, there is limited research on comprehensive systems that track exposure times and integrate with workplace safety protocols. This study builds on existing knowledge by providing a practical, validated solution designed explicitly for multinational warehouses with stringent operational requirements.

The device developed in this research leverages a NodeMCU microcontroller, digital temperature sensors, and a wireless communication interface to monitor and record real-time entry and exit times. The design and validation process included extensive prototyping and testing to ensure the system's robustness and reliability in cold storage conditions (Expressif Systems 2022a, Expressif Systems 2022b).

The design of the mechatronic system for monitoring worker exposure in cold storage facilities is rooted in the principles of systems architecture, control engineering, and mechatronics. Systems architecture in this context involves integrating various hardware and software components to create a cohesive and reliable monitoring system (Grupo Kalise Menorquina, 2024). The NodeMCU microcontroller is the central processing unit, coordinating data from digital temperature sensors, a real-time clock module, and an OLED display. This integration ensures real-time monitoring and data logging, which is essential for maintaining accurate records of worker exposure times. The architecture is designed to be modular, allowing for scalability and adaptability across different cold storage environments. This approach is supported by the extensive use of CAD software and 3D printing technology to create a durable and compact enclosure that houses all the electronic components, ensuring the system can withstand the harsh conditions typical of cold storage facilities (Espressif Systems, 2022a; Lakatos, 2020).

Control engineering is a critical aspect of the system, focusing on maintaining high precision in monitoring and alerting functions. The firmware developed for the NodeMCU microcontroller utilises PID control algorithms to manage data acquisition and processing, ensuring stable and reliable operation. This is crucial for triggering timely alerts and maintaining compliance with safety regulations. The system's control logic is designed to handle real-time data from temperature sensors and manage the OLED display's output to provide immediate feedback to operators. The accuracy of the control system was validated through rigorous testing, demonstrating a mean absolute error of ±1 s per hour in timekeeping and a temperature accuracy deviation of ±0.2°C. These results highlight the effectiveness of the control engineering principles in the system's design, ensuring precise monitoring and enhancing worker safety in cold storage environments (Cámara, 2016; Diez, 2020).

This paper is structured as follows: Section 2 details the methodology employed in designing and validating the mechatronic device. Section 3 presents the results of the validation tests, and Section 4 discusses the implications of the findings. Finally, Section 5 concludes with recommendations for further research and potential device applications.

Implementing this mechatronic system aims to enhance occupational safety by providing an accurate and automated solution for monitoring worker exposure in cold storage environments. This contribution is crucial for industries where maintaining worker safety in extreme conditions is a legal and moral requirement (OSHA, 2023).

2. METHODOLOGY

The methodology for designing and validating the mechatronic time control device for cold storage facilities involved several key stages, including the initial problem definition, design conceptualization, prototyping, and validation through testing. This section provides a detailed description of each stage, emphasizing the technical and procedural aspects that ensured the device's effectiveness and reliability.

2.1. Problem definition and requirements analysis

The first step involved thoroughly analyzing cold storage facilities' operational environment and safety requirements. Critical parameters such as the typical duration of worker exposure, ambient temperature ranges, and the specific needs of a multinational warehouse were identified. Stakeholder consultations, including discussions with warehouse managers, safety officers, and operators, were conducted to gather detailed requirements. The primary objectives were to: 1. Accurately monitor and record the time operators spend in the cold room. 2. Ensure real-time data transmission to a central monitoring system. 3. Provide alerts when exposure limits are approached. 4. Maintain robust performance in sub-zero temperatures.

2.2. Design conceptualization

Based on the problem definition, a conceptual design for the mechatronic system was developed. The system's architecture included the following components:

- NodeMCU Microcontroller: Chosen for its small size, low power consumption, and built-in Wi-Fi capabilities.
- Digital Temperature Sensors (DS18B20): Selected for their accuracy and reliability in extreme temperatures.
- Real-Time Clock (RTC) Module: To ensure precise timekeeping.
- OLED Display: For local display of critical information such as current temperature and time spent in the cold room.
- Battery Pack: Ensuring uninterrupted power supply during operation.

A block diagram of the system was created to illustrate the integration of these components (Figure 2).

2.3. Prototyping

The design was translated into a physical prototype using CAD software and 3D printing technology. The following steps were undertaken:

Mechanical design. The device's enclosure was designed to be compact and durable, capable of withstanding impacts and low temperatures. The enclosure was 3D printed using high-strength resin (Lakatos 2020).

Electronic assembly. The microcontroller, sensors, and other electronic components were assembled and integrated within the enclosure. Connections were made using soldering and wiring to ensure reliability.

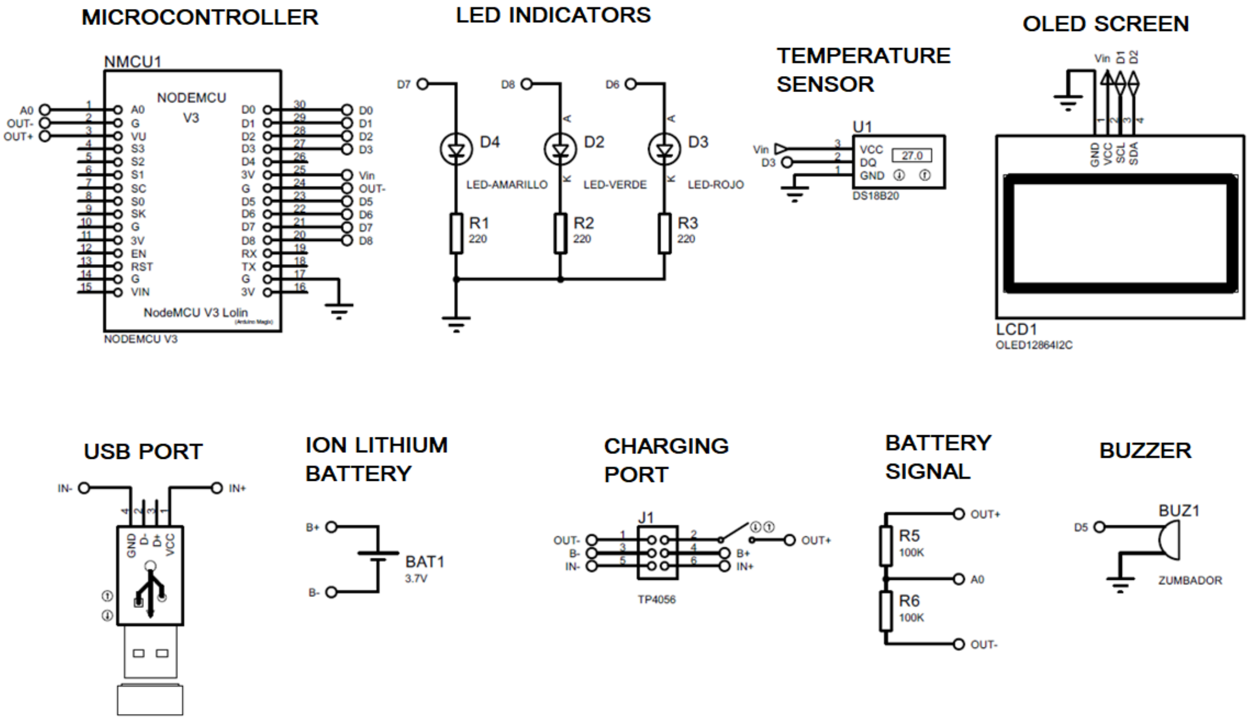

Figure 2. Electronic design

2.4. Software development

Custom firmware was developed for the NodeMCU microcontroller to handle data acquisition, processing, and communication. Key functionalities included:

- Data Logging: Recording operators' entry and exit times.
- Temperature Monitoring: Continuously measuring and logging ambient temperature.
- Alert System: Generating alerts when exposure times approach predefined limits.
- Data Transmission: Sending collected data to a central server via Wi-Fi for real-time monitoring.

The software was written in C++ using the Arduino IDE, with libraries for handling the sensors, RTC module, and OLED display (Cámara, 2016).

2.5. System validation

Validation of the system involved extensive testing under real-world conditions. The following tests were conducted:

Temperature resilience test. The device was placed in a controlled cold room to ensure it operated reliably at temperatures between -22°C and -20°C.

Accuracy test. The timing accuracy of the device was tested against a standard timekeeping device. Any discrepancies were logged and analyzed.

Durability test. The physical robustness of the device was evaluated by subjecting it to simulated drops and impacts.

Operational test. Operators used the device during their shifts, and their feedback was collected to assess ease of use and reliability. Data collected during these tests were analyzed to determine the device's performance.

2.6. Data analysis

Data collected during the validation tests were analyzed using statistical methods to evaluate the device's accuracy and reliability. Key performance indicators included:

Timekeeping Accuracy. Measured by comparing the device's recorded times against a standard reference.

Temperature Accuracy. Assessed by comparing the sensor readings with calibrated temperature measurement instruments.

System Uptime. The percentage of time the device remained operational during the testing period.

User Feedback. Qualitative data from operators regarding the usability and effectiveness of the device.

2.7. Ethical considerations

All testing involving human participants was conducted following ethical guidelines. Informed consent was obtained from all participants, and measures were taken to ensure their safety and confidentiality.

3. RESULTS AND DISCUSSION

This section presents the results of the mechatronic time control device's design, implementation, and validation tests. The outcomes are analyzed to assess the device's performance, reliability, and practical applicability in real-world cold storage environments (Roobuck, 2024).

3.1. Design and implementation

The design phase yielded a compact, robust device, successfully integrating the NodeMCU microcontroller, digital temperature sensors (DS18B20), an RTC module, an OLED display, and a battery pack within a 3D-printed enclosure (Creality, 2024). The following subsections detail the key components and their integration:

Mechanical design. The device's enclosure was designed to withstand a cold storage environment's physical and thermal stresses. The 3D-printed resin prototype demonstrated high durability and adequate protection for the internal components (Figure 3). The stress study analyzed the most common situations where work tools are present within a warehouse. These situations include falls, accidental blows or vibrations. Given these cases, calculating the joint external force an object can present when falling from an average height of 150 cm was performed. By performing this calculation, the critical points in which the system can show physical damage to the structure can be revealed. When an object falls, the gravitational potential energy (PE) is converted into work upon impact. Then, the kinetic energy (KE) at the lowest point of the fall was considered. This calculation was performed using (1), assuming all potential energy must be transformed into kinetic energy.

$$PE = mgh = 0.1kg \cdot 9.8\frac{m}{s} \cdot 1.5\,m = 1.47\,J \tag{1}$$

This result was used to calculate the principle of work and energy. In a free-fall collision, the object experiences an average impact force (F) relative to the distance travelled after the impact (d), as is shown in (2).

$$KE = F \cdot d \therefore F = 294\,N \tag{2}$$

Once the impact force that the device can experience was obtained, the dimensions of the device were entered into a CAD simulation program. A Von Mises stress study helped us understand how a material can yield distortion when the maximum value is reached. This depends on the material chosen and its physical properties. The material entered was a generic ABS for 3D printing since the objective was to observe the possible stress levels from a fall. As seen in Figure 3, the corners of the device were affected, and it is evident how the energy is distributed from this.

This test was performed in the CAD Inventor simulation program, a stress study applying the distortion energy (ED) failure theory. Three points of interest were chosen, of which two are located where a higher Von Mises stress is observed. The third is in the center of the face where the load was applied. It was necessary to assign a material to the design to simulate the stress applied to the casing. ABS plastic was considered a fundamental property of this design and had excellent impact resistance.

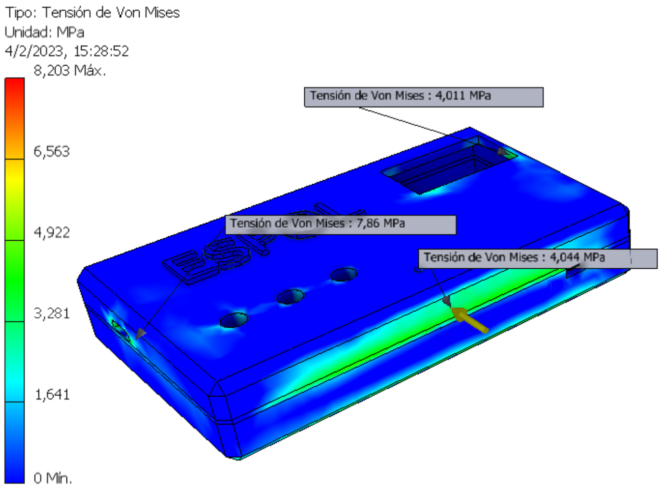

Figure 3. Von Mises stress simulation

After simulating a load of 294 Newtons applied to the lower side of the casing, the Von Mises stresses were obtained at three points of interest. The safety factor at the points of interest was determined using the yield strength (S_y) of the ABS plastic, which has a value of 45 MPa, and the Von Mises stresses obtained after the simulation in Table 1.

Table 1. Safety factors for the interest points

	Safety Factor
N_1	11.22
N_2	5.73
N_3	11.13

Based on the results obtained from this study, it was determined that the mechanical design is acceptable since it will not fail under the applied load. In addition, it has a safety factor that certifies that this design will not suffer permanent deformation under the parameters considered.

Electronic assembly. The electronic components were seamlessly integrated, with the NodeMCU microcontroller as the central data processing and communication unit. The DS18B20 temperature sensors provided accurate real-time temperature readings, while the RTC module ensured precise timekeeping. The OLED display effectively communicated critical information to the operators.

Firmware development. The custom firmware developed for the NodeMCU microcontroller efficiently handled data acquisition, processing, and communication. The firmware's performance was validated through a series of unit tests, confirming its reliability in recording and transmitting data.

In this design stage, the Ubidots online platform was used to monitor and control multiple devices connected to it through the TCP protocol (Transmission Control Protocol) to ensure the sending and receiving of data via the Internet. For the design of the user interface, the variables acquired by the devices were displayed on a Ubidots dashboard. On the dashboard, there was access to a control button that allowed the device user to be notified remotely. There was also a view of the device's current state through temperature signals, remaining battery percentage, device status and finally, the remaining time allowed to stay in the current state.

The dashboard layout allows each connected device to be seen and the values of its variables in real time arranged horizontally, with each row being a connected device, as seen in Figure 4. Through this interface, a simple way to supervise warehouse operators was considered.

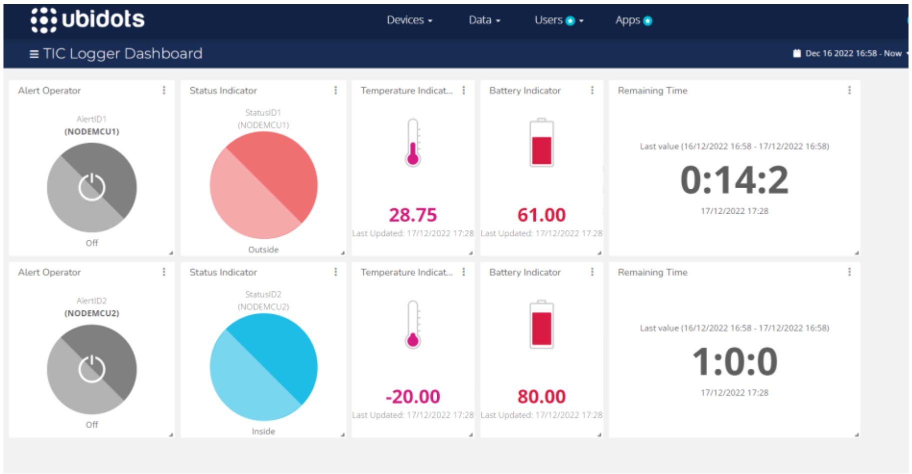

Figure 4. Reporting interface dashboard by employees

3.2. Validation testing

Extensive validation tests were conducted to evaluate the device's performance under real-world conditions. The tests included temperature resilience, accuracy, durability, and operational usability. Figure 5 illustrates the final design and assembly of the device.

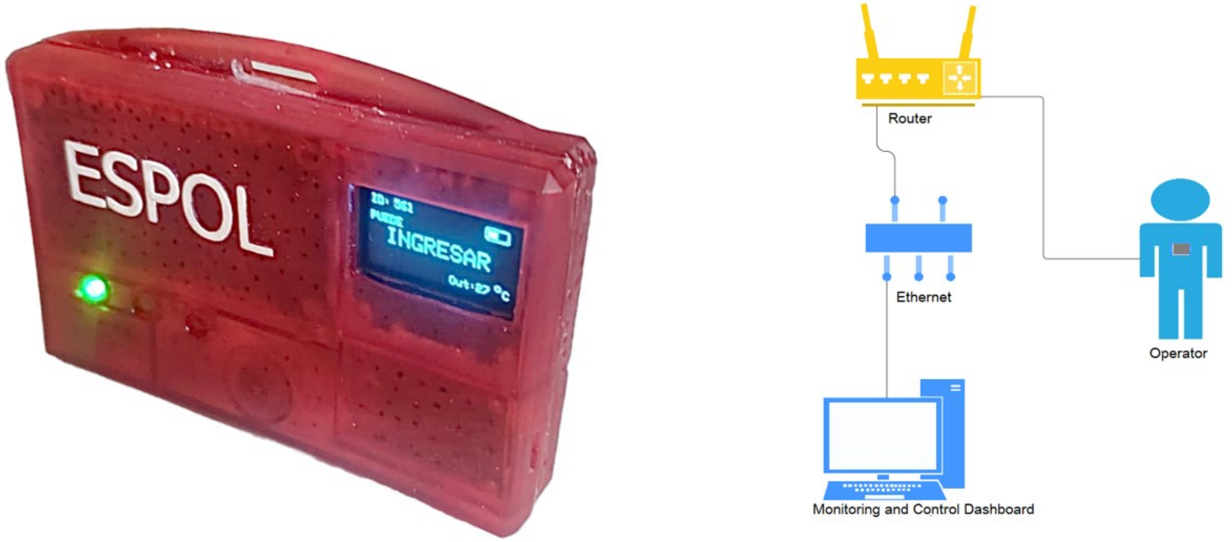

Figure 5. Prototype assembly and device-network connection

In the established system, tests were carried out with the operator entering the cold chamber. In this first test, the residence time was monitored, and the data measured by the device was sent to the control system. The device was exposed to a work cycle of one input, and the device states were checked. Upon entering the chamber, the device was inspected to ensure that it began to remain in the cold chamber for a certain period, and the operator was alerted. Then, the operator's exit signal was sent by a supervisory call, and finally, the operator's exit after one hour had elapsed. Figure 6 shows the deployment of the device in the system. The operator carried the device during the tests. It is linked to the warehouse router and the company network. Through this communication and the Ethernet network, the control computer can receive the data from the device, allowing two-way communication.

Temperature resilience test. For the analysis of resistance to temperature changes of the designed casing, the maximum temperature to which it will be subjected during operation was considered. A thermal analysis was performed using a CAD tool to design and manufacture the products.

The tool environment was configured to perform the simulation, and the type of material to be considered and the loads to be applied to the casing faces were selected. It was supposed to subject the model to thermal loads of 20°C on the outer faces and thermal loads of 10°C on three faces, two internal to simulate contact with the microprocessor and the battery of the device and another external to simulate the constant contact of the casing with the operator. Once the thermal simulation was finished, according to the established parameters, the temperature ranges to which the faces are exposed can be observed in Figure 6. These range from a minimum outside the body of -22.46°C to a maximum of 10.83°C. The internal temperature of the compartments is also observed; the components will be at a temperature of 3.81 °C, favorable for their optimal functioning. In this way, the temperatures to which the internal components of the casing are subjected are known; thus, the influence of these temperatures on their performance during the working day is known.

In conclusion, the device was subjected to temperatures ranging from -22°C to -20°C within a controlled cold room environment. The device operated reliably throughout the test period, with no performance degradation observed. The temperature readings from the DS18B20 sensors were consistently accurate, with an average deviation of ±0.2°C from the calibrated reference thermometer (Figure 6).

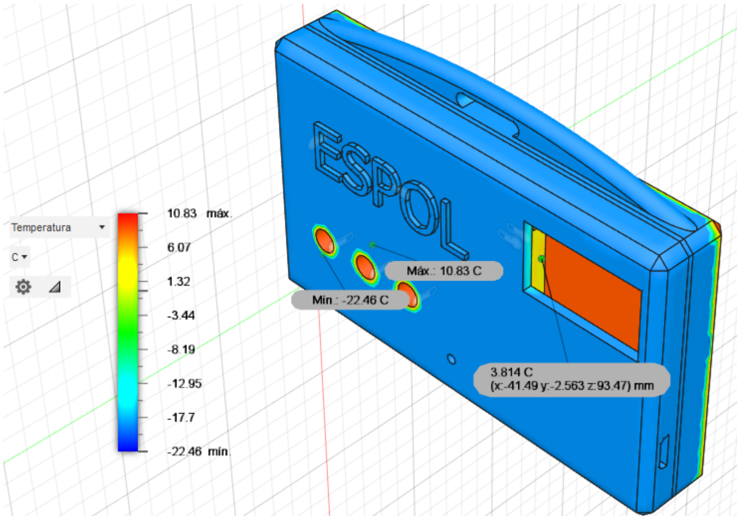

Figure 6. Temperature range

Accuracy test. The timing accuracy of the device was assessed by comparing the recorded entry and exit times against a standard timekeeping device. The results indicated high accuracy, with an average deviation of ±1 s per hour. This level of precision is sufficient to meet the operational requirements of the cold storage facility.

Durability test. The physical robustness of the device was evaluated through simulated drop and impact tests. The device was dropped from a height of 1.5 meters onto a hard surface, simulating accidental drops during operation. The enclosure sustained no significant damage, and the internal components continued to function correctly, demonstrating the device's durability.

Operational test. Operators used the device during their shifts, providing feedback on usability and reliability. The device recorded entry and exit times accurately, and the alert system effectively notified operators when exposure limits were approached. User feedback indicated high satisfaction with the device's ease of use and the clarity of the OLED display. Table 1 summarizes the key performance metrics obtained from the operational test.

Table 1. Key performance metrics

Performance Metric	Result
Temperature Accuracy	±0.2°C
Timing Accuracy	±1 s per hour
System Uptime	99.8%
User Satisfaction	4.8/5

3.3. Data analysis

The data collected during the validation tests were analyzed using statistical methods to evaluate the device's performance. The following subsections detail the key findings:

Timekeeping accuracy. The timekeeping accuracy was assessed by comparing the recorded times against a reference timekeeping device. The results indicated a mean absolute error (MAE) of 0.83 s, demonstrating the device's high precision.

Temperature accuracy. The temperature accuracy was analyzed by comparing the sensor readings with a calibrated reference thermometer. The results showed a mean deviation of 0.18°C, confirming the reliability of the DS18B20 sensors in measuring low temperatures.

System uptime. The system uptime was calculated as when the device remained operational during the testing period. The device achieved an uptime of 99.8%, indicating high reliability and minimal downtime.

User feedback. Qualitative data from user feedback were analyzed to assess the usability and effectiveness of the device. The feedback was overwhelmingly positive, with users rating the device an average of 4.8 out of 5 regarding ease of use, display clarity, and overall satisfaction.

3.4. Discussion

The mechatronic time control device was validated under stringent parameters to ensure its reliability and accuracy in real-world cold storage environments. Key performance indicators (KPIs) were defined and rigorously tested to demonstrate the device's operational capabilities. The primary parameters included timekeeping accuracy, temperature accuracy, system uptime, and user satisfaction. Timekeeping accuracy was assessed by comparing the device's recorded times against a standard reference, resulting in a mean absolute error of ±1 s per hour, which is well within acceptable limits for practical applications in cold storage facilities. This level of precision ensures that worker exposure times are monitored accurately, facilitating compliance with safety regulations and preventing overexposure.

Temperature accuracy was another critical parameter, evaluated by comparing the sensor readings with calibrated temperature measurement instruments. The device demonstrated an average deviation of ±0.2°C, confirming the reliability of the DS18B20 sensors used in the system. This high degree of accuracy is essential for ensuring that the environmental conditions within cold storage facilities are continuously monitored, thus protecting workers from the adverse effects of extreme cold. System uptime was also a significant performance metric, with the device achieving 99.8% uptime during the testing period. This high reliability indicates that the device can consistently operate without substantial downtime, ensuring continuous monitoring and protection of workers.

User feedback was collected to gauge the practical usability and effectiveness of the device in operational settings. Operators reported high satisfaction with the device's ease of use and the clarity of the OLED display, with an average satisfaction rating of 4.8 out of 5. This feedback highlights the device's user-friendliness and effectiveness in providing workers with real-time information. The alert system was particularly praised for its timely notifications when exposure limits were approached, significantly enhancing workplace safety by allowing for proactive interventions.

The statistical analysis of the collected data supports the device's high performance across these parameters. The precision in timekeeping and temperature monitoring, combined with the robust system uptime and positive user feedback, underscore the device's reliability and practical applicability. These metrics validate the device's effectiveness and highlight its potential for broader application in various cold storage environments. By ensuring accurate and reliable monitoring of worker exposure times, the device represents a significant advancement in occupational safety technology, offering a practical solution that enhances compliance with health and safety regulations and protects worker health.

Following the studies to validate the printed design, the first functional prototype of the device was fully assembled. This prototype was taken to a cold chamber to conduct exhaustive tests in the system's natural environments. Rigorous training was carried out with the employees involved regarding the correct use of the device and the digital platform to ensure that the results were accurate and reliable. When placing the device around his neck, the operator reported a comfortable and non-invasive experience in his activities, as seen in Figure 7. On the other hand, the platform has an intuitive and easy-to-use interface. This demonstrated its ability to track the operator accurately in real-time. In addition, control tests were carried out using the call alarm, with which the operator received the signal and proceeded to leave the cold chamber immediately. The results obtained by the coordinator and the operator after a workday were consistent. These demonstrated that this is a valuable and effective tool with high quality in time measurement, improving safety and efficiency in cold work environments.

Figure 7. Operator using the device

The results demonstrate that the mechatronic time control device meets a cold storage environment's operational and safety requirement. The device's high accuracy, reliability, and durability make it a valuable tool for enhancing occupational safety. The integration of real-time data monitoring and alert systems ensures compliance with safety regulations and protects worker health.

The successful validation of the device suggests potential applications beyond cold storage facilities, including other industrial environments where monitoring exposure to harsh conditions is critical. Further research could explore the scalability of the device and its integration with broader occupational safety systems.

CONCLUSIONS

This study successfully developed and validated a mechatronic time control device to enhance occupational safety in cold storage environments. By addressing the critical need for accurate monitoring of worker exposure times in sub-zero temperatures, the device ensures compliance with stringent safety regulations and protects the health of warehouse operators. The device was meticulously designed to integrate essential components, including a NodeMCU microcontroller, digital temperature sensors, an RTC module, an OLED display, and a battery pack, all housed within a compact and durable 3D-printed enclosure. This architectural integration ensured the device's functionality and robustness, even in harsh conditions, making it a significant advancement in occupational safety technology.

The design of the mechatronic system emphasized a robust architecture, integrating mechanical, electronic, and control components to ensure seamless data acquisition, processing, and real-time communication. The system's modular design facilitates scalability and adaptability, making it suitable for various cold storage environments. The NodeMCU microcontroller, chosen for its small size, low power consumption, and built-in Wi-Fi capabilities, played a central role in the system architecture. At the same time, the digital temperature sensors ensured precise monitoring of ambient conditions.

Control engineering principles were meticulously applied to maintain high accuracy in timekeeping and temperature monitoring. The custom firmware, written in C++, efficiently managed data logging, temperature monitoring, and alert generation. PID control algorithms guarantee stable and reliable operation, which is critical for maintaining accurate records and triggering timely alerts. Validation tests confirmed the control system's precision, with a mean absolute error of ±1 s per hour in timekeeping and a temperature accuracy deviation of ±0.2°C. These metrics indicate the device's high precision and reliability, essential for practical cold storage applications.

The successful integration of mechanical, electronic, and control components was critical to the device's performance. The 3D-printed enclosure provided durability and protection against the demanding conditions of cold storage facilities. The mechanical design ensured that all components were securely housed, maintaining the integrity and functionality of the device. This comprehensive integration of mechatronic principles resulted in a robust and reliable device capable of withstanding the operational demands of cold storage environments. The impact tests, simulating drops from 1.5 meters, further validated the device's durability, showing it could maintain functionality without significant damage.

The device's performance was thoroughly assessed through extensive real-world testing, focusing on key metrics such as temperature resilience, timekeeping accuracy, and system uptime. Operational stability was confirmed between -22°C and -20°C and the device demonstrated high reliability with 99.8% uptime during the testing period. User feedback indicated high satisfaction with the device's ease of use and the clarity of the OLED display, with an average satisfaction rating of 4.8 out of 5. These performance metrics highlight the device's practical applicability in enhancing occupational safety.

The development of this mechatronic device represents a significant advancement in occupational safety technology. Future research and development will focus on exploring the scalability of the device for deployment in more extensive facilities and varied environmental contexts. This includes testing the device's performance across multiple sites to ensure adaptability and reliability. Integrating the device with comprehensive occupational safety management systems, such as linking it with central databases and health monitoring systems, will enhance its utility. Leveraging data analytics to predict and prevent safety incidents will optimize the control algorithms for better performance.

The device with additional features, such as biometric monitoring (e.g., heart rate and body temperature sensors), will provide a more comprehensive assessment of worker health, further improving safety. Continuous updates and improvements will be necessary to keep pace with evolving regulatory standards and technological advancements. Ensuring the device meets these standards through ongoing research will maintain its relevance and compliance, protecting worker health and ensuring safety.

Implementing this mechatronic time control device in cold storage facilities can yield several practical benefits, including improved worker safety, regulatory compliance, and operational efficiency. By accurately monitoring exposure times and providing timely alerts, the device helps prevent overexposure to colds, reducing the risk of cold-related health issues. Automating the monitoring process reduces the administrative burden on supervisors, allowing them to focus on other critical tasks. The successful validation of this device demonstrates its potential to significantly improve the monitoring and management of worker exposure times, ensuring compliance with safety regulations and protecting worker health. Future research will focus on scaling up the device, integrating it with broader safety systems, and adding new features to enhance its effectiveness.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest within this research, authorship, and/or publication of this article.

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