IoT systems for efficient preservation of cultural heritage

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Abstract

The protection of cultural heritage remains a particular priority, as works of art are subject to inevitable degradation over time. This deterioration is influenced by the composition of the material, external environmental factors and human intervention. This study introduces an innovative Internet of Things (IoT) system designed to monitor and mitigate the complex causes of artefact degradation, while simultaneously ensuring a conducive museum environment for visitors. The proposed cloud-based solution offers a diverse range of functionalities tailored to the different materials found in museums, such as paintings, metals and textiles. By integrating cloud-based sensors, the system provides real-time data, facilitating rapid responses to variations from optimal conditions. By monitoring key factors such as temperature, humidity, vibration, air pollutants (CO2, NO2, SO2, O3) and volatile organic compounds, this approach facilitates a comprehensive understanding of the main causes of degradation of art objects. This work builds on the MUSEION project, which aims to develop an integrated IoT-based platform for sustainable management of environmental control and climate change adaptation of museum exhibits. The results obtained in this research highlight both the scalability, reliability and efficiency of the prototype system in reducing events related to chemical and physical processes contributing to artefact degradation, as well as the real-time assessment of Indoor Air Quality (IAQ) indices. By proposing an innovative Internet of Things (IoT) based solution for detailed monitoring of cultural heritage, the study makes a significant contribution to the field. The importance of the research is underlined by the thorough investigation and the results obtained, highlighting its potential to improve conservation practices in museum environments, thus providing a comprehensive approach to sustainable museum management and cultural heritage conservation.

Keywords: IoT, Cloud, real-time monitoring, indoor air quality, cultural heritage conservation

1. Introduction

In the realm of art conservation, considering technological advancements in Internet of Things (IoT) and Cloud Computing, a new perspective emerges regarding wireless microclimate monitoring in museums. Wireless sensor networks, specifically developed to monitor air quality and the materials of which museum exhibits are made, demonstrate their efficiency in assessing conservation conditions.

Continuous and real-time monitoring of factors affecting the state of artworks becomes essential for their long-term preservation and for transmitting the cultural heritage value to future generations. In the current technological context, remote monitoring focuses on the Internet of Things (IoT) concept. The implementation of this approach involves installing sensor nodes and gateways for data transfer to the Cloud, facilitating online monitoring and continuous surveillance of artworks. Easy access from the Cloud to data recorded by electronic sensors contributes to enhancing security and implementing preventive measures.

Internet of Things (IoT) involves objects' ability to intelligently communicate with their environment to provide real services via the internet. Remote monitoring and management of the environment become possible through IoT sensors, considering the improvement of cultural heritage conservation. In this context, the importance of Indoor Air Quality (IAQ) indices becomes evident. These indices play a crucial role in evaluating the museum environment and promptly alerting responsible personnel if conservation conditions are unfavorable for certain materials, thus preventing the accelerated degradation of artworks. Careful interpretation and analysis of these data are essential to ensure an optimal conservation environment for historical objects. The architecture presented in the article, with its prototype communicating with a web platform, illustrates how this data can be visualized and interpreted in the form of graphs, tables, or charts. The IoT system, with monitoring stations both inside and outside the museum, highlights low energy consumption, contributing to the efficiency and sustainability of the proposed solution.

The article is structured as follows: Section II provides the current state of knowledge in the field of artifact conservation and presents several alternative solutions to enhance artifact preservation. Additionally, Section III, titled "IoT System for Artefact Preservation and IAQ Analysis," introduces the system used in this article, aiming to enhance the conservation of objects in memorial homes/museums by utilizing data from monitoring stations and calculating Indoor Air Quality (IAQ) indices. Section IV will encompass all the results obtained in this study, followed by the concluding section summarizing the entire article.

2. Related Work

In the contemporary context, various industries and sectors worldwide are confronted with the impacts of climate change and air pollution. Museums and heritage buildings, in particular, face significant challenges, with numerous artifacts at risk of damage or even destruction as a consequence of these environmental and climate alterations.

The preservation condition of artworks displayed in museums is significantly impacted by the quality of indoor air. While temperature and relative humidity are commonly monitored parameters, they are not the sole factors requiring control. Aerosol particulate matter (PM), including its concentration, size distribution, and chemical composition, is a crucial parameter that can adversely influence indoor air quality [1].

The preservation of exhibits in museums is significantly influenced by the air quality within, as airborne substances can lead to the deterioration of artifacts, irrespective of whether they are showcased in display cases. Chiantore et al. [2] elaborate on the significance and repercussions of materials employed in constructing museum display cases, which can be potential sources of harmful substances affecting the integrity of cultural heritage items. Acetic acid, for instance, is known to induce corrosion in bronze antiquities, lead artifacts, and copper alloys stored in wooden cabinets.

The article [3] also examines air quality as a source of pollutants affecting art objects. According to the study findings, particles like calcite and clays, as well as substances such as relative humidity (RH) and O3 resulting from restoration activities around historical museums, contribute to the gradual degradation of museum artifacts. Carbon dioxide serves as an indicator of human presence in a room but has a limited impact on material degradation. Nitrogen dioxide, emitted primarily from industrial facilities, accelerates the deterioration of art objects through oxidation processes. Ozone, classified as a secondary pollutant, degrades materials through oxidation mechanisms.

This paper [4] examines the air quality (temperature, humidity, light, and fungal contamination) within the Museum House in Salacea, Bihor county. It assesses the impact of these factors on the textile materials displayed inside, emphasizing the importance of safeguarding heritage elements and reducing risks to human health for inhabitants, tourists, museographers, and other individuals accessing the interior. The monitoring of temperature and humidity took place from June 3, 2018 to July 2, 2018, utilizing the KlimaLogg Pro thermo-hygrometer with data function logger (seven sensors). Other parameters, such as light intensity, were measured using the Extech SDL400 Luxmeter data logger, and oxygen levels were assessed with the Extech SDL150 Oxygen meter. Fungal contamination was determined through the Koch sedimentation method. Given that low temperatures coupled with high humidity can foster microorganism and mold formation, while high temperatures may dehydrate fibers, diminishing their strength and elasticity, it is imperative to maintain the standard microclimate of temperature and humidity within the museum house.

3. IoT System for Artefact Preservation and IAQ Analysis

The preservation of art objects is intricately tied to environmental parameters. The degradation rate is typically determined by factors such as temperature, relative humidity, radiation, and pollution. These factors act as agents of deterioration, influencing the overall condition of cultural heritage items.

3.1. Relevant Parameters

In the conservation of art objects, it is crucial to include relevant parameters for the preservation of cultural artefacts within acceptable limits, and risk assessment is carried out by comparing measured indicators with target values from literature, guidelines and standards. In this context, continuous monitoring of air quality and deterioration factors is imperative for the preservation of art objects, and the proposed Internet of Things (IoT) system focuses on detecting pollutant levels in museums to proactively address possible risks.

To ensure comprehensive monitoring, two distinct stations were employed—one dedicated to assessing indoor air quality within the museum and another focused on monitoring the external air quality. The parameters measured by these stations are outlined in Table 1, which includes the units of measurement, acronyms, and names of the monitored parameters.

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Table 1. Indoor and outdoor air quality station parameters.

	Indoor	
Name	Acronym	Unit of measure
Battery level	BAT	mV
Air temperature	TC	Celsius
Atmospheric pressure	PRES	Pa
Air humidity	HUM	Procente
Brightness	LUX	lux
Ammonia	NH3	ppm
Ozone	O3	ppm
Hydrogen sulphide	H2S	ppm
Particulate matter (PM1/PM2.5/PM10)	PM1, PM2_5, PM10	µg/m3
	Outdoor	
Name	Acronym	Unit of measure
Battery level	BAT	mV
Air temperature	TC	Celsius
Atmospheric pressure	PRES	Pa

Air humidity	HUM	Procente
Brightness	LUX	lux
Sulphur dioxide	SO2	ppm
Carbon dioxide	CO2	ppm
Nitrogen dioxide	NO2	ppm
Particulate matter (PM1/PM2.5/PM10)	PM1, PM2_5, PM10	μg/m3

Source: Table realized within the MUSEION project

The use of two stations provides a complete understanding of air quality dynamics, both in the controlled environment of the museum and the outdoor environment. This two-station approach ensures that conservation efforts consider not only internal conditions, but also potential external influences on artifact degradation.

3.2. Architecture of the Proposed System

The proposed IoT system leverages a robust cloud-based architecture, offering an array of functionalities at an affordable price. The modularity of the prototype allows for swift configuration adjustments, ensuring adaptability to the specific needs of different customers.

The cloud infrastructure is the backbone of the system, facilitating scalability and accessibility. Cloud solutions enable the storage, processing, and analysis of vast amounts of data generated by the monitoring stations in real-time. This approach ensures that the system remains agile, adapting to the evolving requirements of artefact preservation.

The Museion project has produced a block diagram illustrating the innovative features of the proposed IoT system. This schematic, as shown in Figure 1, highlights the integration of sensors in the cloud, allowing the system to provide real-time information in case of deviations from the nominal values.

The integration of sensors in the cloud is an exceptional aspect of the system design. This integration ensures that data is not only collected, but also processed and analysed in real-time within the cloud infrastructure. This feature enhances the responsiveness of the system to changing environmental conditions, contributing to a proactive approach to artefact preservation.

The innovative nature of the proposed system lies in its ability to transmit real-time data to the cloud. This capability is essential for timely decision making and intervention in response to changing environmental parameters. The transmission protocol, MQTT (Message Queuing Telemetry Transport), ensures efficient and reliable data communication between monitoring stations and the central cloud infrastructure.

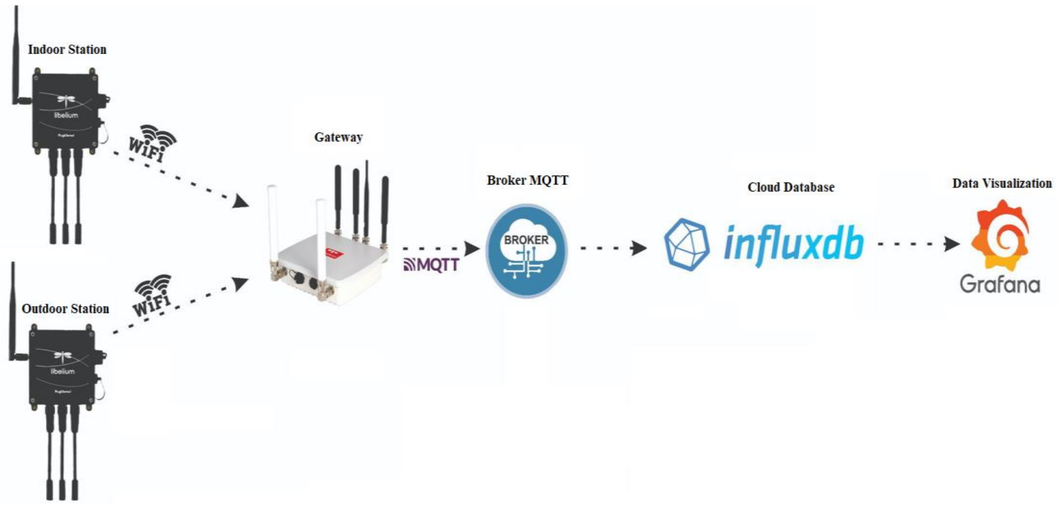

Fig. 1. System architecture
Source: Architecture realized within the MUSEION project

The data collected from the monitoring stations are stored in a dedicated database, namely InfluxDB. This database is designed to retain historical data, allowing for long-term analysis of environmental parameters. The visualization of parameter analysis is achieved through the Grafana platform, offering a user-friendly interface that presents data in the form of graphs, tables, and charts. Thresholds for each parameter can be set within Grafana, enabling the system to generate immediate alerts in case of unfavorable events.

A significant advantage of the proposed system is its scalability and reliability. The modular design allows for easy customization according to the specific needs of different museums. The system's reliability is underscored by the utilization of established communication protocols, ensuring consistent performance in various operational scenarios.

3.3. Definition of the IAQ Index

IAQ (Indoor Air Quality), also known as indoor air quality, refers to the condition and composition of the air in an indoor space such as a building, home or office. IAQ is important for the health and comfort of people who spend a lot of time in these spaces. The IAQ index is a measure that indicates the indoor air quality of a space, and its value can directly influence the health and well-being of the inhabitants or users of that space.

The rate at which materials deteriorate is influenced by a limited set of factors, divided into four distinct categories corresponding to the following agents of degradation: inadequate temperature, inadequate relative humidity, radiation and pollutants. These factors dominate the deterioration process of all materials and can be seen as indicators of the state of preservation of a collection. An overview of conservation conditions can be obtained by identifying the risks associated with these indicators. These indicators can therefore be used to introduce the concept of Key Risk Indicators (KRIs), which are independent parameters that estimate whether certain conservation conditions are likely to damage the collection.

Among the 12 most important critical risk indicators are: relative humidity (RH) too high, RH too low, significant RH fluctuations, temperature (T) too high, T too low, significant T fluctuations, excessive lighting, exposure to ultraviolet light too intense, high concentration of oxidising gases (such as O3, NOx, SO2), high concentrations of organic gases (such as acetic acid, formic acid, formaldehyde), high concentrations of sulphur compounds (such as H2S, carbonyl sulphide (OCS)), and too high concentrations of dust (PM2. 5, PM10, dust particles).

The level of risk can be assessed by comparing measurements of an indicator with the accepted values or range of accepted values for each type of material as specified in literature, guidelines and standards.

Table 2 shows the accepted values or ranges of values for temperature, relative humidity and illumination applicable to the most common materials found in libraries and archives, while Table 3 contains the maximum allowable concentrations for certain pollutant gases.

Table 2. Permissible values/ ranges of temperature, relative humidity and illuminance for the most common materials in libraries and archives.

Materials	Accepted temperature	Accepted relative humidity	Accepted light level
Wood	16-18 ℃	50-60%	<50 lux
Leather	16-22 ℃	40-55%	50 sau 150 lux
Textile	16-20 ℃	40-55%	50 sau 150 lux
Paper	16-22 ℃	35-55%	50 sau 150 lux
Photos	2 ℃ – color photos 18 ℃ – other types	30-50%	<50 lux
Cellulose nitrate	10 ℃	<50%	50 lux

Source: Table realized within the MUSEION project

Table 3. Maximum permissible concentrations for some pollutant gases

Polluting Gas	Permitted Concentration (µg/m^3)
Ozon	25
Dust particles	75
Nitrogen oxides	5
Carbon dioxide	45
Sulphur dioxide	1

Source: Table realized within the MUSEION project

4. Results

The monitoring solution, which includes the implementation of the IAQ algorithm within the system, consists of a network of sensors and monitoring stations that collect data about the environment inside the museum, such as temperature, humidity, lighting levels and concentration of pollutant gases.

The system has been tested in the “Ion Minulescu” Memorial House over a significant period of time, allowing the collection of an extensive amount of data to ensure a more accurate calculation of air quality indices. In the initial phase, a visualisation of all the parameters monitored in the museum was carried out and a high-level evaluation was performed to identify and correct possible errors. Subsequently, the data were presented in the visualisation platform in graphical form.

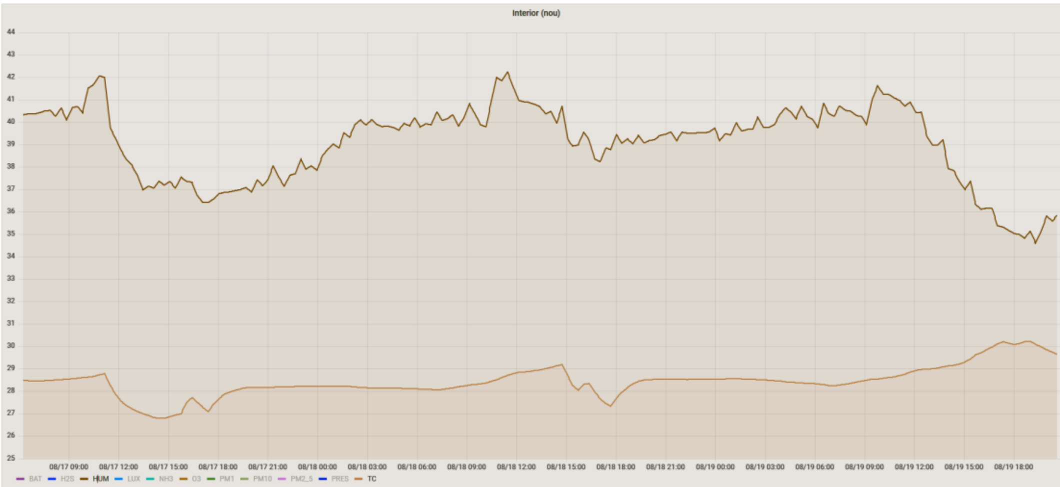

Fig. 2. Indoor temperature and humidity variation
Source: Grafana own platform

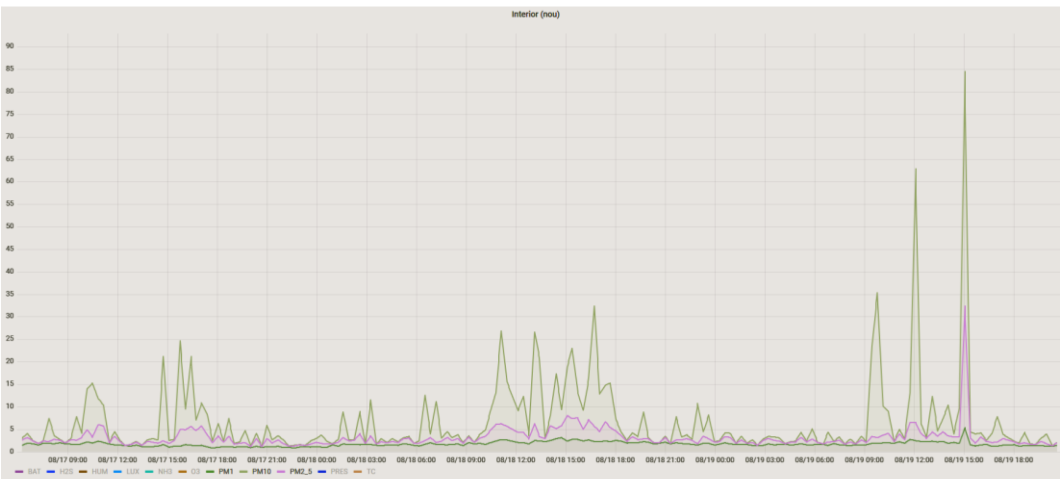

Fig. 3. Variation of PM1, PM2.5 and PM10 indoors
Source: Grafana own platform

IAQ implementation involves a number of essential components, including sensors for measuring temperature and relative humidity, monitoring stations for data collection, an MQTT broker for efficient transmission of information to the Museion platform, the Node-RED platform for data processing and calculation of IAQ scores. The IAQ algorithm defines specific ranges of values for temperature and humidity, and IAQ scores are assigned to these ranges according to air quality and health risk guidelines. Details of these ranges are given in the tables below.

Table 4. IAQ scores according to temperature range

Temperature (0C)	Critical risk indicator/numerical shortfall			
	Ls	Ms	Hs	VHs
< 0	1	1	1	1
0 – 18	0.05	0.25	0.5	0.75
18 – 24	0.05	0.05	0.05	0.05
24 – 30	0.05	0.05	0.25	0.25
30 – 40	0.05	0.5	0.5	0.75
> 40	0.25	0.75	1	1

Source: Table realized within the MUSEION project

Table 5. IAQ scores according to relative humidity range

Relative humidity (%)	Critical risk indicator/numerical shortfall			
	Ls	Ms	Hs	VHs
0 – 10	1	1	1	1
10 – 30	0.5	0.75	0.75	1
30 – 50	0.05	0.25	0.75	0.75
50 – 65	0.05	0.05	0.05	0.05
65 – 80	0.75	1	1	1
> 80	1	1	1	1

Source: Table realized within the MUSEION project

The IAQ algorithm assigns specific scores to the risk categories Ls, Ms, Hs and VHs (low, medium, high and very high) for each relevant range. The implementation of the algorithm was carried out using the Node-RED platform, chosen for its ability to efficiently manipulate data and create processing workflows. The algorithm itself consists of a function that analyzes the data from the monitoring stations and fits them appropriately into pre-defined ranges. The data is transmitted to the Node-RED platform via the MQTT protocol, and the results of the algorithm are also sent to the visualization platform using the same protocol. The information received from the monitoring stations, including temperature and humidity, is processed by the IAQ function in Node-RED. The algorithm compares these values with the defined ranges to determine risk categories and assign appropriate scores for Ls, Ms, Hs and VHs. The flow used by the IAQ algorithm is illustrated in the figure below.

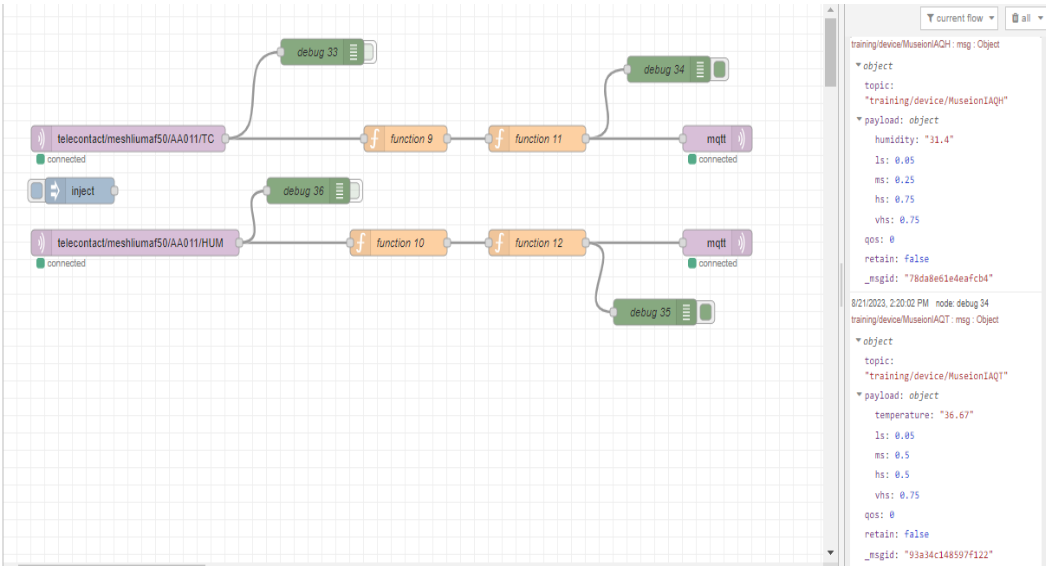

Fig. 4. Implementing IAQ modules in Node-RED
Source: Beia Node-RED flow

IAQ information is presented as graphs and tables in the solution management interface, making it easy to quickly identify potential air quality problem areas and take appropriate action. This presentation allows managers to access the information in an intuitive way and interpret it both in graphical form for visual understanding and in tabular form for specific details. The data in tabular format are illustrated in the figures below.

Time	Umiditate	Ls	Ms	Hs	VHs
2023-08-21 05:00:00	27.44	0.05	0.05	0.25	0.05
2023-08-21 04:00:00	30.11	0.05	0.05	0.31	0.05
2023-08-21 03:00:00	30.55	0.05	0.05	0.50	0.05
2023-08-21 02:00:00	31.50	0.05	0.05	0.50	0.05
2023-08-21 01:00:00	34.08	0.05	0.25	0.50	0.75
2023-08-21 00:00:00	34.91	0.05	0.25	0.50	0.75
2023-08-20 23:00:00	35.51	0.05	0.25	0.50	0.75
2023-08-20 22:00:00	35.64	0.05	0.25	0.50	0.75
2023-08-20 21:00:00	35.48	0.05	0.25	0.50	0.75
2023-08-20 20:00:00	35.36	0.05	0.25	0.50	0.75
2023-08-20 19:00:00	35.03	0.05	0.25	0.50	0.75
2023-08-20 18:00:00	34.57	0.05	0.25	0.50	0.75
2023-08-20 17:00:00	33.97	0.05	0.25	0.50	0.75
2023-08-20 16:00:00	35.49	0.05	0.25	0.50	0.75
2023-08-20 15:00:00	33.03	0.05	0.25	0.50	0.75
2023-08-20 14:00:00	26.25	0.05	0.25	0.25	0.75
2023-08-20 13:00:00	23.19	0.05	0.25	0.12	0.75

1 2 3 4 5 6 7 8

Fig. 5. Visualization of the IAQ scores in the platform according to relative humidity
Source: Grafana own platform

Temperatura IAQ

Time	Temperatura	Ls	Ms	Hs	VHs
2023-08-21 05:00:00	24.76	0.05	0.05	0.25	0.25
2023-08-21 04:00:00	25.19	0.05	0.05	0.25	0.25
2023-08-21 03:00:00	25.34	0.05	0.05	0.25	0.25
2023-08-21 02:00:00	26.21	0.05	0.05	0.25	0.25
2023-08-21 01:00:00	27.03	0.05	0.05	0.25	0.25
2023-08-21 00:00:00	27.71	0.05	0.05	0.25	0.25
2023-08-20 23:00:00	27.44	0.05	0.05	0.25	0.25
2023-08-20 22:00:00	30.11	0.05	0.16	0.31	0.38
2023-08-20 21:00:00	30.55	0.05	0.50	0.50	0.75
2023-08-20 20:00:00	31.50	0.05	0.50	0.50	0.75
2023-08-20 19:00:00	34.08	0.05	0.50	0.50	0.75
2023-08-20 18:00:00	34.91	0.05	0.50	0.50	0.75
2023-08-20 17:00:00	35.51	0.05	0.50	0.50	0.75
2023-08-20 16:00:00	35.64	0.05	0.50	0.50	0.75
2023-08-20 15:00:00	35.48	0.05	0.50	0.50	0.75
2023-08-20 14:00:00	35.36	0.05	0.50	0.50	0.75
2023-08-20 13:00:00	35.03	0.05	0.50	0.50	0.75

1 2 3 4 5 6 7 8

Fig. 6. Visualization of the IAQ scores in the platform according to temperature
Source: Grafana own platform

The implementation of the IAQ algorithm in the project has had a significant and beneficial impact on the quality of the indoor environment. This initiative has enabled the project to substantially improve air quality management, react promptly to potential problems and create a more pleasant and healthy environment for both visitors and museum staff.

5. Conclusions

The proposed IoT system for artefact conservation in museum environments promises efficiency and relevance from the first experiments. Data collected from monitoring stations located both inside and outside the "Ion Minulescu Museum" indicate controlled storage conditions and low levels of pollution. Our research not only stops at identifying critical environmental factors for the various materials in the collections, but also at implementing a real-time monitoring system. This system allows rapid adaptation to environmental changes, and the IAQ algorithm developed contributes to the assessment of indoor air quality specific to cultural heritage conservation needs. However, extending the system for benchmarking across different museum locations remains a challenge. Continued research will be essential to optimise and effectively integrate the system in various museum contexts.

In conclusion, this research represents a significant step towards cultural heritage preservation through IoT technology. Our system not only streamlines the management of environmental conditions, but also opens new perspectives for an innovative approach to artefact conservation and sustainable museum management.

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