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LOW-COST SYSTEM FOR MONITORING ENVIRONMENTAL PARAMETERS AND SENDING DATA TO THE NETWORK IN A SMALL MUSEUM

Ángel Fernández-Navajas, Fernando-Juan García-Diego**, Maitane Urrutia****

*Polytechnical Department, School of Architecture, Universidad Europea de Canarias – Tenerife, Spain.

**Departamento de Física Aplicada, Escuela Técnico Superior de Ingenieros Industriales, Universitat Politècnica de València, Spain;

***Faculty of Mathematics and Computer Science, West University of Timisoara - Romania

Abstract

The preventive conservation of works of art is a subject of great interest in any museum or collection. As a core part of this conservation, it is necessary to monitor the main environmental variables, relative humidity and temperature, whose values can influence the evolution of the state of the pieces. The data collected must be stored and managed appropriately in order to extract relevant information for the conservation of the pieces. In small museums and collections, this task of collection and analysis may not be well covered, both for technical and budgetary reasons. This paper proposes a prototype of very low-cost sensors, with near real-time data sent to a local server, which can be the first step towards proper monitoring within the reach of any small collector.

Keywords

Sensors, low cost, environmental monitoring, small museums, preventive conservation.

1. *Introduction*

In modern societies, museums play a crucial role, as they investigate, collect, conserve, interpret, and exhibit both tangible and intangible heritage (Varas-Muriel et al., 2025). Beyond their traditional functions, two key aspects can be highlighted: their social and economic impact—by generating cultural tourism with significant economic value in the regions where they are located (Sciurpi et al., 2023)—and the preservation of the heritage they contain, where preventive conservation plays an essential role in delaying the deterioration of both organic and inorganic objects (Varas-Muriel et al., 2025).

In recent years, particularly following the COVID-19 pandemic, there has been a significant acceleration in the adoption of digital technologies in cultural heritage management (Domínguez-Jiménez et al., 2021). These technologies have moved beyond their initial function of dissemination to become essential tools for documentation, analysis, and preventive conservation (Garlandini, 2021). Techniques such as photogrammetry, LiDAR, and the generation of "digital twins" enable the preservation of detailed information about cultural assets without the need for physical intervention, while the integration of sensors and infrastructures based on the Internet of Things (IoT) has facilitated continuous and non-invasive monitoring of environmental conditions and the use of museum spaces (Angeloni et al., 2021; Clini & Quattrini, 2021; Domínguez-Jiménez et al., 2021; Resta et al., 2021; Siniscalco & Appollonia, 2021)

Within this new paradigm, environmental monitoring has become one of the fundamental pillars of preventive conservation, as it enables the early detection of risks and supports data-driven decision-making (Garlandini, 2021).

Museums may be subject to various unsuitable environmental conditions that threaten the preservation of their collections (Fermo & Comite, 2022). The most common adverse conditions include, among others:

- Abrupt and intense changes in temperature and relative humidity. Such fluctuations disrupt the acclimatization of objects, causing deformation, cracking, and

crazing (Pavlogeorgatos, 2003; Varas-Muriel et al., 2025).
- Extreme relative humidity: levels above 70% promote the growth of microorganisms and insect activity. Conversely, levels below 30% lead to desiccation and shrinkage in various materials (Kirby Atkinson, 2014).
- Excessive temperature: accelerates chemical degradation reactions and enhances biological activity (Sharif-Askari & Abu-Hijleh, 2018)
- Presence of visitors: people generate heat, water vapor, and CO_2. In small or poorly ventilated rooms, visitors can cause sudden increases in temperature of up to 6°C and relative humidity of up to 15% within periods of 1 to 2 hours (Camuffo, 2019). This aspect has become particularly relevant since the COVID-19 pandemic, which highlighted the need to control visitor flows not only for sanitary reasons but also as a strategy to minimize abrupt environmental impacts and to protect both cultural assets and visitors themselves (Angeloni et al., 2021).
- Deficiencies in ventilation and air quality may lead to the accumulation of CO_2, dust, and other pollutants (Schito et al., 2016).
- Excessive lighting or exposure to UV and IR radiation (Schito et al., 2016).
- Low thermal inertia of the building: lightweight constructions may experience rapid environmental fluctuations due to external influences (Schito et al., 2016).

In this regard, the European Standard EN 15757:2010 states that all museums should collect data on environmental parameters that could affect the conservation of the works (European Committee for Standardization, 2010).

Therefore, as part of a basic policy of preventive conservation, periodic measurements of humidity and temperature should be carried out in any museum or collection in order to determine the thermo-hygrometric conditions of the space (Ceres et al., 2024).

Moreover, these measurements should be conducted in accordance with the guidelines established in the UNE-EN 15758:2011 and UNE-EN 16242:2014 standards (Asociación Española de Normalización, 2011, 2014), which provide guidance on how and where to implement and develop monitoring solutions, specifically in museum environments.

According to UNE-EN 16242:2014, humidity monitoring in museums should be based on the continuous measurement of relative humidity in conjunction with temperature, as both variables are directly interrelated. To obtain representative data, sensors should be placed both in the general air volume of the room and in proximity to the objects, distributed across multiple locations to capture potential gradients and avoiding positions influenced by heat sources, ventilation systems, or air infiltration. It is essential to use calibrated sensors—preferably capacitive electronic devices—and to allow them to reach thermal equilibrium before recording data, thereby ensuring reliable measurements.

Furthermore, the standard emphasizes that measurements should not be punctual, but rather part of a long-term monitoring system, with continuous recording that enables the analysis of fluctuations and the detection of risks such as condensation or hygroscopic movement in materials.

According to UNE-EN 15758:2011, environmental monitoring in museums should include the systematic measurement of both air temperature and object surface temperature, since both directly influence conservation conditions and also indirectly affect relative humidity. Measurements should be integrated into a comprehensive environmental diagnostic plan, clearly defining the issues under study and positioning sensors in representative locations, while avoiding the influence of radiation sources (such as sunlight, spotlights, or heating systems) and ensuring that instruments reach thermal equilibrium prior to data acquisition.

This standard also recommends both spatial and temporal monitoring, with multiple measurement points in the presence of thermal gradients and continuous records capable of capturing daily, seasonal, or usage-related variations (e.g., visitors, lighting). Additionally, it distinguishes between air and surface measurements, with the latter preferably performed using non-contact methods (infrared or quasi-contact), particularly in the case of fragile objects.

Finally, the use of appropriate and calibrated instrumentation with defined accuracy specifications is required to ensure that collected data are reliable and suitable for preventive conservation purposes.

In this context, environmental monitoring emerges as a fundamental tool for defining preventive conservation strategies and ensuring the long-term preservation of cultural heritage objects (Balocco et al., 2020; Tringa et al., 2024).

To address this need, numerous commercially available systems use environmental sensors that collect data at scheduled intervals and transmit it to web-based platforms. However, these systems are typically closed, relying on proprietary hardware and software owned by the companies that market the sensors, which also charge fees for storing and managing the data on their servers.

For instance, the German company Testo offers a humidity and temperature data logging system (161 H1) with connectivity to an online platform. The cost of each logging point is EUR 457.04 (Testo, n.d.), to which an annual fee of EUR 23 per data logger must be added (Verdesoto et al., 2023). Another example is the company TUYA, (Tuya Inc., n.d.) whose sensors, as used in Verdesoto et al. (2023), are inexpensive and well manufactured. However, if cloud storage is required, the cost becomes significant, as these systems are primarily designed for large-scale applications involving substantial data storage. While a free cloud option is available for smaller applications, it only allows data storage for one or two weeks and does not guarantee service continuity. In the cited study, the storage period was reduced from one week to just 24 hours without prior notice.

Many other commercial options exist, but their pricing structures are often unclear, as quotations must typically be requested via email, and their conditions are similar to the examples described above.

For large museums with sufficient financial resources, the cost of sensors and commercial server subscriptions may not represent a significant barrier. However, for small collectors and smaller institutions, these costs can be prohibitive.

2. *Research aim*

The main objective of this research is to present a technical prototype that is both viable and low-cost, designed to monitor basic environmental parameters—namely relative humidity and air temperature—and to transmit these data to a remotely hosted internet-based server. This system is specifically intended for small museums and private collections that lack both substantial financial resources and specialized technical support, and therefore cannot afford commercial monitoring solutions. It is essential to make it entirely clear that the objective is not to conduct environmental monitoring, but rather to present a prototype capable of performing such a function.

In accordance with the guidelines established by UNE-EN 15758:2011 and UNE-EN 16242:2014, air monitoring in museum environments is essential, as air constitutes the primary medium of interaction with objects and largely determines their state of preservation. Although a comprehensive preventive conservation plan would require additional measurements—such as those taken near or directly on the objects—air monitoring represents a fundamental first step, particularly in modest facilities where no prior measurements are conducted. Even without directly assessing the internal conditions of each object, monitoring ambient air allows for the inference of potential risks, since environmental variations are progressively transmitted to materials.

Continuous air monitoring provides an overall and operational perspective on the environmental behavior of exhibition spaces, enabling the detection of fluctuations, the identification of deficiencies in climate control or ventilation systems, and the assessment of external influences such as occupancy levels or outdoor conditions. Even as a standalone system, a well-distributed and properly maintained air monitoring network allows for the establishment of thresholds, identification of trends, and detection of risk events (e.g., condensation or abrupt environmental changes), thereby constituting a fundamental tool for data-driven preventive conservation.

The proposed system is intended to serve as this basic and accessible data acquisition tool, with the additional capability of transmitting information to a web-based server in near real time. This approach enables museum staff to store and consult data remotely at a fraction of the cost of commercial services. The information provided by the system can reveal conservation issues associated with the previously described adverse environmental conditions, thereby allowing responsible personnel to implement preventive or corrective measures.

To validate the prototype under real-world conditions, a pilot installation was carried out in a small museum characterized by limited resources and the absence of any existing monitoring system. It is important to emphasize that this installation was not intended to perform a full-scale environmental monitoring study—which would typically require at least one year of data collection—but rather to validate the functional performance of the system. Specifically, the aim was to test data acquisition, processing, and transmission to an online database under realistic conditions over a shorter time period than that required for a comprehensive monitoring campaign.

3. Materials and methods

3.1 The museum and "Las Fallas"

The selected site for the pilot installation was the "Museo del Artista Fallero" in Valencia, which houses artworks that were rescued from the traditional Fallas festival fires. The "Museo del Artista Fallero" was selected due to its availability and the strong relationship with its governing board, as well as its alignment with the premise of a small museum lacking the budget for a commercial environmental monitoring system. However, the proposed system is not limited to the specific case study presented here and may be extended to a wide range of contexts in which real-time environmental data acquisition and long-term data storage provide clear benefits. Considering the limitations discussed in Section 5 ("Conclusions"), the system can be adapted for use in diverse scenarios, including museums of varying size and typology, private collections, and traveling exhibitions. Furthermore, it may also find application in other domains, such as cold storage facilities and industrial environments, where continuous environmental monitoring and historical data analysis are essential.

"Las Fallas" is a festival celebrated at the end of winter in the city of Valencia and has been declared an Intangible Heritage of Humanity by UNESCO (UNESCO., n.d.). Ephemeral monuments, called "fallas", are erected all over the city, where figures made of fungible materials (cardboard, wood and polystyrene) represent reprehensible scenes of local, national and international life (violence, greed, wars, political corruption...). These monuments are burnt on the night of 19 March, thus expressing the desire to put an end to these attitudes and make way for a new cycle, in the hope that it will be better (Costa, 1998).

By popular vote, some of the figures are saved from the fire and are kept in various museums in the city. The "Museo del Artista Fallero" is located in the northern part of the city, in a neighbourhood known as "Ciudad del Artista Fallero", due to the proliferation of workshops where the Fallas monuments are built. It has received several recognised regional awards and forms part of the Valencian Network of Fallas Museums. In the city there are more museums with this theme, where pieces of fallas are kept, but the outstanding aspect of this museum is that it collects the figures voted by the fallero artists themselves, the ones who make the figures. This makes the collection even more valuable, as it contains a variety of artistic styles: a tour of the rooms reveals life-size pieces or sculptural groups dating back to the first half of the 20th century. In the exhibition you can appreciate the historical evolution of the ninot ("ninot" in Valencian), starting with wooden contraptions for hanging oil lamps, the wax ninot, the cardboard ninot and finally, with the ninot made of expanded polystyrene (white cork).

The exhibits mostly depict human figures, with anonymous characters and other famous people such as politicians, Hollywood actors or fictional characters. These pieces are important because they form a historical and social archive of the city, the whole country and even internationally.

After a refurbishment in 2019, the Museum has, in addition to figures, a series of original sketches of fallas, made in different techniques (pencil, watercolour or gouache) and dating from the 1920s. In addition, some models of the monuments can be admired, made of plaster or plasticine, which are elements prior to the elaboration of the falla, in which the general composition of the falla is studied (Gremi Artesà d'Artistes Fallers, n.d.).

The "Museo del Artista Fallero" belongs to the Asociación de Artistas Falleros and is governed by a Vice-Chancellor's Office that rotates on an annual basis. Its economic resources are scarce, taking into account that it is financed through membership fees, box office income (Ruiz Feo, I., 2020) and some subsidies.

The museum has a sensor that displays instantaneous temperature and humidity data. These data are not recorded, collected or stored in any way, so it is of no use for research purposes.

The premises measure approximately 200 m2 and are distributed over two floors. Access is via the upper floor, which is at ground level, and the lower floor forms a basement. The two floors are connected by a large opening and a staircase (Figure 1) about 3 metres wide. The opening serves not only to provide ventilation and light to the lower floor, but also to place very large figures which, due to their height, which is over 4 metres, would not fit in the dimensions of a conventional floor.

Fig. 1: Interior of "Museo del Artista Fallero". Staircase leading down to the basement.

The difficulty of installing a commercial monitoring system in the premises is twofold: on the one hand, the economic cost is unaffordable and, on the other hand, there is no awareness on the part of the owners of the need to monitor environmental parameters.

In this type of collection, there is a clear need to use very low-cost monitoring systems so that at least the economic barrier does not exist or is very small.

Furthermore, the data should be stored in secure and reliable systems, preferably in the cloud, so that they can be accessed remotely and properly managed and studied. Therefore, the low cost should also be extended to storage on a server hosted on the internet.

The Museum has a home Wi-Fi network, generated by a modem located next to the entrance on the upper floor, at one end of the premises. Due to the size of the Museum, the coverage does not reach the entire premises, with the lower floor having the poorest network quality, especially the areas away from the opening.

3.2 Monitoring system

To power the sensors, a mains connection comprising a wall outlet and a power cable was selected. The power supply provides 9 V–1A and can be used with platforms such as Arduino or Raspberry Pi (Naylamp Mechatronics, n.d.). A wired power configuration was chosen instead of batteries, as conventional batteries do not provide sufficient autonomy and lithium batteries may pose safety risks, including the potential for fire (Tecnifuego, n.d.).

Accordingly, three power cables were installed, each supplying energy to two sensors connected in parallel. The data collected by the sensors are transmitted wirelessly by the ESP8266 chip via the MQTT protocol to a Raspberry Pi (Figure 2), as explained below.

Relative humidity and temperature sensors of the DHT22 type were used because of their low cost and good performance. Each DHT22 package integrates a capacitive humidity sensor and a resistor to measure the temperature of the surrounding air.

As the DHT22 package includes both the humidity and temperature sensors, they were numbered and positioned as follows (Table 1).

The numbering 001 and 002 was reserved for external RH and T data, respectively. These data were obtained by querying a web service (OpenWeather, n.d.), which allows up to 1000 free queries per day.

The location of the sensors on the plane is shown in the figures 3 and 4.

According to UNE-EN 15758:2011, in order to measure air temperature and relative humidity in a museum (rather than object surface conditions), sensors should be placed in positions that are representative of the environment surrounding the artworks, avoiding sources of direct radiation (such as sunlight or direct lighting), located near the objects but without interfering with or coming into contact with them, and in a sufficient number to capture environmental gradients.

However, the limited Wi-Fi coverage within the exhibition spaces (as discussed later) imposed significant constraints on sensor distribution. As shown in Figures 3 and 4, the sensors had to be positioned near the main entrance—where the Wi-Fi modem is located—and around the opening between the rooms, resulting in certain areas remaining unmonitored: specifically, in Figure 3, point 6 (the staircase area in the upper gallery), and in Figure 4, point 3 (the emergency exit area in the basement gallery). and in Figure 4, point 3 (the emergency exit area in the basement gallery).

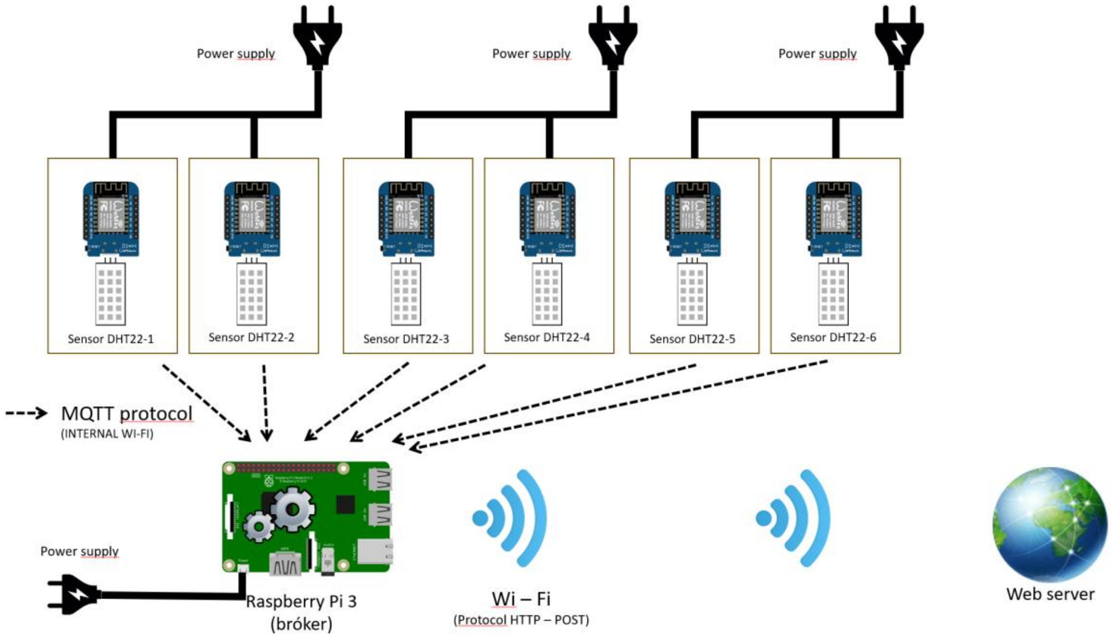

Fig. 2: Wiring diagram of the monitoring system

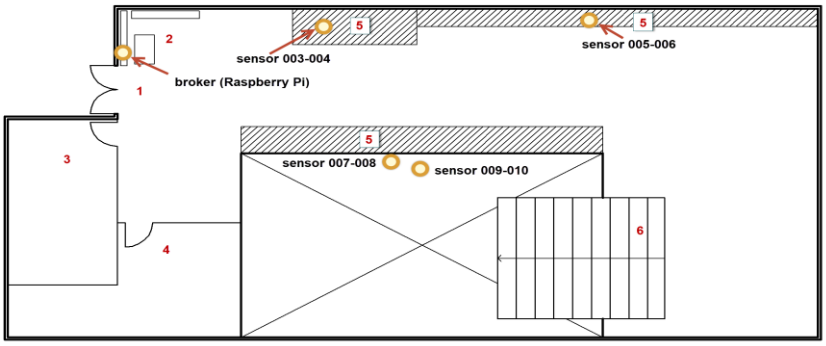

Fig. 3: Entrance plan to the Museum: (1) Main entrance, (2) Reception area, (3) Video projection room, (4) Gateway to services, (5) Exhibition areas, and (6) Staircase leading down to the basement floor.

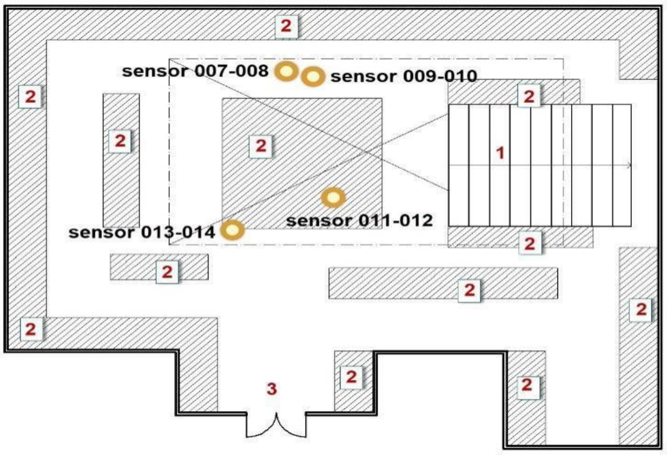

Fig. 4: Basement floor: (1) Down stairs, (2) Exhibition areas, and (3) Emergency exit. Note: sensors 007-008 and 009-010 are hanging between the two floors

Tab. 1: Numbering and position of sensors

Line	Encapsulation	Sensor/Type	Location (*)
1	DHT22-1	003 / RH	Upper floor. Next to the wall on the left and next to the entrance door
		004 / T	
	DHT22-2	005 / RH	Upper floor. Next to the wall on the left and 10 m from the entrance door.
		006 / T	
2	DHT22-3	007 / RH	Opening between the two floors. Hanging at level 0 with respect to the entrance floor.
		008 / T	
	DHT22-4	009 / RH	Opening between the two floors. Hanging at -2 m level with respect to the entrance floor.
		010 / T	
3	DHT22-5	011 / RH	Lower floor. Near the opening.
		012 / T	
	DHT22-6	013 / RH	Lower floor. About 3 m from DHT22-5.
		014 / T	

(*) See figures 3 and 4 for more information.

It is well established that the prototype is unable to transmit data under conditions of very poor Wi-Fi coverage, a limitation that would likewise affect commercial systems. Therefore, in the context of environmental monitoring, it would be necessary to implement technical solutions, such as relocating the modem to a more central position relative to the exhibition spaces or installing Wi-Fi repeaters, particularly in the basement level. In the present case, however, no modifications to the museum's technical infrastructure were permitted. Consequently, the system had to be adapted to the constraints of the site, which ultimately determined both the routing of the sensor connections and the placement of the data acquisition points.

3.3 Sensor calibration. Maintenance and fault management.

This work aims to present a Do It Yourself (DIY) monitoring prototype and to validate (V&V) its potential usefulness for preventive conservation in a small museum context. In line with this objective, no formal calibration of the sensors was carried out, as the collected data were not intended for detailed analytical interpretation, and the system can operate with either calibrated or non-calibrated sensors.

Nevertheless, although the sensors are described by the manufacturer as pre-calibrated, it must be clearly emphasized that proper calibration would be essential for any rigorous monitoring application.

The simplicity and low cost of the system result in minimal maintenance requirements. In the event of sensor failure, individual devices can be easily replaced with others of identical characteristics.

Sensor malfunction can be detected either through anomalous data transmitted to the system or through the absence of data. Since data are collected in near real time, it is possible to implement alert mechanisms to indicate when a sensor is not functioning correctly.

Based on practical experience, the sensors employed can operate reliably for approximately one year without significant issues. As a preventive maintenance measure, it would be advisable to replace all sensors on an annual basis.

3.4 Wi-Fi coverage of the Museum

For network coverage, the museum has a home modem from the company Movistar (modem type HGU) (Banda Ancha, n.d.) and has contracted a tariff of 300 Mbps download and 30 Mbps upload.

This is an absolutely basic tariff whose sole purpose is to provide coverage for the employees' mobile phones.

The modem is located in a glass cabinet next to the reception desk and the entrance door. This location, at one end of the room, means that coverage is at a maximum by the door and at a minimum in the basement. The raspberry pi, which acts as a broker, was placed next to the modem.

As explained below, the performance of the sensors was more or less good depending on the level of Wi-Fi coverage, which is summarised in Table 2. This table was made with standard upload and download speed measurement software provided by a commercial telephone company (Pepephone., n.d.).

Tab. 2: Wi-Fi coverage of the rooms. The color of the background (green, yellow, red) indicates the quality of coverage (good, acceptable, very bad).

Zone	Ping (ms)	Type	Average (Mbps)
Sensor 003-004	10	Download	26.5
		Upload	21.5
Sensor 005-006	15	Download	1.06
		Upload	0.1
Sensor 007-008 and 009-010	13	Download	13.3
		Upload	4.9
Sensor 011-012	16	Download	9.74
		Upload	3.92
Sensor 013-014	20	Download	8.12
		Upload	3.3
Basement next to emergency exit	25	Download	1.25
		Upload	0.0

Several readings were taken at each sampling point because the data collected were highly variable. Table 2 shows how the Wi-Fi signal strength varies in the different areas. Given the poor coverage quality in the basement next to the emergency exit (Figure 4.3), it was not possible to place a sensor in this area and instead it was decided to leave sensor 013-014 next to 011-012, under the opening. Special attention should be given to sensors 005–006, which, despite being located on the top floor with theoretically better coverage, in practice exhibited very poor Wi-Fi signal quality for reasons that are not entirely clear (as there are no structural obstacles between this area and the modem).

Due to the cable length and the lack of available power outlets, it was not possible to relocate this sensor to another area; therefore, it was decided to keep it in its original location.

3.5 Data collection

The DHT22 sensor does not incorporate any storage or management system for the records collected, so some kind of platform is needed to collect the data. In this case, a low-cost chip with Wi-Fi connection was chosen: the ESP8266, with the Wemos D1 (Bricogeek., n.d.) package.

This board can be powered at a voltage between 5V and 3.3V and has several components in a very small size, including a Wi-Fi antenna and a micro-USB connector that allows programming and communication with a PC.

Thanks to this, they were installed with the MicroPython v1.23.0 firmware (open source, (MicroPython., n.d.)) and programmed in Python language to collect data from the sensors every certain period of time.

These data are not processed; they are sent, as collected, to an intermediate platform—a broker—which is described below.

The data are sent to the broker via the MQTT protocol (MQTT., n.d.), which works through the premises' wi-fi network (Figure 2). The Wemos platforms are programmed to read data from the sensor and send it to the broker every 60 seconds.

To shape the DHT22-Wemos assembly, a soldered connection board was manually formed between the DHT22 sensor and the ESP8266 chip. A small LED light was also added to signal the correct functioning of the board and an LM7805 voltage regulator to convert the input voltage from 9V to 5V (Figure 5).

As explained above, 2 boards were placed in parallel in each of the 3 wiring lines, making a total of 6 humidity sensors and 6 temperature sensors.

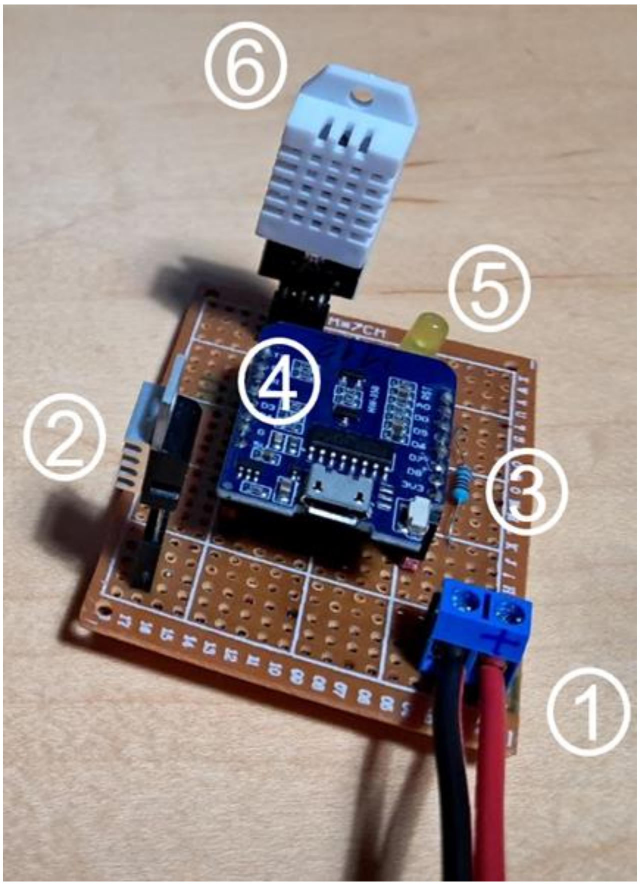

Fig. 5: Boards with the sensor and the ESP8266.(1) Power, (2) Voltage regulator LM7805, (3) Resistance 120Ω for the led, (4) Wemos D1 board with ESP8266 chip, (5) Led light, and (6) RH and T sensor, DHT22

3.6 Broker platform

A Raspberry Pi 3A+ platform (Raspberry Pi Foundation, n.d.) was chosen for data reception due to its low cost and versatility. The Raspbian 11 Bullseye operating system (open source (Raspberry Pi, n.d.)) was installed on this platform, making it a fully functional microcomputer. It was programmed in Python language, as was the data collection platform, the Wemos D1.

The data was received using the MQTT protocol. For this, it is necessary that both the platform that sends the data and the one that receives it are connected to the same wi-fi network, in this case, to the Museum's network.

The broker, the Raspberry, was programmed to be in permanent listening mode, so that any time it receives data sent by the Wemos D1 platforms, it collects and stores it.

Every 30 minutes, the data collected are processed and sent to the database hosted on a web server.

The data processing was done in Python language in a file called broker.py. Data from each sensor was received every 1 minute and arrived identified with the sensor number. As it was received, it was stored in a separate matrix for each sensor.

At the end of the 30-minute cycle, the average value and standard deviation were obtained from each matrix.

Therefore, for each sensor, 3 data were obtained every 30 minutes: average value data, number of data and standard deviation of the matrix.

All these data were sent together in a JSON file to the web server, using the HTTPS POST protocol and in a single request. In this way, the transaction load on the server is lightened.

3.7 Server configuration

To avoid the constraints associated with commercial monitoring services, a data collection and storage system was implemented using a commercial yet low-cost hosting solution. Specifically, a standard hosting service (LucusHost, n.d.) was employed, without any specialized features, and part of this hosting environment was already allocated to a small business website (Amianto Valencia, n.d.).

This hosting, in its most economical mode (less than 100€/year), allows storage of up to 15GB of data, infinite MySQL databases and infinite PostgreSQL databases. MySQL is very suitable for the development of web applications (Wang & Zhang, 2010) and in our case, easier to use than PostgreSQL.

Therefore, a database was created in MySQL, with a table to collect the data from the sensors, both humidity and temperature.

More tables were created to make the system scalable in the future, but for the purpose of this work, the described table is sufficient.

Sending the data to the server every 30 minutes is a very low workload, so there was no problem at all.

However, the database cannot receive the data on its own.

For this it was necessary to create an API, which collected the data sent from the broker.

This API was created in PHP language (Gao & Zhang, 2015), using the free code framework Codeigniter in version 4 (CodeIgniter, n.d.), which read the JSON data file sent by the broker from the Museum and, without any processing because the data was already filtered, sent it to the MySQL database. Codeigniter comes with libraries to connect natively with this type of database, so the programming was simple.

With regard to data security issues, since data are transmitted via the HTTPS protocol, the transmission is secure and cannot be intercepted by conventional means.

Furthermore, the server is equipped with a SSL/TLS certificate, and the MySQL database is password-protected.

These systems are backed by authenticated access to the server through a username and password, thereby providing a level of security consistent with standard web-based storage systems.

3.8 Cost of system components

Table 3 shows the cost of all the components of the system, including the sensors, the broker and the internet-based server fee.

Most of the components were purchased from Aliexpress (Aliexpress, n.d.), some from Amazon (Amazon, n.d.) and a minority from a physical shop.

All software used is free and sometimes open source, so there were no costs associated with this item. Thus, it is evident that the total cost of the system is a tiny fraction of a commercial system.

Tab. 3: Cost of all the components of the system.

Component	Cost EUR	Ud	Price EUR
For sensors			
Sensor DHT22	1.29	6	7.74
ESP8266 - Wemos D1	1.15	6	6.90
Lm7805 Voltage regulator	1.17	6	7.02
LED light	0.02(*)	6	0.12
Resistance 120 Ohms	0.01(*)	6	0.06
5 mm pitch input connector for PCB board	0.10(*)	6	0.60
Male and female connection pins for PCB board	0.05(*)	24	1.20
Bakelite PCB board with perforations	0.15	6	0.90
Solder for soldering	0.50(*)	6	3.00
For system wiring			
Charger AC DC 220V to 9V volts	2.63	3	7.89
5.5x2.1mm female power plug adapter	0.24	3	0.72
12V red-black connection cable (15 m)	5.00	1	5.00
For the broker			
Raspberry Pi 3A+	35.00	1	35.00
Charger 5V 3A for Raspberry Pi	2.92	1	2.92

(*) approximate cost. It is purchased in large quantities.
Total cost of monitoring system: 79.07 EUR (6 sensors)
Database hosting cost (lucushost.com):
.com domain: 16.81 EUR/year
Hosting 15 GB: 93.65 EUR/year
Web hosting cost: 110.46 EUR/year

4. Results and discussion

4.1 General

The data acquisition system was operational for just over one month, from 6 November 2024 to 16 December 2024. It was not possible to maintain the system in operation for a longer period, as an agreement had been reached with the museum management, whose term was due to end on 20 December 2024, at which time new elections were to be held to appoint a new governing board.

Clearly, this time interval is insufficient to conduct a comprehensive environmental monitoring study; however, the objective was not to draw conclusions regarding the environmental conditions within the museum, but rather to evaluate the performance of the prototype, identify its limitations and potential areas for improvement, and ultimately assess the viability of the proposed low-cost system.

4.2 Data collected against wi-fi coverage

For each installed sensor, the data shown in Table 4 was collected; this table also shows the Wi-Fi coverage of each sensor.

The maximum number of data possible for each sensor is determined by the amount of data that was collected with sensors 001 (RH) and 002 (T), because these sensors, as explained, were not real sensors, but a reading from the weather service website.

Tab. 4: Data collected by sensors

Sensor	Num of data collected	% data collected	Wi-Fi coverage (*)
001-002	1608	100%	N/A
003-004	1487	92.4%	Good
005-006	22	1.3%	Very bad
007-008	1121	69.7%	Acceptable
009-010	1373	85.4%	Acceptable
011-012	695	43.2%	Bad
013-014	263	16.3%	Bad

(*) See Table 2

It should be noted that each DHT22 package, which integrates both a RH and a temperature sensor, collected the same amount of data for both types.

Looking at the data in Table 4, it is easy to see the great influence that the Wi-Fi signal has on the performance of the device that sends data to the broker: the Wemos D1 board sends its data correctly with good Wi-Fi coverage, and is very sensitive to the quality of the network.

Particularly noteworthy is the very poor coverage of the place where the pair of sensors 005-006 was placed, which was on the top floor about 10 metres away from the pair 003-004, which was the one that worked best due to its good coverage.

The circumstances explaining this large difference in coverage are not entirely clear, but were attributed to the proximity of a major pillar of the building, whose metal core could have acted as a screen for the Wi-Fi network.

To rule out a hardware failure, this pair of sensors was completely replaced within a week of the start of monitoring, and the problem was not fixed, so the source of the problem became clear.

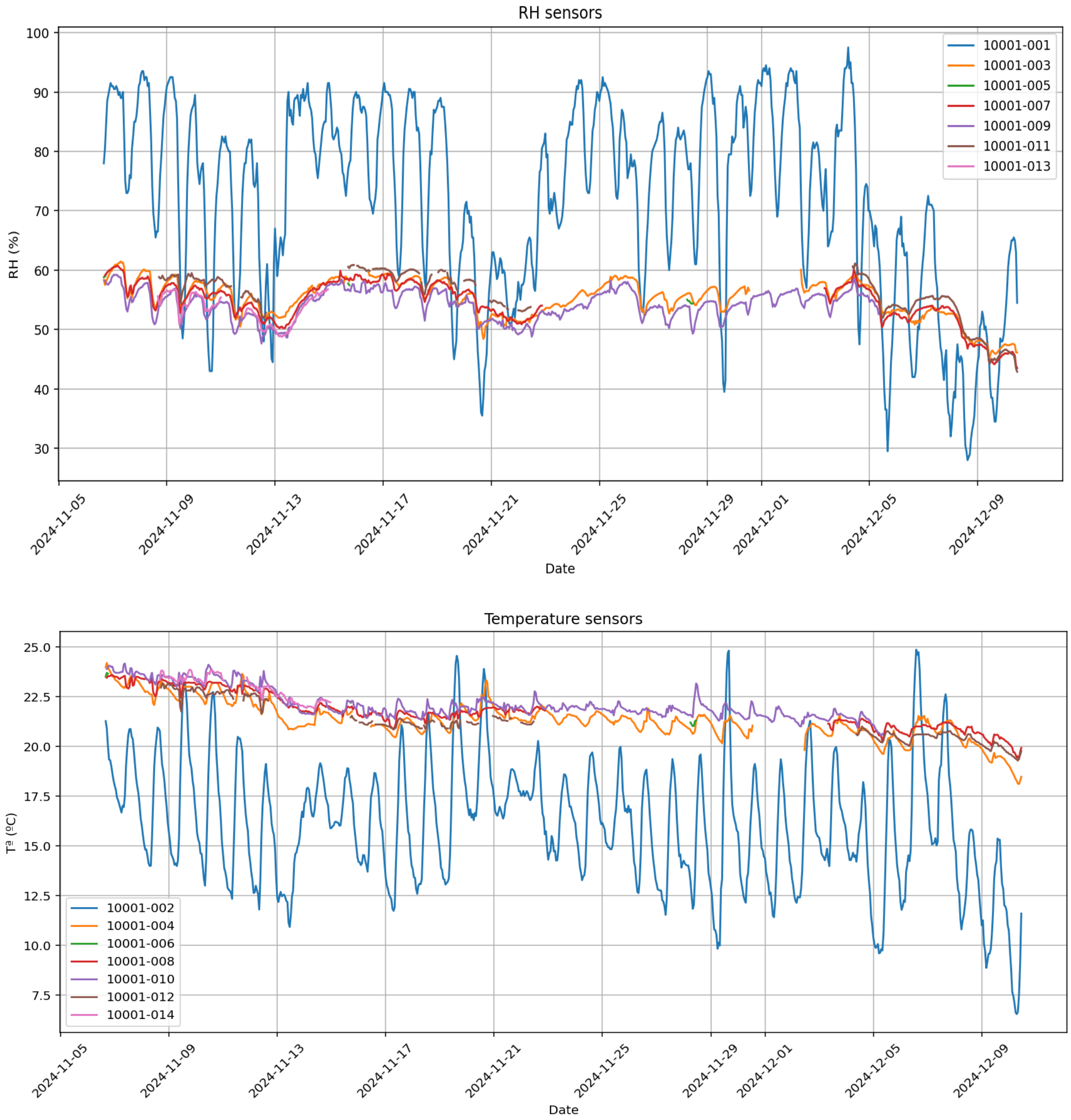

Fig. 6: Line graph for RH (up) and T sensors (down).
Note: In the graphs, the sensors appear with the designation 10001-001, 10001-002, ..., 10001-014 which corresponds to the designation that appears throughout the text of 001,002, ..., 014. This is because, in the database, the project code (in this case, the term 10001) is prefixed to the numbering of each sensor.

Pairs 007-008 and 009-010 worked well because they were left suspended in the gap between the two floors of the museum, with no elements interfering with the Wi-Fi network. Finally, for the last two pairs of sensors, 011–012 and 013–014, which were installed on the basement level, there were concerns regarding their performance, as the network coverage was particularly poor.

Without wishing to carry out in-depth studies because, as indicated above, the monitoring time was insufficient to reach any conclusions regarding the environmental conditions, and for a general overview, some graphs of the collected data are presented in the figures 6 and 7.

Fig. 7: Line graph for RH (up) and T sensors (down) inside the museum

Figure 6 shows the line graphs of all collected data. Sensors 001 and 002, for humidity and temperature respectively, show much larger amplitudes because they correspond to data from outside the museum.

Logically, inside the museum, both humidity and temperature variations are smoother, being damped by the effect of the building.

In both graphs, the vertical scale is distorted by the external data. In order to pay attention to the data collected by the sensors, these plots are repeated by removing the external data from the representation, and the result can be seen in Figure 7. In both figures, a consistent daily evolution of the measurements can be observed, with no apparent anomalous data.

5. Conclusions

This paper presents the development of a very low-cost prototype system for monitoring environmental parameters in small museums. It is important to emphasize that the objective of this work is not to conduct a comprehensive environmental monitoring study, as the necessary conditions for such an undertaking were not met: there was insufficient Wi-Fi coverage to collect data across the entire exhibition space, and the available monitoring period was limited to only 40 days. Therefore, the aim is not to draw conclusions regarding the conservation conditions of the analyzed environment, but rather to demonstrate the technical feasibility of an alternative system capable of reproducing the basic functionalities of existing commercial solutions at a significantly lower cost.

In this context, the proposed system is conceived as a proof of concept aimed at validating the capability for acquisition, processing, and transmission of environmental data under real operating conditions. Despite the limited testing period (just over one month) and the constraints associated with the low-cost components employed, the results obtained demonstrate that the prototype is capable of collecting consistent, high-quality data and transmitting them in near real time (every 30 minutes) to a standardized database hosted on a conventional web server.

The main contribution of this work lies in demonstrating that it is possible to implement a functionally equivalent system, in operational terms, to commercial environmental monitoring solutions, while avoiding the high costs associated with proprietary hardware and cloud-based storage and management services. In this regard, data transmission to web-based platforms is a key feature, as it enables the replication of typical functionalities of commercial systems, such as alarm generation, periodic reporting, and the execution of specific analyses accessible in near real time by conservation professionals.

Furthermore, the development of the prototype has made it possible to identify certain limitations inherent to low-cost solutions that should be considered in future implementations. These include, in particular, the dependence on a Wi-Fi network with adequate coverage throughout the monitored space, as well as the requirement for wired electrical power supply. Both factors directly influence sensor placement and the reliability of data acquisition.

Nevertheless, despite these limitations, the present study confirms that the implementation of such systems is technically feasible and may represent a realistic alternative to commercial solutions in contexts with highly constrained financial resources. In this way, a methodological and technological foundation is established for the future development of accessible tools that facilitate environmental monitoring in small institutions and collections at an affordable cost.

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