Laborda *et al. Heritage Science* (2022) 10:197
https://doi.org/10.1186/s40494-022-00837-9

Heritage Science

RESEARCH **Open Access**

From concept to validation of a wireless environmental sensor for the integral application of preventive conservation methodologies in low-budget museums

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Abstract

The effective implementation of preventive conservation strategies requires tools to continuously measure the environmental conditions to which the cultural objects are exposed. In this sense, the European Horizon 2020 project CollectionCare aims to provide an affordable preventive conservation service for individual objects focused to small museums with limited budgets. Although the use of data loggers has been a must in the past, new deployments tend to use wired and wireless sensors that provide real-time information and the ability to instantly analyse the data, allowing immediate action to be taken in the event of a threat towards a cultural object. For already constructed buildings, wireless systems have the advantage that, a priori, deployments are simpler, faster and cheaper, but have to deal with complex heritage environments with long distances to be covered and very thick walls to cross. In many cases, commercial systems of this type are not economically viable for small museums with limited budgets. Moreover, conservators who try to approach such solutions are often overwhelmed by unclear technical specifications that do not allow them to determine whether the solution fits their environment or not, giving rise to great frustration. Among others, the CollectionCare includes the design of a specific low-cost wireless sensor, being the aim of this article to present to both technical and non-technical readers, the design choices made regarding the housing, attachment method, power source, wireless transmission technique and selection of the environmental sensors following European standards. Also, the effective implementation of the device in three stages to prove the concep until to get a near-production version is presented. The developed device has been deployed in museums in Belgium, Italy, Greece, Latvia, Denmark and Spain, and the validation results are presented, showing that it is feasible to have a cost-effective proposal that it is easy to install and configure and can operate for 10 years without the need for maintenance or battery replacement except if it is needed to comply with annual recalibration if standards such as ISO 11799:2015 are required.

Keywords: Cultural heritage, Preventive conservation, Indoor microclimate, Real-time monitoring, Sensors, Wireless, Internet of things

Introduction

Cultural heritage degrades inexorably with the passage of time, and all we can do is "to keep for a while what you want to keep forever" [1]. The nuance comes in how to do this which will depend on the resources available, but is most likely to be through preventive conservation (PC) techniques.

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Preventive conservation (PC) aims to prevent and minimise the risk of irreversible damage to cultural heritage due to environmental factors such as temperature (T), relative humidity (RH), light (L), ultraviolet radiation (UV), air pollutants (AP) and vibrations (V), etc. A good PC strategy for collections would involve implementing recommendations to provide environments that ensure the long-term stability of cultural objects and also establishing appropriate control procedures to monitor and correct these conditions [2] following guidelines [3–7], reference literature [8–10] and museum standards such as [11–17]. Unfortunately, there are no single conditions that guarantee the conservation of all cultural heritage, as each scenario and each cultural object will have different characteristics that will result in different conservation needs. Moreover, the paradigm shift from a museum concept oriented to preserve and display heritage to a vision more focused on the transmission and dissemination of knowledge with the citizen at the center, complicates the balance between heritage conservation and human comfort [18, 19]. To this vision we must add the need to improve energy efficiency [20–22] and the effects of climate change.

Establishing the "safe" levels of light, air temperature, relative humidity, vibration limits, air pollutants, etc. to reduce the risk [23, 24] for the collection and the museum building is highly dependent on the museum policies but always bonded with the need to measure environmental parameters, preferably in an integrated way, that affect the cultural assets as a necessary step to establish the preventive conservation (PC) strategies and actions within the context of the environment of an object or a group of objects [25, 26]. In many cases, the building is a cultural asset that, apart from being cared for, should be continuously monitored to avoid the appearance, for example, of fungi harmful to health and the biodeterioration of the objects [27, 28].

There are different approaches of systems for environmental monitoring. One approach is based on the use of wired sensors, being relatively simple, robust, and exhibit minimum maintenance, as no battery replacement is required. Sensors can be complex because power supply can be provided through the wires and data can be transmitted as shown in some applications in cultural heritage [29, 30]. Another approach for cultural heritage monitoring is the use of commercial dataloggers [31, 32], which are autonomous devices powered by batteries with the advantages of being easy to install, wire-free, and small. The main disadvantage is their limited data storage, the use of batteries with a certain lifespan, and the need to manually download recorded data from each datalogger.

Given the technological evolution undergone in recent years in the field of Internet of Things (IoT) [33, 34] and cloud computing, new perspectives appear with respect to wireless microclimate monitoring of cultural heritage that perfectly complements others concepts in a wide approach such as the "smart city" concept for cultural heritage monitoring and management to embedded experiences in Smart Tourism Destinations [35]. Apart from avoiding wiring, the main advantage is the possibility to access the data in real time, which allows the detection of abnormal situations that require urgent action.

The deployment of efficient wireless sensor nodes in cultural heritage contexts is not straightforward [36–43]. Sensor nodes use radiofrequency (RF) to transmit information that has to travel relatively long distances and/or pass through thick walls, moreover, the energy requirements must be kept low to give the nodes a long life-span. Moreover, most typical standards for the development of wireless sensor networks (Bluetooth, WiFi, Zigbee, 6LowPan, etc.) use the RF band of 2.4 GHz or 5 GHz. Both bands exhibit problems in case of long distances, thick walls and low power requirements. For example, [36] proposes an interesting monitoring system for the Mosque–Cathedral of Cordoba (Spain) based on open-source hardware sensor nodes that showed unpractical due to the tick walls. SubGHz bands seems the best option for these scenarios as we demontrated in a previous research [43] where we designed an ultra-low power sensor node appropriate for heritage building monitoring. This node was initially designed for monitoring the equilibrium moisture content in wood and the detection of termites [39].

Nowadays, it is possible to find different devices and complete solutions in the market for the monitoring of environmental parameters in cultural heritage scenarios. In the case of the devices, the focus of this paper, it is possible to find data logger-based tools widely used as an option for cultural heritage monitoring. Typical devices utilised in cultural heritage for this purpose are the Testo 160 and Testo Saveris H; SensMax$^{®}$ SensGuard; Eltek Darca Heritage; and Onset Hobo ZW and MX series, among others. We deliberately included wireless devices in this small list. These solutions tend to be oriented to measure a single environmental parameter or closely related parameters, e.g., temperature and relative humidity, or light and UV radiation but a correct prediction of deterioration should incorporate all parameters, for example, light degradation can be triggered at certain temperature levels.

As indicated, wireless devices are the current trend and, a priori, a suitable choice. However, not all wireless technologies used in these devices are suitable for any space or location, and if they are, the cost is exorbitant.

Ideally, a simple and inexpensive wireless deployment adapted to the specific needs of preventive conservation operating for many years without maintenance would be the best solution.

The European Horizon 2020 CollectionCare project [44, 45] aims to create this ideal device. CollectionCare project aims to develop an innovative PC decision support system targeting the needs of small to medium-sized museums, which often cannot count on a sophisticated environmental monitoring system or on qualified personnel to maintain it. The system will integrate current research and technological advances in sensor nodes, wireless communications, cloud computing, big data and material degradation models into a single affordable system, to suggest appropriate conservation guidelines for museum collections. To accomplish this, the CollectionCare system intends to continuously monitor the environmental conditions for selected cultural objects in different scenarios (display, storage, handling or transport), through an internet of things (IoT) sensor node device placed near them following the criteria suggested by the restoration theories for preserving the identity of cultural heritage (distinguisibility, compatibility, reversibility and minimum intervention) [46].

In this article, we aim to explain understandably to conservators what decisions we have made to create a wireless sensor specific to the project's needs. We will then present the design of the sensor and the results obtained in the partner museums of the project. The conclusion will focus on summarising what has been achieved and on understanding the limitations of the design decisions.

Methods

Desired characteristics of the device

This section aims to summarise the design decisions that have been made on the following key aspects: how the environment is to be measured, how the device is to be encapsulated, how it should be attached to the object, which wireless technologies are suitable and, finally, how the device is powered. All these aspects will be illustrated to facilitate the understanding of the consequences of the choices for measuring the environment.

From the point of view of environmental measurement, temperature (T) and relative humidity (RH) are considered the main parameters affecting the degradation of most cultural objects. After these, light (L), ultraviolet radiation (UV), vibrations (V), pollutants (POL), volatile organic compounds (VOC) and particle matter (PM) are also of interest, depending on the type of object.

T and RH are critical for hygroscopic materials, and this is why they were considered the first ones to be addressed. To decide how to measure them, European standards EN 15758:2010 [12], EN 16242:2012 [13], EN 15757:2010 [14] and EN 16893:2018 [15] were considered when selecting the sensors.

We must bear in mind that the measuring device must not be in contact with some objects to be monitored. Although at the beginning of the project proposal it was intended that in some cases the wireless sensor node should be attached to the cultural object, some members of the advisory board and partner museums during a Partnership Workshop in Copenhagen, stressed the importance of avoiding attaching the sensor node to some cultural objects by preferring to place it close to them [46]. In this sense, the reasonable way of estimating the surface temperature of the object itself is to measure surrounding air temperature near the object and the effect of the radiation (infrared, light and ultraviolet) that heats the object, so only an approximation of the real T can be obtained (e.g. a black object will become warmer than a white one in the presence of infrared radiations produced by the sun or artificial light).

Based on the evaluation of the proposals of the standards EN 15758:2010, EN 15757:2010 and EN 16242:2012, Table 1 summarises the minimum characteristics of the T and RH sensors to be selected. For RH, there are several options, but we decided to choose the accuracy level "2" (high) from Table 1 of the EN 16242:2012 standard and extra ranges to deal with all the scenarios of the CollectionCare PC management system.

We established a starting sampling rate of an hour for T and RH to comply with the standards. In any case, the proposed sampling interval goes beyond the capability to detect sudden changes that can affect very sensitive objects; for example, a sheet of paper will be affected in a few minutes by a change in RH and T, as discussed in ASHRAE [11]. The design of the CollectionCare sensor node should be flexible enough to conveniently monitor these changes if required by the needs of the degradation models under evaluation.

Concerning L and UV, they produce known degradation problems in cultural objects, such as yellowing, whitening, chemical decay, etc., that are cumulative over time and their influence depends on the type of material affected by the source of light.

For L measurement, the main references have been the European standards EN 12464–1:2002 [16] and EN 16163:2014 [17]. As a general rule, the ideal in an object exhibition scenario is to have only visible light, so the purpose of the CollectionCare sensor node should be to measure the deviation from the ideals. As a reference, the classic illuminance level recommended for museums should be 50 lx for vulnerable materials such as paper/prints and 150–200 lx for moderately vulnerable materials like paintings [47, 48]. Although the golden rule for

Table 1 Minimal sensor requirement for measuring temperature and relative humidity

Parameter	Temperature	Relative humidity
Units	Celsius degrees, t, °C	percentage
Reference European norm	EN 15758	EN 16242
Sensor	Resistance thermometer	Capacitive electronic hygrometer
Calibration (ISO/IEC 17025)	Periodic maintenance calibration	
Operating range temp	−20 °C to 60 °C	5–95% −10 °C to 50 °C
Uncertainty	0.5 °C, desirable 0.2 °C	2%
Repeatability	0.1 °C	1%
Resolution	0.1 °C	1%
Sampling interval	1 h or less	–
Response time	< 60 s	–
Stability	± 2 °C/year	≤ 2%/year

illuminance in art exhibitions is 50–200 lx, depending on the type of material, because theoretically, the human eye can perceive colour with such a level of illuminance, we should consider the problem related to the elderly or the contrast with dark objects. Therefore sometimes it is interesting that a level of up to 4,000 lx could be strategically acceptable. So, this level of 50–200 lx should be considered as the benchmark in choosing a sensor able to discriminate between levels near this range.

For ultraviolet radiation, the typical approach in museums is to measure this radiation in relation to light intensity and express it in microwatts of UV per lumen of light (μW/lm). As a reference for the choice of a sensor, measuring around 75 μW/lm should be sufficient in the project context [47]. It is interesting to note that standards such as EN 16163:2014 do not regulate radiation limits, and only provide recommendations. This is understandable because it is very difficult to provide strict limits for different scenarios such as temporary object exhibitions, art galleries or permanent displays.

Although not described for reasons of extension, other variables considered were vibrations, as the intention is to monitor the transport of cultural objects, and also pollutants and VOCs were tested (nitrogen dioxide and acetic acid). Pollutants, particulates, fungal attacks, and bacteria have adverse implications on indoor air quality and collection risks [49, 50], therefore, monitoring gases such as: sulfur oxides (SO_x), nitrogen oxides (NO_x), ozone (O_3), hydrogen sulfide (H_2S), soot, acid and alkaline particles, formaldehyde, and volatile organic compounds are of interest.

Enclosure

From the point of view of the housing required for the final product, it must be an object that allows the proper location of several sensors and electronic components inside it to monitor environmental conditions uninterruptedly and with reliable data capture. On the other hand, as the final product is for use in museums, it should be aesthetically appropriate according to their needs [46] and, at the same time, an easy device to place and attach everywhere they need it, such as exhibition and storage rooms, showcases, or transport systems. In addition, being a device that will constantly accompany the objects, it is necessary to have a housing that does not generate any harmful product that threatens the conservation status of these cultural artefacts.

Hence, the materials to be used in constructing the different museum fixtures and fittings that are in direct contact with or near the cultural objects (such as showcases, storage systems, etc.) must be carefully selected because many materials, such as wood, coatings, plastics, adhesives, etc., can emit Volatile Organic Compounds (VOCs) that may cause damage to cultural artefacts, triggering chemical reactions in the different constituent materials, thus generating slow deterioration of the artefacts [51].

Plastic is one of the most commonly used materials for designing and manufacturing sensor housings for use in museums. However, in recent years, different types of plastics have been identified as a source of indoor pollution, as their ageing process generates some low molecular weight compounds [52].

Due to the different properties and chemical stability of different plastics, we decided to choose a small group of plastics to start studying and working with them. These plastics were: acrylonitrile butadiene styrene (ABS), polypropylene (PP), polyethylene terephthalate (PET) and polycarbonate (PC). These have been used recently as prototype materials for designing housings in museums, which is why they were chosen for the initial studies.

Considering the results of [53], these four plastics generate very low concentrations of harmful VOCs. However, the final properties of plastic products can never be separated from the process by which they are made [54].

Attachment

In addition, it is necessary to establish a suitable attachment system(s) using inert and 100% reversible materials [46, 55] and the possibility of changing the location of the sensor node in the future.

In that sense, the most commonly used systems for attaching sensors within different spaces are by mechanical or adhesive means. The ones considered are attachment systems with screws, magnets, Velcro straps, and double-sided adhesive tapes. Therefore, with these requirements in mind, we establish a few more:

- The first attachment approach will be designed to fix the sensor node on a wall
- The assembled sensor node will be easily attached and detached from the wall without the need for special tools
- Both methods of fixing, with screws or with double-sided adhesive tape, will be supported. Although no harmful adhesives will be used
- The sensor node must be able to be installed on top of a surface (for example a showcase) by itself without the need for additional parts

In any case, there is no actual solution exempt of risk [55].

Wireless telecommunications options

Once decided the physical magnitudes to measure and the housing and attachment of the device, we continue from the fact that the use of a device with a wireless connection is a must and that, as far as possible, this device should transfer data in real-time to a cloud infrastructure for immediate processing. All this while keeping the cost of ownership (cost of the devices and maintenance) low.

Based on the specific characteristics of each museum and space, such as wall materials, floor levels, distances, etc. of the partner museums, we identified and characterised the aspects that negatively affect the wireless connectivity range. This will establish the technical requirements that must be considered for the wireless technology for these spaces and, by extension, for most small and medium museums. Some of the main physical factors limiting transmissions are distances to the receiver, the type of materials of the building, the type of material of the artefacts and the positioning of the device.

In any case, it is important to note that it is impossible to warrant data transmission and, depending on the choice of technology, we only can minimise data loss or interruptions.

The application of wireless technology for preventive conservation often involves using the same wireless technologies we use daily, i.e. Bluetooth, WiFi and GSM. GSM can be discarded due to its power requirements, leaving Bluetooth and WiFi.

There are excellent Bluetooth Low Energy (BLE) dataloggers such as the Hobo MX1101 that employ this approach. However, downloading data from these devices requires a Bluetooth-enabled mobile phone or computer from a distance of less than a few tens of metres. In other words, they simply avoid having to connect a cable to download data, but do not eliminate the need for manual downloading by an operator.

WiFi is the other main option; for example, we use the Testo 160 TH in some projects. In this case, the data download is done using the WiFi infrastructure of the building, which for us is its main disadvantage, as they depend on the operation and availability of this infrastructure and the disadvantages of WiFi itself.

Both WiFi and BLE use the 2.4 GHz (or 5 GHz) radio frequency spectrum are unable of reaching long distances or reasonably traversing walls, which is an advantage for common use cases, but not in PC.

To conveniently address cultural heritage spaces, sub-GHz RF technologies are more appropriate; for example, the Hanwell Pro solution, well-known in cultural heritage, uses this approach using proprietary protocols. This is the best approach, but it is neither affordable nor standard, so it is unsuitable for the project's needs.

After analysing the different possibilities, we decided to design the device based on the so-called Low-power wide-area network technologies (LPWAN). LPWANs are a key element of ecosystems like smart cities, smart farming, smart agriculture, etc. These technologies try to be:

- Low-power: this stands both for energy requirements and transmission power (radiofrequency energy radiated)
- Wide-area: despite the restrictions mentioned above, they can communicate to long distances
- Low cost: adding "talking" capability to the object is cheap both for hardware and for the cost of communications (operator subscriptions)

In any case, they are not exempt of drawbacks, mainly:

- Low transmission rates: order of bps (e.g. 100 bps)
- Limited "duty cycles": that is, how often they can transmit

- Very asymmetric: better uplink behaviour (data from the sensor to infrastructure) than for downlink (data from infrastructure to the sensor)

Today's leading and realistic LPWAN technologies are NB-IoT, LoRaWAN and Sigfox. Of these, LoRaWAN and Sigfox are the best candidates from our point of view for the requirements of PC in complex spaces. These technologies use the unlicensed RF spectrum of 868 MHz in the European space and must adhere to ISM 868 MHz RC1 ETSI regulation EN 300 220-2. This is another drawback of this technology, as different countries use different RF bands and regulations.

Energy sources

Finally, the battery is also a critical design choice because we need to ensure that the device lasts for as long as it should, with a set minimum lifespan of 10 years. Key requirements for the election are: the smallest footprint possible, high energy density, extremely low self-discharge, safety, wide operating temperature range (to cope with Latvian museum partner) and sufficient maximum current to deal with radio transmissions.

Dealing with the 10 years of operation requirement rules out all secondary cell batteries (rechargeable) and most primary cell ones because of their self-discharge phenomenon. Table 2 is a very simplified list of conventional primary cell batteries and lithium-based ones that tries to highlight to the reader the consequences of using typical batteries to power a data-logging device for heritage applications. Based on these figures, only lithium-based primary cells can be considered if we are looking for a safe, high-density, low-self-discharge battery and other key aspects.

The CollectionCare wireless sensor node

Based on the design goals briefly described in the previous section, we applied a methodology for the creation of the CollectionCare wireless sensor node widely used in the industry for product development. According to this methodology, the design and the elaboration process is divided into a sequence of phases to ensure organised coordination: concept development, system design, detailed design and testing, refinement and optimisation. As a result of this methodology, the development of the sensor node included three milestones: the "basic" sensor node, the "advanced" sensor node and the "optimised" sensor node which enabled us to validate and refine the concept.

This section is mostly devoted to presenting the final result and some highlights on previous stages. Among other things, the final stage, called "optimised", aims to optimise costs and make the product industrialisable using a reduction of connectors, putting sensors on board, using a printed PCB antenna, etc. to provide a simplified manufacturing process but a very user-friendly result. Figure 1 shows the appearance of the first version and the last version of the wireless sensor node.

This section, in contrast to the requirements section, presents the electronic design of the device before going into the encapsulation and the attachment method. Figure 2 shows a block diagram of the sensor electronics.

The core of the design is a StMicroelectronics STM32L072 ultra-low power microcontroller coordinating the rest of the components of the node. Among others, the microcontroller gets physical information from

Fig. 1 Appearance of the "basic" sensor node (left) and the "optimised" sensor node (right)

Table 2 Key properties of consumer-grade and selected primary cell batteries

Battery technology	Nominal voltage (per cell)	Energy density (Wh/L)	Self-discharge	Operating temperature	Safety
Zinc-carbon	1.5	0.33	< 3.8% per year	−7 to + 50 ºC	− −
Alkaline	1.5	1.5	< 2.4% per year	−10 to + 45 ºC	−
Li-FeS$_2$	1.5	475	< 1% per year	−40 to + 60 ºC	+ + +
Li-SO$_2$	2.8	330	< 3% per year	−40 to + 70 ºC	+ +
Li-SOCl$_2$	3.6	1,120	< 1% per year	−60 to + 150 ºC	+ +
Li-MnO$_2$	3.0	725	< 1% per year	−40 to + 85 ºC	+ +

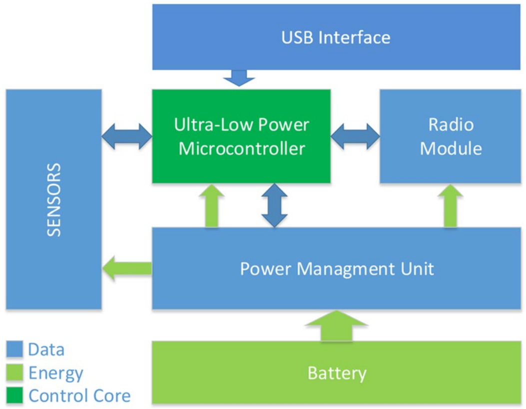


Fig. 2 Block diagram of the electronic part of the sensor node

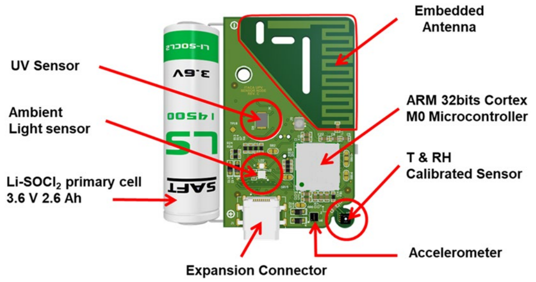


Fig. 3 Electronics of the final version of the sensor

the environment using electronic sensors, controls a radio module to send information wirelessly, and manages the sleep cycles of the system to save as much energy as feasible.

The sensor block includes the electronic sensors that transform physical magnitudes into electrical/digital ones and the electronics to adapt the output of the sensors to the requirements of the microcontroller block.

The radio block is based on a Semtech SX1276 radio chip that provides the modulation techniques to access a LoRa/LoRaWAN-based and a Sigfox-based radio infrastructure. To optimise the cost and performance of the design, a printed quarter wavelength antenna was designed, and specific installation recommendations for conservators have been produced.

Energy is another key block of the system that includes a primary cell-type energy source and electronics to adapt the voltages required by the other components of the system without incurring excessive energy waste. For the primary cell, we chose an LS14500 Li-SOCl2 cell from Saft. This is a 3.6 V, 9.36 Wh. lithium thionyl-based cells with a very high energy density and very low self-discharge, which covers the requirement described in the previous section.

Finally, an external interface is included to both simplify energy provision during test stages and to expose a connection for external sensor probes. Figure 3 shows the aspect of the electronics.

The sensor block is the key part of the design providing the measurement capabilities of the wireless sensor node. It should be noted that the choice of sensors tries to strike a difficult balance between performance, energy consumption and, mainly, cost. Industrial sensors- with high accuracy and robustness could seem more appropriate but unfeasible in a realistic massive deployment of wireless sensors.

To measure T and RH, Sensirion SHT3x series of miniature digital humidity and temperature sensors have been selected (Fig. 4 shows the typical accuracy). These sensors are pre-calibrated, linearised and temperature compensated and provide outstanding performance and long-term stability compared with most competitors. Specifically, SHT31 and SHT35 models cover the requirements of the PC standards both for T and RH. In any case, a calibration protocol should be followed to establish real uncertainty according to ISO/IEC guide 98–3 [56].

During the evaluation of the sensor, it was found that there was no inaccurate dispersion of the data. It was also possible to validate that the accuracy of the Sensirion sensor is suitable for use in T and RH monitoring in museum scenarios, as it operates within the range of T and RH values set by preventive conservation standards.

To measure the illuminance, a Vishay VEML6030 sensor from Vishay was selected. This is a high-accuracy ambient light digital 16-bit resolution sensor in a miniature transparent 2 mm × 2 mm package. It can operate under temperatures between −25 °C to 85 °C, being appropriate to cover all partner installations including The Ethnographic Open-Air Museum of Latvia.

To measure ultraviolet radiation, a GENUV GUVA-S12SD sensor was chosen. This is a Schottky type photodiode based on Gallium Nitride material, optimised for operation in photovoltaic mode and with high responsivity. The GUVA-S12SD sensor has been designed to measure only UV-A radiation although its responsivity, with low sensitivity, includes UV-B radiation wavelengths. However, the measurement of UV-B radiation is not very significant since 10% of the UV-B radiation that reaches the earth's surface is absorbed mainly by gases such as ozone, water vapour, oxygen and carbon dioxide, so it is unlikely that this type of radiation reaches the objects inside the museums.

The device also includes an accelerometer model II2DLPC from StMicroelectronics to cope with the requirements of transport monitoring.

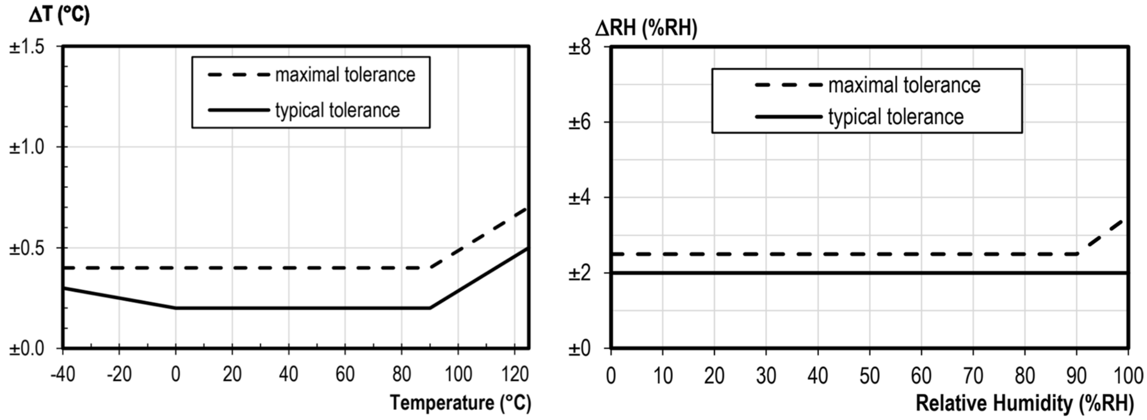


Fig. 4 Typical accuracy of the Sensirion SHT31 sensor

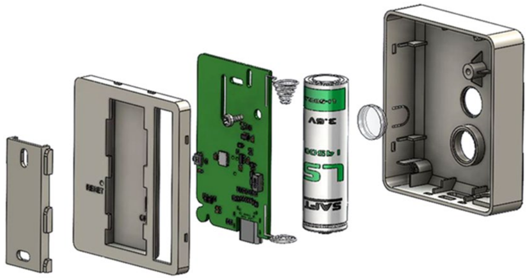


Fig. 5 Box, cover and slide of the final version of the wireless sensor node

Finally, an expansion connector has been included to both provide firmware upgrades and to allow the extension of sensor functionalities such as the measurement of VOCs, CO_2, etc. or any research-specific purpose functionality. This expansion connector was specifically used to detect acetic acid.

Adequately housing the electronics following the desired specifications has required several redesigns to achieve a small form factor, adequate discrete aesthetics and excellent performance from the point of view of lifespan and wireless communications.

The last version of the housing was produced in ABS plastic using the vacuum casting technique (ABS injection) with printed silicone moulds. Using ABS allowed us to achieve the requirements of compatibility with the heritage objects.

Figure 5 shows an exploded view of the three-parts that compose the housing: the box as the front part that supports the PCB, the cover that closes and protects the sensor from the back part and the slide that attaches the sensor node to vertical or horizontal surfaces as an attachment piece.

A critical aspect in the design of this housing is the placement of sensors to measure the environmental magnitudes adequately. For T and RH, the interior and exterior of the sensor housing must be physically connected and in continuous exchange. This has been achieved through a vent on the sensor node housing that will allow the entry of the outside air to be measured so that the local temperature and relative humidity will be equal to the environmental temperature and relative humidity. It is also important to mention that, for each temperature or relative humidity change in the environment, the sensor requires a certain amount of time to equilibrate with the new environmental conditions (response time), so it is desirable to have the shortest possible sensor system response time. To achieve quick response times, several design considerations must be considered such as allowing airflow over the sensor, a design with a single aperture, an aperture(s) as large as possible and no material which can absorb humidity inside the dead volume. To measure air temperature, special care should be considered to reduce the effect of the radiation and the inertia of the probe. Following the design principles of the sensor node, the T and RH probe is a small circuit independent of the rest of the electronics and housing, and is strategically placed at the bottom of the node to minimise inertia and the effect of radiation.

To measure L and UV, an installation of windows is necessary so that the sensor can capture the correct light and ultraviolet radiation. In our design, we decided to use independent windows for L and UV. When designing the sensor node housing it is important to consider that the size of the window for light entry has to be carefully calculated. This size will mainly depend on the distance from the top surface of the sensor to the outside surface of the window and the desirable field-of-view, which will usually be 45°. The shape of the window is also an important factor to mention, as it will affect the calculation of the window specifications. Ideally, the window should be rectangular, as the sensor has a rectangular spread. However, sometimes for aesthetic reasons a circular window is desirable. If this is the case, the radius of the window must be large enough so that the entire sensor field-of-view fits inside the circle, avoiding shading on the active area. The window material, should be completely transmissive or with a known attenuation that can be calibrated. In our case, we decided to use plastic for the light sensor and quartz glass to allow us to measure UV radiation (100–400 nm wavelength).

As for the attachment, the proposed solution was to design a hybrid system that allows the portability of the sensor node and, at the same time, it can be fixed to the wall using an additional part. The attachment system consists of a part fixed on the wall (2), and a mobile part, which will be the sensor housing itself (1), as shown in Fig. 6.

To fix the mobile part, we can use screws or industrial-grade 3 M Command double-sided tape resistant to T and RH changes that ensure reversibility without affecting the surface where it is attached. The attachment system was designed for the basic sensor node and intensively tested for 2 years in a deployment of sensors at the Alava Fine Arts Museum and the Alava Arms Museum and which proved to work perfectly.

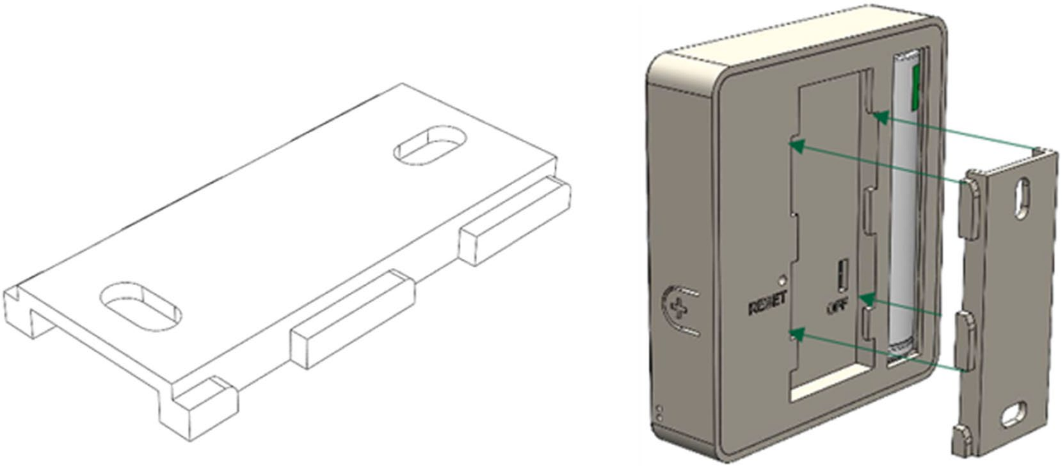


Fig. 6 Attachment pieces

Fig. 7 Attachment methods: screws (left), 3 M double-sided adhesive strips resistant to T and RH changes (right)

Figure 7 (right) shows the double-sided tape attachment options for the final sensor node.

Results and discussion

The sensor node presented in this article is only part of a comprehensive proposal for applying preventive conservation techniques through monitoring proposed in CollectionCare. Before presenting the specific results on the sensor, we have considered briefly presenting the rest of the components of the proposal from a technical point of view.

The case studies where the sensors have been deployed will be described later, followed by the performance results obtained and the specific discussion for each result.

CollectionCare cloud infrastructure

The CollectionCare wireless sensor nodes use both Sigfox and LoRaWAN wireless technology to transfer collected environmental information to the cloud infrastructure. The cloud infrastructure is made of blocks such as virtual computers, databases, etc. deployed on the Amazon Web Services (AWS) platform.

Data arriving in the cloud is pre-processed in an AWS EC2 virtual machine (VM) and can be directly accessed in a user-friendly way by technical users whith a web-based Grafana [57] dashboard especially developed for this project. Figure 8 shows the dashboard aspect displaying data collected by a sensor deployed in a partner museum.

Pre-processed data is then fed to AWS Non-SQL DynamoDB databases that can efficiently accommodate the millions of collected values in a very flexible way ready for analysis and future modifications.

The implemented proposal includes other databases recording the association of sensors with associated cultural objects, and the material composing such objects.

Collected environmental information and individual cultural object information is processed in another AWS EC2 VM using degradation computer models for wood, canvas, paper and metal, and preventive conservation standards such as EN15757:2010 to predict long-term degradation and suggest correction actions.

Both raw data collected information and the results of the application of algorithms are shown to the staff in charge of the collection through a web interface. Figure 9 is an example of basic collected data (up) and recommendations (down) based on the processing of collected data and the type of materials of the objects. These recommendations are based on the output of multi-material predictive models algorithms running on the cloud, with the historical environmental data collected and the real-time data analysis. These multi-material predictive models are complex algorithms that take environmental time series data and cultural object type of material as input. They are capable of giving figures of how the physical properties of the material are going to deteriorate over time. By analysing the output of these different models, the system can determine whether there is a risk of degradation or not and provide PC recommendations.

Case studies

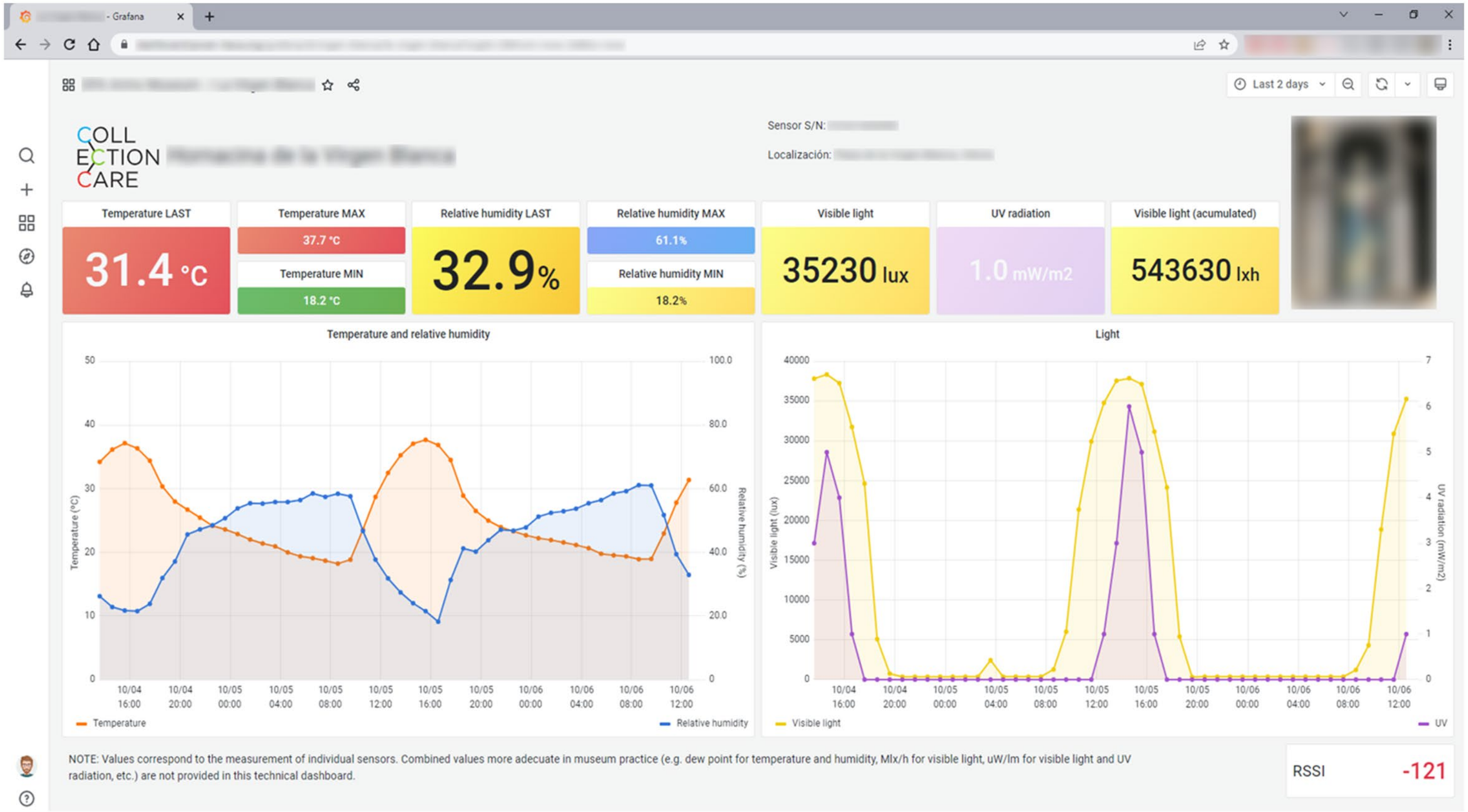
Apart from intensive testing at the ITACA laboratory, different versions of the CollectionCare sensor have been deployed in partner museums to validate their operation and the friendliness for the end user in charge of the installation.

The partner museums of the project are The Danish Royal Collection at Rosenborg castle in Copenhagen, Denmark; the Historical and Ethnological Society of Greece. Athens, Greece; Álava Fine Arts Museum of Diputación Foral de Álava, Spain; Álava Arms Museum of Diputación Foral de Álava, Spain; the Royal Museum of Art and History, Brussels, Belgium; Institut Valencià de Cultura, Valencia, Spain; and the Ethnographic Open Air Museum of Latvia, Riga, Latvia. This partnership of museums allowed us to evaluate very different climatic zones in Europe and different approaches to the preservation of the objects.

Figure 10 shows the installation or positioning of some of the sensors in the partner museums.

The first version of the wireless sensor (Fig. 1 left) was only deployed in Álava Fine Arts Museum and Alava Arms Museum in Spain in July 2020 and is still operational today (more than 2 years later). It is worth mentioning that the initial plans were to deploy in more museums, but the COVID pandemic forced us to rethink the whole project and the city of Álava was close enough for the team in charge of deploying the monitoring infrastructure to arrive by private car in the middle of a partial lockdown. Figure 11 shows a picture of this team together with the staff of both museums taken at the Alava Arms Museum.

This first version utilised LoRaWAN wireless technology and was used mainly to test out the concepts set out in the previous sections. Among others, we tested early deployment protocols of the sensors (guidelines for adequate positions in the building), attachment approach (based on double-sided tape in that case), radio mapping and performance, the battery life in a real deployment, and cloud operation from the point of view of sensor data storage. The results obtained were very satisfactory and allowed us to fine-tune the following design iterations and how to proceed in subsequent deployments. The results for the following iterations are described below.



COLLECTION CARE [redacted]

Sensor S/N: [redacted]

Localización: [redacted]

Temperature LAST: 31.4 °C

Temperature MAX: 37.7 °C

Temperature MIN: 18.2 °C

Relative humidity LAST: 32.9%

Relative humidity MAX: 61.1%

Relative humidity MIN: 18.2%

Visible light: 35230 lux

UV radiation: 1.0 mW/m2

Visible light (acumulated): 543630 lxh

NOTE: Values correspond to the measurement of individual sensors. Combined values more adecuate in museum practice (e.g. dew point for temperature and humidity, Mlx/h for visible light, uW/lm for visible light and UV radiation, etc.) are not provided in this technical dashboard.

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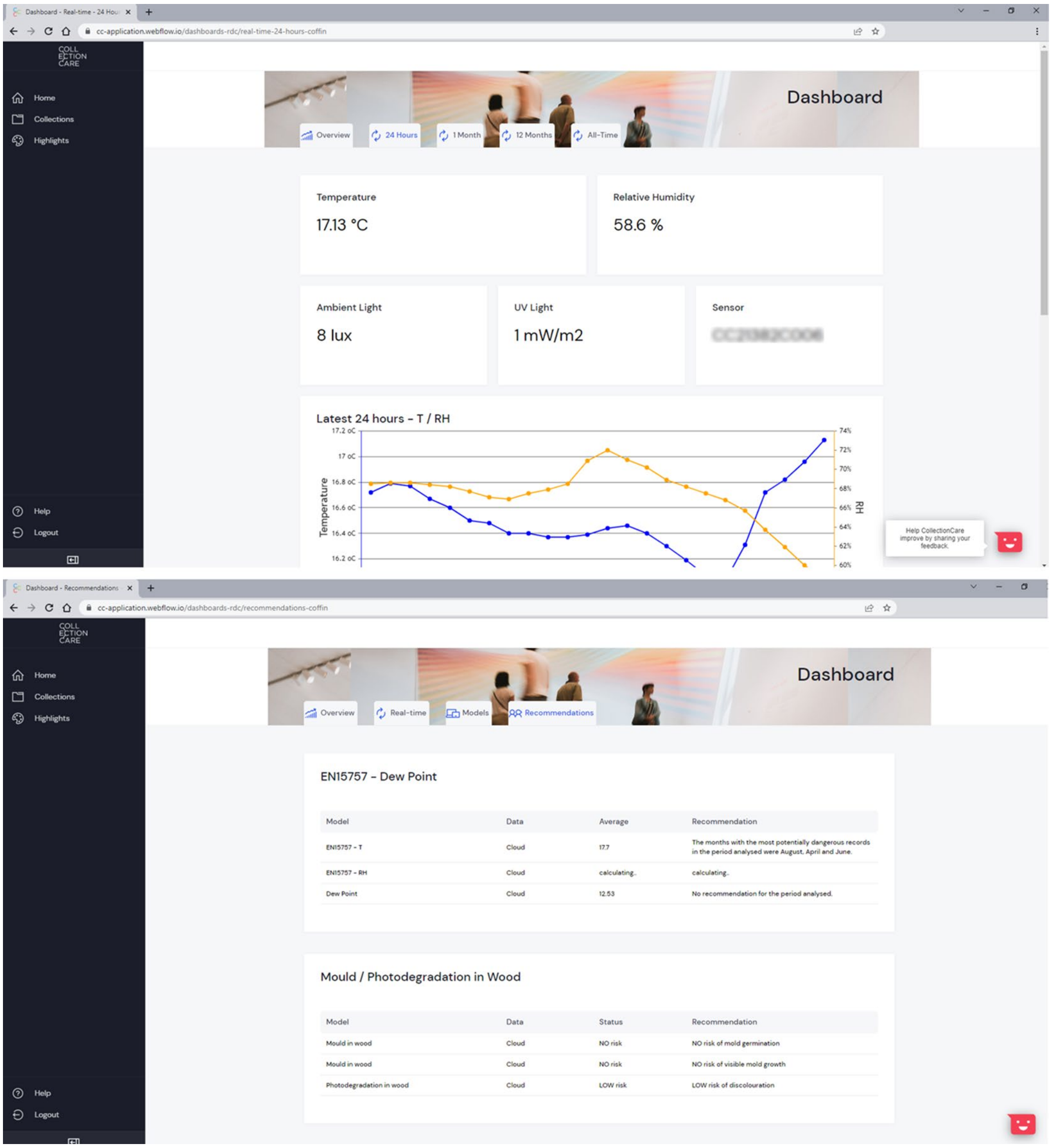
Fig. 8 Grafana dashboard showing real-time environmental data collected at a partner museum



Temperature
17.13 °C

Relative Humidity
58.6 %

Ambient Light
8 lux

UV Light
1 mW/m2

Sensor
[redacted]

EN15757 – Dew Point

Model	Data	Average	Recommendation
EN15757 - T	Cloud	17.7	The months with the most potentially dangerous records in the period analysed were August, April and June.
EN15757 - RH	Cloud	calculating..	calculating..
Dew Point	Cloud	12.53	No recommendation for the period analysed.

Mould / Photodegradation in Wood

Model	Data	Status	Recommendation
Mould in wood	Cloud	NO risk	NO risk of mold germination
Mould in wood	Cloud	NO risk	NO risk of visible mold growth
Photodegradation in wood	Cloud	LOW risk	LOW risk of discolouration

Fig. 9 CollectionCare dashboard showing basic information about collected data (up) and recommendations based on data processing (down)

Practical information on radio wave propagation obtained in this first deployment, a previous experience of propagation at Rosenborg Castle in Copenhagen and knowledge of building construction materials allow us to predict whether a deployment will work properly. Although it was initially planned that the RF specialist team would travel to all the museums, the COVID pandemic prevented this, so this knowledge was essential to ensure the success of the rest of the campaigns, as it would be the museum staff who would be in charge of the installation. The rest of the deployments were carried out with Sigfox radio technology, and their operation was predicted from the company's service maps. As an example, Fig. 12 shows the Sigfox coverage map of Rosenborg Castle in Copenhagen (Denmark).

From the point of view of the lifespan of the wireless sensor node, the deployments carried out in the Álava museums allowed us to evaluate the power requirements of the specific version of this sensor node and the firmware used. We achieved an estimated lifespan of 7–8 years for the following operational parameters:

- One sample per hour of temperature (T) and humidity (H).
- One sample per hour for light (L) and ultraviolet radiation (UV).

Fig. 10 Deployment of CollectionCare sensor nodes in some partner museums

Fig. 11 Staff in charge of deploying the first version of the monitoring system at Alava Arms Museum

- One transmission of data per hour.
- Battery voltage of 3.6 V.
- LoRaWAN mode for wireless communications.
- Spreading factor 12, bandwidth of 125 kbps and output power of −14 dBm for LoRa radio.

Fig. 12 Sigfox service map of the area of The Rosenborg castle in Copenhagen (Denmark)

For the sake of clarity, Fig. 13 shows a capture of energy requirements for a cycle of data capture and transmission for LoRaWAN radio mode. Most of the time, the wireless sensor data spends time in standby mode, that is, doing nothing but consuming battery. After a timed wake-up, sensors are activated and utilised to measure data, then data is packed and transmitted wirelessly requiring an important amount of energy,

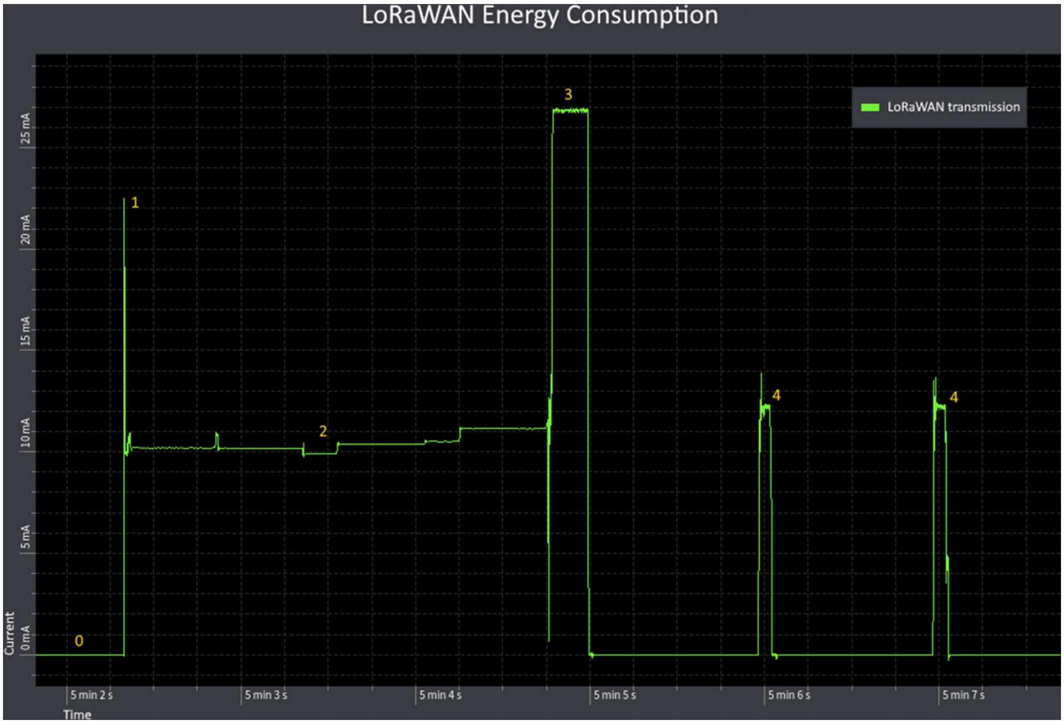


Fig. 13 Capture of energy requirements of the CollectionCare sensor node. (0) Standby current, (1) Sensor turning on, (2) Sensor measuring, (3) Transmitting throught LoRaWAN network, (4) LoRaWAN receiving windows

then, for LoRaWAN class A, two receiving windows are opened for the data downlink.

Considering the measured energy requirements, we first worked out the standby current for the next version of the sensor node redesigning the electronics to allow complete power cut capability of the peripheral management. As a result of these changes, the standby current has now been reduced to below 4 μA.

The other factor that involves a considerable amount of energy is data transmission. In the particular case of

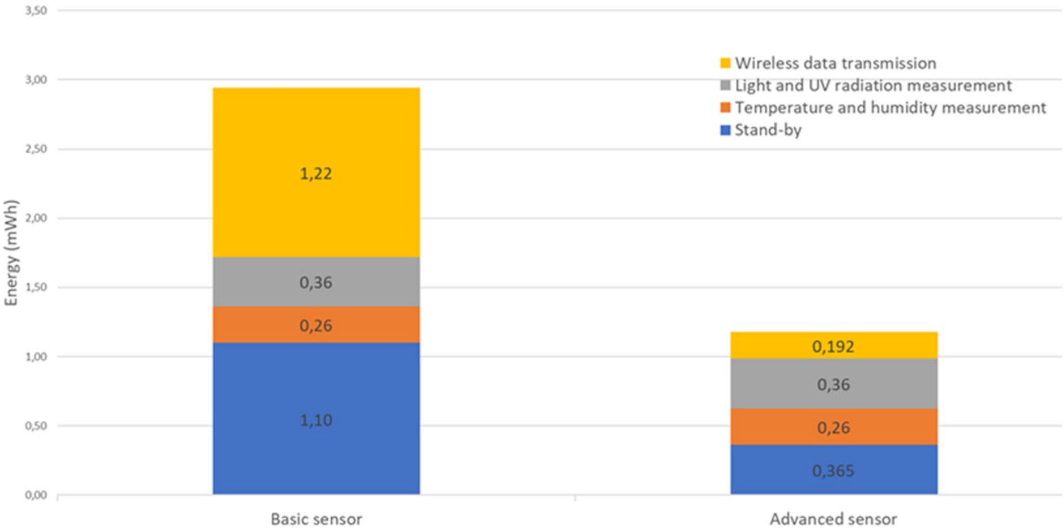


Fig. 14 Daily energy requirements in mW/h of the first version of the node (left), and the next iteration (right)

Alava's museum deployments, we applied a maximum transmission power and the highest spreading factor of SF12. This configuration allows maximum distance at the expense of more time invested in the transmission and thus, more energy usage. There are many options to reduce this energy requirement, for example, packaging two samples of data and sending them every 2 h. Still, we decided to keep the same configuration used in Alava's museum deployment and optimise the use of the radio link. For this purpose, the Adaptive Data Rate (ADR) capability of LoRaWAN networks was used to reduce the amount of energy invested in communications based on the level of the signal received by the gateway. ADR, among others, adjusts the spreading factor and the data rate, reducing the time required for each transmission. A spreading factor of SF8 has been found realistic in most scenarios, requiring in our case an amount of 8.0 µWh of energy per transmission. Figure 14 shows both the daily energy requirements of two versions of the sensor node where optimisations have been applied.

For this particular configuration, an expected lifespan is 19 years but, given this long-lifespan, the self-discharge effect cannot be considered negligible. Still, we can consider that the 10-year target is achievable without the need for additional techniques. In any case, there is room for enhancements and it is important to consider that some measurements such as L and UV should be applied at least every 15 min to follow European standards.

The redesign of the first version of the sensor was industrially produced in two versions named advanced and optimised. A total of 12 sensors per partner museum were shipped to the partner museums of the CollectionCare project and were installed by the museum staff following the instruction manual and advanced deployment protocols. All these sensors were part of the demonstration phase of the complete CollectionCare monitoring, analysis and reporting system.

After a period of operation of these sensors, their performance was evaluated using the Data Extraction Rate (DER). The DER calculates the percentage of messages successfully received by the network. The maximum is 100%, but in this case, it should ideally be greater than 90%. It must be assumed that not all the messages sent by the sensors will be correctly received by the network, and a small percentage of the messages will be lost due to various circumstances (radio coverage, packet collisions, failure of the network gateway, etc.).

Table 3 is a summary of a representative set of sensor nodes deployed in the different partner museums. The table also contains the Received Signal Strength Indicator (RSSI), that is, a parameter indicating the level of the received radio signal, where higher values indicate better signal reception. The location keys are: IEEE: Historical and Ethnological Society of Greece (Athens, Greece), OAML: The Ethnografic Open-Air Museum of Latvia (Riga, Latvia); RDC: Rosenborg: The Royal Danish Collection (Copenhagen, Denmark); DFA: Alava Arms Museum and Alava Fine Arts Museum (Álava, Spain); KMKG: Royal Museums of Art and History (Brussels, Belgium); IVC: Institut Valencià de Cultura (Valencia, Spain).

Table 3 Summary of DER for some sensors installed in different partner museums

Sensor ID	Location	Intallation date	Test duration (days)	DER (%)	RSSI
CC2214D019	IEEE	2022–05-13	158	97.2	−105 dBm
CC2214D020	IEEE	2022–05-12	159	89.5	−120 dBm
CC2214D022	IEEE	2022–05-12	152	91.2	−120 dBm
CC2214D029	OAML	2022–05-11	144	32.7	−140 dBm
CC2214D033	OAML	2022–05-11	154	91.2	−127 dBm
CC2214D037	OAML	2022–05-11	161	89.8	−127 dBm
CC2214D039	RDC	2022–05-10	162	99.9	−100 dBm
CC2214D041	RDC	2022–05-07	125	90.7	−105 dBm
CC2214D044	RDC	2022–05-06	166	98.8	−90 dBm
CC2214D048	RDC	2022–05-10	162	99.3	−110 dBm
CC2214D049	DFA	2022–05-07	152	99.5	−125 dBm
CC2214D055	DFA	2022–05-07	164	100.0	−125 dBm
CC2214D057	DFA	2022–05-03	142	94.7	−128 dBm
CC2214D058	DFA	2022–05-03	146	84.2	−126 dBm
CC2214D059	KMKG	2022–05-06	165	72.5	−93 dBm
CC2214D062	KMKG	2022–05-06	122	98.0	−110 dBm
CC2214D065	KMKG	2022–05-26	145	96.8	−72 dBm
CC2214D070	IVC	2022–05-20	104	100.0	−90 dBm
CC2214D076	IVC	2022–05-20	151	97.1	−85 dBm
CC2214D078	IVC	2022–06-16	124	89.0	−110 dBm

The obtained DER was excellent in most real scenarios, reaching values above 90%. In the cases where the value was low, this was due to the RSSI signal level (−140 dBm), as in the case of the CC2214D029 sensor at the Ethnografic Open Air Museum of Latvia. The default radio transmission scheme in Sigfox technology is to transmit three times the same data at different frequencies, therefore, these excellent figures were expected when the signal level was sufficiently high. In any case, the technology used inherently has this possibility of packet loss. Still, it is feasible to use redundancy strategies or force confirmed transmissions at the expense of consuming more energy to increase the DER.

Conclusions

Measuring environmental conditions is essential to implement preventive conservation strategies. To do this efficiently and economically, the Collection-Care project proposes an infrastructure based on low-cost wireless sensors and a cloud computing platform to collect the data, analyse it using degradation algorithms and conservation standards, and provide recommendations.

This work has presented the needs and results in an attempt to achieve a low-cost wireless measurement system capable of adequately sensing environmental conditions. As far as possible, an attempt has been made to present it in such a way that the conservator understands the choices made and the consequences of the type of choice made.

The performance results of the wireless sensor demonstrate that the use of LPWAN, LoRaWAN and Sigfox technologies, in this case, work adequately in large spaces and with thick walls. Museum staff need only worry about the positioning of the sensor, not whether or not it will be able to transmit. In any case, a RF site survey is adequate to fully understand the behaviour of radio waves within a facility before installing wireless devices. An RF site survey also detects the presence of interference coming from other sources that could degrade the performance of the system.

To minimise maintenance costs, battery life above 10 years has been achieved for the conditions proposed in the article. Other working conditions will reduce the battery life, but this still prevents this task from being repetitive. In any case, depending on the needs of the museums, the requirement of some standards to recalibrate the sensors every year should not be overlooked.

Another significant result is the DER obtained which, although excellent in most cases, entails that some measurements may be lost. Strategies such as redundancy and confirmed transmissions are being worked on to reduce these losses if necessary.

As a final result, an industrialisable wireless sensor has been obtained with a production cost of less than 50 Eur. per unit produced in Europe. Mass production would further reduce its cost.

Acknowledgements
Not applicable.

Author contributions
JL; electronic design, cloud development, text writing. AG; reporting, manufacturing materials election, attachment concept, conservation guidelines, writing. RM; sensor box design, device production. AP; museum coordination, models need, paper review. AP; project leader, funding acquisition, firmware development, main writer. All authors read and approved the final manuscript.

Funding
This research was funded by the European Union's Horizon 2020 research and innovation programme under Grant agreement No. 814624.

Availability of data and materials
Data is available within this manuscript and upon request.

Declarations

Competing interests
The authors declare e that they have no competing interest in this work.

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Received: 19 October 2022 Accepted: 24 November 2022

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