Horizon 2020

COLLECTION CARE

Innovative and affordable service for PC monitoring of individual Cultural Artefacts during display, storage, handling and transport

Advanced sensor node, validated for publishing real-time data to the cloud

Deliverable number: D4.5

Version 1.0

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Abstract

Deliverable 4.5, entitled "Advanced sensor node, validated for publishing real-time data to the cloud" is within the framework of WP4, task 4.4. The aim of this deliverable is to present the improvements needed for the "basic" sensor node, which were provided by the results obtained from the tests and validations performed in the laboratory (sub-task 4.3.4, D4.3) and the museums (Task 4.3, D4.7, Task 5.1, D5.1). This is done in order to develop the "advanced" sensor node.

The document includes seven sections. The first section corresponds to the introduction that describes the methodology used to develop the CollectionCare sensor node and specifies the point at which the development of this sensor node is being carried out. Section two entitled "Improvements of the sensor node design. "Advanced" sensor node, aims to describe the initial design decisions to developed the first version of the "advanced" sensor node. Following, section 3 specifies the improvements required for the antenna and introduces the two types of antenna that are being considered for the development of this second sensor node prototype. The section 4 focuses on compiling all the research carried out to identify the types of pollutants to be monitored and the most suitable sensors to be used for this purpose. Section 5 is dedicated to an initial analysis and practical tests to address the problem of vibration and shock monitoring. Subsequently, in section 6, the power requirements of the "basic" sensor node are evaluated to determine whether or not it is necessary to apply energy harvesting techniques to prolong the life of the sensor node.

Finally, there is a conclusion section summarizing the work done to date and provides a brief description of the next steps.

Abbreviations and Acronyms Glossary

ALS	Ambient Light
AP	Air Pollutants
API	Application Programming Interface
bBm	Decibel-milliwatts
CO_2	Carbon Oxide
COVID-19	Coronavirus Disease 2019
D	Deliverable
DER	Data Extraction Rate
FPC	Flexible Printed Circuit
FTD	Field Test Device
g	Gravity of Earth (9.8m/s^2, unit)
GA	Grant Agreement
Hz	Hertz (unit)
I2C	Inter Integrated Circuit (protocol)
kHz	Kilohertz (unit)
L	Light
LoRa	Long-Range
LoRaWAN	Long-Range Wide-Area Network
LPWAN	Low-power wide-area network
MEMS	Microelectromechanical System
mm	Millimetres (unit)
NO_X	Nitrogen Oxides
O_3	Ozone
PCB	Printed Circuit Board
PM	Particulate Matter
PM2.5	Particulate Matter 2.5 microns
ppb	Parts Per Billion (unit)
ppm	Parts Per Million (unit)
RF	Radiofrequency
RH	Relative Humidity
SGF	Sigfox Wireless SA
SO_2	Sulfur Dioxide
SPI	Serial Peripheral Interface (protocol)
T	Temperature
UART	Universa Asynchronous Receiver Transmitter
UPV	Universitat Politècnica de València

URO1	Sapienza Università di Roma
USB	Universal Serial Bus
UV	Ultraviolet
V	Volts (unit)
VM	Virtual Machine
VOC	Volatile Organic Compound
WP	Work Package

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1. Introduction

Deliverable 4.5 is one of the outcomes of WP4, which aims to create an appropriate wireless sensing infrastructure to collect continuous data on the physical magnitudes that may affect the conservation of cultural objects. To achieve this objective, a methodology was established to develop the CollectionCare sensor node, which is documented in D4.1. This methodology divides the design of the CollectionCare sensor node in a sequence of four phases that are linked to each other in an organised manner to obtain a high-quality final product (see Fig.1).

The results provided in this deliverable are part of the third phase of development of the CollectionCare sensor node corresponding to the "Detailed Design" phase. To reach this point, the entire concept development phase was first carried out, resulting in the design of the "basic" sensor node, the first prototype, with its housing and attaching system, which was later validated in high-density scenarios to evaluate its performance. These evaluations made possible to determine the improvements needed to increase the performance of the prototype in terms of the wireless behaviour, the communication between node and cloud, and the transmission loss rate. All these results, together with the improvements to be made to the electronic design and the introduction of new sensors for air pollutants and vibrations, will allow the development of the second prototype of the CollectionCare sensor node called the "Advanced" Sensor Node.

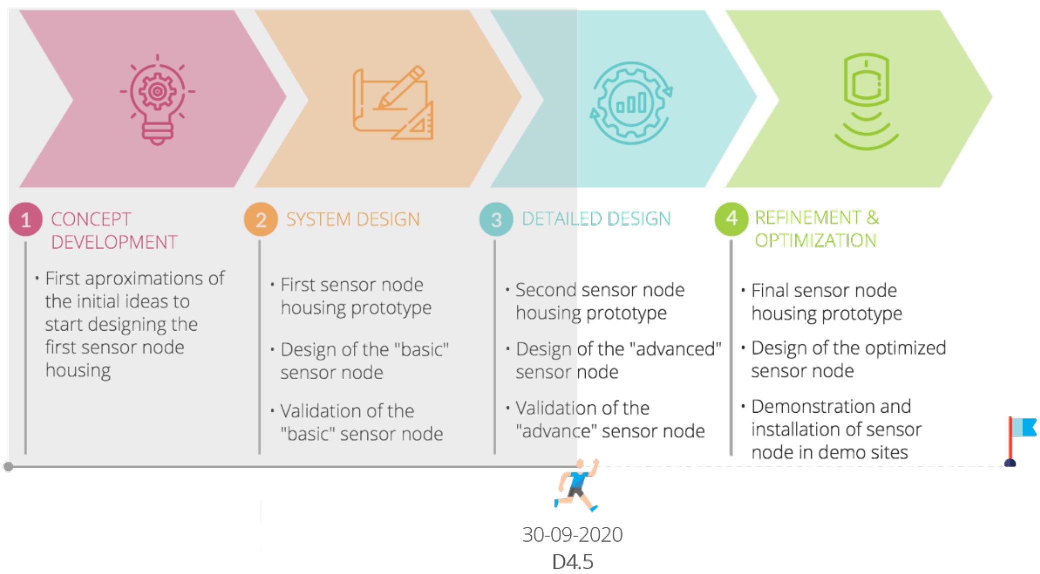


Figure 1. Methodology phases for the development of the CollectionCare sensor node design

Considering all the above, this deliverable presents initial concepts and developments of the "advanced" sensor node. Therefore, to date it has not been possible to produce this prototype, so, as the name of this deliverable indicates, "Advanced sensor node, validated to publish data in real time in the cloud", no validation of the publication of data in the cloud from the "advanced" sensor has been performed. However, the tests carried out in the validation of the “basic” sensor node, conducted in July 2020 (D5.1) in the Alava Fine Arts Museum and in the Alava Arms Museum in Spain, made it possible to satisfactorily validate the transmission and visualisation of data in real time from the sensor node to the cloud. This proposed connection of the sensor node to the cloud will be implemented in the "advanced" sensor node, so it is believed that it will have the same performance and good results.

The situation experienced from March 2020 to date, due to the COVID situation, has been responsible for the delay in the task of the development and production of the "advanced" sensor node. For this reason, only initial developments and concepts of what will be this second prototype has begun. It is expected that the production of this sensor node will take place at the end of this year and its validation at the beginning of 2021. This could imply a delay in these activities with respect to the initial calendar established in D4.1.

2. Improvements of the sensor node design. "Advanced" sensor node

In this section, initial design decisions are provided to highlight the steps taken to create a first version of the advanced sensor node. Following the methodology proposed in the D4.1, this is an iterative task that will involve the refinement of the sensor node design.

Laboratory tests, initial test deployments at the Museo delle Origine in Rome (Italy) and the Museo de Informática in Valencia (Spain) and the final practical deployment at the Alava Fine Arts Museum and the Alava Arms Museum (Spain) made it possible to detect the pros and cons of the design in order to take a step forward in the development of the advanced sensory node.

2.1. Electronic design

Most electronic design decisions have proven to be correct, so minimal changes will be applied to this electronic design.

Considering that the objective is to achieve a commercial product, the most relevant design changes are focused on reducing the cost of the product by eliminating some components and integrating the sensor for temperature and relative humidity measurements and the sensors for light and ultraviolet radiation measurements.

From the point of view of functionality, one of the eliminated components is the SiLabs CP2102 serial to USB converter. This component allowed to connect directly a serial terminal to the sensor in order to reconfigure some parameters and to obtain visual information about the status of the node. It was decided to provide this functionality using an external adapter to avoid incurring the cost of the component in each of the sensors manufactured.

Another important change is in the sensors. It is considered that the chosen temperature and relative humidity sensor described in deliverable D4.7 is appropriate, but we observed an erratic operation of the AMS manufacturer's light sensor. In addition, the manufacturer of this sensor announced that this model is not recommended for the new designs.

2.2. Mechanical changes

From an industrialisation point of view, the use of connectors and small electronic boards to contain the sensors, greatly increases the cost of the system due to the cost of the connectors themselves and the significant cost of additional manufacturing effort. Figure 2 shows the basic sensor node with the marked connectors to be removed.

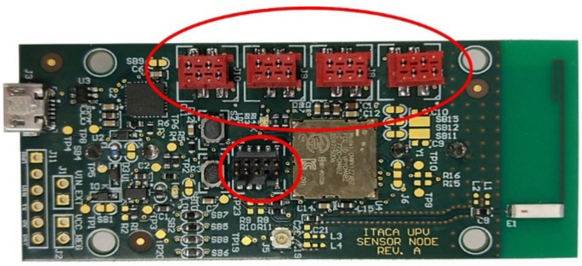


Figure 2. Internal electronic board of the basic sensor node with connectors to be eliminated marked

The eliminated connectors correspond to four sensor ports and the corresponding to the debugger port.

As mentioned in the previous sub-section, some of the sensors will be incorporated into the electronic board. For additional sensors (VOC, acceleration, etc.) a single connector is provided in one corner of the board.

The debug connector will be replaced by pads in the circuit able to accommodate a needle programmer thus eliminating the need of connector. Also, pushbuttons have been moved to the side of the board to simplify their access.

Figure 3 is a representation of the board being developed. We decided to maintain a relatively large size to accommodate the same battery used in the previous sensor node and to have a large enough ground plane to benefit from the performance of the new built-in antenna. The size of this board is 55 x 49 mm.

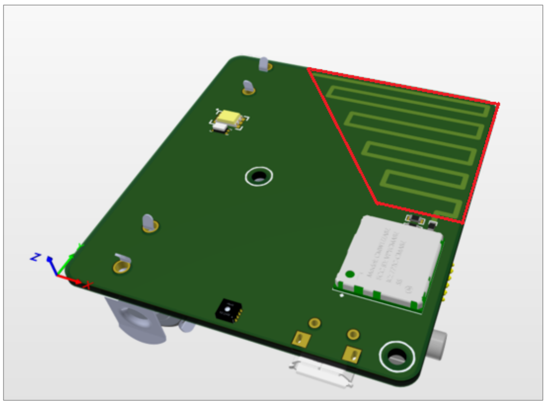


Figure 3. Render of the advanced sensor node prototype. Area reserved for the embedded antenna marked in red

2.3. Attachment method

The attachment system designed for the basic sensor node and intensively tested in the deployments of the Alava Fine Arts Museum and the Alava Arms Museum proved to work perfectly, so no changes are planned for this version.

We assume that the deployments in the rest of the museums and, especially, the exchange of objects for the transport demonstration of artworks will allow the improvement of the attachment system.

3. Development and improvement of the antenna

The basic sensor node antenna was designed around a ceramic chip antenna and with the recommendations of the antenna manufacturer. Figure 4 shows the aspect of the embedded antenna.

Figure 4. Embedded antenna of the basic sensor node

As tested and validated in the practical deployment described in D5.1, the wireless behaviour of the basic sensor node proved to be sufficient to cover complex buildings. However, the received signal is weak compared to the field test device (FTD) used for the radio mappings of the museums. It is important to note that the FTD uses a larger external dipole antenna, so higher signal values should be expected.

In any case, it is considered appropriate to maintain the original plans to use an optimised antenna for the "advanced" sensor node in order to increase the level of the radio signal, reducing the energy requirements.

Two approaches are being followed for the optimization of the antenna: specially designed embedded antenna and external commercial antenna.

3.1. Embedded antenna

The advanced sensor node is being developed with the addition of a full printed circuit board antenna. The objective is to optimize the radioelectric performance of the design and reduce the cost of the design. This task is very challenging and requires the expertise provided by Sigfox partner.

A typical feature of this type of antenna is the need for a suitable ground plane. Larger ground planes provide better functionality, in contrast, with a small ground plane, the efficiency of the antenna decreases, requiring more power to transmit, which is a critical aspect of the CollectionCare sensor node.

A smaller device is even harder to certify because is more prone to noise and to inefficient transmissions. A low performance of RF can difficult this certification, so we considered that the “advanced” sensor node is the right stage to deeply work on this aspect.

CollectionCare’s sensor node operates at frequencies below 1GHz, so ideally it needs ground plane lengths of 100 mm (at least a quarter of the wavelength) or more to obtain good performance. Taking into consideration this aspect, we focused the design of the “advanced” sensor node defining first the size of the printed circuit board (PCB) and the positioning of the antenna to get good performance and adequate radiation patterns. The initial design also includes the placement of problematic elements such as the battery. Figure 4 shows a rendering of the board where the up-right area is reserved for the antenna. The circuit will be placed in the housing in a way that reduces the effect of the wall or the object where the sensor will be attached.

Regarding the housing, not all materials behave in the same way, so we added a new restriction to the choice of housing to ensure that it is fair to the object and suitable from the point of view of wireless transmission.

It is considered that proceeding in this way, that is, defining the design of the antenna first, will increase the possibility of obtaining carrier approval for the device.

3.2. External antenna

Like the basic sensor node, the advanced sensor node will include a miniature Hirose U.FL connector to allow to plug an external antenna. It is expected that this design decision will allow dealing with the most complicated scenarios.

For this purpose, we selected two types of antennas: flexible printed circuit (FPC) antennas and terminal antennas.

Figure 5 is an example of FPC antenna. The FPC antennas can be fixed using adhesive inside the plastic housing of the sensor node. Depending on the requirements of the particular application, the positioning of the antenna can be changed in order to get the desired radiation pattern. The antenna needs to be able to radiate in six spatial direction, so it is important to keep three or four of these without obstructions of metal or electronic components.

Figure 5. FPC antenna for the ISM band

Figure 6 shows examples of antenna placement. The antenna needs a minimum distance from the electronic circuit to operate properly.

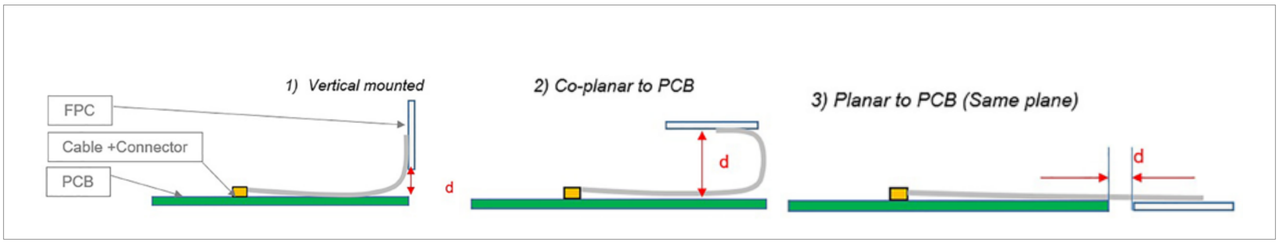


Figure 6. Examples of antenna mounting (source: Antenova Ltd.)

Tests have been carried out with the FPC antennas shown in Figure 7 The signal levels are significantly increased showing that it is a valuable option. In any case, no tests have been performed inside the housing because the objective is to test this on the "advanced" sensor node.

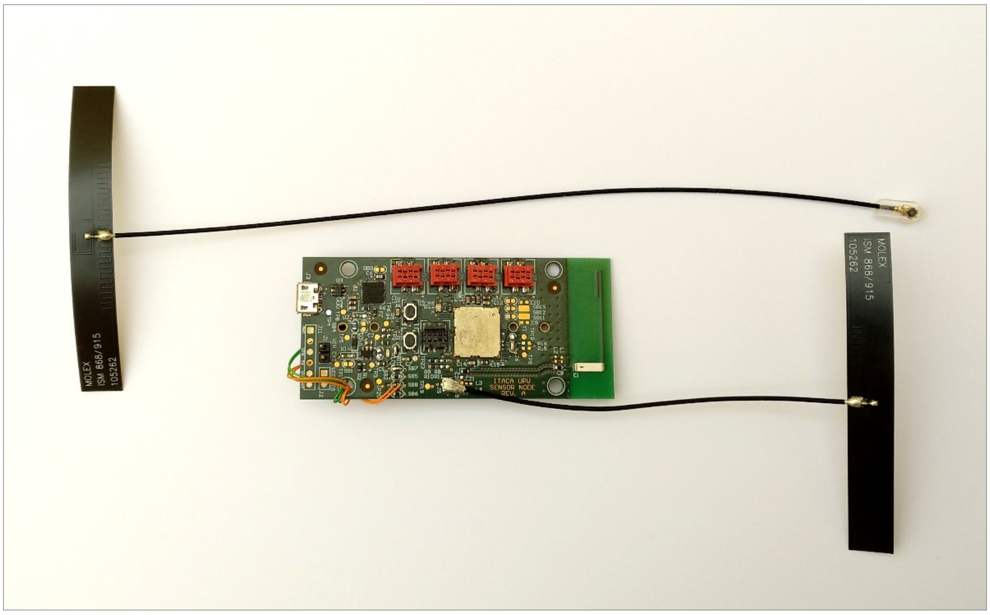


Figure 7. FPC attached to the ConnectionCare sensor node

For the most demanding environments we have decided to use terminal type antennas as shown in Figure 8. These antennas are mounted on the outside of the sensor node housing.

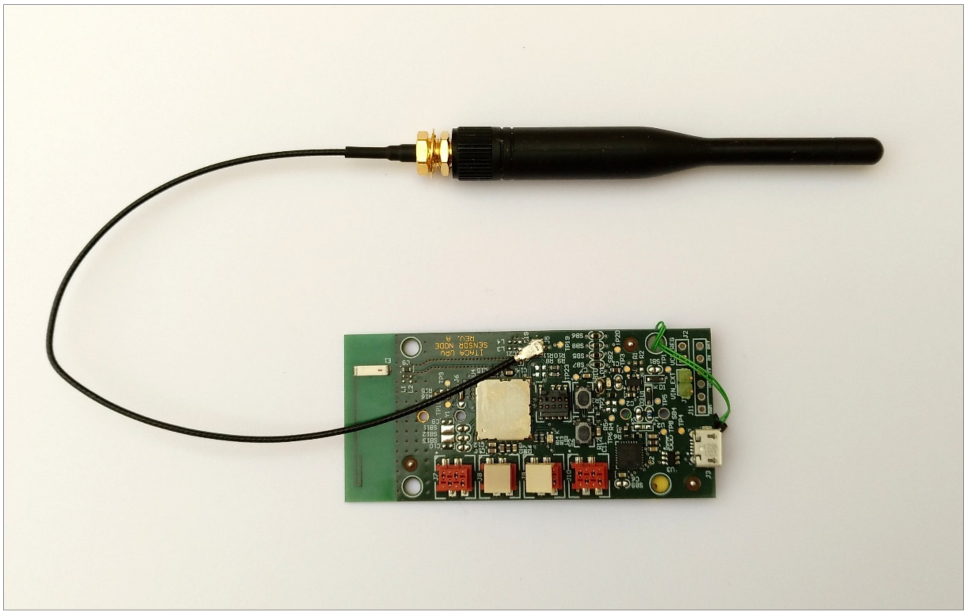


Figure 8. Terminal attached to the ConnectionCare sensor node

The tests with these antennas allow the greatest distances to be reached and very thick walls to be penetrated.

4. Air Pollution sensors

Gaseous pollutants and particulate matter are well recognized threats to the collections preserved in the museums, since they play an important role in the deterioration of works of art, sometimes even irreversibly. Therefore, the monitoring of gaseous pollutants and particulate matter provides a detailed characterization of their concentrations inside the museums leading to define measures for mitigating degradation and improving the conservation of preserved artworks.

There are several gaseous pollutants that may pose risks for museum collections. Some of them can be transported from outdoors inside the museums mainly in naturally ventilated rooms. Other pollutants can be indoor-generated due to museum activities, cleaning procedures and degradation of building materials or objects, or transported by visitors. The same considerations concern particulate matters, that can be originated from indoor sources as well as vehiculated by external air.

Deliverable 1.1 (D1.1) of the CollectionCare project reports the air pollutants threatening the conservation of artworks. Specifically, among gaseous air pollutants there are inorganic compounds, such as NO_X (nitrogen oxides), O_3 (ozone) and SO_2 (sulfur dioxide), and organic compounds, such as organic acids (acetic acid (CH_3COOH) and formic acid (HCOOH)), aldehydes and VOCs. The suspended fine particles PM2.5 is also included. However, CO_2 (carbon dioxide) is also taken into account in accordance with the ANNEX 1 (part B) of the Grant Agreement and because the measurement of CO_2 in museums can be used as a proxy parameter of the number of visitors who can affect the microclimate conditions inside the museum.

A survey on state-of-art of sensors for monitoring gas pollution and particulate matter in the air has been conducted taking into consideration the general technical features of the sensor performance as well as its price and energy consumption. The aim of the survey is to provide useful data on the candidate sensors for air pollution measurements. The screening results have allowed to identify a list of sensor candidates which can help the partner UPV to elect the air pollution sensor with desired features to be integrated into the CollectionCare advanced sensor node.

The search strategy on the state-of-the-art sensors commercially available for monitoring air pollution is described in detail in the next section and structured by using Flow Chart Prisma. Then, a list of suitable sensor candidates for monitoring both gaseous pollutants and particulate matters to integrate the advanced sensor node, is provided.

At the end, a table is provided for a comparison among the sensors' candidates in view of the most proper choice of the sensor to be incorporated in the advanced sensor node.

4.1 Search strategy to identify the sensor candidates

This section describes the main steps of the search strategy adopted to select commercially available sensors for monitoring air pollutants.

The following major issues are taken into account:

a. Dynamic range: the range of operation of the sensor between the least and greatest value of the concentration and hence providing the capability of detecting the minimum concentration of air pollutants as suggested in the current guidelines and reported in the most relevant publications on the topic.

b. API and interface: sensors have to be equipped with general-purpose interfaces in order to be easily integrated to the advanced sensor node.

c. Low power supply and low unity cost: the advanced sensor node should be a trade-off between the energy requirements consumption to preserve batteries and the cost of the sensor itself to be affordable by small-medium size museums.

The web search on sensors for air pollutants was performed using the Google platform.

The following terms were used as the key criterion of the search to identify the commercially available sensors. The main keywords used also in the combinations:

- sensors for indoor air pollution monitoring;
- sensors for airborne aerosols monitoring;
- sensors for gaseous pollutants
- sensors for particulate matter (PM);
- air pollution and PM Low-Cost sensors;
- microsensors.

The search steps of the survey for identifying the sensor candidates are outlined in Figure 9 by PRISMA Flow Chart (Liberati et al., 2009).

The first step of the web search, based only on the keyword "sensors for indoor air pollution monitoring", produced a long list of sensors. An additional focussed search matching the other above-mentioned keywords, led to scrutinize and identify the devices described in this document. The starting point of the selection was targeted to all those sensors that have the dynamic range covering the concentrations that can be detected in museums and as suggested by guidelines.

Afterward, the search was limited to the sensors with the low commercial unity cost and low power supply. We extracted the features of the sensors from the datasheets provided by the sensor manufactures and where information was missing or incomplete, we contacted the manufacturer to request information on the product. Moreover, all those sensors that have general-purpose interfacing systems were included for the eligibility.

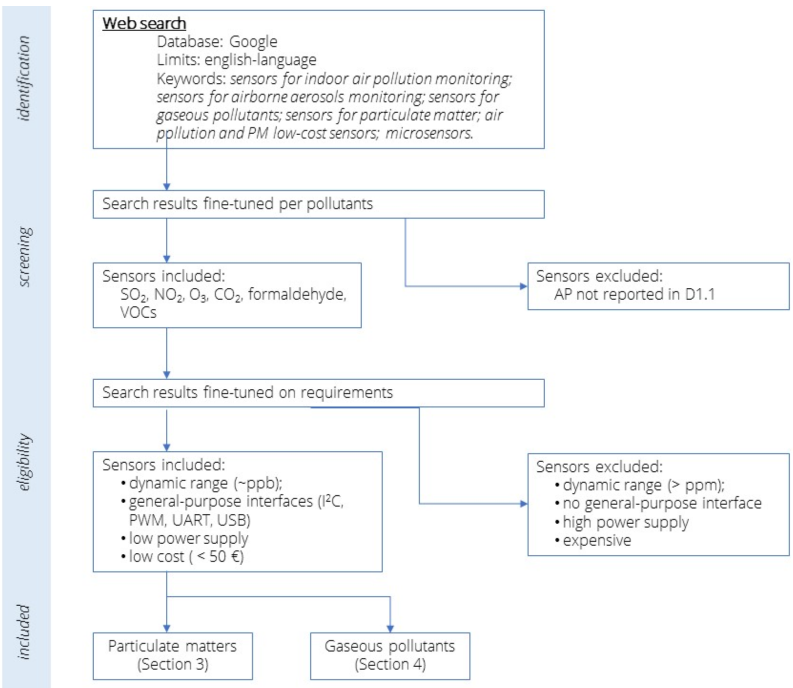


Figure 9. PRISMA Flow Chart of search strategy for the sensor candidates

4.2 Air pollutant sensors

The search has identified the following manufacturers of sensors:

- Measuring particulate matter with the desired features:
  - Honeywell (https://sensing.honeywell.com/sensors, USA);
  - Nova Fitness Co. Ltd (http://inovafitness.com/en/a/index.html, China);
  - Plantower (http://www.plantower.com/en/, China);
  - Sensirion (https://www.sensirion.com/en/, Switzerland);
  - Winsen(https://www.winsen-sensor.com/, China).
- Measuring gaseous pollutants with the desired features:
  - Amphenol (https://www.amphenol-sensors.com/, USA);
  - AlphaSense (http://www.alphasense.com, UK);
  - Cairpol(http://cairpol.com/en/, France);
  - Homotix (https://www.homotix.it/, Italy);
  - IonScience (https://www.ionscience.com/ , UK);
  - Plantower (http://www.plantower.com/en/, China);
  - Renesas (https://www.renesas.com/eu/en/, Japan);
  - Sensirion (https://www.sensirion.com/en/, Switzerland);
  - Spec (https://www.spec-sensors.com/, USA).

4.2.1 Sensors for measuring particulate matter

The suitable candidates of low-cost sensors for particulate matters are summarized in Table 1 in terms of their technical and operating features in order to allow a comparison among the sensors' candidates in view of the most proper choice of the sensor to be incorporated in the advanced sensor node. In the last column of the table, a list of the latest peer reviewed papers (source SCOPUS), where sensors are used in research and real-life activities, are acknowledged.

Table 1. Summary of the technical features of the sensors for particulate matter

Sensor model Fine PM	Resolution (μg/m^3)	Dynamic Range (μg/m^3)	Power Supply (V)	Interface	Size (mm x mm x mm)	Unity Cost (€)	References
Honeywell HPMA115S0-XXX	1	0-1000	3-7	UART	43x 36 x 23.7	30-45	Giusto et al., 2018 Hapidin et al, 2019 Báthory et al., 2019 Omidvarborna et al., 2020
NOVA Fitness SDS011	0.3	0.0-999.9	4.7-5.3	UART	71 x 70 x 23	26-32	Badura et al., 2018a Badura et al., 2018b Kuula et al.,2019

Plantower PMS5003	1	≥1000	4.5-5.5	UART & PWM	50 x 38 x 21	20-25	Bulot et al., 2019 Feenstra et al., 2019 He et al., 2020 Magi et al., 2019 Malings et al., 2019 Sayahi et al, 2019
Sensirion SPS30	1	0.0-999.9	4.5-5.5	UART8 and I^2C	41 x 41 x 12	30-45	Kuula et al.,2019
Wisen ZH03A	1	≥1000	4.5-5.5	UART	50 x 32.4 x 21	20-25	Badura et al., 2018a Badura et al., 2018b

The comparison among the technical characteristics of particulate sensors Table 1 and the technical-scientific evaluations extracted from peer reviewed papers lead to suggest that, the two best candidates for monitoring particulate matter satisfying most of desired requirements are: **Nova Fitness SDS011** and **Sensirion SPS30**.

4.2.2 Sensors for measuring gaseous pollutants

The suitable candidates for gaseous pollutants are reported in Table 2 in terms of their technical and operating features in order to allow a comparison among the sensors' candidates in view of the most proper choice of the sensor to be incorporated in the advanced sensor node. In the last column of the table, a list of the latest peer reviewed papers (source SCOPUS), where sensors are used in research and real-life activities, are acknowledged. Table 2 also includes sensors at high resolution (~ ppb) that will be used in laboratory tests to evaluate the performance of corresponding low-cost sensors.

The election of sensors for gaseous pollutants was made after the consultation with WP2 partners.

Table 2. Summary of the technical features of the sensors for gaseous pollutants

	Pollutant	Sensor model	Resolution	Dynamic Range	Power Supply (V)	Interface	Size (mm x mm x mm)	Unit Cost (€)	References
Inorganic compounds	CO_2	Amphenol Telaire T6613	NA	0-2000 ppm	5	UART @ 19200 Baud, I2C slave up to 100 kHz	57.15 x 34.67x 15.24	30-45	None
	CO_2	Plantower DS-CO_2-20	1 ppm	400-5000 ppm	4.5-5.5	UART & PWM	30 x 20 x 10	20-25	Masic et al., 2019
	NO_2	Spec 3SP_NO_2_5 F	< 20 ppb	0-5 ppm	10 to 50 µW **	UART	20 x 20 x 4	18-20	None

	NO_2	Cairpol Cairnsens NO_2	20 ppb	0-250 ppb	5	USB, UART	32* x 62	20	Bauerová et al., 2018 Bauerová et al., 2020
	NO_2	AlphaSense NO2-A43F ***	5 ppb	0-200 ppb	5	-	20 * x 20	50	deSouza et al., 2017
	O_3/ NO_2	Cairpol Cairnsens O_3/NO_2	20 ppb	0-250 ppb	5	USB, UART	32 * x 62	20	Bauerová et al., 2018 Bauerová et al., 2020
	O_3/ NO_2	RENESAS ZMOD4510	NA	20-500 ppb	21 mW**	I2C interface: up to 400kHz	3.0 x 3 x 0.7	8-10	None
	SO_2	Spec 3SP_SO_2_20	< 20 ppb	0-20 ppm	10-50 μW**	UART	20 x 20 x 4	18-20	De Fazio et al., 2020
	SO_2	Cairpol Cairnsens SO_2	50 ppb	0-1000 ppb	5 V	USB, UART	32* x 62	20	Bauerová et al., 2018 Bauerová et al., 2020
Organic compounds	Formaldehyde	HOMOTIX	≤0.01ppm	0-5 ppm	3.7 - 9	UART	2.7 x 4.0 x 1.1	20-30	None
	VOCs eCO2	HOMOTIX CCS811	NA	0 to 1187 ppb 400 to 8192 ppm	0.034-46 mW**	I2C	2.7x 4.0 x 1.1	20	None
	VOCs	RENESAS SGAS707	NA	0-100 ppm	400 mW**	I2C and UART	3x 3 x 0.7	10	None
	VOCs	Sensirion SGPC3	1 ppb @ 0 - $2x10^3$ ppb 6 ppb @ $2x10^3$- 11 x 10^4 ppb 32 ppb @ $11x10^4$ - $60x10^4$ ppb	0-60 x 10^4 ppb	1.9	I2C	2.45 x 2.45 x 0.9	10-15	None

VOCs	IonScience MiniPID 2 HS ***	0.5 ppb	0 - 3 ppm	5	Modbus	20* x 21	550	None

*diameter, ** power consumption, *** sensors at higher resolution to be used to evaluate the performance of corresponding low-cost sensors

4.3 Choice of air pollutants and the sensors

The final selection of proper sensors to measure the air pollutants in the museums was performed after the consultation with WP2 partners.

It was agreed to focus for the monitoring only on gaseous pollutants and not on particulate matter, since they will not be included in the degradation models. Specifically, among gaseous pollutants, the following pollutants were selected as the most critical AP to be monitored in relation to metal objects: acetic acid (CH_3COOH) and nitrogen dioxide (NO_2). In particular, UW will include these two pollutants in their degradation model and related experiments. Concerning paper objects, SO_2 and NO_x appear to be relevant air pollutants. However, as SO_2 is difficult to be monitored in an indoor environment since it is present in low concentrations it will not be included. In case of wood as well as for canvas paintings pollutants are not critical.

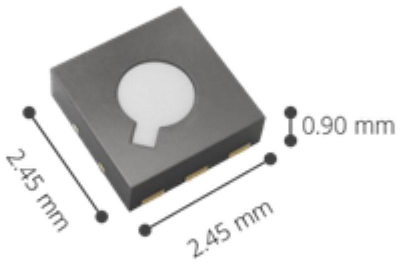
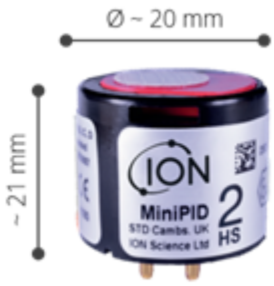
In conclusion, two air pollutants were recommended by WP2:

- acetic acid (CH_3COOH)
- nitrogen dioxide (NO_2).

Therefore, the sensing unit chosen for the monitoring of acetic acid (CH_3COOH) implementing the CollectionCare basic sensor node (advanced sensor node) is the **SGPC3** distributed by **Sensirion**. This choice comes out from its technical features – i.e. good resolution and dynamic range in accordance with the concentration typically detected in museum environment, general-purpose interface – and its potential widespread use (low-cost) in the gas detection inside museums.

The MiniPID 2 HS, distributed by IonScience, has better features in terms of the resolution and the dynamic range, however it is not as economical as SGPC3. Consequently, this sensor will be employed as an additional sensor only for testing systematically the performance of SGPC3 by the URO1 team in the framework of the project.

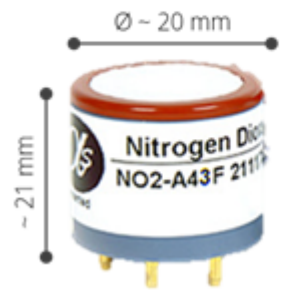
Table 3. Pictures of the sensing units for CH3COOH detection: SGCP3 to be implemented in the advanced sensor node and MiniPID 2 HS for testing systematically the performance of SGPC3

SGPC3 – Sensirion	MiniPID 2 HS – IonScience
	

Therefore, the sensing unit chosen for the monitoring of nitrogen dioxide (NO_2) implementing the CollectionCare basic sensor node (advanced sensor node) is the **3SP_NO2 _5F NO_2** distributed by **Spec Sensor**. This choice comes out from its technical features – i.e. good resolution and dynamic range in accordance with the concentration typically detected in museum environment, general-purpose interface – and its potential widespread use (low-cost) in the gas detection inside museums.

The NO_2 A43F, distributed by AlphaSense, has better features in terms of the resolution and the dynamic range, however it is not as economical as SGPC3. Consequently, this sensor will be employed as an additional sensor only for testing systematically the performance of 3SP_NO2 _5F NO_2 by the URO1 team in the framework of the project.

Tabla 4. Pictures of the sensing units for NO2 detection: 3SP_NO2 _5F NO2 to be implemented in the advanced sensor node and NO2 A43F for testing systematically the performance of 3SP_NO2 _5F NO2

3SP_NO2 _5F NO_2 – Spec Sensor	NO_2 A43F – AlphaSense
	

The evaluation of the performance of the elected sensors has recently started and is still under study in order to be included in the CollectionCare advanced sensor.

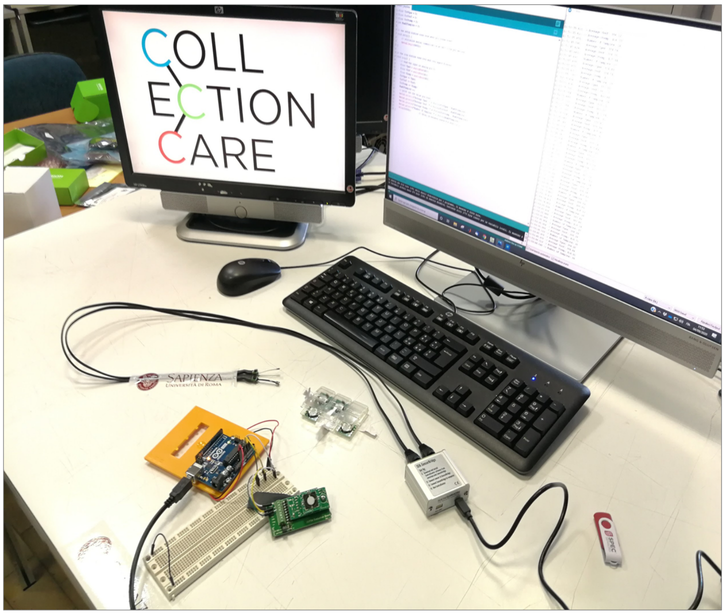


Figure 10. Preliminary experimental tests with the elected sensors for gas detection conducted in the laboratory of the URO1 team

5. Characterization of motion parameters

According to Task 4.4 of WP4, the CollectionCare advanced sensor should include the ability to monitor vibrations that may occur during the transport of artworks between cultural institutions for loans. This vibration monitoring must be present at the different stages through which the object passes during its institutional exchange from handling, packing, loading, exchange of means of transport (e.g. from truck to plane) to unpacking. During these situations, the object may experience different vibrations and impacts.

This section is dedicated to an initial analysis and practical tests to address the problem of vibration and shock monitoring. Monitoring vibrations during the transport stages of cultural objects is a preventive conservation action that will make it possible to detect in real time when they occur, in order to take measures to prevent them from continuing and thus ensure better conditions during the transport of these objects.

Apart from temperature (T) and relative humidity (RH), the "advanced" sensor nodes are expected to be able to measure acceleration parameters and transmit these data, continuously and in real time, to a receiving device which will be located in the transport driver's cabin. Ideally, the set-up should be capable of monitoring all stages of the artworks exchange, including the very critical ones such as handling, packing and loading of the object.

For this preliminary proposal, we start with a wireless communication from the sensor nodes to the device in the driver's cabin using the LoRaWAN technology currently implemented in the sensor nodes. Sigfox is not a feasible option in this case. It must be taken into account that the use of LoRaWAN will only allow us to validate the connectivity between both, the sensor node and the device in the driver's cabin, but it could be inadequate for this type of problem. The aim is to check whether the underlying LoRa radio is suitable or not in this type of scenario.

As a restriction, real-time connection to the CollectionCare cloud infrastructure is not considered because it is unrealistic in many situations during a transport due to the lack of continuous network connectivity. For this reason, this should be considered a design feature of the proposal.

5.1 Desired characteristics

5.1.1 Physical parameters to be measured

During the transport of cultural objects, various phenomena can occur that could affect their conservation status, mainly changes in temperature, and relative humidity, as well as impacts and vibrations.

All these degradation agents can be controlled in different ways in order to protect and avoid damage to these cultural artefacts. Assuming that temperature and relative humidity have been adequately covered, it is essential to protect cultural objects from shocks and vibrations by adapting the packaging systems to the object itself as these affect each artefact differently.

Several bibliographic sources have been analyzed to check the main characteristics that affect the cultural objects during their transport. In particular, how vibrations affect different types of cultural objects.

The departure point has been the reference "Art in Transit": Studies in the transport of paintings" of Marion Mecklenburg (1991). For example, this document states that for vibration to cause damage to a canvas painting there must be three factors: the painting must have a natural frequency in the range of frequencies produced by the transport vehicle, the vibration of the transport vehicle must contain frequencies that cause resonance in the painting and the magnitude of the resulting vibration must be high enough to cause damage.

Canvas paintings under normal stress have their lowest natural frequency in the range of 1-50 Hz, depending on their size. This is in the range of frequencies that appear in transport with trucks and trains, 1-100 Hz and 1-500 Hz respectively. However, frequency vibrations of 1 to 50 Hz of sufficient magnitude to damage the artworks do not normally occur.

In Lasyk (2008), laser distance measurements are used to monitor canvas deformation during transportation. It is checked the effect of the sizes of the canvas, the type of packaging (e.g fixed in a wooden case or wrapped in tissue and packed into cardboard boxes) and the importance of the manipulation and orientation of the artworks as indicated by other authors such as Saunders (2005).

As discussed in the literature, each type of object has a different resonance frequency, e.g. board paintings are sensitive to much higher frequencies, which can be attenuated by the damping systems used in the packaging.

In Thickett 2002, the shock/vibration levels causing damage to cultural objects inside the museums were analyzed. They carried out an extensive programmed of vibration measurements in the British Museum during the construction of the Grand Court. During this construction works the levels measured that caused damage, expressed as acceleration, were between 0.2 and 0.6 g. This indicates that it is not necessary to have large vibration magnitudes to cause damage to the cultural artefacts.

Another interesting source in this regard is the work of Kamba et al (2008), which presents the record of acceleration of different overseas transport. The approach of the measurement and data analysis carried out by these authors is an excellent reference. The measurement of maximum acceleration, root mean square acceleration and applied power spectral density can be used as a reference to estimate the required computing power of the sensor node to analyse the collected information.

All the authors stress the need to carefully analyze the conditions of handling and transportation of the cultural objects at all stages, e.g. from the time a painting is removed from the wall to the time it is exhibited at the receiving institution. All these stages should be considered in our approach.

The effect of these shocks/vibrations on the object depends, on the one hand, on the magnitude and frequency of the resulting force applied, while, on the other hand, it depends on the material characteristics of the object, such as rigidity and mass. When strains exceed a certain critical level, characteristic of the object, mechanical damage occurs. It is also important to note that the effect of vibrations and shocks are considered to be cumulative.

Based on this preliminary review of the literature, it is determined that it is necessary to measure frequencies in the range of 1 to 500 Hz and be able to detect accelerations of ±1g in any axis as a first proof of concept.

5.1.2 Sensor node lifespan

The sensor node lifespan is probably the most critical aspect of development. Although the device is not located in a place that is difficult to access, as it is integrated into the packaging system of the objects, it is expected that the device will not require continuous recharging and will allow a complete transport cycle to be completed.

Therefore, it was decided to propose an autonomy of one-month transport cycle. This objective will greatly limit the design options in three aspects: the sensor energy requirements, the wireless transmission rate and the data processing capacity of the on-site sensor node. The right balance between these three aspects will need to be found in order to obtain a realistic solution with the technology available today.

Approaches such as the one used by Kamba et al (2008), where data are only collected at certain intervals, may be the only feasible approach with the technology available today.

5.1.3. Wireless transmission

The device must be capable of transmitting data in real time by wireless means. The transmitting device shall be located in the packaging system of the cultural objects, while the receiver shall be located in the driver's cabin. Under these conditions it has been established that the protocols and technologies to be used must allow transmission over distances of more than 10 meters, taking into account the attenuations produced by the bodywork of the transport vehicle.

The real-time requirements in this case should be considered to be of a soft type in order to apply the right balance between the instantaneous analysis time and the warning information provided to users. For example, we consider that it is acceptable to report shocks caused by bumps in the road after a few seconds.

5.2Prototype proposal

In order to approach the needs described in the previous section, a first prototype with the needs for the advanced sensor has been built. The main objectives of this proposal are to evaluate the reachability of the wireless signal inside a metallic vehicle and to integrate a suitable sensor able to measure the required shock/vibration magnitudes.

5.2.1. Sensor selection

Based on the characteristics of the signal to be measured, a sensor with triaxial accelerometer functionality was selected.

It was decided to select from StMicroelectronics' wide range of micro-electromechanical systems sensors (MEMS). The considered models were: LIS2DH, IIS2DH, LSM6DOSX and IIS2DLPC. The key parameters of these sensors are summarised in Table 5.

Table 5. Comparison of selected MEMS acceleration sensors

Reference	LIS2DH	IIS2DH	LSM6DOSX	IIS2DLPC
Type of sensor	Triaxial accelerometer	Triaxial accelerometer	Triaxial accelerometer & gyroscope	Triaxial accelerometer
Measurement range	±2/±4/±8/±16	±2/±4/±8/±16	±2/±4/±8/±16	±2/±4/±8/±16
Low consumption mode @50Hz	6 µA	6 µA	26 µA	3.5 µA
High performance mode consumption @50Hz	11 µA	11 µA	170 µA*	120 µA
Power down mode consumption @50Hz	0.5 µA	0.5 µA	3 µA	50 µA
Sensitivity in low power mode @±2g	16 mg/digit	15,67 mg/digit	0,061 mg/digit	0,244 mg/digit

Sensitivity in high power mode @±2g	1 mg/digit	0,98 mg/digit	0,061 mg/digit	0,244 mg/digit
10-years commitment	No	Yes	No	Yes

* 0,55 mA using the gyroscope

As shown in Table 5, both the IIS2 and LIS2 families from StMicroelectronics are lower power devices, being the series LSM6DOSX less power efficient. Taking into consideration that energy is a key aspect of the design, it was decided to discard this series despite the inclusion of a gyroscope that could be interesting in some applications.

Moreover, the IIS2 series is part of the "10-year commitment", meaning that the availability of this sensor is maintained during this period, which guarantees the investment effort for a long time. We have experienced this problem in the choice of the visible light and UV sensors for the basic sensor node, so it is hoped that this choice will minimise this problem.

Finally, the IIS2DLPC sensor has a better sensitivity than the IIS2DH. In addition, it has a lower power consumption in low power and off modes. On the other hand, the IIS2DLPC has a higher power consumption in the high-resolution mode at low frequencies, but lower at high frequencies, 120 µA constant between 12.5 and 1600 Hz compared to 4 µA at 10 Hz up to 185 µA at 1344 Hz for the IIS2DH. The IIS2DLPC also has a low noise function. Therefore, the IIS2DLPC sensor will be selected which also includes many operating modes.

5.2.2. Sensor node prototype

The sensor node prototype has been developed using the first prototype of the basic sensor node and the addition of extra modules such as the II2DLPC sensor. This prototype follows the same approach as those tested at the Museo delle Origine in Rome (Italy) and the Museu d'Informàtica in Valencia (Spain), enabling the exploration of its performance prior to the definitive development of an electronic design such as the ones deployed at the Álava Fine Arts Museum and Álava Arms in Álava, Spain.

Figure 11 shows the evaluation module of the II2DLPC sensor and its placement on top of the basic node prototype.

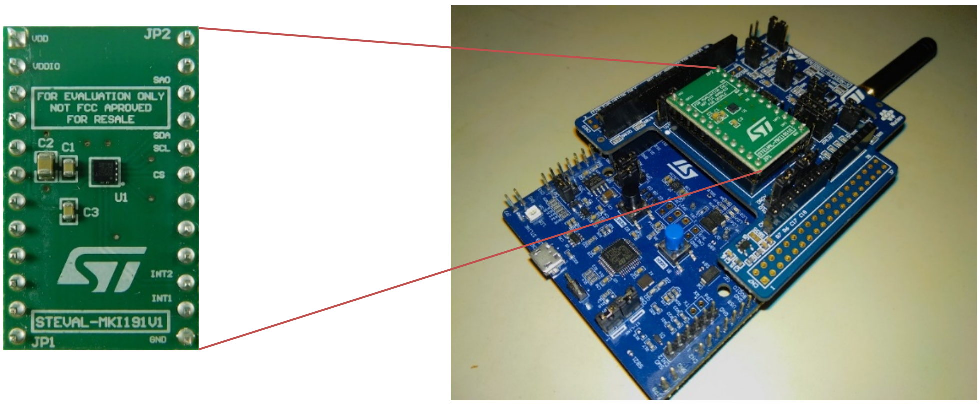


Figure 11. Evaluation module of the II2DLPC sensor (left) and module fitted on top of the basic sensor node prototype

5.2.3. Device in the vehicle's driver's cabin

A proof-of-concept device has been developed for the cabin to collect and analyse the data transmitted by the sensor nodes.

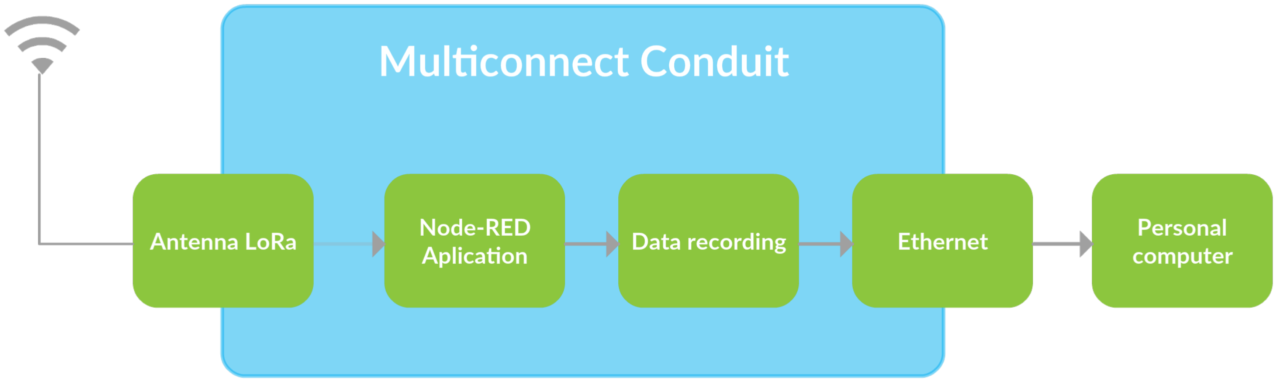


Figure 12. Diagram of the in-cabin device developed as a proof-of-concept

For the LoRaWAN gateway we adapted a Multitech's Conduit AEP 247A-868-EU-GB that includes the possibility of incorporating applications. Figure 13 shows the aspect of the gateway plugged to an external rechargeable battery to avoid the dependence of the irregularities of power provided by the vehicle.

Figure 13. Multitech's Conduit AEP modified LoRaWAN gateway used to test the proposal

A simple Node-RED application shown in Figure 14 has been developed in the gateway to decode the received payload of the sensor nodes and store it internally and transmit it to a link.

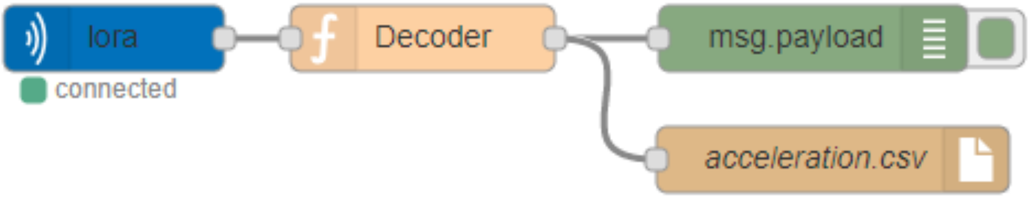
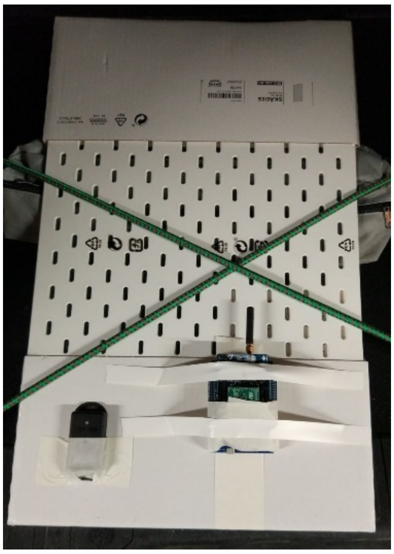


Figure 14. Node-RED application developed for the gateway

5.3 Test results

5.3.1 Set-up

To test the operation of the system, a piece of wood was used to imitate a canvas box and a Yost Labs 3-Space data Logger and the sensor node were attached to it. The set was loaded onto a Peugeot Partner van as shown in Figure 15 and a small route was taken around the University. The modified gateway, battery and personal computer laptop was installed in the driver's cabin as shown in Figure 15.



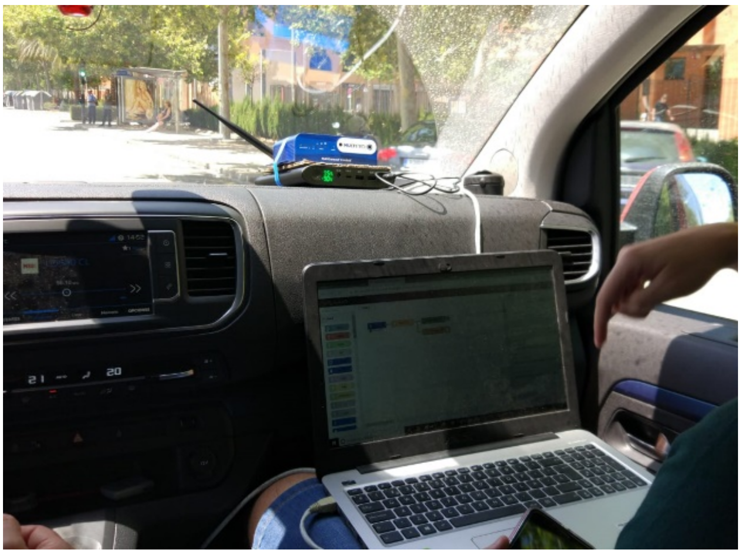


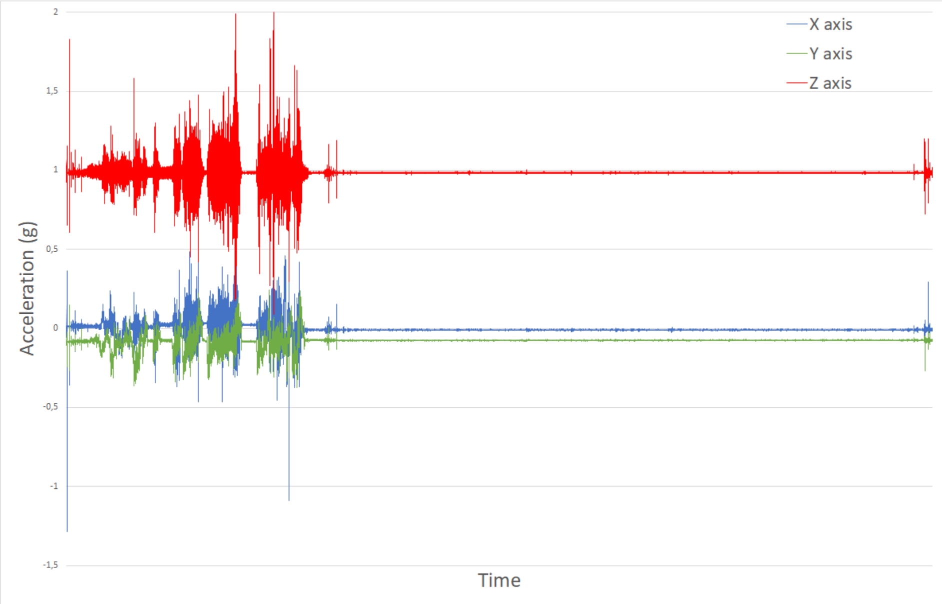
Figure 15. (left) Test piece with datalogger and sensor node attached and boarded in a van. (right) Gateway and laptop installed in the driver's cabin to receive sensor data

5.3.2. Acceleration measurement

It was not feasible to transfer the raw data collected by the sensor node using the LoraWAN-based collection due to the fact that the portal does not allow for more than one transmission per minute. This is reasonable considering the European radio frequency regulations. It was decided to send average values every minute to test the wireless connectivity.

To collect the raw data obtained by the sensor we enable a wired serial link and connect it to another laptop in the van's storage area. Figure 15 shows examples of the trip.

It was found that the magnitude of the vibrations was less than 1g according to the results.



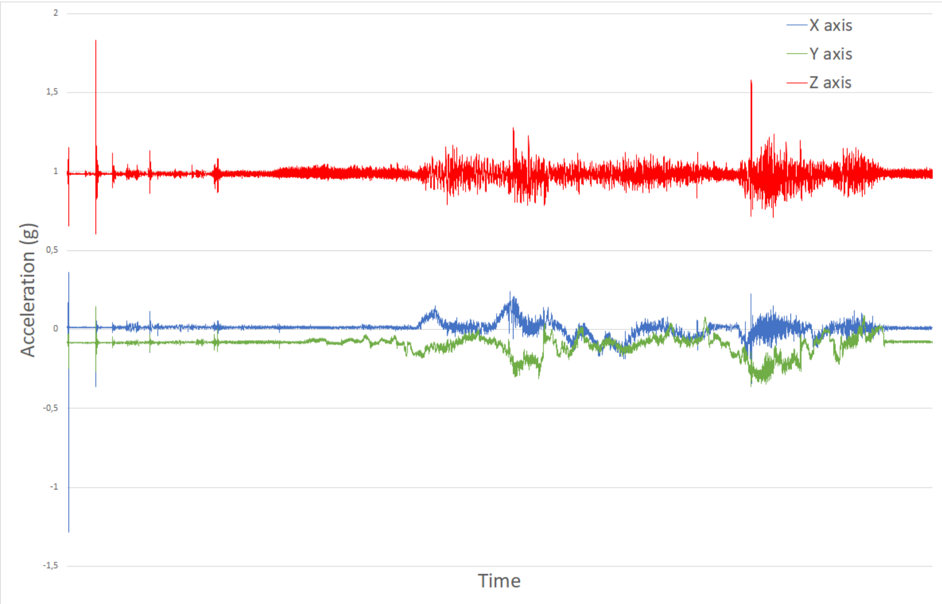


Figure 16. Measurements obtained during the route using the sensor node and a wired serial connection

The measurements were consistent with the ones obtained with the datalogger, proving the correct operation of the sensor node.

5.3.3. RF coverage

The main aspect to be tested was the wireless coverage of the proposal. Inside the vehicle, the level of signal was around -30 dBm. This is a very high signal level indicating that the radio technology is adequate in this sense.

To check the practical distance, we moved the receiver outside the cabin and kept the simulated artwork inside the vehicle. In this particular case, a distance of more than 300 meters away from the van was reached. Figure 17 shows the van and the reached distance.

Figure 17. Achieved communications distance between the artwork monitored inside the van and the receiver placed outside

5.3 Conclusions

An acceleration sensor has been selected and integrated into the CollectionCare sensor node. It has been verified that the measurements are being collected correctly and that the wireless technology applied is capable of dealing with the problems of metal vehicles.

It has been confirmed that the radio technology used is incapable of transferring raw acceleration data in real time, and it is necessary to process it within the sensor node and send the syntheses of this data. It is expected that this data processing will consist in the execution of energy-intensive algorithms, such as Rapid Fourier Transformations. This type of algorithms are sometimes incompatible with the requisite of a low power device, so an appropriate balance between energy and the amount of data analysed must be applied.

6. Energy optimization

The deployments carried out in the DFA museums, for the validation of the "basic" sensor node, allowed us to evaluate the power requirements of the specific version of this sensor node and the firmware used.

As stated in deliverable D5.1, we achieved an estimated life-span of 7 to 8 years for the following operational parameters:

- LoRaWAN mode for wireless communications.
- Spreading factor 12, bandwidth of 125 kbps and output power of -14 dBm for LoRa radio.
- One transmission of data per hour.
- One sample per hour of temperature (T) and humidity (H).
- One sample per hour for light (L) and ultraviolet radiation (UV).
- Battery voltage of 3.6 volts.

A Saft LS14500 primary cell was used for the deployment. This is a Lithium thionyl-based cell with very high density of energy and very low self-discharge, being ideal for this type of application. Saft LS14500 has a nominal voltage of 3.6 V and a nominal energy of 9.36 Wh.

Based on these operational parameters and the used battery, we provided an estimate of daily energy requirements. In deliverable D5.1 was provided the Figure 18 that summarizes these requirements depending on each state of the sensor node.

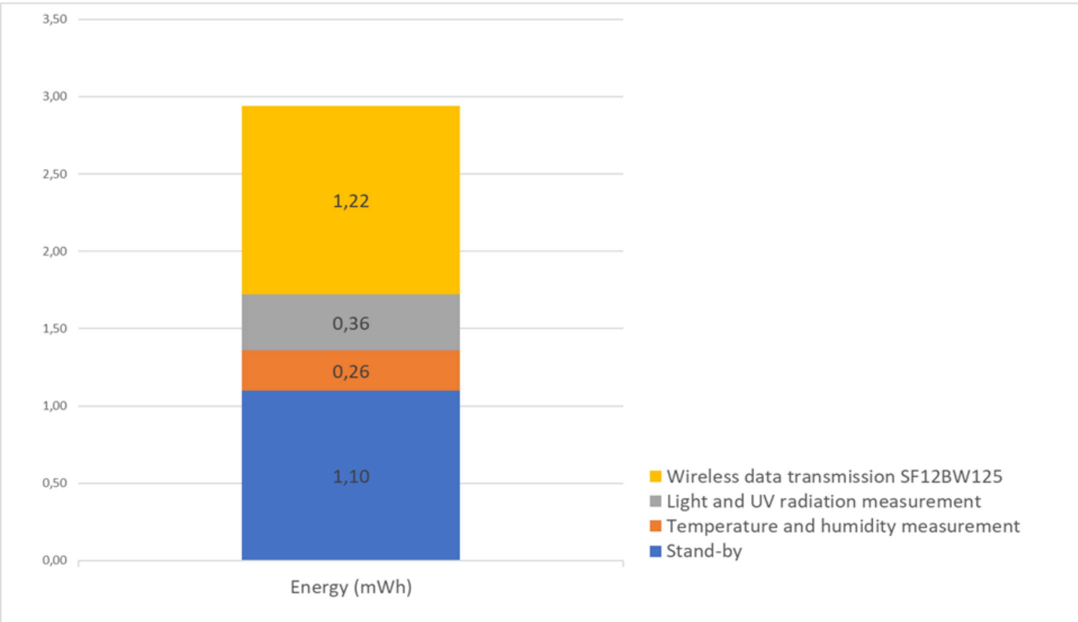


Figure 18. Estimated daily energy requirements of the sensor nodes installed in the DFA's museums

These measurements show that near 80% of the energy is invested in the stand-by state and the wireless data transmission state. These two aspects should be the focus to increase the battery life of the node.

In order to analyse the energy behaviour of the sensor node, we instrumented the basic sensor node and used a Qoitech Otii power analyzer. Figure 19 shows the aspect of the instrument connected to the basic sensor node.

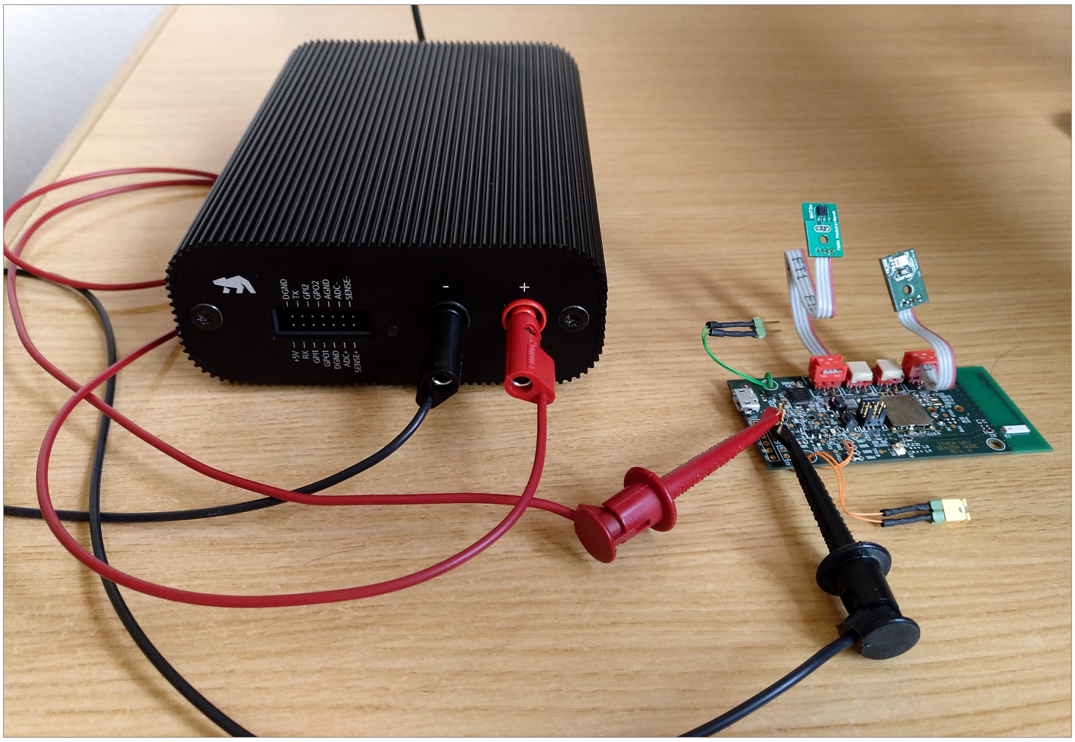


Figure 19. Qoitech Otii power analyzer connected to the basic sensor node

Figure 20 shows an example of an energy profile using the Otii device. This corresponds to the activation of sensors and wireless data transmission. The first half corresponds to the activation and usage of the sensors, the 29 mA peak corresponds to data transmission and the two 12 mA peaks correspond to two reception windows.

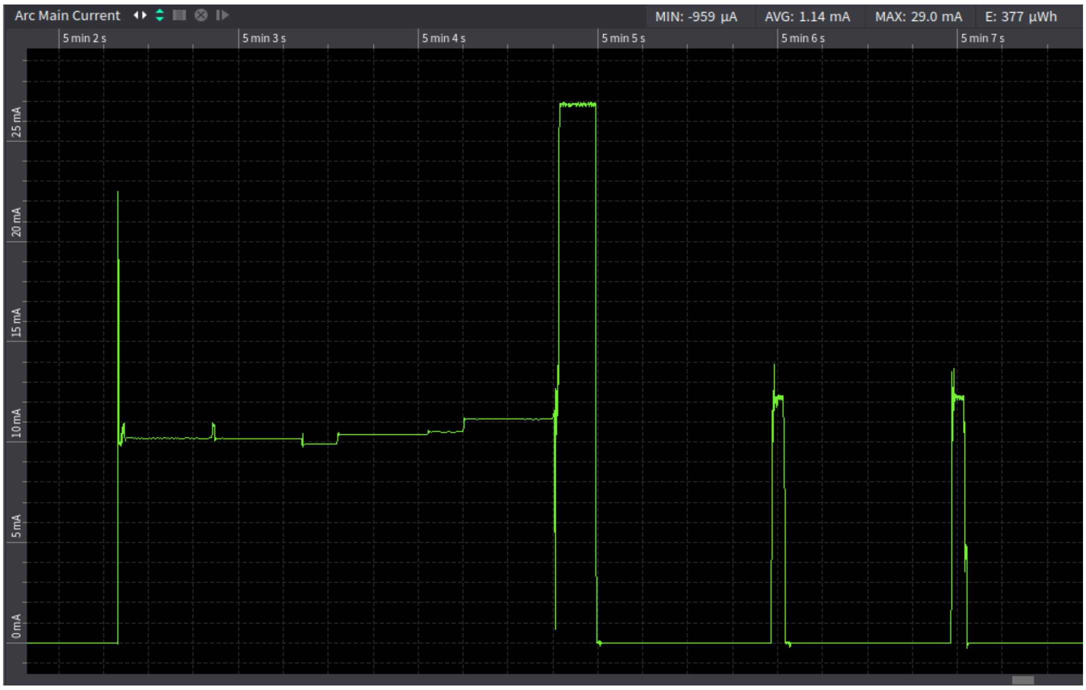


Figure 20. Measured sensing cycle and wireless data transmission of the ColecctionCare's sensor node

We first worked the stand-by current for the advanced sensor node. The electronic design of the "basic" sensor node was improved and changes in the peripheral management were added to allow complete power cut capability. As a result of these changes, stand-by current has been reduced now below 4 μA.

The other factor that implies a huge amount of energy is data transmission. In the particular case of the DFA's museum deployments, we decided to apply maximum transmission power and the highest spreading factor of SF12. This configuration allows maximum distance at the expenses 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 it every two hours, but we decided to keep the same configuration used in the DFA's museum deployment and optimize 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 signal received by the gateway. ADR, among others, adjusts the spreading factor and the data rate, being able to reduce the time required for each transmission. This enhancement has been already applied to DFA's deployment.

A spreading factor of SF8 has been found realistic in most scenarios and it has been measured. The amount of energy required for this type of transmission is 8.0 μWh. Figure 21 corresponds to the capture of energy requirements for such types of cycles of data transmission.

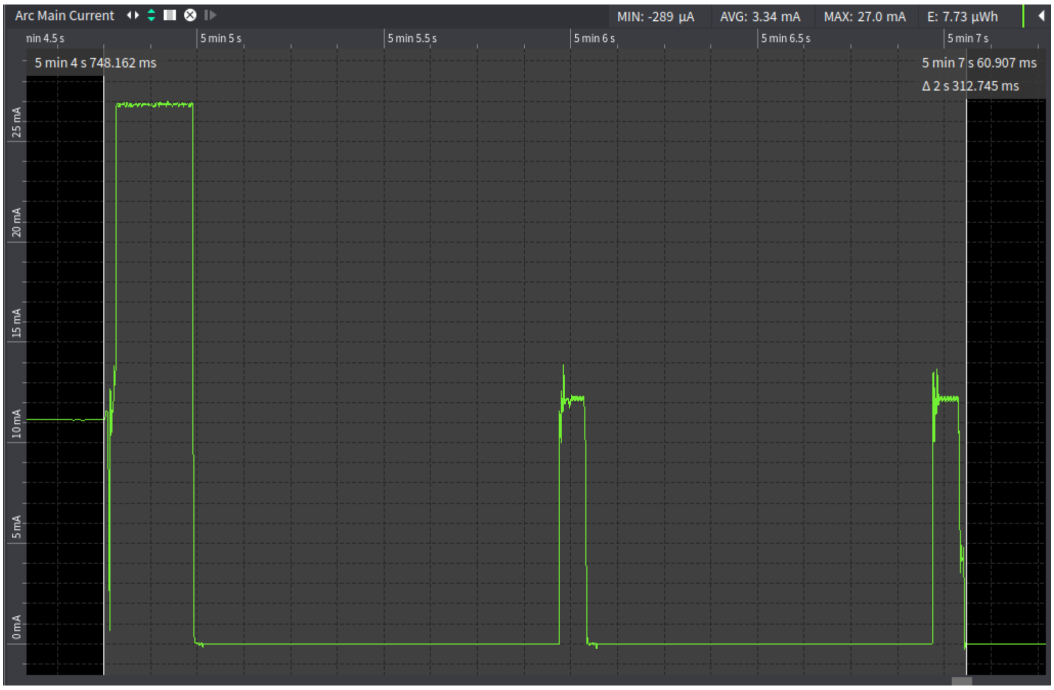


Figure 21. Measured wireless data transmission of the ColecctionCare's sensor node for SF8

Given these enhancements, the Figure 22 compares the amount of energy between the "basic" sensor node and the "advanced" one for a day cycle. Less than a half of energy is required using these enhancements.

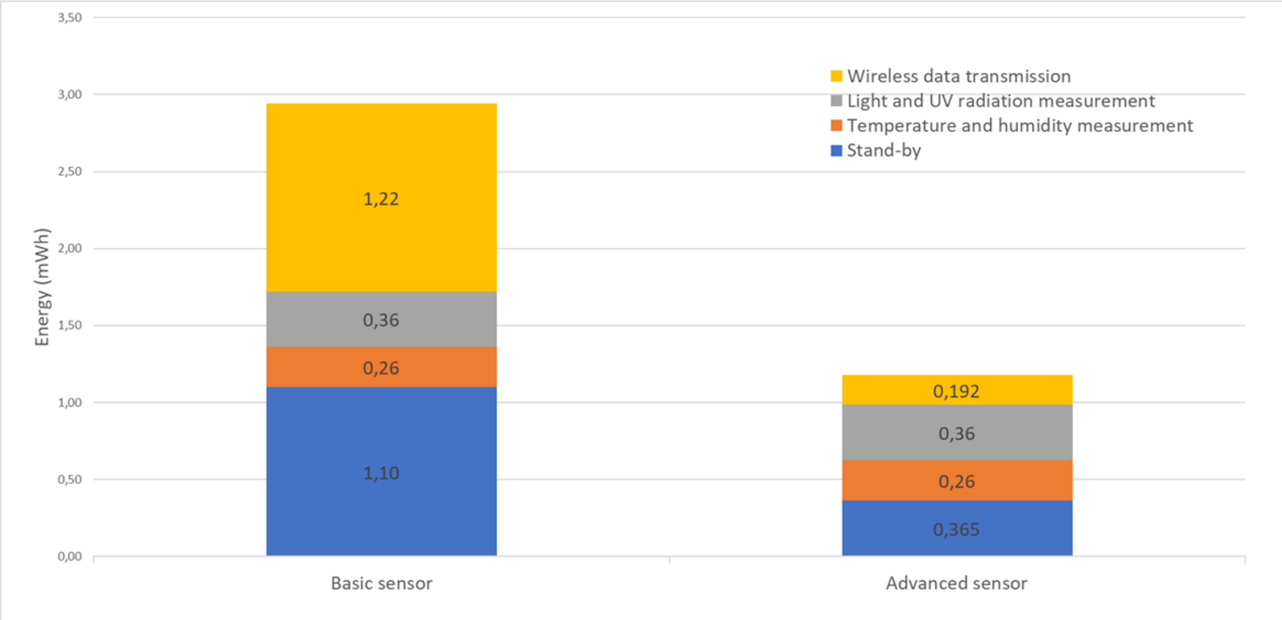


Figure 22. Comparison between the estimated daily energy requirements of the basic sensor node and the advanced sensor node

Assuming the same type of battery used in the DFA's deployment, the expected life span of the "advanced" sensor node is 19 years. Given this long-life span, the self-discharge effect cannot be considered negligible, but we can consider that the 10-year target is achievable without the need for additional techniques, specifically harvesting techniques.

To assure these results, a stress test is being carried out in a reference sensor node increasing notably the sensing and transmission cycle and using a battery of the same technology but less capacity. In any case, that experiment will require at least two months of continuous operation.

An important conclusion of this study is that a key aspect to increment the lifespan of the sensor nodes is to increase the efficiency of the radio link as much as possible. This should include enhancements both in the "advanced" sensor node and in the gateway.

7. Conclusions

The analysis of the current "basic" sensory node has been carried out thanks to the validation conducted in Alava's museums and laboratory tests. This has allowed the evaluation of those areas in which it is necessary to improve the design for the review of the second sensor node prototype.

The actual design of the sensor node has been validated and some components and mechanical connectors as well as some manufacturing processes have been identified and will be removed to lower costs.

It has also been seen that the data transfer system to the cloud works well, so the same method will be followed for the advance sensor node.

Also, the sensory node attachment system has been found to be adequate, although some small design changes are expected to be made to improve behaviour during transport.

In addition, the design of an embedded PCB antenna has been initiated which will improve the radio frequency coverage of the sensor node and reduce the cost of the materials bill.

Furthermore, the gaseous pollutants that play an important role in the deterioration of the artworks have been identified, and a comparison of commercial sensors that can measure these parameters has been carried out by defining a specific selection criterion. As a result, two commercial sensors have been selected and tested in the laboratory to be included in the advanced sensor node.

The ability to monitor vibrations has also been studied and a comparison has been made between MEMS motion sensors. As a result, a motion sensor has been selected to be included in the advanced sensor node.

Finally, energy consumption has been measured on the first prototype of the sensor node and some improvements has been identified in order to lower energy consumption optimizing the lifespan of the device.

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