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Authors	Gawade, Dinesh R.;Buckley, John;Rather, Nadeem N.;Ziemann, Steffen;Zabeo, Alex;Barton, John;Iacopino, Daniela;Schuhmann, Katharina;Anders, Manfred;Burke, Micheal;Quinn, Aidan;O'Flynn, Brendan
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A Battery-Less NFC Sensor Transponder for Museum Artefact Monitoring

A Review of NFC Sensor Technology and a Proposed Solution

Dinesh R. Gawade[1], John Buckley[1], Nadeem Rather[1], Steffen Ziemann[2], Alex Zabeo[3], John Barton[1], Daniela Iacopino[1], Katharina Schuhmann[2], Manfred Anders[2], Micheal Burke[1], Aidan Quinn[1], Brendan O'Flynn[1]

[1]Tyndall National Institute, University College Cork, Cork, Ireland,
[2]ZFB Zentrum für Bucherhaltung GmbH, Bücherstraße 1, 04347 Leipzig, Germany,
[3]Ca 'Foscari University of Venice, Dorsoduro 3246, 30123, Venice, Italy
E-mail: [1]dinesh.gawade@tyndall.ie, [2]ziemann@zfb.com, [3]alex.zabeo@unive.it

***Abstract*— This paper presents a novel, low-cost, battery-less Near-Field Communication (NFC) sensor transponder for museum artefact monitoring of Cultural Heritage objects. The proposed solution combines a unique combination of packaging materials and NFC technology to enable a low-cost preventive conservation solution that is practical to implement, something that is not possible at present. Cultural Heritage objects and artefacts are valuable objects housed by museums and are often stored in uncontrolled climatic conditions, which may lead to degradation of these objects. Preventive conservation is a new strategy that aims to avoid future degradation of these types of valuable objects. Recently, NFC sensor transponders have shown an increased use in food and pharmaceutical cold supply chains for monitoring, but these commercial solutions are expensive to implement and cannot be easily adapted for museum artefact monitoring. In this work, we present a battery-less, long shelf life, low-cost sensor transponder for monitoring the temperature and humidity conditions inside cardboard artefact storage boxes. In developing the proposed solution, the state of the art NFC sensor technology is first reviewed in detail, and a battery-less NFC sensor transponder is proposed with a cost of less than €5 in quantities of 10k. In addition to this, early-stage prototype results are also presented.**

Keywords- Artefacts; Battery-less; Cultural Heritage; Energy Harvesting; High-Frequency RFID; Internet of Things; Museum; NFC; Preventive conservation; Sensor Technology.

I. INTRODUCTION

Degradation of movable tangible Cultural Heritage (CH) objects can significantly increase by unfavorable and unstable climatic conditions, environmental pollutants, pollutants emitted from artefacts and their packaging materials. An effective and affordable Preventive Conservation (PC) strategy is highly necessary to minimize the ageing and degradation of such artefacts. In small and medium-sized museums, only a very small percentage of all museum objects are on display; the vast majority are in storage. The stored artefacts are often exposed to daily and seasonal temperature and humidity fluctuation. Currently used Passive Sampling Devices (PSDs) and monitoring systems are expensive and cumbersome to calibrate and also fail to deliver the correct sensing in a timely manner [1]. One critical disadvantage of monitoring the storage conditions by PSDs is the necessity of opening the box for analysis.

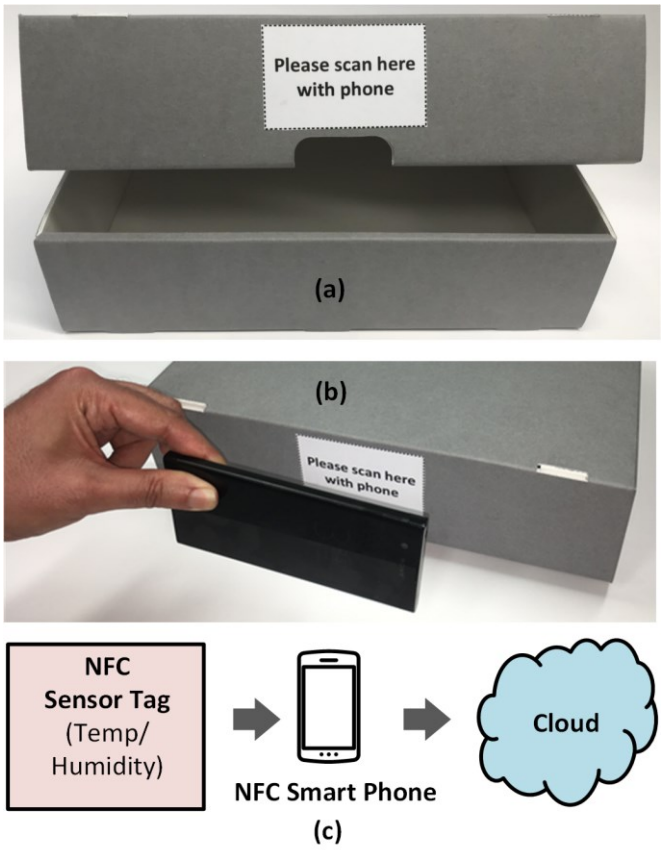


Figure 1. Depiction of proposed NFC temperature/humidity sensor solution. (a) Cardboard artefact storage box with proposed NFC sensor attached, (b) NFC sensor scan using a Smartphone, (c) Depiction of NFC sensor-to-cloud data flow.

This can lead to a loss of the desired microclimate, and reading the sampled results would be time-consuming. The values obtained by PSDs further do not represent the current Volatile Organic Compounds (VOC) concentrations inside the box but show an accumulation during the measurement time, which can not be related to a current concentration at a specific moment. For making rapid decisions, such as whether an absorbent must be replaced or if any further adjustment is required, these values have to be as reliable as possible.

The APACHE (Active & intelligent Packaging materials and display cases as a tool for preventive conservation of

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Cultural Heritage) project is a Horizon 2020 project focused on the reduction of costs for maintaining and controlling constant climate conditions for CH artefacts. This project also focuses on 'long-term storage' as a tool of preventive conservation for a wide range of tangible CH artefacts [2]. The proposed solution is shown in Figure 1. The cardboard box contains the cultural artefact, along with a smart NFC temperature and humidity sensing label as shown in Figure 1(a). The transponder will be read using an NFC Type 5 (NFC-V) enabled smartphone and the data will be uploaded to the cloud for storage and analysis, as shown in Figure 1(b) and 1(c).

A key motivation for this work stems from the fact that the diversity of the objects themselves, as well as their degradation mechanisms, are quite large and mainly influenced by Temperature (T) and Relative Humidity (RH). For these reasons, specific strategies for their preventive conservation during storage in appropriate containers have to be established. Each material, like cellulose-based paper or wood objects, photographs, leather, or contemporary art out of plastics, require a different specific climate for optimized long-term storage conditions [3]. In collections with different materials, all these specific requirements cannot be met, even if air conditioning and climate control are available for the room. However, as the latter is not affordable by the majority of small and medium-sized museums, the APACHE project aims to create specific optimized climate conditions in each storage item. This strategy allows collectors to build up a climate control system for their collection step by step in accordance with their financial resources.

Furthermore, within this project, the developed storage boxes and containers shall enhance the buffering of temperature and humidity fluctuations and therefore reduce their accelerating effect on the material degradation process. Already small temperature fluctuations can cause significant changes in relative humidity conditions, which, in turn, can cause mechanical stress in art objects by elongation and shrinkage processes. For example, if an art object is packed under standard climate conditions (23°C, 50% RH) and the temperature decreases by about 10 degrees during transport or day/night change, which is not unusual, the relative humidity in an airtight enclosure would increase to 90% [4] [5]. At colder temperatures, condensation on the artefact surface could lead to mould growth, and hence, catastrophic damage. Moreover, air pollutants and VOCs like plasticizers or organic acids lead to further destruction, especially of cellulose-based materials [6][7]. As a consequence, a remarkable effort is made in the development and application of novel temperature regulating, humidity, and pollutants absorbing materials to exclude damaging impacts as far as possible [8]. For the definition of thresholds, which allow expressing if humidity or VOC concentrations are in a critical range, materials modeling simulations, and the development of damage functions as a decision-making tool are included. In the end, a possible acquirement of sensed temperature and RH data will ensure the preservation of microclimates found in archive boxes. In this method, the archive boxes can remain closed permanently.

Wireless Sensor Technologies (WST) such as Near-field communication (NFC) technology are essential to monitor the inside microclimatic conditions of a closed archive box. NFC is a short-range wireless communication technology that has evolved from existing contactless identification technologies [9]. Additional NFC standards ensure the interoperability of NFC-enabled devices and enable communication between them. The NFC standard defines the data rate (26.48 to 424 kbit/s), data frame formats such as NFC Data Exchange Format (NDEF), modulation, initialization, and collision control during initialization [10]. NFC uses magnetic coupling between two loop antennas located within each other's proximity or vicinity. It follows the ISO/IEC 18092 communication mode and ISO/IEC 18000-3 mode 1 protocol and operates at 13.56 MHz Industrial, Scientific, and Medical (ISM) band [11][12]. NFC has shown increased growth in the past few years due to the incorporation of NFC readers into smartphones and increasing significance of the Internet of Things (IoT). NFC technology not only enables consumers to perform payments, access stored data, and connect electronic devices, but also helps to sense various parameters. The decisive advantage of NFC against PSDs is that the data can be remotely read and analyzed without direct physical contact or the need to open the storage box. The resources and costs required to use, maintain, and read the sensors are thus significantly reduced compared to traditional monitoring systems. STMicroelectronics have recently introduced NFC sensor integrated circuits that are suitable for this application [11]. With this interdisciplinary approach, APACHE will lead to an active and intelligent solution for storage and archive boxes, where NFC sensing acts as an intelligent tool to replace currently used PSDs. An NFC sensor transponder represents a fast, convenient, sustainable, and precise alternative to check actual concentrations, temperatures, and humidity in archive boxes. An atomized sensing would give further information about the inside conditions during e.g. heating periods or an institution´s closure times, which can be very useful for management decisions.

In this paper, the technical requirements of this application are first defined in Section II. A detailed review of the literature is described in Section III to survey the existence of prior work (both academic and commercial works) in the area of NFC sensor technology. Section IV describes the proposed solution architecture where a low-cost, battery-less NFC temperature and humidity sensor transponder is outlined for a museum artefact monitoring application. Early prototype results are described in Section V.

II. TECHNICAL REQUIREMENTS

Early detection of temperature and humidity fluctuations is of crucial importance to successful PC in museums. The technical requirements of every component related to this are described in the following subsections.

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A. Storage Box

Corrugated board material represents an environmentally friendly, recyclable, and inexpensive material, which exhibits tremendous stability, needed for stackable boxes and the storage of heavier artefacts. Corrugated board in aging resistant archive quality (following DIN ISO 16245) furthermore provides the opportunity to enable an alkaline reserve, which acts primarily as an absorbent for acidic emissions, arisen from paper degradation [13]. The production of archive boxes out of corrugated board allows the design of individually sized boxes, which provides the significant advantages of a space-saving storage solution combined with the best possible protection of the objects by a reduced volume of "packed air." To detect microclimate fluctuations, the sensor transponder needs to be located at the inner surface of the box, such as in the fore-edge area of a storage box: The surface of potentially degrading material should be maximal at this point, which gives the most representative critical Temperature and Relative Humidity values.

B. NFC Radio and sensor

The implementation of sensors transponder into storage boxes requires the development of low cost, (typically less than €5 per piece), and high durability and stability of typically greater than 5 years. The sensor transponder should be able to sense and transmit the surrounding temperature and humidity of packed artefacts with metadata such as storage boxes unique ID, artefacts type and location using NFC technology. Thus, to transmit this small payload rapidly, a low bit rate is expected, typically less than 25kbit/s. As this application does not encounter a sudden fluctuation in temperature and humidity, no data logging is required. The sensor transponder must be battery-less and capable of harvesting up to 10mW power from a reader (NFC Enabled smartphone) magnetic field.

Furthermore, harvested power will be utilized to power up the sensor and microcontroller. The sensor transponder should be able to communicate, without any collision with adjacent sensor transponders. The NFC radio should have at least 4 Kbit memory and should support dual access (RF and I^2C). A communication distance of typically 4 cm is also required. The size of the sensor transponder must comply with ISO/IEC 7810, ID-1 card size standard (85.60 mm×53.90 mm). It should be assembled on a flexible PCB substrate and must be flat with a self-adhesive layer, hence, making it easy to be attached inside and on the front of storage boxes. The NFC sensor transponder must be compliant to NFC-V specification and should also comply with the ISO/IEC 15693 air interface. Therefore, it operates in the vicinity of the reader and provides the desired data rate, communication distance, and interoperability with NFC-V enabled smartphone. Transponders based on the ISO/IEC 14443 air interface have a shorter read range (typically, 3 cm) and thus unsuitable for this application.

The implementation of sensor transponders into storage boxes requires low cost, high durability, long shelf-life, and high sensitive temperature and humidity sensors. The readable temperature range should be -10°C to 60°C with a sensitivity of 0.5°C. The readable humidity range should be 0 to 100% RH with a sensitivity of 0.5 %.

C. Smartphone Application

In order to allow small to medium collections with low available resources and still have a chance to monitor the status of their artefacts, a widely available cheap solution resides in the use of NFC readers embedded in everyday smartphones. Raw data received from sensors should be managed by a specific smartphone app compatible with different smartphone brands and operative systems. Data should initially be stored in the smartphone's internal memory and displayed to the user for an immediate consultation. This allows performing of readings in conditions where reduced or absent external connections are available in the artefacts storing facility. Once the smartphone comes back to sufficient connectivity conditions, the internally stored data is automatically sent to the cloud server for storage and further processing. The smartphone app should be able to tag each reading properly with the timestamp and distinctive details about the analyzed artefact. The app should also be able to receive information from the cloud about status and previous readings related to artefacts to allow a fast check from the operator.

D. Cloud Processing

The remote server, receiving data gathered through the smartphone app, might be located inside an intranet (local cloud) or on the Internet (cloud). In both cases, the same infrastructure is needed, which should be composed of a web server, an application server, and database storage. The web server waits for incoming data through a specially designed API software interface. The smartphone app establishes a secure connection with the server through the API and then utilizes the channel to funnel the gathered raw data to the server. On reception, the webserver passes information to the application server, which immediately stores the raw data in the database and successively processes it to generate all requested information for decision support. Finally, the processed information is correctly displayed to users through dynamic charts and tables, while alarm messages are broadcasted as soon as danger thresholds are reached for any of the assessed artefacts.

III. TECHNOLOGY REVIEW

A thorough review of the literature is described in the following subsections to survey the existence of academic and commercial prior work in the area of NFC and Radio Frequency Identification (RFID) sensor technology.

A. Literature Review of NFC sensor Technology

In 2013, an early review of NFC technology, related academic studies, white papers, and innovative issues was reported in [14]. In [15], a detailed survey on NFC sensor transponders for IoT, cold supply chain and wearable applications is presented. This paper also presents a brief summary of NFC sensor integrated circuits and their main

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specifications. Later in [16], a review of recent progress in NFC sensor technology has been reported. In this paper, NFC sensor transponder antenna design, manufacturing techniques and development of new material along with their application in wearable devices and food safety has been discussed. Likewise in [17], RFID sensing techniques, innovative application, fabrication techniques, commercial solutions and technical challenges have been reported.

In [18], an NFC sensor transponder design and a six-month pilot result for long term preventive care of fine art objects have been reported. The developed transponder evaluates inside and outside temperature and humidity buffering performance of microclimatic enclosure constructed to protect a late 16th Century panel painting. It is based on the ISO/IEC 15693 standard and compliant NFC forum NFC-V specification. This study explicitly explains the critical role of object-specific sensor transponders in improving long term preventive care of fine art objects. In [19], the authors presented the design and implementation of RFID and sensor web-based cultural relics management system. In this, RFID has been used for cultural relic identification and life cycle management during storage and circulation. Video and sensing parameters such as temperature, humidity, vibration, and displacement are transmitted using both wired and wireless communications. For preventing theft, a camera is deployed in collaboration with RFID and a vibration sensor. This system has been installed in a museum in Yongding District, Fujian Province, China. Furthermore, in [20], an RFID based museum environmental monitoring system is reported. Here, a flexible RFID platform is presented, which enables operation specific direct plugging of sensors into monitoring station. The pilot trials of this system under various environmental conditions has taken place in the Hong Kong film archive and Hong Kong Museum of history and was finally installed in the Hong Kong Science museum in 2015.

Several papers report the design and performance of NFC/RFID sensor transponders, specifically for cold supply chain (food, pharmaceutical, beverage etc.) and environmental parameters monitoring. In [21], a flexible RFID sensor transponder for temperature monitoring is reported. The proposed transponder is based on the ISO/IEC 15693 standard and is compliant to NFC-V specification. The transponder prototype was realized by hybrid technology combining a printed antenna, surface mount RFID integrated circuit and flexible battery assembled with the help of Ag-based conductive epoxy adhesive. The size (85.60 mm×53.90 mm) of the designed transponder complies with ISO/IEC 7810, ID-1 card size standard. Smartphone and Web applications have similarly been developed for reading sensor data. Escopedo et al, [22] present a flexible NFC sensor transponder for Oxygen, Carbon Dioxide, Ammonia, and Relative Humidity monitoring. It is based on the ISO/IEC 15693 standard and compliant NFC forum NFC-V specification and includes a smartphone application. Likewise, in [23], an RFID based critical temperature indicator for the food supply chain has been reported. In [24], a low cost, passive NFC sensor transponder for pH monitoring based on a colorimetric sensor and smartphone application has been developed. In [25], Eldebiky et al, implemented an environmental monitoring system with the help of Hybrid System-in-Foil (HySiF) components, such as microcontroller, on-chip temperature, on-foil humidity sensors and NFC radio. In [26], an RFID patch for food spoiling monitoring with the help of a temperature sensor has been reported.

Recently, battery-less NFC sensor transponders and their various applications have been reported in the literature. In [27][28], battery-less sensor transponders for volumetric water content (soil moisture), temperature and relative humidity monitoring has been presented. Also, this work has shown that the magnetic field generated by NFC enabled smartphones is enough to supply energy for the transponder. Further, in [29], a battery-less chronic wound monitoring system has been presented. In order to monitor the chronic wound, the proposed solution acquires temperature and pH information of the wound, and consumes 5 mW of power. In [30], a battery-less NFC transponder for classifying fruit ripeness grade based on color measurement has been presented. Likewise, in [31], a battery-less diaper has been reported where diaper moisture is detected by capacitance variation.

B. Commercial solutions based on 13.56 MHZ NFC/ HF RFID

Table I shows NFC and High-Frequency (HF) RFID-based commercial sensor transponders. Various organizations have developed and marketed such a solution, particularly for cold supply chain or temperature-sensitive product monitoring. Gosense Wireless Ltd, UK developed and demonstrated TH-Stat ID for fine art preventive care [18][32]. Reviewed commercial solutions have a limited shelf life of a maximum of 3 years [33][34] and only a few of them are battery-less [32][35]. However, all these solutions are quite costly and, therefore, cannot be easily adapted for low cost museum artefacts monitoring.

TABLE I. NFC / HF RFID BASED SOLUTION

Manufacturer	Cost €	Life (Years)	Passive	Sensor	Ref.
Monarch Instrument, USA	71	3	No	T, RH	[33]
Microsensys, Germany	48	3	No	T, RH	[35]
	24	NA	Yes	RH	[34]
GoSense, UK	23	NA	Yes	T, RH	[32]
UID, USA	18	1	No	T	[36]
Intellilog, Germany	17	1	No	T	[37]
Avery Dennison, USA	15	1	No	T	[38]
Identiv, USA	8	1	No	T	[39]
This work	**5**	**5**	**Yes**	**T, RH**	**[2]**

TABLE II. UHF RFID BASED SOLUTION

Manufacturer	Cost €	Life (Years)	Passive	Sensor	Ref.
Powercast, USA	73	NA	Yes	T, RH	[40]
	73	NA	No	T, RH	[41]
Datalogic, USA	22	5	No	T	[42]
Farsens, Spain	17	1	No	T	[43]

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C. Commercial solutions based on 860-960MHZ UHF RFID

Table II shows the Ultra High-Frequency (UHF) RFID based commercial sensor transponders, developed mainly for cold supply chain monitoring. The UHF RFID transponders can provide read range less than 10m [41] [40], but the cost of the UHF reader is too high [44]. Thus, UHF RFID is not suitable for low-cost museum artefacts monitoring.

IV. Proposed System-Level Solution

The proposed system-level architecture of NFC temperature and humidity sensor transponder is described in the following subsections.

A. Near field Communication and Hardware

The proposed solution block diagram and system architecture are shown in Figure 2. The NFC radio Analog Front End (AFE) consists of an RF interface and the energy harvesting circuitry, which will connect to the loop antenna. The energy harvester will harvest energy from the magnetic field (H-field) of an NFC-V enabled smartphone with the help of an internal rectifier and capacitor. The harvested voltage will further be regulated using a low dropout regulator and will be used to power up an ultra-low-power Microcontroller Unit (MCU), as well as a temperature and humidity sensor. The NFC radio ASK demodulator will demodulate the messages from the reader and responds to the reader with the help of load modulation. The load modulation is achieved by varying the impedance of the loop antenna [45]. When the magnetic field strength from the reader is sufficient, the harvested energy will be available to power up the MCU, NFC radio, temperature, and humidity sensor. The NFC radio, temperature and humidity sensor will be interfaced with MCU using the Inter-Integrated Circuit (I^2C) Protocol. Having powered up, the NFC radio sends RF events signal to the MCU. The sensor will start sensing temperature and humidity and its raw value will transmit to the MCU through the I^2C. The MCU will determine temperature, relative humidity and generate an NDEF message. The generated message will contain payload such as sensed data, artefacts type, box UID and their location. The MCU will write the NDEF message in the user memory area of the NFC radio [46] [11], and the NFC-V Smartphone will read this memory with the help of a dedicated read message command. In this way, the smartphone will read the data from the NFC sensor transponder at a 26kbit/s bit rate. The hardware will be implanted on a flexible PCB substrate, such as polyimide (130µm thickness) with a self-adhesive layer. The size of proposed sensor transponder will be 85.60 mm×53.90 mm. The system architecture of the proposed transponder is shown in Figure 2b. After analysing technical information and several experiments with different NFC sensor evaluation boards, the ST25DV04K NFC radio from STMicroelectronics was chosen [11]. This radio is capable of harvesting up to 10mW power from NFC-V enabled smartphone magnetic fields.

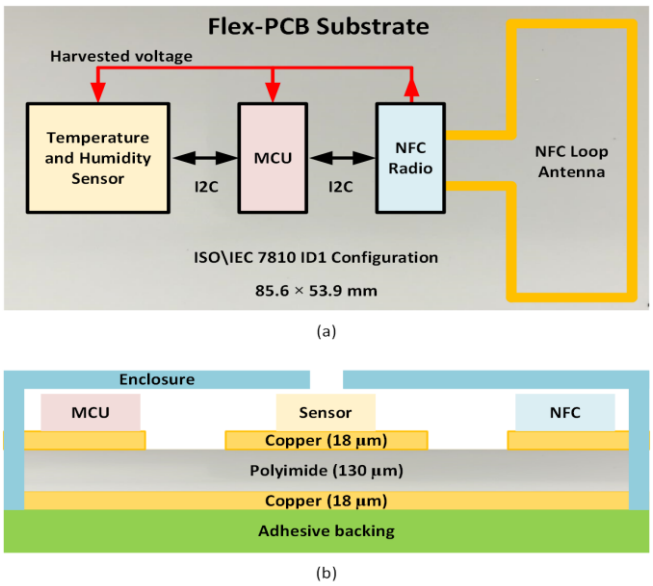


Figure 2. (a) Block diagram, (b) System architecture of the proposed NFC temperature/humidity sensor.

The unit cost of ST25DV04K is €0.43 and aggregated cost of other selected tag electronics such as MCU (€1.05), voltage regulator (€0.26) and passive components (€1) are €2.31 per device for 10k quantity. Also, the 2-layer flexible PCB manufacturing and components assembly cost will be less than €0.90 per device for the same quantity.

B. Smartphone Application

The smartphone application will rely on specific libraries for NFC data gathering as well as for storage and communication of retrieved information for both the Android and iOS smartphone operative systems. Data will check for consistency to avoid false or incomplete readings; right after this check, a timestamp will be attached to the retrieved data. Information about the ID of the artefact and all specific readings will come from the NFC sensor transponder. The smartphone application starts up automatically when approaching a suitable NFC sensor transponder, and autonomously performs the first reading and displays the raw contents of the reading. The app user can decide through a setting whether to automatically upload each reading instead of having to send out the currently displayed reading manually. Once the app is activated, the user will decide to perform (and upload) several successive readings by clicking the corresponding user interface button.

C. Cloud Processing

Data uploaded by the smartphone app to the cloud Linux web server will immediately be stored in a relational MySQL database, which will regularly be backed up. The connection and data transfer occurs thanks to a specific RESTful web API implementing all required rules for a proper service endpoint [47]. The gathered information is elaborated by the server immediately after being stored, and results obtained by the application of the mathematical

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models embedded in the application server will also store and back up in the same database as the readings. User interface dashboard, dynamic charts and tables will also update live with the new upcoming readings, and a routine, which checks whether the alert thresholds are met is run and automatically sends alert signals (emails, phone notifications, etc.) to the registered users. The server role will be completely transparent to the source of information as the smartphone app hides the lack of direct connection with the NFC sensors. Thanks to timestamps related to each reading coming from sensors with different sampling frequencies, the application server will be able to integrate heterogeneous information in a single coherent interface and decision support framework.

V. EARLY STAGE RESULT AND DISCUSSION

The early evaluation kit based working prototype shown in Figure 3. This working prototype is a proof of concept, and experimental results show that the harvested power from NFC-V enabled the smartphone's magnetic field is enough to run the transponder without a battery. A graph of power consumption for the device is shown in Figure 4. In order to measure temperature and relative humidity, the prototype transponder requires a peak power of 2.37 mW.

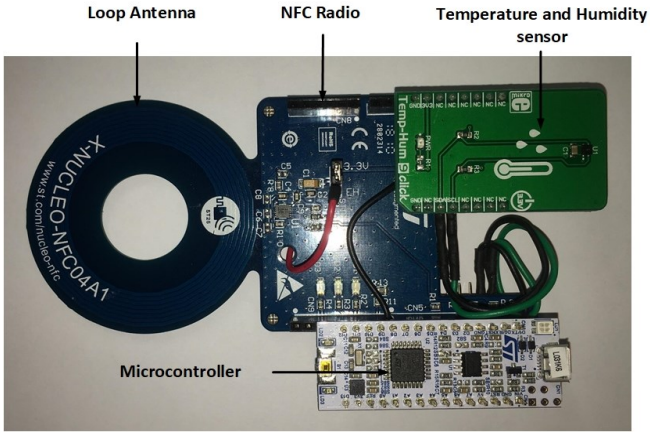


Figure 3. Early NFC sensor transponder prototype (Evaluation kit based)

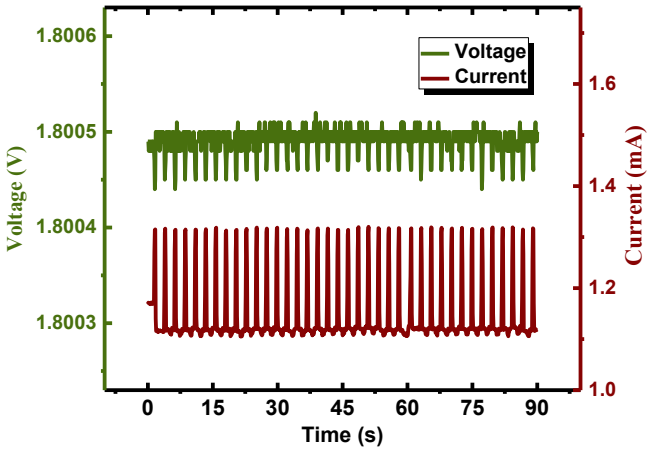


Figure 4. Prototype NFC sensor transponder power consumption graph

Also, the experimental communication distance obtained for the prototype transponder is up to 28 mm with a Vodafone X9 smartphone and up to 37 mm with the iPhone XR. The battery-less NFC sensor transponder signifies a sustainable and specific alternative to measure actual concentrations, microclimatic parameters inside closed artefacts storage boxes. These solutions could be beneficial, especially for small and middle-size museums, which cannot afford air conditioning systems and those in countries that have very humid climates. To exclude mould growth on paper, for example, the maintaining of adjusted relative humidity values is crucial and can be monitored in this way. Also, the deterioration of plastic composed artefacts emitted VOC´s during this process could lead to health detriment if accumulated and even affect surrounding paper-based objects which are prevented if those VOC´s are chemically immobilized at the source.

VI. CONCLUSIONS AND FUTURE WORK

This paper has presented the architecture and early prototype (Evaluation kit based) result of a novel battery-less, low-cost, and long shelf-life NFC sensor transponder for museum artefact monitoring. The proposed transponder total cost is less than €5 per device for 10k quantities. The prototype transponder consumes 2.37 mW peak power to read temperature and relative humidity along with metadata. The experimental read range obtained for the prototype transponder is up to 28 mm with a Vodafone X9 smartphone and up to 37 mm with the iPhone XR. In order to improve communication range, future work will focus on the development of low power embedded hardware, loop antenna and optimization of the firmware. In the next phase, a smartphone application and cloud platform will be developed, and system-level testing and calibration will be performed. A new low-cost temperature and humidity sensor will be developed using Laser Induced Graphene (LIG) electrodes to overcome conventional sensor limitations such as accuracy, size, power consumption, shelf-life and cost. In another development, chemical modification of the above electrodes will be performed targeting the electrochemical detection of VOCs. New artefacts storage boxes using RF friendly material will also be developed during the project. The first hardware prototype will be available in Q1 2020.

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