An IoT Monitoring and Control Platform for Museum Content Conservation

Ghada Alsuhly, Ahmed Khattab
Electronics and Electrical Communications Engineering Department,
Cairo University, Giza, 12613, Egypt
gada.sy@hotmail.com, akhattab@ieee.org

Abstract— **Museum content preservation is a duty towards present and future generations. Museum collections may deteriorate due to bad environmental conditions or improper human interventions. In this paper, we develop an Internet of Things (IoT) based system for museum indoor ambience monitoring and control and artifact safety. In the proposed system, the information about the artifacts' environment and their safety conditions are collected in real time and sent to a gateway. This information is preprocessed and aggregated in the gateway before being relayed to a cloud where it is stored and analyzed. According to the analysis outcomes, proper decisions are made and sent back automatically to the actuators to set the museum ambience accordingly or to fire alarms. Manual actuator remote control is also available to the museum managers through a web-based interface. The proposed system prototype was built and tested to demonstrate that the system fulfills its intended purposes.**

Keywords— Internet of Things; WSN; sensor node; actuator node; museum; smart city; cloud computing.

I. INTRODUCTION

Museums are not only places where the treasures of the past are conserved and viewed for entertainment, but also important educational tools for art and history. Over time, museum collections will deteriorate for plenty of reasons such as environmental conditions, human vandalization and natural degeneracy. To stop or at least slow down the degradation rate of artifacts and extend their life, museum collections must exist in a proper microclimate of temperature, humidity and light [1]. As a result, monitoring and controlling the museum's ambient conditions is the most important task to prolong the lifetime of the museum contents. Not long ago, museum environmental parameters were measured using conventional measurement equipment, such as psychrometers and hygrometers [2]. These traditional ways suffer from many problems such as their large size, the need for human effort and the inability to provide continuous measurements.

The Internet of Things (IoT) describes a world wherein anything of everyday life has the ability to intelligently communicate and coordinate with the surrounding environment and people to provide modern services using the Internet infrastructure. Using sensors and actuators, the IoT allows remote monitoring and management of the things and their environment. This fact can be exploited to manage the museum ambience, and thus improve culture heritage conservation. Using sensors in museum ambience monitoring has many advantages over traditional monitoring. Some of these advantages are: the low cost, insignificant visual impact, low power consumption, high flexibility, no need for infrastructure, ease of deploying the sensor nodes and the ability to continuously monitor and control the museum environment.

In this paper, we design an IoT layered architecture that categorizes the requirements and functions of the system to three layers: (1) A physical interface layer that collects the museum ambience data and implement the actions and decisions developed to control the museum ambient conditions, (2) A network management layer that serves as the interface between the physical interface layer and the Internet, and (3) A data processing layer that stores the data, processes it to develop feedback decisions, and provides the tools to make the data accessible to interested humans through the Internet. A unique feature of our work is that data processing is done at two levels: locally at the gateway for prompt actions in response to time-critical conditions, and globally through a cloud-based backend.

This architecture is used to build a real time prototype of the museum ambience monitoring and control system to maintain the museum environmental conditions stable within predefined thresholds. Since there is a conflict between the needs of artifacts preservation and the visitors comfort in a museum building [3], we propose a scheme in which we predict the presence of visitors in each section inside the museum and automatically adjust the environmental parameters, such as light and temperature, accordingly. Moreover, vandalization or even a slight touch of a museum collection will trigger an early warning to the museum manager to prevent theft attempts. The museum manager can configure the system using a web-based interface such that the alarm is automatically fired upon the detection of an early warning of artifacts' displacement or a forbidden access to some spaces in the museum such as storage rooms. We present a set of experiments that demonstrates the system's ability to keep the museum ambience within the target ranges and to issue warnings upon vandalization attempts. Our results also show the low power consumption of the system which is attributed to our choices of the used components and having the nodes operating in the sleep mode as much as possible.

The remainder of this paper is organized as follows. In section II, we describe the related literature of IoT-based smart museum systems. The proposed system architecture and components are presented in section III. The experimental results of the developed prototype are described in section VI. Finally, Section V provides our main conclusions.

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II. RELATED WORK

There are many works in the literature that aim to use wireless sensor networks in museums to enable and exploit the advantages of continuous monitoring. Earlier, it was common to process the data collected by the sensors locally without being connected to the Internet, as in [4 – 6]. More recent works are aiming to make museums join the "IoT Age" to exploit the interesting capabilities of the Internet such as cloud computing. In general, IoT-based applications in museums can be classified into three categories: museum environmental monitoring, interactive museum, and museum surveillance applications.

A. *Museum Environmental Monitoring*

Due to the importance of monitoring museum environments, a number of researches have proposed IoT platforms to achieve this goal. In [1], the authors proposed an IoT system to monitor the temperature, relative humidity and light in a museum. Similarly, the platforms presented in [7] and [8] have the capability of monitoring museum air temperature and relative humidity. However, these platforms were designed to collect data and push it to the Internet. None of the above IoT platforms included control functionalities depending on the monitored data. This contrast with our work which aims to process the collected data and act accordingly to ensure certain museum ambient conditions depending on the showroom occupancy.

B. *Interactive Museum*

Other works developed IoT platforms to enhance the museum visitors' experience such as [7, 9 – 11]. That was achieved by providing the visitors with wearable devices [9] or an application installed on their smartphones [7, 10 – 11]. These systems exploit recognition and localization approaches to deliver the proper details such as the artist and historical context related to the artwork being currently watched by the visitor.

C. *Museum Surveillance*

Even though it is common to use wireless sensor networks for security purposes [12, 13], the existence of IoT systems for museum surveillance is very rare in the literature. This is attributed to the challenges that still face the IoT such as the security issues and the delayed response. An example of IoT based museum surveillance system is presented in [8]. That system suggested that each artifact is provided with different sensors such as vibration sensor, video camera and an RF Identification (RFID). However, such a system needs an infrastructure and unconstrained power supply which makes it unsuitable for all museums.

III. IOT MUSEUM CONTENT CONSERVATION SYSTEM

In this paper, we develop an integrated IoT system for museum ambience monitoring and control with the support of anti-theft capabilities. Unlike the existing systems, we follow a layered architecture approach inspired by [14]. However, our layered architecture is a functional one rather than being component-based as in [14]. More specifically, our proposed system consists of only three layers: Physical interface layer, network management layer, and data processing layer.

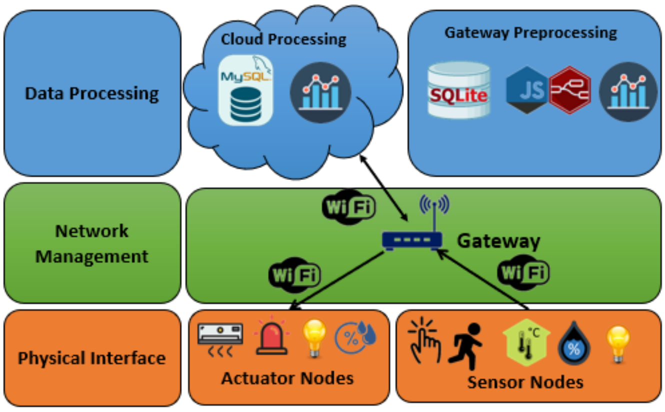

Fig. 1. Proposed IoT system architecture.

The three functional layers of the proposed IoT system, and how they are implemented on the different system components, are illustrated in Fig. 1. In what follows, we briefly explain the role of each layer of the proposed architecture, then we present the implementation details of each layer.

A. *System Functional Architecture*

As illustrated in Fig. 1, our proposed IoT architecture is composed of three layers:

1) Physical Interface Layer: The first layer of the proposed architecture is the physical interface layer. This layer is responsible for three main functions. First, it collects the required data of the museum ambience and converts it to digital format (if needed) in order to input such data to the system. The second role of this layer is to implement any received actions or decisions obtained from the system, and accordingly control the museum ambience or issue warnings. In addition to data collection and action implementation, the physical interface layer of our architecture is also responsible for wirelessly communicating the collected data to the system and wirelessly receiving any action commands from the system. This contrasts with the four-layer approach presented in [14] which uses a separate layer for that purpose. Hence, the main components of the physical interface layer are the ambience monitoring sensors, the ambience control actuators, and microcontrollers equipped with wireless interfaces.

2) Network Management Layer: The network management layer is responsible for gathering the collected data from the first layer, preprocessing and packaging it in the format needed for the Internet-based backend system where heavy processing is taking place. This layer also receives the control commands from the Internet-based backend system and forward them to the actuators that are responsible for implementing them in the physical interface layer. This implies that the network management layer is implemented at the gateway node that connects the museum ambience monitoring and control system and the Internet.

3) Data Processing Layer: The third layer of the system is the data processing layer which is responsible for storing the collected data, analyzing it to develop actions, and visualizing the data. Furthermore, this layer provides an application program interface (API) and other software tools through which the museum data can be obtained by any Internet-enabled device or actions can be applied remotely by authoried devices. It is worth mentioning that the data processing layer is mainly residing on an Internet-based backend system. However, the data management layer in our architecture is also capable of processing local data at the gateway node and acting accordingly to ensure timely actions for time-critical conditions. This saves the time needed to send the data to the Internet-based banckend and wait for the action command in response.

B. Physical Interface Layer Implementation

Our implementation of the physical layer consists of two types of microcontroller-based nodes: sensor nodes (responsible for data collection) and actuator nodes (responsible for the implementation the feedback actions and decisions). Each node is capable of wirelessly communicating with the network management layer implemented at the gateway. The sensor node and the actuator node of our system are implemented as follows:

1) Sensor Node: The sensor node is responsible for gathering the artifact preservation and safety information. As shown in Fig. 2, our sensor node consists of ESP32 wireless microcontroller, sensors and a battery. ESP32, from Espressif, is a low cost and low power wireless Microcontroller Unit (MCU) with an integrated Wi-Fi chipset [15]. The ESP32 contains a Tensilica LX6 dual-core microprocessor, a built-in antenna, an RF core, amplifiers, filters and power management modules. As shown in Fig. 2, The following sensors are attached to the sensor node in our system:

- **Temperature and Humidity Sensor:** Monitoring and stabilizing the temperature and humidity of the museum ambience is essential for the artifact conservation process. Since most materials stay well for longer time at lower temperatures, museum contents should be kept cool to decrease deterioration reaction rates. Consequently, temperature is an important factor that affects the materials' natural aging speed. Moreover, fluctuations in the relative humidity cause changes in the shape of the artifacts and accelerate chemical reaction rates [16]. In our proposed system, the temperature and humidity are automatically set to suit the requirements of artifacts' preservation when the museum (or a particular section) is not occupied by visitors. However, the temperature and humidity are automatically changed for the visitors' comfort (based on the number of occupants) if there are visitors in the museum.

- **Light Sensor:** Light is an important source of natural energy which offers the required energy to accelerate the deterioration process of the materials and cause painting colors to fade [16]. Our system will automatically keep the light off as long as there are no visitors in the museum, and a dim light will be used if there is somebody but not in the current section. Once a motion is detected in a certain museum section, the light intensity will be increased to the maximum in that section.

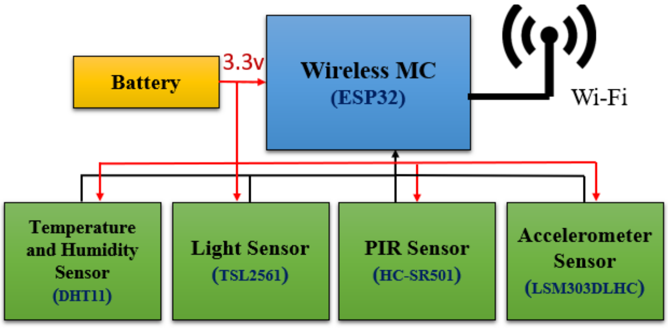

Fig. 2. Block diagram of the sensor node.

- **Passive Infrared (PIR) Sensor:** Since we need to control the museum ambient conditions depending on the visitor's presence or absence, PIR sensors are used for occupancy detection. It is known that these sensors suffer from low sensing accuracy. However, in our proposed system each sensor node contains a PIR sensor. Then, the presence of multiple sensor nodes in each section increases the accuracy of discovering someone's presence in that section. Another issue is that the PIR will not sense the existence of the visitor if the visitor is standing motionless in front of an artifact. To overcome this obstacle, our system takes into consideration that the visitor may stand without moving by defining a mean visitor standing time. The mean visitor standing time is a system parameter that is set by the museum management.

- **Acceleration Sensor:** A tri-axis acceleration sensor is used to detect any theft attempt, displacement, or even illegal touch of the museum contents. Whenever the acceleration exceeds a predefined threshold, an event is triggered to notify the museum manager.

To prolong the lifetime of the system, the sensor nodes are configured to operate in the sleep mode and wake up periodically every 20 minutes to collect the temperature, humidity, and light data. On the other hand, the acceleration and PIR sensors are always functioning and trigger the sensor node to wake up upon detecting the respective events.

2) Actuator Node: The actuator nodes perform actions to change the ambient conditions inside the museum environment. More specifically, we control the temperature of an air cooler, the humidity using a dehumidifier, the light intensity of a LED lamp, and an alarm that fires upon attempts to touch the artifacts. Figure 3 shows the block diagram of the actuator node in our system. The wireless MCU is the same for both the actuator and sensor nodes. However, the power source typically has more energy budget than that available for the sensor node since the actuator node is a part of a large equipment like the air cooler or the dehumidifier which are powered from the electricity grid. The MCU in Fig. 3 switches the relay ON or OFF to turn the air cooler (or dehumidifier) ON or OFF according to the control command from the gateway. For example, when the humidity reaches an upper acceptable level, the MCU receives a command to switch on the dehumidifier until the humidity reaches lower acceptable level (these levels determined by the museum management), then another command will switch off the dehumidifier. Similarly, the MCU fires an alarm and controls the light intensity, by changing the duty cycle of a pulse-width modulated (PWM) signal, according to the received commands.

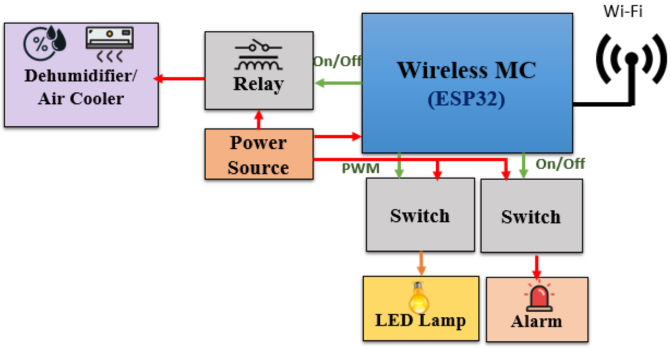

Fig. 3. Block diagram of the actuator node.

C. Netwrok Management Layer Implementation

The network management layer establishes the connection between the wireless sensor and actuator nodes in the physical interface layer and the software and hardware modules of the data processing layer. To achieve this connection, we use Wi-Fi wireless communication protocol to connect the different nodes to a gateway, and the gateway to the Internet. The IoT gateway is the place where the data from all nodes is aggregated, preprocessed and framed to be sent to the Internet-based backend system such as a cloud. Recall that the gateway in our proposed functional architecture is partially implementing functions for the data processing layer in addition to the network management layer functions. Therefore, the gateway should be able to temporarily store and process large amounts of data. Consequence, the gateway should have sufficient processing and storage resources. In our system prototype, we use Raspberry Pi 3 MODEL B [17] with Raspbian OS as a gateway. Raspberry Pi 3 has four high-performance ARM Cortex-A53 cores running at 1.2 GHz with 32 kB Level 1 and 512 kB Level 2 cache memory and 1 GB LPDDR2 memory module. In addition, it can connect to the Internet using Ethernet or Wi-Fi connections.

In order to exchange the data and control commands between the nodes and the gateway, we use the Message Queue Telemetry Transport (MQTT) protocol [18]. The MQTT protocol is an open source, power-saving and extremely lightweight which makes it ideal for IoT real-time applications. MQTT uses a "publish/subscribe" pattern to a central broker called MQTT broker. To build our broker, we installed the open source Mosquitto broker [19] on the Raspberry Pi. All nodes are connected to the broker using a star topology. The sensor nodes publish the collected data to certain topics in the broker. Whenever a sensor node publishes data to a topic, this data is processed, and messages are pushed to the related actuation topics, and hence, received by the concerned actuator node.

D. Data Processing Layer Implementation

The data processing layer is responsible for receiving the sensors' data and transforming the received data into a human understandable format. It is also responsible for storing the data in the database, processing received data and deciding the suitable feedback to control the museum ambience accordingly.

To avoid long delays and achieve faster response to urgent actions and for more reliable and secure control, the gateway stores the received data using SQLite Database manager. Then, the data is preprocessed and some decisions (such as firing the alarm) are made in the gateway rather than in the cloud. Afterwards, the data is relayed to the Internet-based backend system using HTTP protocol for long-term storage and extensive analysis, as shown in Fig. 4. In our prototype, cloud hosting is employed using a web hosting server from Hostinger [20]. In the cloud, a PHP API is created to insert the data to MYSQL database before being analyzed and displayed in a webpage.

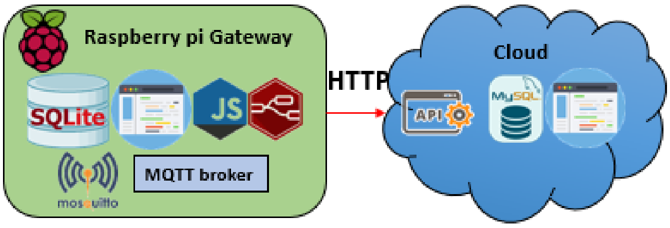

Fig. 4. Proposed data processing layer.

Furthermore, we use the Node-RED framework [21] to implement the data processing layer on the Raspberry Pi gateway. The gateway in our system is able to process the sensors information, take proper local time-critical actuation decisions and build a web-based interface to view continuous graphs for the monitored parameters. Node-RED is an open source flow-based programming tool. Each flow is composed of a number of nodes. Some nodes can be selected from the open-source library and configured or programed using JavaScript to build the desired application. Figure 5 shows the museum manager monitoring interface in which the museum ambience data is visualized in graphical and numeric forms.

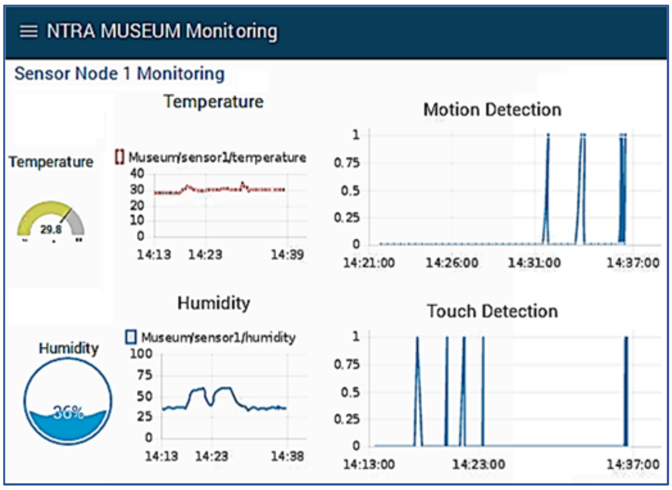

Fig. 5. Web-based monitoring interface.

IV. PROTOTYPE EXPREMENTAL EVALUATION

To evaluate our proposed IoT layered architecture, a prototype has been implemented and a set of test scenarios was applied. A sensor node, attached to a statue showcase, and an actuator node were used for the evaluation process. The sampling period of the environmental parameters collected by the sensor node was set to 20 seconds for the sake of more clear illustrations. The presented graphs were captured from the designed web-based monitoring interface.

A. Light Intensity Sense and Control

The first experiment aims to examine the ability of the system to sense, process, and control the light automatically depending on a number of configurable parameters. Our prototype assumes that the light intensity in each museum section is specified according to the presence of visitors in the section and in the museum in general. As long as the museum is empty of visitors, the light will be switched off in all sections. Once a motion is detected in the museum, but not in the current section, the light will be set to the minimum threshold. Whereas the light will be at maximum threshold once a visitor enters the section of interest. The light stays at the maximum threshold during the mean visitor standing time T_{mean} after the last motion detection. Then, the light will turn to dim for the same time T_{mean} before it is switched off if no motion was further detected. Figure 6 illustrates the mechanism of the automatic light intensity control according to the visitors' existence in a particular museum section. Using the web-based control interface, the mean visitor standing time was set to 2 minutes, the maximum light intensity to 400 Lux and the dim light to 100 Lux.

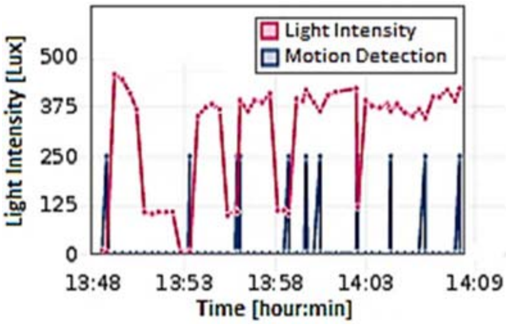

Fig. 6. Automatic control of museum lighting.

According to our measurements averaged over 10 trials, it takes about 2.95 seconds, starting from a visitor movement in front of the artifact until the light is set to the to the specified level. This time includes the time taken by the sensor node to wake up due to a motion detection, collect the sensor readings, and send the collected information to the gateway. In addition to the time taken by the gateway to process and send back the command to the actuator node to modify the light intensity level. The same control scenario takes more than 10 seconds when the processing is done in the cloud instead of the gateway.

Figure 7 demonstrates the ability to allow the museum manager to manually control the light using the web-based interface. Using a slider button in the interface, the user can select one of the 256 available light intensity levels and see the effect on the light intensity in less than 100 ms. In Fig. 7, the light intensity was manually increased in equal steps.

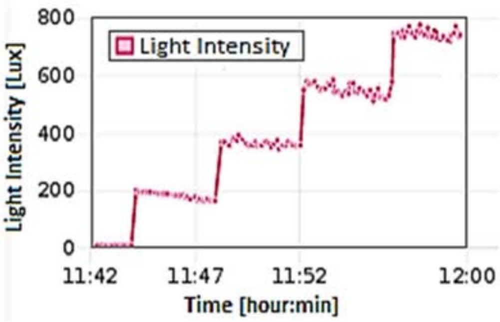

Fig. 7. Manual control of museum lighting.

B. Temperature and Relative Humidity Sense and Control

In contrast to light, temperature and humidity should be kept as steady as possible to preserve the museum contents. Figure 8 illustrates how our prototype stabilizes the relative humidity (RH) on a certain level determined by the museum manager depending on the museum content. Initially, the relative humidity of the showroom was about 80% before starting automatic control of the RH to be 45%. The deviation of the RH around the required threshold was less than ±2% which is acceptable for museum conservation.

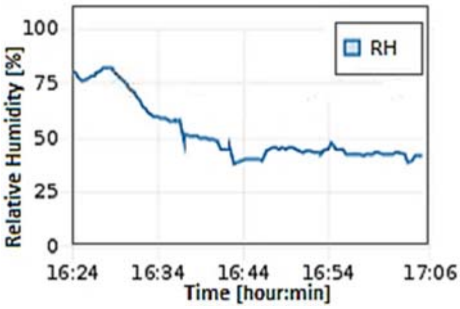

Fig. 8. Automatic control of museum humidity.

A similar scenario is used to illustrate how the system automatically stabilizes the temperature around the level needed for artifact health once it reaches a certain high level due to the existence of visitors. In Fig. 9, the temperature exceeded 30° C before the system works to settle it down to 20° C. Note that the system slowly changes the temperature and RH as rapid changes in these parameters are more harmful to the artifact health compared to having high values [16].

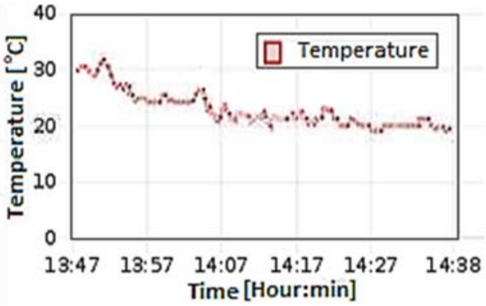

Fig. 9. Automatic control of museum temperature.

C. Touch Detection

To preserve the museum contents from human devastation, the acceleration data is used to detect any touch. Once the acceleration exceeds a certain threshold, the sensor node wakes up and sends the acceleration value at that moment. This value is used to predict whether the touch was for a theft attempt, vandalism or just unintended touch. The museum manager may choose to receive a notification and an email for each kind of touch. In addition, an automatic alarm option may be selected for theft or sabotage attempts. Figure 10 depicts some examples of the artifact displacement with different motives. A single touch detection event with low acceleration level implies that an unintended touch happened. At the contrary, the detection of multiple touch events in addition to a higher acceleration rate implies that the artifact is in real danger.

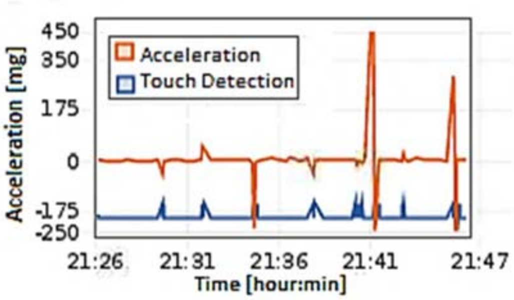

Fig. 10. Touch detection using an accelleration sensor.

D. System Lifetime

Finally, we measure the lifetime of the system which is determined by the lifetime of the sensor node. Our measurements show that the current consumption of the sensor node is 5.09 mA and 135.25 mA in the sleep and wakeup modes, respectively. This results in a lifetime of approximately 9.8 days (the node is powered by three 600 mAh 3.2 v LiFePO4 batteries) compared to only 20 hours as in [1].

V. CONCLUSIONS

In this paper, we have presented a layered IoT architecture for museum content conservation. We have defined the three layers of our architecture and explained the implementation details of each layer. We have built a prototype of the proposed architecture to illustrate its different performance aspects. The performance evaluation results have demonstrated the efficiency and accuracy of the proposed system despite its simplicity. Our future work will include reducing the power consumption of the system to enable the use of energy harvesting techniques. In addition, machine learning will be used to optimize the control actions of the system.

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