Self-adaptive Sensing IoT Platform for Conserving Historic Buildings and Collections in Museums

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Abstract: As historic buildings and collections in museums are normally of deteriorated structure or materials, any sudden change of weather or environment, such as oxygen level, temperature, humidity, air quality, etc., may cause damages to them and it may not be recoverable. Internet of Things (IoT) is common in solving problems by collecting environmental data using sensors. The data is live and immediate for visualizing the environment, which is suitable for conserving the buildings and collections. However, there is no one-for-all IoT solution for this conservation problem. In this paper, we propose the design of the sensor device in the IoT platform for conserving historic buildings and collections in museums. The sensor device is self-adaptive, running continuously without any interruption causing by the instability of power and network connection. The platform is currently implemented for the conservation project in the Science museum, University of Coimbra, Portugal. It has been running over a year and the conservation work is going well.

1 INTRODUCTION

Internet of things (IoT) is an architecture that allows intelligent systems to collect environmental data from sites at real time and to make immediate decision to achieve the goals. In a typical IoT system, there are a number of pervasive presence of things or objects, called sensor devices in this paper, that are of communicating capability to connect to edge servers or backend servers in an IoT network. Data collected and generated by the sensor devices will be sent to the servers through wireless or wired connection, creating a big data for further processing.

There is no one-for-all IoT solution for conserving historic buildings and the collections in museums. Depending on their types of materials and kinds of environmental data to be collected, the sensor device is designed. There are a number of existing solutions (Tse et al, 2018) (Maksimović & Ćosović, 2019) (Neri et al, 2009) (D'Amato et al, 2012) (Tse & Pau, 2016) (Pereira et al, 2017) (Aguiari et al, 2018) that are engineered to deal with this materials and data issues in their IoT systems.

To accurately collect the data (e.g. temperature, humidity, location, CO2, pm2.5, etc.), the sensor devices must be enabled with appropriate sensing capabilities using sensors. As the devices generate data continuously, the amount of data is unlimited but the storage is limited that may raise a storage issue. Moreover, deploying IoT systems in historic buildings is very challenging as the buildings may be short of power and network connection from time to time. Data loss is likely to happen, resulting in the failure of conservation.

To tackle the power and network connection issues, this paper will disclose the design consideration of the sensor device in the IoT platform. The Self-adaptive sensing method will be proposed which enables the sensor device to operate continuously even though the power and network connection are not stable. By estimating the size of data generated by sensors and the amount of energy consumed by the sensor device when backup power

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is used, the design of the sensor device can be optimized to work longer time until the main power and network connection are back. This project is the on-going research project for the Science Museum of the University of Coimbra in Portugal. The IoT platform has been deployed in the Museum and has been running over a year.

The remaining of this paper is organized as follows. In Section 2, we review the threats to historic building and collections in museums and the types of sensor to prevent the threats. After that, the self-adaptive sensing IoT platform will be discussed, which includes the architecture of the platform in Section 3, and the self-adaptive sensing method in Section 4. In Section 5, the ongoing research project will be introduced as it implements the IoT platform. Finally, we conclude this work in Section 6.

2 BACKGROUND

To conserve the historic buildings and the collections in museums, it is crucial to study their structure, quality and condition. There are many different kinds of threats to the buildings and collections. Common threats are fire, air pollution and visitor crowd that can cause different levels of damage to them, depending on their condition and types of material (wooden, papers, textiles, photos and leathers, etc.). Thus, the sensor device equipped with the oxygen sensor, nitrogen oxide sensor and humidity sensor, or some others sensors that can help against the threats, is highly recommended.

2.1 Oxygen Sensor

Most of the historic buildings are of wooden structure and they are flammable. After years of erosion, their structure becomes deteriorated if their maintenance is not properly done. When there is a fire, serious damages would be caused to them and the result would be unrecoverable. Thus, the fire safety guideline is always in place. It describes the principles and practices of fire safety for historic buildings and for those who operate, use, or visit them (Macau Cultural Affairs Bureau, 2019, October 5) (National Fire Protection Association, 2019, October 5).

In China, burning incense is a Chinese custom. Some Chinese temples allow visitors to burn incenses. Staff are required to pay attention to any unattended fire combustion caused by incense burning. Moreover, clearance of the entrance of temple is required as streets are narrow in some old areas. Fire truck can hardly reach.

Therefore, in case of fire, controlling the oxygen level is one of the feasible solutions to tackle the fire problem (Jensen & Holmberg, 2006). The study revealed that the air supply is one of the crucial factors that can feed a fire, as oxygen in the air can develop fire combustion. By reducing the oxygen level in the air from 21% (normal) to 15%, the fire development can be limited, while sufficient oxygen is provided for evacuating people.

To control the level of oxygen, we may use the oxygen sensor for monitoring the level at a site. The sensor would be installed at some particular corners near the places that are likely to have fire combustion. The reason is that the oxygen level over there is normally lower than other places. The sensor will report the level constantly. If there is a fire, the level is supposed to drop unexpectedly. In this case, some procedures can be applied to control the air supply in the site.

2.2 Nitrogen Oxide Sensor

Air pollution is an environmental problem in developing cities that is mainly caused by highly congested traffic (Pau & Tse, 2012). Tons of vehicle exhausts are generated from the traffic every day, which will produce tons of poisonous gas, called nitrogen oxide. There are a number of studies (Tétreault, 2003) (Szczepanowska, 2013) (Thickett & Lee, 2004) (Florian, 2006) (Lavédrine, 2003) (Peng, 2017) conducted about how nitrogen oxide causes damages to the materials commonly found in museum, which include papers, textiles, photos and leathers.

Nitrogen oxide will not cause damage to the materials immediately. However, it is very likely that, after exposing the materials for a certain period of time, degree of damages can be developed. Nitrogen oxide can weaken papers, textiles and photos, causing the colour fading in intensity. For leathers, it can create cracks on their surface. Therefore, protection is needed (National Fire Protection Association, 2019, October 5).

As nitrogen oxide is one of the key factors in maintaining historic buildings and collections, it is suggested to monitor the level of nitrogen oxide. Similar to the monitoring of oxygen level, the nitrogen oxide sensor can be used. By setting up an acceptance level of nitrogen oxide, some procedures can be applied if it is out of the level.

2.3 Humidity Sensor

Historic buildings and museums in World Heritage are favourite tourist spots that would attract crowd of visitors (UNESCO, 2019, October 5). If the visitors are not well managed in a site, the current state of the buildings or the collections inside the buildings may be adversely affected by the humidity generated by visitors, especially for books or textiles. High humidity causes both dust mite populations and mold colonies to grow (Public Broadcasting Service, 2019). Thus, limiting the number of visitors at a time slot in a site becomes crucial. In order to limit the number of visitors, the manual head count method at the entrance or at the ticket booth is commonly used.

2.4 Thermal Sensor

Recently, existing solutions using thermal camera can give the thermal map of a site (Abdelrahman & Schmidt 2018). A thermal map can be used to detect, track, and recognize humans without creating the privacy issue (Gade & Moeslund, 2014). If a number of thermal cameras are installed at somewhere giving an overview of the place, we can compute the total number of visitors at any time in a site (Tse et al, 2018). The humidity generated by visitors can be estimated. In addition, the thermal camera can be used for survey purpose, generating a statistic about the favourite of visitors by counting their stopping time for the collections. This minimizes the work involved in staffing.

As the environment of developing cities is complicated, conducting the conservation of historic buildings and collections in museums is likely to be harder. Using the right sensors in monitoring or collecting data would be necessary. Once the sensor device is designed and put in place, unlimited amount of data will be generated by sensor devices.

3 THE ARCHITECTURE OF IoT PLATFORM

The Self-Adaptive Sensing IoT Platform consists of a number of sensor devices and servers locally and remotely. The sensor devices are distributed in sites and operate continuously. Figure 1 depicts the architecture of the IoT platform.

In Figure 1, the architecture consists of a number of sensor devices installed in a number of sites. Depending on the conservation requirement for a site, the sensor device is equipped with some sensors, such as oxygen sensors, nitrogen oxide sensors and thermal cameras. Each sensor device is implemented by an Arduino or Raspberry Pie device. In order to enable the sensor devices to perform their role efficiently, each sensor device is equipped with a battery for backup power. The battery capacity is determined by the power consumption of the sensors in the device. Currently, the battery can support the operation of the sensor device for three days, which is good enough for the weekends.

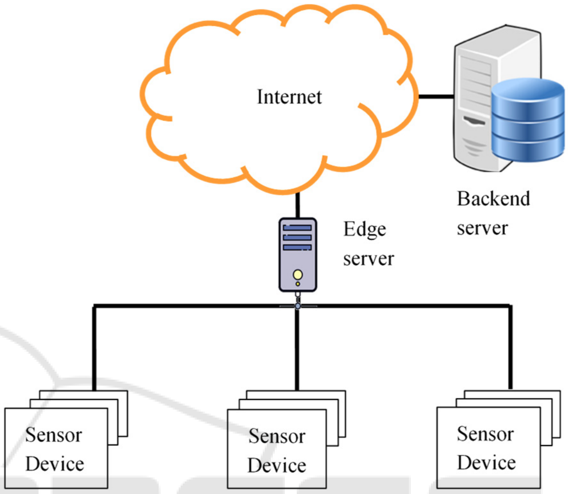

Figure 1: The Architecture of the IoT Platform.

To be scalable and stable, the sensor devices are loosely connected to the backend server using the wireless network connection, mainly relying on the Wi-Fi network. Depending on the situation, if reliable Wi-Fi network is not provided or not stable, 4G cellular network is then preferred. For contingency and efficiency purpose, an edge server is used if needed. The edge server pre-processes the data and check if the network connection is ready. If so, processed data is then sent to the backend server for further processing. The data is manipulated into a general form that allows analysis before storing. There is a local storage equipped in the sensor device and its size is big enough for 7 days of data. When a network connection is available, data will be forwarded to backend servers. In the meantime, huge amount of data is generated every day. It would raise a performance issue on data retrieval in the IoT platform. There are many solutions to resolve this issue and data snapshots are used in the platform. To minimize the data to be generated and extend the operation time of the sensor devices on backup power, we propose the self-adaptive sensing method.

4 SELF-ADAPTIVE SENSING METHOD

The Self-adaptive sensing method in the IoT platform enables the sensor device to operate continuously even though the power and network connection are not stable. Once the device is up and running, unlimited amount of data will be generated. If a network connection is available, the device may forward the data to the edge server, if any, for preliminary processing or to the backend server for processing. If not, data will be stored in local storage. As local storage size is limited, it may get full quickly depending on the size of data generated by sensors every time. As mentioned previously, sensors in the IoT platform will be strategically selected against threats. One of the selection criterions for sensors is the data size in one generation.

4.1 Data Size

The data size in one generation for a sensor is fixed. If a sensor generates b bits of data, for a number of data generations, t, in one day, the total amount of data, d, to be generated can be expressed as below.

$$d = \sum_{1}^{t} b_t \tag{1}$$

If a sensor device is equipped with $X = \{x_1, x_2, \ldots, x_n\}$ sensors, the total amount of data, D, to be generated in bits per day will be expressed as below.

$$D = \sum_{1}^{n} d_n \tag{2}$$

It is noted that the local storage, S, in a sensor device is suggested to be bigger than D in order to maintain data integrity for a certain number of days, c, such that

$$S > D \times c \tag{3}$$

Since D is determined by the fixed outputs $B = \{b_1, b_2, \ldots, b_n\}$ from $X = \{x_1, x_2, \ldots, x_n\}$ in one day, for each sensor in X, t becomes a critical valuable for D, affecting the determination of S, if c is constant. To determine the value for t, it is necessary to consider the wakeup time (another criterion) which is about the power required by a sensor when it operates.

4.2 Power Consumption

Another selection criterion for sensors is its power consumption as it is directly relating to the capacity required for backup power. In mathematical equation, the amount of power consumption, P, depends on the sensors selected to work in the sensor device, which is calculated from the amount of energy, $E = \{e_1, e_2, \ldots, e_n\}$, in kilowatt (kW), required by each sensor in $X = \{x_1, x_2, \ldots, x_n\}$ for t and the amount of energy, G, required by the system of a sensor device, such that

$$P = G + t \times \sum_{1}^{n} e_n \tag{4}$$

To ensure the backup power is sufficient to support the operation of the sensor device for a certain number of days, c, the capacity required for backup power, BP, in milliamp per hour (mAh) for the raspberry pi at 5 volts is expressed below.

$$BP > \frac{(P \times c) \times 1000}{5} \tag{5}$$

Nevertheless, the capacity of backup power is limited. To minimize the energy consumption and extend the operation time in offline, the running cycle for a sensor in next section will be considered.

4.3 Running Cycle

In the Self-adaptive sensing IoT platform, there is a running cycle for each sensor in the sensor device. In the running cycle, there are five phases which are 1) Data collection, 2) Data generation, 3) Data storing, 4) Sleep and 5) Wake up. Figure 2 shows the five phases in the running cycle.

In phase 1, the sensor tries to collect environmental data. Once, data is collected, the sensor generates data in phase 2. In phase 3, the data is then forwarded to servers if the network connection is available. If not, the data will be stored at the local storage (See Equation (3)) in the sensor device. If the network connection becomes available in the next cycle, all local data generated in previous cycles, will be flushed and forwarded to the servers (edge server or backend server). In phase 4, the sensor will be put to sleep. When it is time out, a wake-up call will be sent to the sensor in phase 5. One cycle is finished and another cycle will begin.

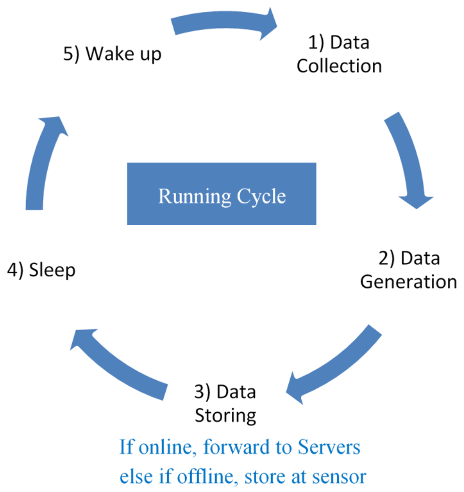

Figure 2: The Running Cycle for a Sensor.

In each phase, it takes a certain amount of time to complete its process when the power connection is stable. If the power and network connection is not stable in historic buildings, limited backup power is then needed for the sensor device. In case of power cut after hours, the backup power would operate its sensor device for data transfer when the network connection is available, and for data storing locally when the connection is not available. To extend the operation time of a sensor device, the device is better put to sleep when the data variance is stable. It minimizes the use of local storage, *S*, and saves the backup power, *BP*.

To put sensors to sleep, an issue on the wakeup time for a sensor will be raised. Another selection criterion for sensors is the wakeup time it takes after they sleep. Some sensors may take only a few milli-seconds to wake up and some may take a minute. This may create a time synchronization problem on the data. To maintain the integrity and accuracy of data, the amount of sleep time may be reduced to allow more time for a wakeup call. Therefore, when selecting a sensor, a balance between the sleep time and the wakeup time in the overall operation is needed. Figure 3 gives an overview of the operation time in a running cycle.

In Figure 3, there are three sensors connected in a sensor device, which are Sensor A, Sensor B and Sensor C. Their running cycles are of the same length, even though the portion of time for phases in a cycle varies. In Sensor A, it requires 20% of the time to wake up and 60% of the time to sleep. In Sensor C, it takes 60% of time to finish a wakeup call, which is 3 times more than its sleep time. In this case, reducing the sleep time to compensate the time taken for a wakeup call can uniform the cycle length. It avoids the data integrity and accuracy problems, and saves energy consumption.

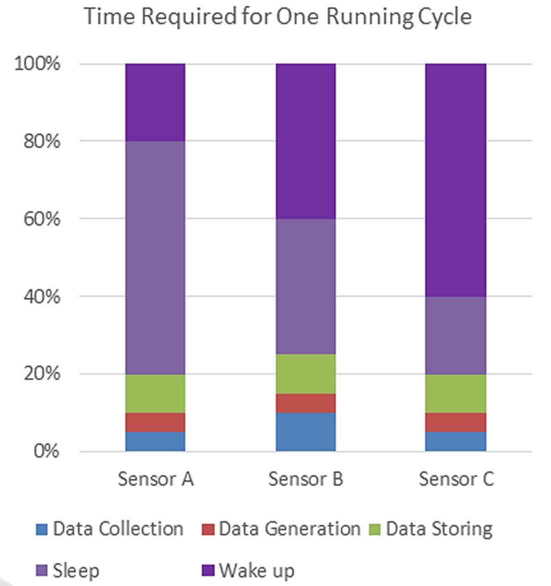

Figure 3: Operation Time in a Running Cycle for 3 Sensors.

5 ONGOING RESEARCH PROJECT

This paper is based on the ongoing research project for the Science Museum of the University of Coimbra in Portugal, which is a collaboration between Macao Polytechnic Institute, Macao SAR, China and University of Coimbra, Portugal. The project is designed for the conservation of the collections inside the Museum using this self-adaptive sensing IoT platform. Preliminarily the platform connects to a number of sensor devices, monitoring the temperature, humidity and indoor air quality (AIQ) inside the Museum, as required by the Decree Law n. 78/2006 at April 4 in Portugal. As can be seen in Figure 4, the sensor device (in green colour) was being installed in the Museum in 2018.

The Science Museum is open to the public during weekdays. When it is open, the power and network connection are available for the Museum operation. When it is closed, the power will be turned off and network connection will be cut. The IoT platform runs in the Museum and data is continuously collected and generated by the sensor device. As the platform is self-adaptive, the platform will switch to run on the backup power when the power is down.

Figure 4: Installation of the Sensor Device in the Science Museum of the University of Coimbra, Portugal.

The backup power for the sensor device is sufficient to support its operation only for three days over the weekend. As the running cycle suggested, data is collected, generated and stored. When there is no network connection, data is then stored in the device locally. Afterwards, the device checks for the network connectivity. If it is available, data in local storage will be immediately flushed and forwarded to servers.

Processed data in backend server is then downloaded by an application in a mobile phone for reference use. As can be seen in the mobile application in Figure 5, the data, such as the current PM figures, temperature and humidity, collected by the sensor device inside the museum is shown. The data is also illustrated in the line chart for a particular period of time. It enables the management to have an in-depth look of the environment in the Museum, assisting them to design policies to meet the conservation objectives.

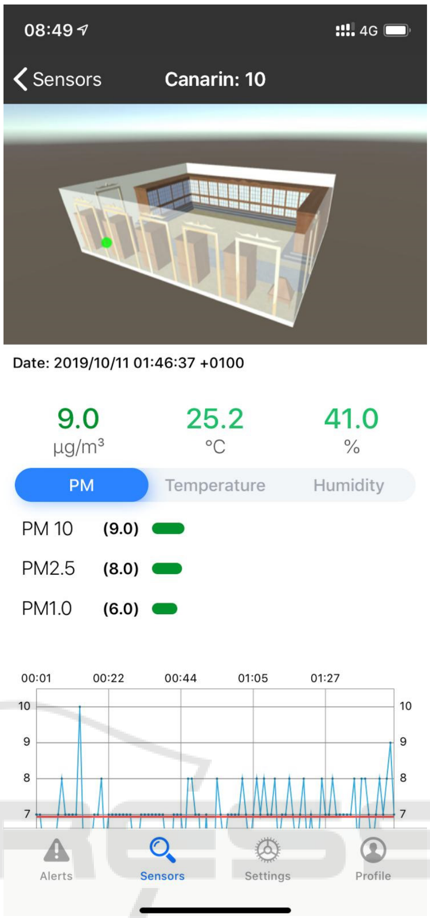

Figure 5: Monitoring Result of the Sensor Device.

6 CONCLUSIONS

The historic buildings and collections in museums need immediate conservation as there are many threats that can cause damages to them. The self-adaptive sensing IoT platform provides a solution to the conservation work. The platform implements the self-adaptive sensing method which enables its sensor devices to adapt itself to the environment with unstable power and network connection. This is a break-through in deploying IoT technologies in such an environment without causing any interruption to the conservation work. As the IoT platform has been deployed in the Science Museum, University of Coimbra, Portugal since 2018, it is shown that the conservation work is running well. This work is still in-progress and the development of sensor device is on-going as scheduled.

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