IoT System for Maintenance Monitoring of Historic Buildings – Smart Monitoring

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Abstract. Maintenance monitoring is an essential task in the field of preservation of historic buildings. The continuously developing IoT-based systems for monitoring already exist in many areas, like the maintenance of complicated mechanical systems or large industrial facilities, but there are only a few examples of the application of such methods in the field of cultural heritage preservation. In this paper, the possible elements and system of an automatized maintenance monitoring network are tested by analyzing the possible options of the survey units and the system to be established in cases of altering circumstances of the investigated site, highlighting the factors which have to be considered in the case of developing a network on-site. Finally, typical application cases were distinguished, and configuration options were suggested for the automated maintenance monitoring systems.

1. Introduction
The monitoring of historic buildings is an essential task in the case of valuable but vulnerable historic building stock. Proper regular monitoring enables immediate reaction for the intervention needs, which results in less deterioration and loss of historic fabric (Forster-Kayan, 2009). The development of diagnostic methods for maintenance purposes enables more effective monitoring (Vidovszky, 2016). There are already several examples for the application of IoTs in maintenance monitoring, as the monitoring of complex mechanical systems (Civerchia et al. 2017) or larger office buildings (Ko, 2009), but the time is seemingly arrived to use this technology in the field of the maintenance of historic buildings and sites too (Campos, 2009; Makadam, 2015; Perles 2018 et.al.; Bruno et al. 2018).

The usual monitoring approach needs a regular human presence, basically every single space of the historic sites for inspections. In contrast to that, in the case of applying IoT systems for maintenance purposes, several aspects can be monitored by IoT modules functioning as automated survey stations (Vidovszky-Pintér, 2020).

Automated IoT-based systems can support not just the maintenance activity, but even the control can be made more effective, resulting in a continuous survey and control on the most vulnerable or most problematic parts of the buildings. The advanced partially automatized monitoring has the advantage of the fastest possible reaction for the necessary interventions, which can result in even less need for change or loss of historic fabric.
In the case of automated maintenance monitoring, automatic survey stations and/or data loggers have to be established and organized to network in the investigated site. Depending on the location, the responsible organization, and the local circumstances, the system can be managed with local or remote control.

In this paper, the options of an automated maintenance monitoring system and the initial experiences with its possible configuration elements are analyzed.

2. Methods
Among the possible tools (survey stations), we can distinguish fixed and mobile units. Regarding the system's need, there are different ways of remote control of the survey stations. The system practically consists of IoT-based survey stations or data loggers, and in the case of larger systems, a central unit (i.e., data server). According to the circumstances, the server can be placed on the site or basically to any other location with a proper internet connection. The buildup of the system depends on many factors, like the site characteristics or the working method of the staff responsible for the monitoring.

2.1. Fixed units
Fixed survey stations are running surveys on a specific location and are equipped with sensors and/or cameras applied to measure or record environmental parameters. The sensors are applicable for measuring various factors, e.g., wind speed, climatic conditions, or the presence of different gases. The cameras can visually inspect the changes of various phenomena on the surface, like moisture, salt effloresces, crack movements, etc. There are many fields IoT based survey can be applied for on a heritage site:

- monitoring external weather conditions (temperature, rain, wind, air humidity, air pressure)
- monitoring of interior climatic conditions (temperature, air humidity, air quality)
- statical state measurements (measuring crack changes)
- monitoring maintenance needs (like gutter control)
- monitoring biological pests or fungus (mold control)
- monitoring deterioration state (moisture, salt, mold, stone detachment)
- seismic resonance measurement
- heat loss surveys
- etc.

For our examination, we applied two fixed survey stations. The first one was the unit prepared for our previous research (Vidovszky-Pinter 2020), a Raspberry Pi Zero W single-board computer, which was equipped with a Raspberry Pi V 2.1 camera module, a Grove Base Hat for the connection of the peripherals, a relay for the switching of the external lamp, and an SHT31 Grove FC temperature and humidity sensor (Fig 1a).

In the case of the second unit, we made some modifications. We chose a stronger Raspberry Pi 3A+ single-board computer equipped with a Raspberry Pi V 2.1 night camera module, a relay, and a DHT22 temperature and humidity sensor for measuring temperature and relative air humidity (Fig 1b).

2.2. Mobile units
Mobile units are similar to fixed ones but are also equipped with sensors and end-effectors, which making them able to change their location. Mobile units are applicable if the survey has to be done repeatedly in more than one location, not very far from each other in a site.

Mobile units can be programmed for certain autonomous works, but they can be applied by remote control too.

For our experiments, a Raspberry Pi 3B+ single-board computer based mobile unit was applied, which was equipped with a Raspberry Pi V 2.1 noir camera module and a Grove Pi to connect the
peripherals, like sensors, LCD, and motor driver (Fig 1c). The unit contains environmental sensors like DHT11 temperature and humidity sensor, moisture sensor, and light sensor. For safe movement, IR sensors were applied to avoid fell down in staissteps, and an ultrasonic sensor enables obstacle avoidance.

2.3. Systems and server
In maintenance monitoring, the system records environmental and visual data that supports the monitoring of historical buildings for preservation purposes. The goal of this research was to test the options of the possible survey system network. We tested three units and two different scenarios.

The first unit was used for testing a scenario when only single survey stations are located on the site, with direct access for the remote connection.

This claim could be satisfied by establishing a VPN connection between the remote computer and the survey station.

The second unit simulates the situation when the units have an internet connection, but no full access bi-directional connection can be established between the computers on the site and remote computers.

For this situation, we established a server in our lab, with remote VPN access, that allows us to check it every now and then, where all the data is transferred by the on-site survey stations regularly joining to the server as clients.

Figure 1 demonstrates the built survey stations.

3. Discussion
Analyzing our experiments and the possible sites to investigate the possible claims, we defined categories, assuming some survey stations at each site that either worked alone or had to communicate with a server or other stations. We distinguished five cases within three main categories and suggested five configurations for the system (Figure 2).
3.1. Experiences with the sample units
In the case of the first survey station, two 30 days long tests were executed. The remote connection was provided through a wifi router, which needed fix IP address and had to be forwarded to the router. In this way, we established direct access to the unit with a VPN. The advantage of this method is that the unit can be programmed from a remote place too. It means that codes can be changed from any location with an internet connection (by mobile phone or computer), and we had continuous remote access to all the data on the survey station.

In the case of the second survey station, the system was equipped with a server. This system was tested for 30 days. The unit needs an internet connection, but it is insensitive to its type. The advantage of this configuration is that the local units do not need more than any stable wireless connection (local wifi). The disadvantage is that they cannot be programmed remotely. The serving application cannot be changed or updated, only in-situ. In this system, the survey stations have to be self-starting. Namely, the application has to start automatically at boot. There is an option for remote access to the server and the data stored on the server, but there is no remote access to the survey stations on site.

With the mobile unit, we had only preliminary experiments yet. Mobile survey stations might need remote control by an operator to change their places. For testing of such activity, we wrote a web-based application in python (Fig. 3.), which was used at a survey of an attic performed from the ground floor of the building.

In the case of autonomous work of this unit, the navigation has to be supported by various equipment. The application of lidar units or systems supporting artificial intelligence has excellent future potential but would make the survey stations expensive. In case of applying non-expensive elements, as we did in our research, the options are much more limited, like following marked out black lines by IR sensors or using ultrasonic-based obstacle avoidance methods. The options of autonomous work of the mobile unit are under testing at the moment.

3.2. General considerations
The system on a specific site has to be developed based on the given circumstances: the needs of the maintenance activities, the amount and character of the survey stations, and the technical factors, like the available internet connection.

The monitoring of a building depends on several factors, like the age, the material, the complexity, or the state of the historic fabric. The goal of the investigation also might give different tasks.

The collected data might be wanted to be used on the site, but in other cases, access might be needed to get the data from various places. For instance, if an international research group with diverse geographic locations is continuously working on the same collected database.
Figure 3. Navigation application for the mobile unit

The internet connection on the site is either a fixed network connection or a mobile network only. In some cases, not even the mobile web is stable enough to establish a proper connection to a remote computer.

According to the above mentioned and based on our investigations, five different situations were distinguished. The configurations applied for the five situations are demonstrated in Picture 2 and in Table 1.

### Table 1. The possible survey configurations on the site

| configuration | description |
|---------------|-------------|
| A i)          | An on-site server is established with a wifi router. The survey stations are communicating with the server and with each other via the local wi-fi-network (Fig. 2 a) |
| A ii)         | The same configuration as A i) but with an established VPN access to the on-site server (Fig. 2 a) |
| B i)          | A remote server is established. The survey stations are communicating with the server via VPN, and the nodes are communicating with the server and with each other via the local wi-fi network (Fig. 2 b) |
| B ii)         | The same configuration as B i) but with an established external VPN access to the remote server too. (Fig. 2 b) |
| C             | No server is established, the survey station(s) are either forwarded by a local wifi router or connected directly to the internet, and VPN communications are established directly to survey stations (Fig. 2 c) |
For configuration A i), we do not need an established internet connection on the site. This configuration is applicable in an isolated heritage site, with no option for establishing a proper internet connection.

Configuration A ii) is recommended if the internet connection on the site enables a VPN connection to the server. It does not just allow the remote connection to the server, but via the wifi router, we can reach the survey stations too (assuming single-board computer-based survey stations with operation systems). The survey stations also can be mobile units.

Configuration B i) is a typical solution if there is an internet connection on the site, but no remote access can be established (either the survey stations work with microcontrollers instead of single-board computers, or it is not possible to get the right from the supervisor of the local network to reach the computers of the site from outside). In this case, our tools can connect to the internet via a local wifi network, but we cannot have direct access to them, and there is no option for remote work on our tools. We can still have regular feedback at the remote server, which is not on the site.

Configuration B ii) is applicable if we need access to the data collection from any place, then a VPN connection can be established to the server which is not located on the site.

Configuration C is applicable if we have a low number of survey stations. We can have access to each of our survey stations directly by static IP addresses. If the units have no LAN connectors or mobile survey units are applied (there is no option to be connected directly), we need the tools to be forwarded by a wifi router.

Table 2 summarises the options in the case of the various systems.

| system | suggested number of the survey stations | need for reliable internet connection on the site | need for VPN access | remote access to the data | option for remote controlled mobile units in the system |
|--------|----------------------------------------|-----------------------------------------------|---------------------|-------------------------|-----------------------------------------------|
| A i)   | 2<                                     | no                                           | no                  | no                      | no                                            |
| A ii)  | 2<                                     | yes                                          | yes                 | yes                     | yes                                           |
| B i)   | 0<                                     | no                                           | no                  | no                      | no                                            |
| B ii)  | 2<                                     | yes                                          | only at the remote server | yes                     | no                                            |
| C      | 5>                                     | yes                                          | yes                 | yes                     | yes                                           |

4. Summary
Systems developed for smart monitoring of historic buildings enable a more accurate, more continuous maintenance monitoring on the heritage sites. This paper discussed the experience with some basic elements and some possible configurations of such a system. According to our observations, the optimal establishment of these systems predominantly depends on the characteristics of the historic site.

5. Possible extension of the research
The system demonstrated here can be tested adequately in a real environment, for which purpose our on-site tests will be continued to extend our experiences on the system and its elements, especially on the mobile survey units.
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