DEVELOPMENT OF IOT-BASED CONDITION SURVEY UNITS TO MONITOR SALT DAMAGES ON PLASTERED AND RENDERED SURFACES•

IOT ALAPÚ ÁLLAPOTRÖGZÍTŐ ESZKÖZÖK FEJLESZTÉSE VAKOLT FELÜLETEK SÓKÁROSODÁSÁNAK MONITOROZÁSÁRA

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Abstract

Moisture and salt-induced damages are common problems at heritage sites and buildings. Efficient solutions for complex salt-related problems frequently require the in-situ monitoring of surface changes (i.e. the behavior of salts and moisture) along with the periodical presence of an observer on-site, which is a time-consuming procedure. In the frame of this study, two simple, automated units were developed in order to investigate the changes caused by salt crystallization on a plastered laboratory test surface and an interior masonry structure. We present the development of remotely managed, automated, single-board computer-based condition survey units and the preliminary experience obtained during the test phases under laboratory and on-site conditions. The tests showed that our low-budget systems are able to monitor the alterations on the surfaces and detecting the climatic changes during the measuring period. The comparison and correlation of climatic data and digital images allow a direct interpretation of the behavior of salts on the surface.

Kivonat

Örökségi területeken, védett épületek esetében általános problémának tekinthetők a nedvesség és sókárosodások okozta gondok. Az összetett sókárok hatékony kezelése gyakran igényli a sérülékeny felületek folyamatos helyszíni monitorozását (a só- és nedvességhatások viselkedésének követését), amely egyrészt időigényes tevékenység, másrészt a megfigyelő rendszeres, helyszíni jelenlétét teszi szükségessé. Jelen kutatás keretében két egyszerű automatizált megfigyelő egység fejlesztésére kerül sor a sókristályosodások által okozott változások laboratóriumi tesztfelületen és helyszíni, beltéri falfelületen való megfigyelésének céljából. A távolról vezérelhető, automatikus egylapos számítógép (single-board computer) alapú állapot-megfigyelő állomások fejlesztésével kapcsolatos előzetes tapasztalatokat mutatunk be laboratóriumi és világhálóval támogatott helyszíni körülmények között. Az előzetes eredmények alapján az általunk fejlesztett alacsony költségvetésű rendszerek alkalmasnak tűnnek a tesztfelület változásainak monitorozására és a klimatikus körülmények állapotadatainak egyidejű rögzítésére. A digitális képek és a klímaadatok összevetése lehetővé teszi a sókárosodások és a klímaparméterek közötti közvetlen összefüggések értelmezését.

KEYWORDS: CONDITION SURVEY OF BUILDINGS, AUTOMATED DIAGNOSTIC SYSTEM, IOT-BASED BUILDING MONITORING

KULCSSZAVAK: ÉPÜLETEK ÁLLAPOTFIGYELÉSE, AUTOMATIZÁLT DIAGNOSZTIKAI RENDSZER, IOT ALAPÚ ÉPÜLETMONITOROZÁS

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Introduction

Problems caused by the combination of moisture and damaging salts are well-known phenomena at heritage sites and historic buildings. The appearance of moisture and salt damage in historical and contemporary structures can be provoked by several factors, which have been discussed by many studies in detail (e.g. Hees at al. 2009; Grassegger & Schwarz 2009; Siedel 2009; Lopez-Arce et al. 2009, Brüggerhoff et al. 2009, Ferdyn-Grygierek et al. 2020).

The exact identification of salts and the interpretation of their role in provoking damages require a sophisticated approach that has to take into account many parameters of complex mineral systems. The most critical factors determining and influencing the behavior and distribution of salt systems are:

- petrophysical characteristics of the affected materials;

- the possible presence of chemically reactive and/or soluble components contained in them;

- climatic conditions of the external environment and thermo-hygric parameters of the pores;

- kinetics of reactions to achieve equilibrium under given external and internal conditions.

Due to this complexity, the successful solution of salt-related problems in conservation and civil engineering requires the combination of qualitative and quantitative analysis of the components, the determination of their distribution, and the study of their behavior under the given environmental parameters (Bläuer-Böhm 2005).

The investigation of salt-laden mineral materials comprises different analytical methods used to determine the crystalline salt phases directly by e.g. optical and electron microscopy, XRD and FTIR, or measuring the ionic composition of aqueous solutions by ion chromatography or ICP-MS (Steiger et al. 1998, Bläuer-Böhm 2005). While phase analyses offer a prompt and accurate identification of salts, and this information is often indispensable when interpreting the behavior of a complex salt system, they can only provide selective data about components crystallized on a surface at a certain time (Bläuer-Böhm 2005). On the contrary, bulk chemical analyses recording water-soluble salt components allow more detailed insight into the nature of a salt system. Nevertheless, the behavior of such systems can only be accurately interpreted if the measured quantity of ionic salt components is obtained as a function of the changing climatic parameters. Although there are thermodynamic models that can fulfil the above requirements (Bionda 2002-2005; Steiger 2009), exact sampling, accurate analytical work, and sufficient experience are indispensable factors to obtain clear results (Steiger & Heritage 2012). Consequently, the in situ, automated (long-term) monitoring of changes occurring on (rendered) surfaces of masonries along with data acquisition can provide direct information about the climatic dependence and behavior of moisture and/or salt-induced damages in the structure without knowing the exact compositions of the salts in the substrate.

Some research already established a proper system for diagnostics and monitoring of the condition of historic buildings and sites (Hees at al. 2009; Laue at al. 2009; Juling & Franzen 2009; Bruno at al. 2018), and recently the automation of some aspects of the monitoring has also been tested by Internet of Things (IoT) based technologies such as wireless sensor networks (WSN) (Madakam et al. (2015). Further interesting aspects can be found in the research of Zehnder & Schoch (2009), who applied an automated system for on-site monitoring of efflorescence on stone surfaces using suspended hand-cameras, or in the investigation of Perles et al. (2018) who applied networks of sensor nodes for data collection purposes on a heritage site.

The goal of the research was to develop a system to collect climatic data and monitor the changes (i.e. the behavior of salts and moisture) on a wall surface without continuous human presence at the same time. The used tools are IoT-based automated inspection units with Wi-Fi and web-connection, which, according to our future development plans, can later be elements of a system for the regular remote monitoring of historic sites and buildings.

The IoT devices demonstrated here were used to take digital images and detect the temperature and relative humidity automatically in previously defined time intervals making a continuous human presence on the sites unnecessary. Consequently, the above configuration allows a remote interpretation of the collected data and the constant analysis of the surface condition.

Research method

The IoT devices for condition monitoring

In the frame of the project, two units were developed. The base unit was comprised of a Raspberry Pi Zero W single-board computer (SBC) equipped with a Raspberry Pi V 2.1 camera module. The first unit (**Fig. 1.**) was used in a laboratory environment; the second one (**Fig. 2.**) was installed for on-site monitoring. In both cases Raspbian Linux operation system was installed on a 16-gigabyte micro SD card that was used for data storing at the same time.

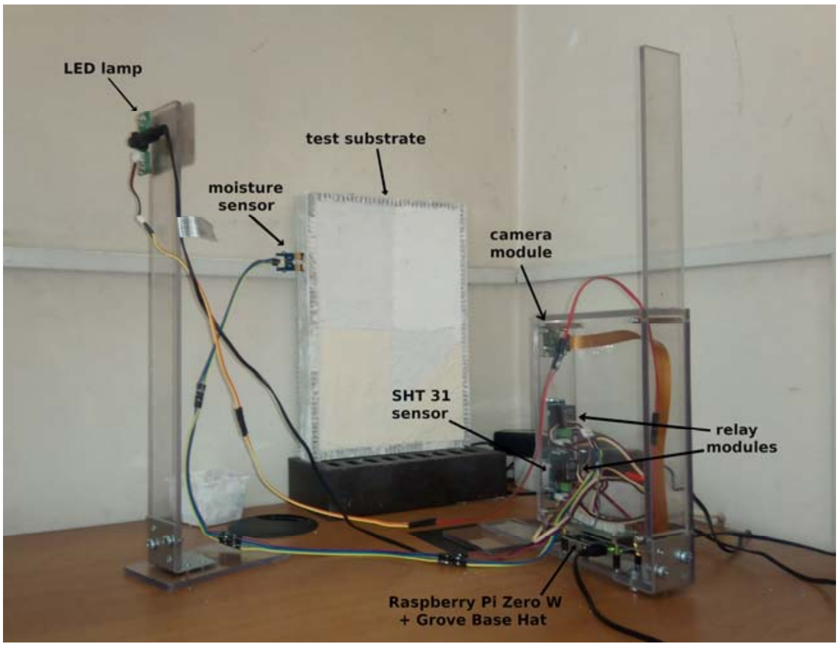

Fig. 1.: The first survey unit (IoT device): The LED lamp, the test substrate and the condition survey unit with the sensors and the camera

1. ábra: Az első állapotrögzítő egység (IoT eszköz): A LED-lámpa, a tesztfelület és az állapotrögzítő egység a szenzorokkal és a kamerával

In this setup the two units are more than a data logger or a sensing node, as both were equipped with cameras and were running a full functioning operating system.

In the first unit, the Raspberry Pi was extended with a Grove Base Hat to connect the sensors with the relays. Relative air humidity (RH) and temperature (T) were measured by a CMOSens® chip-based capacitive SHT31 Grove I^2C temperature and humidity sensor (accuracy is ±2% RH and ±0.3°C). The moisture in the test plaster was recorded by an analogue conductivity moisture sensor (Grove Moisture Sensor v1.4) placed 20 mm into the substrate (**Fig. 1.**). To ensure stable light conditions for the digital images, an LED lamp was used that was supplied by electric power individually.

Two relays were used to switch the LED light and to switch off the power of the moisture sensor to reduce the possibility of its corrosion in the substrate.

The second unit (**Fig. 2.**) was equipped with a DHT22 capacitive temperature and humidity sensor (accuracy is ±2% RH and ±0.5°C) and a 3.3V relay for switching a USB LED light connected directly to the SBC, so the light this time was fed from the same power supply as the Raspberry Pi Zero.

The cost of the first monitoring unit was round €130, not counting our own work with the assembly. Nevertheless, it was aimed to mitigate the expenses at the other hardware by reducing the number of its components to the minimum requisite, so this second unit cost around €100.

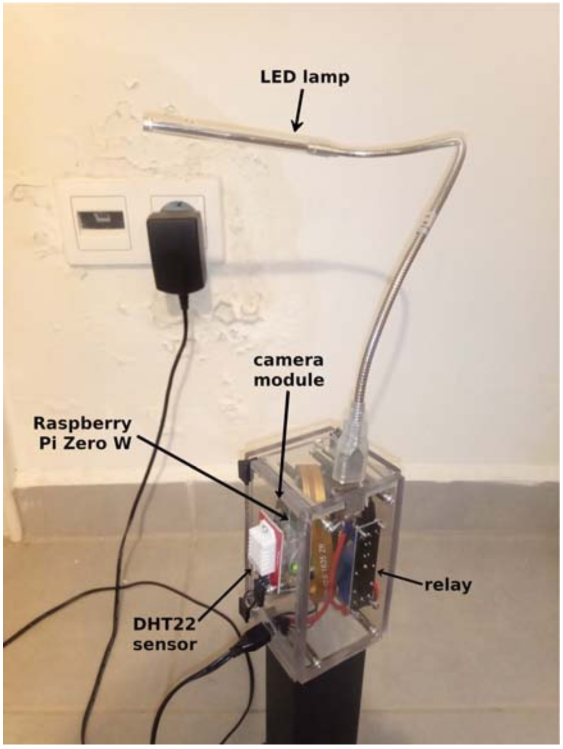

Fig. 2.: The second survey unit (IoT device): LED lamp and condition survey unit

2. ábra: A második állapotrögzítő egység (IoT eszköz): LED lámpa és állapotrögzítő egység

Data acquisition of the units

For taking digital photos, recording the measured values of the sensors, and controlling the relays of the system, Python codes were written. Both survey units recorded the values of the sensors every two hours and took one digital photo every day. The data were recorded to a text file; the images were saved in a folder on the single-board computer. The first unit was running for preliminarily defined durations. In the case of the first unit, the system was running for 11 months from June 2019 to May 2020. The second unit has been running since the end of April 2020.

The devices – in case of there is internet access on the site – can be controlled remotely, which option was also used for regularly checking the operation, because there are always planned and unplanned events after which rebooting of the system is needed (e.g. power cuts at network maintenances, etc.). To control the units comfortably from a personal computer, manage the software and up- and download data from the system, the VNC Viewer application was used. This was particularly useful to access the units from a distance during the days of the epidemic during the spring of 2020.

The test substrate

To test the first automated survey unit a plastered test surface was produced. The test mortar substrate was prepared in a frame made of aluminum sandwich panels. The plaster was produced of lime putty and quartz sand with a binder to aggregate ratio of 1:4 and applied in two layers. The surface finish of the substrate was prepared differently in the four quarters of the plaster with rendered, smoothed, yellow ochre paint applied in various diagonal patterns (**Fig. 1.**) to create alternating optical environment for the expected efflorescence.

The preparation of salt tests on the test plaster

In the side of the frame of the sample substrate, 45mm deep holes were bored in order to inject saline solutions and water into the plaster. Initially, sodium chloride (NaCl) was injected, followed by calcium nitrate ($Ca(NO_3)_2{\cdot}4H_2O$) solutions several times. Saline solutions of low concentrations were used deliberately in order to avoid an abrupt efflorescence on the surface. However, because after the first three weeks of test period, no changes could be detected on the surface, it was decided to use a saturated NaCl solution to accelerate the crystallization of the salt. Additionally, once a week (altogether 58 times during the experiment), 6 ml of ordinary tap water was also injected to the substrate to ensure enough moisture in the capillary pores and to have the salts transported towards the surface.

The on-site test

The second IoT device (**Fig. 2.**) was placed at a site where recently an unexplored moisture problem had been detected. The possible reason is the malfunction of the building installations in an 80 years old, slightly neglected building, where presumably leakage from a water pipe caused a continuously extending stain and efflorescence on the wall (see **Fig. 2.**).

Results and Discussion

Due to the short-time experience with the second device, only the experimental experience obtained with the first unit will be discussed in detail.

Due to the low effectiveness of the original diluted salt solutions used to provoke a salt efflorescence on the surface, in the first three months (i.e. from June to September 2019) no visible changes could be observed on the digital images automatically taken of the test plaster surface. Only the addition of a series of saturated NaCl solution and tap water injections in several steps provoked the first observable efflorescence on the test surface. Fig 3. shows the development of the NaCl efflorescence during the period of September 3 and 30, 2019. While in the first days of the month (**Fig. 3a**) no visible surface change was observed, a couple of days later (**Fig. 3b**) small crystals appeared on the plaster. In the following weeks (**Fig. 3c-e**) and months (**Fig. 4.**) the efflorescence grew continuously. Regarding the deliquescence point of NaCl (75% RH) it is obvious that the relative humidity (RH) during the test period was clearly below 50% RH and thus below that point where sodium chloride could dissolve due to hygroscopicity.

This indicates that the crystallization of the salt was only controlled by the evaporation of water on the surface and subsequent dissolution / re-crystallization phenomena could not be observed because of the low and fairly stable RH. Since the test substrate used cannot model real conditions in a masonry, the above observation was only used to test the function of the device and correlate the visual observations with the climatic measurements.

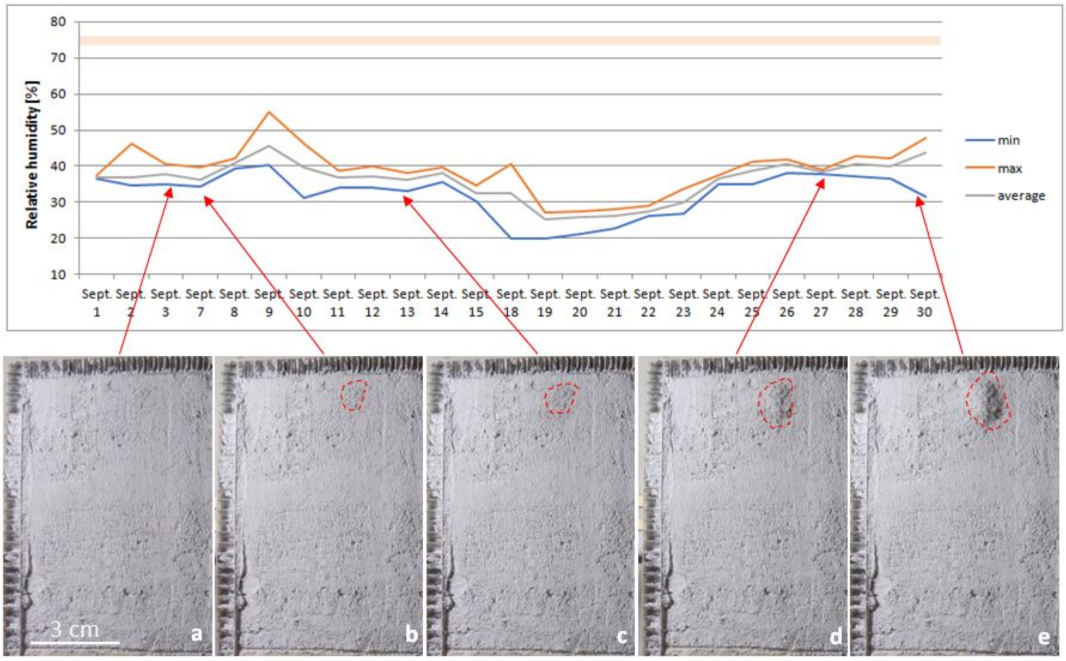

Fig. 3.: RH measured in September 2019 and digital images taken in the same period show the appearance and growing of NaCl efflorescence on the test plaster surface (a) September 3; (b) September 7; (c) September 13; (d) September 27; (e) September 30. The pink line at ca. RH 75% show the deliquescence point of NaCl

3. ábra: A 2019 szeptemberben mért relatív páratartalom és az azonos időszakban készített felvételek jól mutatják a vakolt felületen a nátrium-klorid megjelenését (a) szeptember 3.; (b) szeptember 7.; (c) szeptember 13.; (d) szeptember 27; (e) szeptember 30. A rózsaszín vonal kb. 75% relatív páratartalomnál a NaCl elfolyósodási pontját mutatja

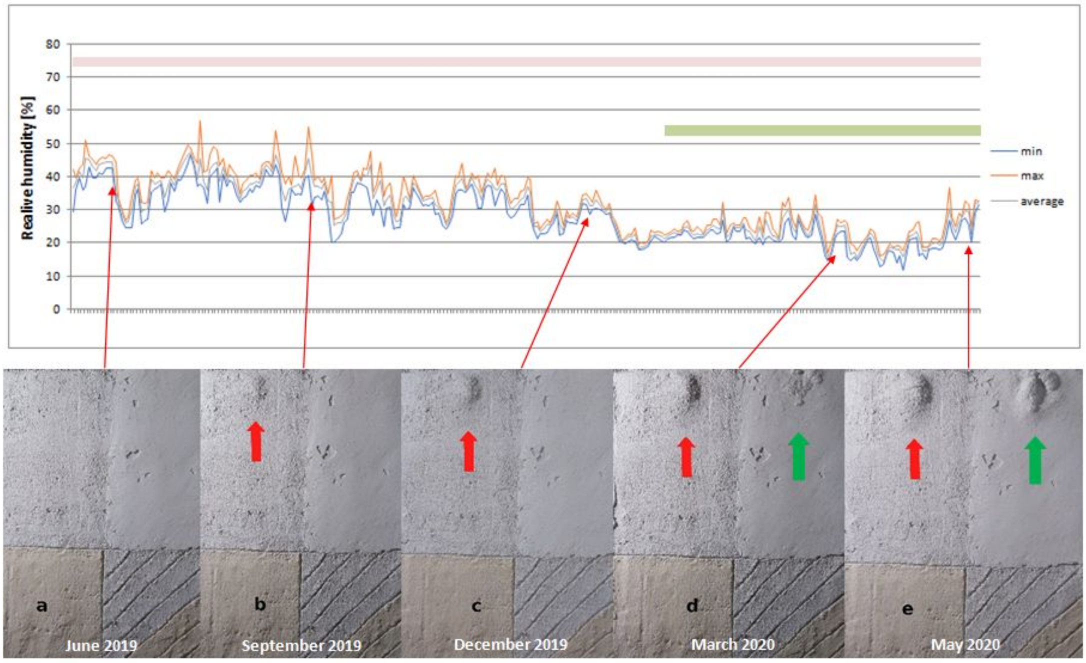

Fig. 4.: Variation of RH between June 2019 and May 2020 and the crystallization of NaCl (red arrows) as well as calcium nitrate (green arrows) on the test surface. The pink line at ca. RH 75% shows the deliquescence point of NaCl, the green one at 53% that of calcium nitrate. Raking light pictures were taken by the first survey unit. (a) state 1: June 2019; (b) state 2 - September 2019; (c) state 3 - December 2019; (d) state 4 - March 2020; (e) state 5: May 2020.

4. ábra: A páratartalom változása 2019 június és 2020 május között, valamint a nátrium-klorid (piros nyilak) és a kálcium-nitrát (zöld nyilak) kristályosodása. A rózsaszín vonal kb. 75% relatív páratartalomnál a nátrium-klorid, a zöld vonal 53% releatív páratartalomnál a kálcium-nitrát elfolyósodási pontját mutatja. Az állapotrögzítő eszköz által oldalfényben készített képek: (a) 2019 június; (b) 2019 szeptember; (c) 2019 december; (d) 2020 március; (e) 2020 május

Nevertheless, the constant low RH in the laboratory room correlates well with the increasing amount of salt on the surface during the measuring period.

The same phenomenon was observed in the case of calcium nitrate (**Fig. 4.**). Although, the decision for a salt having a relatively low (i.e. 53% RH) deliquescence point (see green line in **Fig. 4**.) was deliberate, even this value was too high to observe crystallization and dissolution phenomena due to RH fluctuations. Consequently, calcium nitrate efflorescence appeared on the surface after a series of injection in March 2020 and remained in crystalline phase until the end of the test series.

Due to the short period of testing (i.e. five weeks) only limited experience could be obtained with the second unit.

Nevertheless, in this short time both the camera and sensors worked properly, and the changes on the surface were visualized (**Fig. 5.**).

Comparing the RH data and digital images, the continuous growth of the stain and subsequent salt crystallization at RH values between 28 and 55% can be observed. Although the composition of efflorescence was not determined, the continuous crystal growth at relatively low RH indicates that the salts causing the damage are stable at these climatic conditions and are therefore probably of non-, or slightly hygroscopic types with higher deliquescence points (i.e. alkali sulphates, alkali nitrates, etc.).

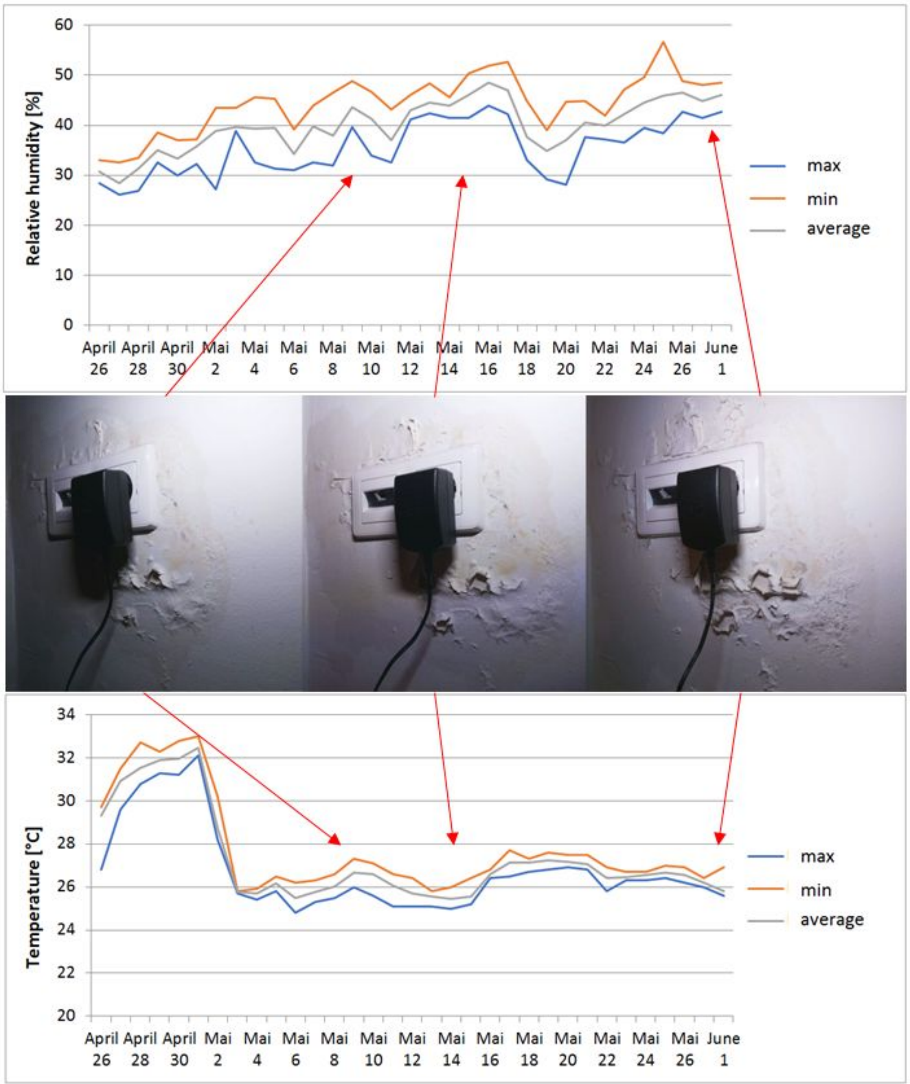

Fig. 5.:
Variations of RH and temperature values from the second unit and the expanding coat on the wall

5. ábra:
A relatív páratartalom és a hőmérséklet változásai, valamint a felpattogzó festék és vakolati mállás a falon a második egységnél

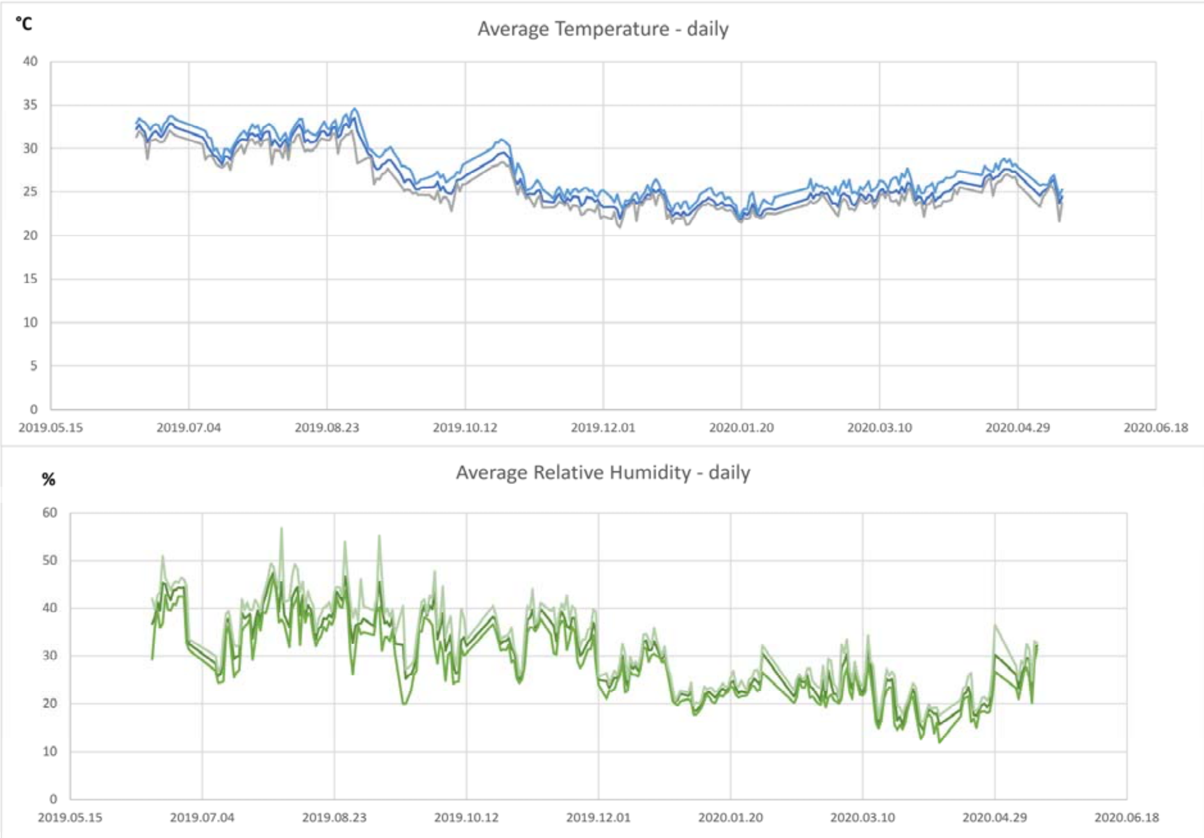

Fig. 6.: Data from the first unit - Changes in the climatic parameters (daily minimum, maximum and average values: temperature = blue, relative humidity = green)

6. ábra: Az első egység által rögzített adatok - a klimatikus körülmények változó paraméterei (napi minimum, maximum és átlag értékek, hőmérséklet = kék, relatív páratartalom = zöld)

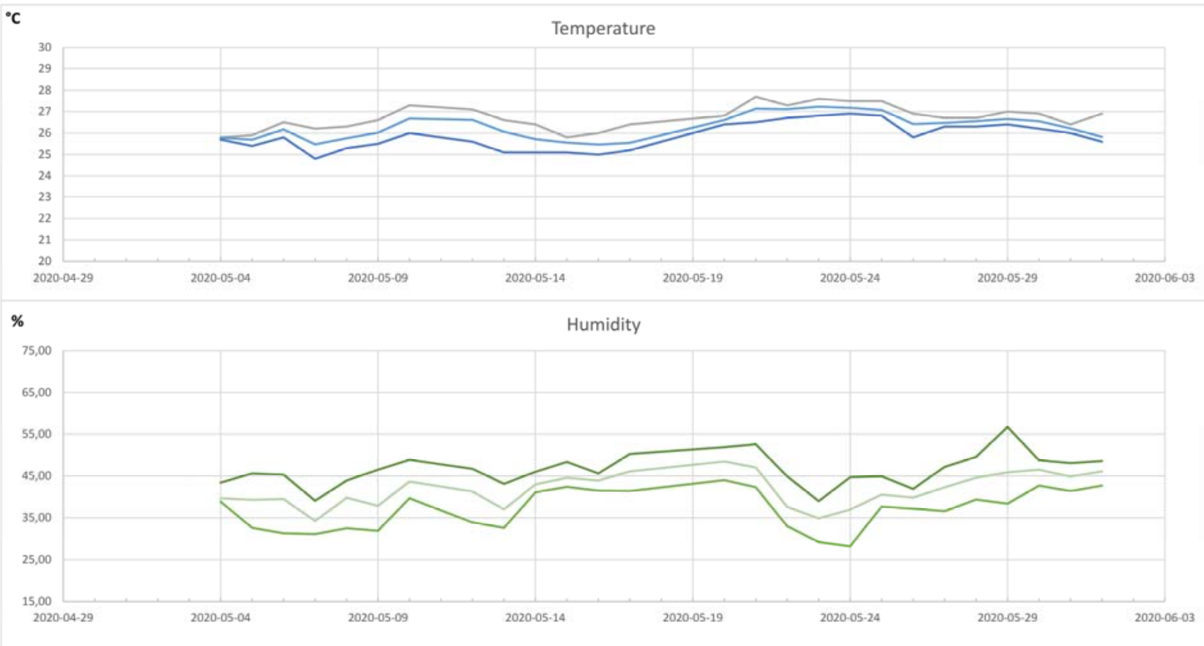

Fig. 7.: Data from the second unit - Changes in the environmental circumstances (daily minimum, maximum, and average values: temperature = blue, relative humidity = green).

7. ábra: A második egység által rögzített adatok - a klimatikus körülmények változó paraméterei (napi minimum, maximum és átlag értékek, hőmérséklet = kék, relatív páratartalom = zöld)

The sensors

In the case of the first unit, the SHT31 Grove I^2C temperature and humidity sensor worked properly. The daily environmental circumstances were recorded without failure. The average values of the daily recorded temperature and humidity data are demonstrated by the diagrams in **Fig. 6.** The contact moisture sensor, however, seemed to be idle, because of the low sensitivity to the moisture in the solid structure. These data were validated by secondary measurement with a Voltcraft MF-90 capacitive moisture meter. According to the validating instrument, at a distance of 15-20 cm from the location of the injections the moisture content of the sample substrate was approximately 30%; close to the efflorescence (at the place where the built-in sensor was placed) the value was approximately 45%. The built-in sensor, however, showed no relevant changes regarding the values. Testing this sensor independently from the system showed that even at 100% moisture the values did not fluctuate, so this sensor type, which was developed to indicate soil moisture, was considered to be inadequate for our goals. This observation corresponds with the experience of other authors (Bayer et al. 2010) indicating that sensors based on conductivity measurements have only limited accuracy in measuring the moisture content. Nevertheless, it has to be mentioned that the measurement of moisture in a masonry by devices based on conductivity or capacity are always affected by other factors (i.e. the presence of damaging salts) that can alter the results (Bayer et al. 2010). Therefore, data obtained by the above methods need to be interpreted critically, however, additional methods (i.e. salt analyses, measurement of moisture by gravimetry, etc.) may help interpret and/or correlate the values.

The DHT 22 sensor in the second unit worked adequately for measuring both temperature and humidity data (**Fig. 7.**). Therefore, its environmental data can be used to compare their relation to the surface phenomena (Fig. 5.).

Conclusions and outlook

Based on the preliminary results and experience of our investigation, it can be stated that automated monitoring is possible with the means of custom made, simple single-board computer-based and sensor-equipped IoT devices, like the ones presented in this paper. Comparing the two versions, it can be stated that both devices were equally appropriate for the tasks. They are capable of recording the development of efflorescence and the changes of surface deterioration of salt-laden surfaces of historic and modern masonry structures as well as the changes of environmental data, such as temperature and relative humidity. Salt damages triggered by climatic variations and/or moisture in the masonry can be easily recorded. Results may support conservators, conservation scientists, and maintainers to take appropriate actions to reduce possible damages. The use of such systems has an undisputed benefit when sampling is limited due to e.g. the artistic value of the surface and/or the ability to have constant human presence at the site is hard to realize. Additionally, long-term monitoring also supports the knowledge and experience obtained by analytical measurements and thermodynamic models.

A further attempt was taken to create a smaller and cheaper condition recording unit with a simpler architecture based on microcontroller instead of single-board computers. The use of an *ESP-32-CAM* and *Sipeed Maix* development boards were considered as possible alternatives, equipped with a DHT22 humidity and temperature sensor, and a USB lamp switched by a relay module as it was accomplished in the case of the second unit. In this case, the price of the unit would be round € 70-75; however, based on the initial experiences, this type of device will need further testing and development to serve our goals.

Based on the first successful tests and experience obtained by the prototype and the beta unit, it is planned to conduct further on-site tests under real circumstances to provide valuable information about the coherence of the climatic data and the changes on the surface of salt attacked masonry substrates. Additionally, on-site monitoring will be completed by sampling and subsequent laboratory analyses (i.e. IC, SEM-EDS, XRD, etc.) of effloresces and substrates; chemical data be interpreted by a thermodynamic model (Steiger, 2009) in order to validate and better understand the result of the non-destructive monitoring.

The long-term goal of the project is to organize the monitoring units into a wireless sensor network (WSN) system for continuous on-site surveys not only at salt-laden historic masonries, but for general monitoring of historic buildings.

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