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LOOKING AT YOUR MONUMENT FROM YOUR OFFICE DESK

A system to monitor on-line salt decay on walls

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Abstract. This paper introduces a scientific application of networked computer technology composed of digital cameras, light sources and climatic sensors for studying the salt crystallization processes on the historic walls of the cathedral of Basel, Switzerland. Salt crystallizations can destroy walls including wall paintings. So far short-time behavior of salts on historical objects has not been monitored due to technical or financial limitations. Pervasive computing technology enables the real-time monitoring including remote control of the set-up and data transfer through Internet. This offers new possibilities in research, such as studies of short time behavior, analysis of digital movies and automated post-processing.

1. Introduction

Cultural heritage is endangered by salt attack. Wall paintings which are integral parts of monuments are particularly sensitive to crystallizing salts. They are prominent works of art and at the same time the very vulnerable skin of an architectural structure. Our project aim is to monitor salt activity on a historical object with a greatly increased accuracy as well as on-line and non-destructively. Our special challenge was to develop the appropriate tools by using “cheap consumer electronics”. This paper describes the realized monitoring set-up and its use in an important historical building: the crypt of the cathedral in Basel, Switzerland (Figure 1 left).

Salts originate from the environment (soil, atmosphere and various other sources) and from the building materials themselves (stones, mortars, concrete etc.). Moisture which penetrates and percolates buildings is always a diluted salt solution. Salts accumulate, concentrate, crystallize and produce damage where water evaporates. When salts crystallize in porous structures, they exert pressure on pore walls. If the crystal growth pressure is higher than the tensile strength of the material, cracks and visible damage are the
result (Figure 2). When salts crystallize on the surface, they alter the visual appearance of the surface.

Classical visual monitoring of the salt activity (2 - 4 observations per year) including analogue images combined with continued climatic measurements revealed major seasonal crystallization cycles which related to major air humidity cycles due to heating (Arnold et al. 1991). Based on this knowledge, measures to improve the climatic conditions have been undertaken in Basel since about ten years. As a result of this previous research, indoor climate variations could be smoothened by means such as closing doors and windows, impeding thermal impacts and by a temporarily operating humidifier. This concept resulted in a considerable passivation of accumulated salts and hence an over-all mitigation of damage. However, salts kept on crystallizing on a lower intensity level and at shorter cycles. The external influences which trigger them are not yet understood. In accordance with other researchers (Sawdy and Price 2005) it was realized that small climatic variations cause crystallization cycles which had been overlooked until now due to a very rough monitoring concept.
In order to better understand these processes, we developed a monitoring system composed of digital cameras, light sources and climatic sensors, all controlled by a computer on site which is connected to the Internet. The concept of automated monitoring is not new (Trapp 1994; Berling and Newe 1994; Heritage 2000; Gowing 2003). However, it has not yet been implemented successively for the considered topic. Our system allows an accurate and continuous visual monitoring of the salts on-site and the correlation of the visual information with local climatic data. This offers a number of novel possibilities:

1. remote measurement and remote control
2. higher frequency in data acquisition
3. on-site processing of data
4. post-processing of data
5. scalable and modular setup

With the new ability of Internet-based remote measurement and remote control, the need for traveling is massively reduced in relation to the amount of information that is achieved. In addition, the frequency of monitoring is accelerated strongly from few observations per year to virtually continuous monitoring. Current setup takes data and images every 6 hours. Furthermore, the potential of post processing the large amount of data is enabled. By this, methods known by data-mining are expected to show scientific novelties.

2. Experimental Set-up

2.1. PHYSICAL SYSTEM

The general idea of the physical set-up is to combine digital cameras, light sources and climatic sensors in a single system which can be controlled and connected to a computer. As this system has to be positioned in historical objects open to the public, one requirement is that the instruments are protected in a closed box. A second requirement is that the cameras have to be easily moved to different positions because the precise location where salts will crystallize might change during the measuring period. These have led us to design a box made of aluminum profiles and black plastic sheets which can be easily mounted and dismounted (Figure 3). Within the box up to three cameras can be located and easily moved in the three directions. An array of iron blocks at the bottom of the box provides mechanical stability, an important characteristic if images of exactly the same locations want to be taken for long periods of time. The cameras are digital cameras (Nikon D70s) with 6 mega pixels provided with either a macro zoom objective (28-105 mm), a wide angle objective (12-24 mm) or a micro objective (20 mm f/2.8D inversed). This is because we would like to get at the same time close-up images to monitor the growth and dissolution of the single crystals and overview images to detect changes in the overall salt distribution.
cameras are set to record raw images and are connected by USB to the ports of the controlling computer (Figure 6).

![Figure 3. Left: Installation of computer in void under staircase. Right: Detail of camera 1 and climatic sensors (lower right).](image)

Crystallizing salts appear as thin whiskers and powders on the surface of the wall. Typical dimensions of crystals are 1-100 microns in thickness and 0.1-10 mm in length. They are imaged at best when they are illuminated by raking light. Another important characteristic of the light source is to provide as little heating as possible (which would influence the local climatic conditions), constant color and as little emission in the UV region of the electromagnetic spectrum as possible. Indeed, UV emission is responsible of fading of pigments, a degradation which has to be absolutely avoided. This has led us to choose fluorescent bulb light sources produced by Osram in the series Lumilux® (FH14W/865 HE) with a power of only 14 watt. According to the spectra given us from the producer, below 400 nm they have an emission lower than 5 milliwatt/5nm*sr*1000cd apart from a peak of 30 milliwatt/5nm*sr*1000cd at 365 nm. The lights are located on the side of the box and are switched on only during the exposure time of the cameras. Switching is done automated by the central computer.

It is known that crystallization and dissolution cycles of salts depend, among other factors such as water transport and ionic system in the wall, on the local relative humidity and temperature. The system therefore also comprises small temperature and relative humidity sensors which can be placed in great vicinity of the wall. The sensors produced by Hygrosens Ltd. are capacitative sensors and thermistors combined in a single body with the shape of a pen-stick. They have an accuracy of ±2% RH and ±0.3°C. They have a USB socket and are connected to the controlling computer (Figure 6).

At the moment we have installed this system in the crypt of the cathedral in Basel, Switzerland, and monitor crystallization cycles at three positions at the north wall. Figure 4 shows this section of the wall with positions of the cameras used and the distribution of efflorescing salts. Classical surveys of the wall in the period from May 2005 to May 2006 have evidenced the presence of different areas of active salts: one area with epsomite efflorescence (MgSO₄·7H₂O; camera 1), a second area with mainly mirabilite/thenardite efflorescence (Na₂SO₄·10H₂O/Na₂SO₄; cameras 2 and 3) and a third area with gypsum efflorescence (CaSO₄·2H₂O; camera 4). In addition to a climatic sensor which is representative of the room, the microclimate near the wall is monitored with two combined RH and T sensors at different distances from the wall and one surface temperature sensors in contact with the wall in the mirabilite and epsomite areas.
2.2 DIGITAL SET-UP

In brief, a local network is set up on site that records data (numbers and images), stores this data locally and copies the data on a data-server at ETH Zurich at given times (four times a day). The transmission is done through a standard Internet connection using a local DSL access. At ETH Zurich the data is analyzed. The settings of the installation in Basel can be adjusted from anywhere using an Internet browser.

In this set-up the research institute at ETH Zurich, located in Zurich, Switzerland, is connected to Basel Cathedral through the virtual space of the Internet. While the distance between the two physical spaces is to be completed within one hour travel time (Figure 5), the monitoring system allows virtual permanent presence and interaction (remote control). Based on
connectivity with conventional computer technologies, instruments such as thermometers, hygrometers, light sources, light-switches, cameras and control unit were carefully selected to fulfill both the requirements of scientific research and digital controllability. Digital controllability was defined to use Internet standards for communication and storage. This includes file formats (such as .raw and .jpg), means of communication (TCP/IP, browser based interaction, ftp, DynDNS-service, VPN IPsec, USB) and hardware (Dell® PC using RedHat® Linux, Draytek ADSL router, Barix® IP power-switch). Sensors such as digital cameras and sensors for measuring humidity and temperature were chosen due to quality reasons and open connectibility to the customized software.

Based on previous experiences in handling pervasive computing technologies (Schoch 2006a), we defined the topological structure of storing data. Being aware of the fast changes of digital technologies, simple file-formats were chosen that nevertheless offer high-quality storage. This includes a well-reflected file-naming system. For handling the values obtained from the temperature and humidity sensors, comma-separated-values-files (.csv) were chosen. The cameras are set to take raw images. These are kept as master copies and no operations are effectuated on them. The raw images are copied in TIF format and in JPG medium quality format for the purpose of analysis and use. All files follow the naming-format “city_sensor_year_month_day_hh_mm_ss.xxx” which allows easy handling of files independently of operating systems and expert-software (e.g. bs_Camera_1_2006_09_21_16_18.NEF).

The physical installation in the cathedral was essentially possible due to the intensive and successful collaboration with the cathedral workshop. Thanks to their professional help, both hidden space in the crypt was made useful for storing devices and the visible installation a public showcase for visitors (Figure 1 right).

Figure 6 presents the technical set-up of physical devices. The large number of cables installed guarantees constant transmission of data but results in a need of structured planning and installation. Wireless sensors are still too expensive and have loss in quality of service. Luckily, the spatial conditions in the Romanesque crypt offer various niches for storing cables and devices in a non-invasive manner.
Figure 6. Topology of the IT infrastructure on three locations.

The central software runs on the server on site. Using the functionalities of the cron-deamon on Linux systems, the triggering of repetitive tasks is automated. Modular software-architecture allows easy modification and expandability of both software and hardware. The module for taking images is based on “gphoto”, a freely available tool that connects to most digital cameras. The module for switching light easily connects through http-protocols to an IP-enabled power switch. Other software modules handle the data acquisition from the USB sensors and the file transfer to the server at ETH Zurich. External computer scientists embedded the system in order to assure stability of the system. This was done as none of the project’s core members are educated programmers. For overall control, a web-browser is used for controlling the modules and therefore allowing comfortable interaction.

3. Architectural Dimension

With the advent of pervasive computing, the discipline of architecture is facing new challenges. As pervasive computing shows the need for designing new services, the classical process of creating spatial entities is expanding. The expansion is based on the possibilities and limitations this “new material” (Schoch 2006b) is offering. Its invisibility as well as sustainable impact (Schoch 2006a) is one characteristic of the potential. The installation described in this paper is seen as another proof of the basic thesis that computers integrated into build environment have a strong positive
sustainable impact. Its impact is characterized by offering the cultural heritage to a larger audience over longer time; its energetic impact is defined by the extended life-cycle within different major renovation works.

Figure 7. Comparison of images which were simultaneously taken on 8 June (left) and 10 July 2006 (right) by camera 1 (top; image width 10 cm), camera 2 (upper middle; image width 12 cm) and camera 3 (lower middle; image width 50 cm). They show two different stages of salt efflorescence. Efflorescences are more intense on 8 June and have partly disappeared till 10 July. This correlates with a humidity increase of the climatic evolution (bottom).
4. Results

Single photographs taken every 6 hours in the crypt of the cathedral of Basel were “stitched” to Quicktime® movies in order to visualize alterations of efflorescences taking place within days and weeks. As an example, this time-lapse photography shows the following evolution in the period from 23 May to 23 July 2006 (Figure 7):

**Camera 1:** Efflorescence covers the whole surface but is most developed in a fringe-like zone (outlined in Figure 7). In this zone it becomes denser until about 8 June (after 16 days). In the same zone, a dark spot (probably due to moisture increase) develops around 8 - 12 June. Thereafter the efflorescence decreases in the active zone, i.e. it is gradually dissolved. Short-time changes in the form of visible fluctuations of a few days are superimposed to this general evolution.

**Camera 2** shows an “agitated” (fluctuating) alteration of salt crystal aggregates particularly in an upper zone (outlined in Figure 7). In the first 16 days the efflorescence becomes denser. It looks like aggregates are pushed up and twisted by new crystals growing underneath. Thereafter the efflorescence is gradually disappearing. Aggregates in the air (above the surface) are contracting and agglutinating; crystals in contact to the stone surface are vanishing, i.e. dissolving. At the same time a bright area at the lower left corner gets darker.

**Camera 3** shows a bright (looking dry) stone surface during the first 16 days which darkens afterward.

This evolution corresponds to an indoor climatic change from dryer conditions (70 - 75% RH) at the beginning towards 80 - 90% RH after the 12 June. Near-surface sensors in vicinity of camera 3 recorded lower temperature (minus 1 - 1.5°C) and higher humidity (plus 5% RH) compared to the values in the center of the room.

**Camera 4** (which was installed at the end of August) has an image width of 7 mm and thus provides a resolution of 2.3 microns per pixel. The sequence taken during the first half of September shows detaching and falling off sand grains as well as salt crystals of 10 - 30 microns which appear, move in position by some tens of microns and disappear again.

In conclusion, the realized on-site, long-term and high resolution photographic monitoring discloses even minimal changes and phase transitions of salts. This new insight must be substantiated and closely evaluated during the ongoing project.

5. Open questions and practical issues

At present there are still basic technical and scientific questions to be answered:

- How stable and reliable is the whole system, its components, its coupling and interplay in the long run? How rapidly can defects be localized and repaired?
- What is the resulting design for an improved system? Which technical improvements (new devices on the market) should be tested and implemented?
How can the basic system be applied to other risks and damage processes? (e.g. detachment of wall paintings; condensation and wetting phenomena)
How does moisture (which penetrates the walls from the outside) influence the salt activity?
How to zoom-in further onto environmental (physical and chemical) conditions of crystallization and dissolution?
Which computational means of post-processing can be applied in a meaningful way using the large amount of data collected? Processes known in Computer Graphics and Computer Vision can deal with computer based interpretation of 2D images. What is their impact on the research in cultural heritage?
How will wireless sensor networks change the possibilities in monitoring built heritage?

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