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IoT-powered remote sensing system and portable tools for real-time evaluation of strain imaging sheets affixed to old outdoor structures

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ABSTRACT

Photonic crystal-based strain visualization film is promising for detecting the age-related deterioration of large man-made structures and public infrastructures.[1] However, as the number of target structures increases, monitoring them all will become a major problem. We propose two solutions: (1) a portable solar-battery-powered automated monitoring station to monitor the color of photonic coatings, and (2) the application of real-time image analysis using mobile phones to record color changes. Both solutions make use of the power of small computers, while the former assists us with efficient data collection, and the latter helps non-experts to inspect structures without using expensive spectroscopes.

The portable monitoring station consists of a micro-computer connected to a 3G mobile network, a USB camera and a solar battery system installed in a waterproof box. Photographs of the strain visualization film are taken once every hour and, at all other times, the computer disconnects the camera to save electricity. We placed four monitoring stations in the shade of a bridge or a tree and ran them continuously for more than a year.

The application displays a real-time image in which only the strain-free area of the film is extracted. As a result, the region under strain and the background appear in white. This software runs on many mobile computers with built-in cameras and with OSs including Android, iOS, Windows and Linux. This is possible due to the versatility of the computer vision library we used, namely OpenCV, which widely used in robotics and automatic car-driving.

Keywords: photonic crystal, structural color, strain sensor, internet of things, outdoor monitoring system, bring your own device, real time image analysis, computer vision

1. INTRODUCTION

The Genoa bridge collapse in August 2018 has raised safety concerns over the maintenance of old bridges. Battery-free deterioration sensors have attracted attention but may become less interesting if there is no way of acquire data remotely and/or from a large number of sensors. This has been true for our sensor, namely photonic crystal-based strain visualization film, whose color changes when stress acts along its surface[2] (see Fig. 1). Since this function is promising for detecting signs of the age-related deterioration of large man-made structures and public infrastructures,[1] we must develop a technique for remote diagnosis and smart data acquisition to avoid the need to visually inspect each structure individually.

Here we propose two solutions. The first is a remote sensing device, namely a portable solar-battery-powered automated monitoring station to monitor the color of the film. The device consists of a micro-computer connected to a 3G mobile network and installed in a water-proof box, a USB camera and a solar battery system. Power-saving technology is the key to realizing this device.

The second is a portable analysis tool with which non-experts can evaluate the film and report the results to data archivists via e-mail. Namely, the tool is an application installed in their mobile phones/tablets that extracts changes in the film color by using real-time image analysis.

Both solutions make use of the power of small computers, while they have different approaches to data acquisition; (a) automatic operation with IoT technology and (b) making use of human resources with a “bring your own device” (BYOD) approach (see Fig. 2). We believe that these are complementary solutions for the maintenance of large old man-made structures.

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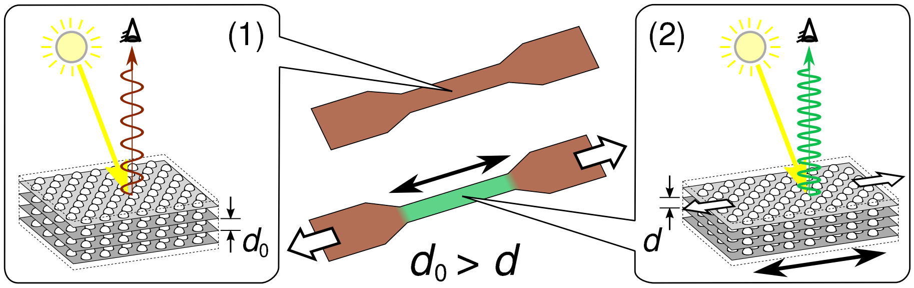

Figure 1. Mechanism of stress induced color change in photonic crystal film in which sub-micron polystyrene colloidal particles are arrayed in silicon elastomer. (1) The film's original color principally depends on the lattice spacing, d_0, which determines the wavelength of the reflected light. (2) As the film is elongated by the application of tensile stress, its thickness decreases and its lattice spacing, d, thus becomes less than d_0 and the wavelength of the reflected light is reduced.

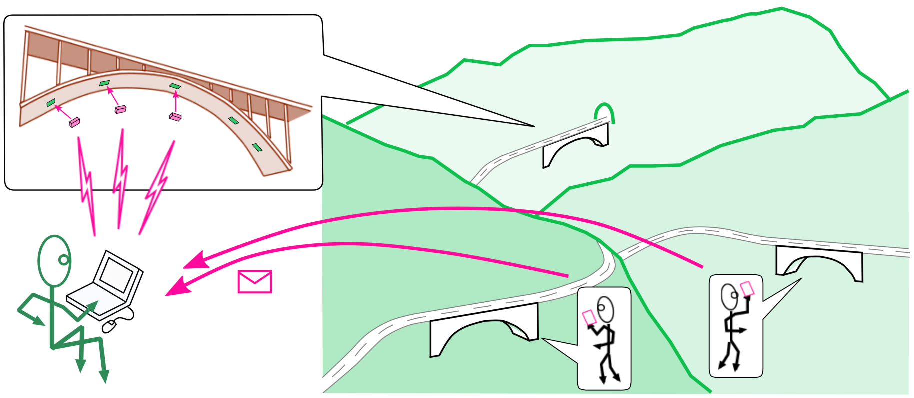

Figure 2. Two methods of data acquisition from strain visualization films distributed over a wide area: (top left) IoT-powered monitoring stations and (bottom right) portable analysis tools on mobile computers.

2. AUTOMATED MONITORING STATION

2.1 Requirements

Since the target structures are located outdoors, we cannot expect an AC power line and a LAN/WiFi network to be available. Thus, the automated monitoring station should be powered with solar panels and the film images should be sent over a mobile network. In Addition, the entire system should be waterproof. From a practical point of view, the station can be placed in the shade, namely exposed to limited solar radiation. Therefore, the power consumption should be minimized. As for the data acquisition interval, once an hour during the daytime is sufficient because the deterioration rate is very slow.

2.2 System configuration

To meet the above requirements, we used a power-efficient micro-computer with a USB port, a 3G communication module, and a general-purpose input/output (GPIO) interface; OpenBlocks IoT BX1 (Plat'Home Co., Ltd.; size: 42 x 96 x 11 mm). Figures 3 and 4 show a system configuration diagram and an illustration outlining the automated monitoring station. To conserve electricity, the connections to the USB camera and the 3G network are established only when they are needed. The USB connection is controlled by one of the GPIO ports via a handmade switching circuit (see the bottom of Fig. 4). The process of taking and transmitting a picture is performed hourly. The power consumption is 0.1 W when the system is idle.

The solar battery system in this station is a commercial product designed for Raspberry Pi, another well-known micro-computer. All the components except for the camera and the solar panels are packaged in a waterproof box as shown on the left in Fig. 4.

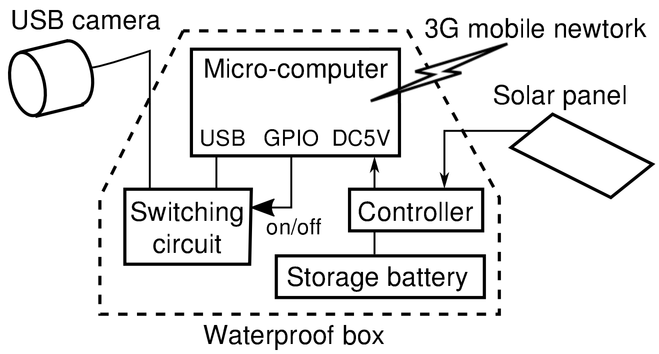

Figure 3. System configuration diagram of the automated monitoring station developed in this study.

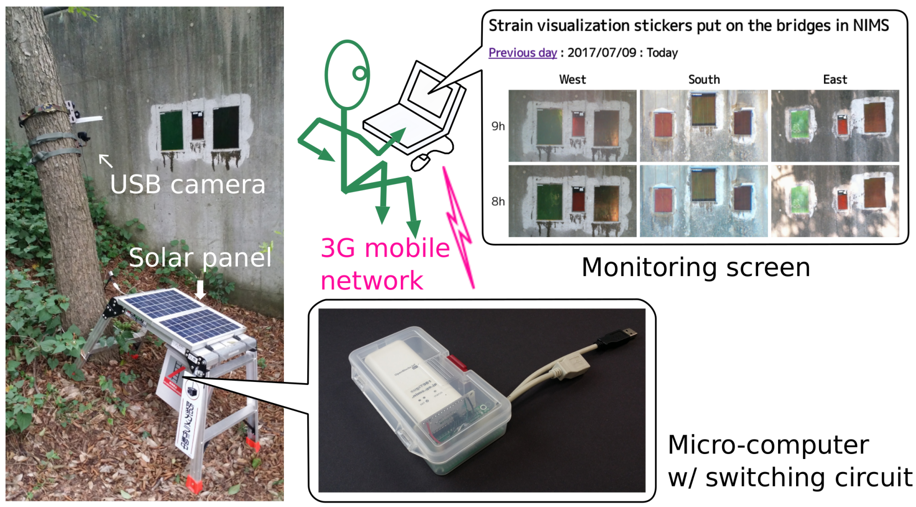

Figure 4. Illustration of the remote sensing system developed in this study.

2.3 Demonstration

Four monitoring stations were placed in an exposure test site in our institute.[1] Since they were located under a tree or a bridge (see the left side of Fig. 4), direct sunlight was available only in the early morning and/or late afternoon. Thus, additional solar panels were installed to increase the power generation.

The USB camera must be both water resistant and highly sensitive because the target films are located mostly in the shade, and our power saving policy does not allow any additional illumination. We found a suitable product, WAT-03U2D (Watec Co., Ltd.), that can take a color photograph even at night using the light provided by a street lamp located some distance away, namely with an illumination of at least 0.1 lux. Accordingly, we collected photographs taken under two different light sources, a fixed light and moving sunshine. The former group of photographs are useful for examining the change over time because they were taken from a fixed point with fixed illumination. The photographs were stored in a server, which provided a monitoring screen via a web browser (see the top right of Fig. 4).

The first monitoring station was established in May 2017, and four systems are currently operating stably after the correction of certain software bugs that were causing irregular battery consumption.

3. PORTABLE ANALYSIS TOOL

3.1 Requirements

In terms of inspecting the film with the naked eye in the open air, it is very hard to establish fixed-point and fixed-light source observation over a long period of time. Thus, we need to look carefully for a discolored area within the film. This requires computer-aided image analysis, preferably with widely available hardware such as smart phones and tablets. And the analysis should preferably be completed immediately.

3.2 Image analysis

Firstly, we have to specify the color of the strain-free area of the film. To that end, it is useful to consider the color using the hue, saturation, and value (HSV) model rather than the red, green, and blue (RGB) model (see the bottom left of Fig. 5). The color range of interest is specified as the region with the most frequent hue values in the histogram of the pixel numbers in the photograph of the film, since the strain-free area occupies most of the photograph (see the bottom center of Fig. 5). Secondly, the pixel positions of interest are specified based on the hue value range, which is represented as "Mask" on the upper center in Fig. 5. Lastly, the strain-free area is extracted by a multiplication of the original photograph and the mask. In the final image, the white area represents the film area with tensile stress and the background. This extraction procedure is called "histogram back-projection".[3]

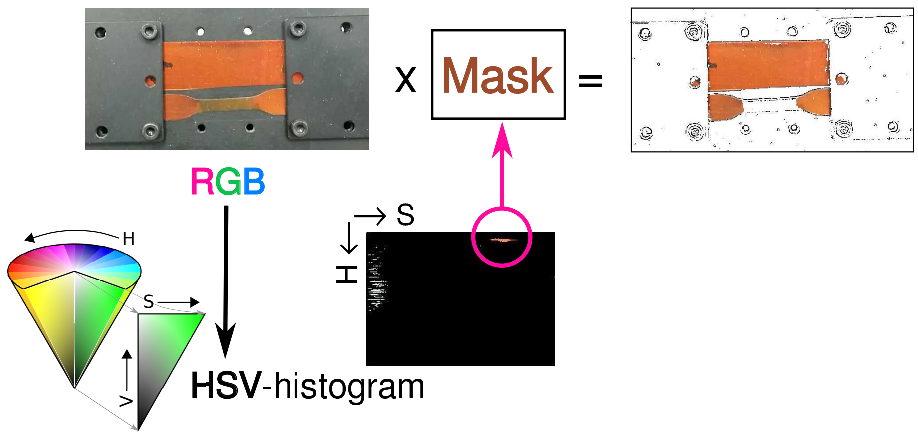

Figure 5. The procedure for extracting the strain-free area of the film (see text). In the final image in the top right, the result of edge-detection is additionally superimposed to allow ease of comparison with the original photograph.

Secondly, we have to recognize subtle color gradations on the film. This is realized by using a modified version of the above image conversion procedure. After specifying the minimum hue value range that covers all the pixels in the film, the color gradation is converted to an appropriate color scale to increase the visibility. Figure 6 shows an example; an aluminum bar was bent after affixing a piece of strain visualization film to it. The original hue value range, 348–54 (orange to yellow), is converted to a color scale ranging from blue via gray to green except for the central value, H = 21.

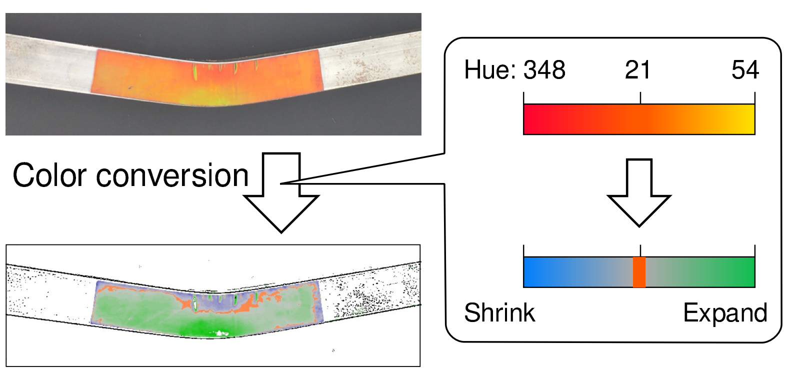

Figure 6. Color conversion for enhancing the visibility of strain distribution induced on the film affixed to the surface of an aluminum bar.

3.3 System configuration

The above calculations are easily performed on mobile computers with the aid of a computer vision library called OpenCV.[4] We developed an application for the several systems listed in Table 1. Its source codes consist of two parts; image processing codes independent of specific hardware and others controlling the camera and user interface that differ depending on the operating system. The former codes are written in C++ language while the latter are written in the various languages required for each integrated development environment. Various functions of OpenCV library are called from the codes for image processing and camera control written in C++ and Java.

Table 1. List of systems and programming languages used for developing the present image analysis software.

System	UI & camera control	Image processing
android	Java (OpenCV)	C++ (OpenCV)
iOS	Swift	
Windows 10	C#	
PC* + USB camera	C++ (OpenCV)	

* Windows, Mac, Linux

3.4 Demonstration

Figure 7 shows the application running on a smart phone. The left-side image shows a strain visualization film affixed to a test piece made of mortar, in which a crack was introduced after the film had been fixed in place. The right-hand image is the result of the real-time extraction of a strain-free area of the film. A clear white silhouette appears whose length is easily determined. The central hue value and its width are 30 and 38, respectively, and they are optimized manually by tapping one of four green buttons on the side of the screen, or semi-automatically.

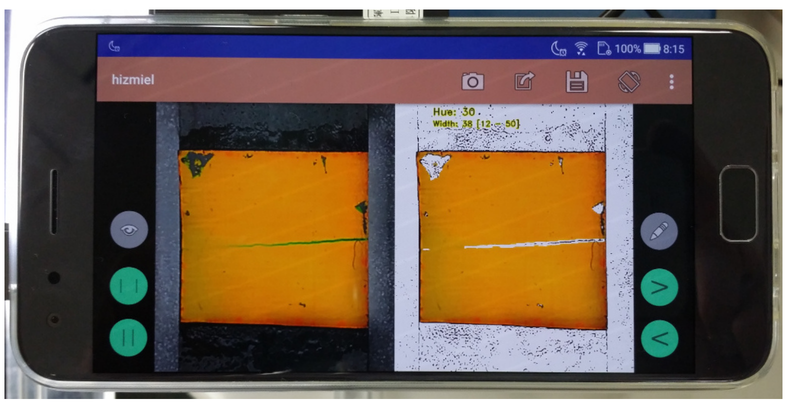

Figure 7. The screen of the application described in this study showing a picture of strain visualization film on the left and the result of image analysis on the right (see text).)

In addition, we can analyze photographs stored in this mobile computer including image files sent from the automatic observatory stations described in Sec. 2.

4. CONCLUSION

We described two approaches for enhancing the "added value" of photonic crystal-based strain visualization film with the aid of microcomputers, namely, efficient image data collection from a number of old outdoor structures on which the films are installed. One employs IoT- and solar-powered automatic observatory stations and the other uses software for visualizing strain along the film's surface, which involves asking non-experts to collect data based on a "bring your own device" (BYOD) policy.

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REFERENCES

[1] Fudouzi, H., Tsuchiya, K., Todoroki, S., Hyakutake, T., Nitta, H., Nishizaki, I., Tanaka, Y., and Ohya, T., "Smart photonic coating for civil engineering field: for a future inspection technology on concrete bridge," in [*Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems*], *SPIE Proceedings* **10168**, 1016820, SPIE (Mar. 2017). http://doi.org/10.1117/12.2259822

[2] Fudouzi, H., "Optical properties caused by periodical array structure with colloidal particles and their applications," *Advanced Powder Technology* **20**, 502–508 (Sept. 2009). http://doi.org/10.1016/j.apt.2009.08.002

[3] Swain, M. and Ballard, D., "Indexing via color histograms," in [*Proceedings Third International Conference on Computer Vision*], 390–393 (Dec. 1990). http://doi.org/10.1109/ICCV.1990.139558

[4] Kaehler, A. and Bradski, G., [*Learning OpenCV 3: Computer Vision in C++ With the OpenCV Library*], Oreilly & Associates Inc (Jan. 2017). http://shop.oreilly.com/product/0636920044765.do