http://dx.doi.org/10.21611/qirt.2017.018

ANALYZING A TIME SERIES OF THERMOGRAPHS TO IDENTIFY THE DEFECTS OF BUILDING EXTERIOR LAYERS

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ABSTRACT

Thermography is designed to record the surface temperature information of the photographed objects. It is difficult to efficiently extract the useful information related the defects presented in the building outside walls because it is hard to analyze many thermographs at a time. Principal component analysis (PCA) has been widely used to analyze the hyperspectral satellite images by generating the new image that is composed of major characteristics extracted from hundreds of bands contained in the hyperspectral images. In this study, a scheme is proposed by applying PCA on the collected thermographs such that large data can be limited into the few enhanced thermographs, and then object-based image segmentation is introduced to analyze those enhanced thermographs such that the boundaries of the segmented regions can be described and lied on those enhanced thermographs. The image segmentation presented in the paper can efficiently group those pixels with collecting similar surface temperatures into the same regions such that each thermography can be composed by few groups. In each segmented group, the average surface temperature of each segmented region can be used to replace the surface temperature recorded in each pixel. Furthermore, the environmental effects acting on the given thermal image can be estimated by the proposed model. In doing so, those regions with the highest surface temperature information can be considered as defects located on the exterior building layer. Different non-destructive testing methods are, then, applied to those identified locations to verify the processed results. From the experimental results, the proposed approach does offer a reliable way to locate the defects presented on the building exterior layers because the results obtained by applying impact echo method are almost the same with the processed results of the proposed approach.

KEYWORDS: PCA, Image Segmentation, Non-Destructive Testing Methods

1. INTRODUCTION

Monitoring the health conditions of buildings is an important step to the sustainable managements of buildings, especial for those aged buildings. Those aged buildings always contain lots of defects which will cause permanent damages to them, and those defects are hard to be efficiently identified. There are several methods usually used to identify the defects of buildings. Non-destructive testing (NDT) methods are parts of them and have widely been employed to evaluate the aged buildings because of its reliability. The major advantages of employing NDT methods are that those methods do not only permanently alter the inspected objects but also provide the defect information. In general, NDT methods can be classified as Visual inspection, Proof Load Test, Vibration Testing, Impact Testing, Ultrasonic NDT, Conductivity and Radar [1]. Those NDT methods can be applied to the exterior layers of buildings by examining a piece by a piece to identify the related information of defects. It is a time-consuming and tedious work to locate defects. Remote sensing is a technology to remotely retrieve the surface information of objects without contacting the objects. Thermography is a kind of remote sensing and is used to record the surface temperature information of objects.

Infrared thermography is a technique which is used to identify defects by observing the radiant heat pattern emitted from the sample. By inspecting a sequence of thermal images, changes in the recorded temperatures in the thermal images reveals the existence of possible surface flaws [2]. In general, infrared thermography is divided into passive and active thermography. The difference between passive and active thermography depends on the external heating or cooling source. Active thermography utilizes external heating or cooling sources rather than the natural environment when testing the materials [3]. Passive thermography involves heating or cooling only through changes in the natural environment [4]. In detecting the defects illustrated on the exterior layers of buildings, infrared thermography can provide surface temperature information of the interested objects

http://dx.doi.org/10.21611/qirt.2017.018

photographed by the thermal infrared camera. From the recorded surface temperature information, the defects can be identified according to the surface temperature distributions: the surface temperatures contained in the defect regions are usually higher than the surface temperatures of their surrounding neighbors [5]. How to efficiently extract useful information from the given thermography is an important step to analyze the thermography.

Principal component analysis (PCA) has been employed in thermal non-destructive evaluation (TNDE) to qualitatively enhanced thermal images from a series of thermal images recorded by a thermal camera. PCA can generate a series of images containing feature characteristics from the given thermographs. Those images generated by employing PCA do keep the spatial pattern of the thermal flows. Recently, PCA is applied to analyze the thermography to detect the defects illustrated on the outside layers of reinforced concrete (RC) structures [6][7]. For an RC structure, the surface temperatures of the building are slowly increased during the heating procedure; similarly, the surface temperatures are slowly decreased during the cooling procedure. This phenomenon always occur on RC structures because RC structures have high thermal emissivity. The assumption that the recorded thermographs do not have huge changes during recording is supposed to be made before PCA approach can be used. The characteristics images can be processed to locate the defects presented on the outside layer of buildings.

Image segmentation can group those pixels with similar surface temperature such that the given thermography can be divided into few sub-regions, and the temperature distribution in each segmented sub-region is homogeneous. Vese and Chan proposed the multiphase segmentation approach to segment a given image into several regions in which the pixel distributions are homogeneous by introducing two level set functions [8]. Li et al. introduce the semi-local information contained in the given image, regional constants and level set functions into hyperspace to find the optimal approximation of the segmented images [9]. In this paper, the characteristic images were segmented by applying Li's algorithm to cluster the characteristics images such that the regional boundaries can be determined. In doing so, the defects illustrated on the outside layers of a building can be identified. The remainder of this paper is organized as follows. In the next section, the schematic way of the proposed approach and the related theories are introduced. Section 3 illustrates the experimental results are presented. Finally, some conclusions and related discussions are provided in Section 4.

2. SCHEMATIC APPROACH TO ANALYZE THERMOGRAPHY

Thermography can be used to identify the defects by analyzing the surface temperature distributions recorded by a thermal camera. In this paper, the authors propose to extract the features contributing the variance of a series of thermal infrared images such that those thermal images can be compressed to several principal components that can be used to present the characteristics of the photographed objects. Then, the image segmentation is applied to those thermal images generated by applying PCA approach such that regional boundaries of surface temperature distributions can be extracted. PCA is briefly introduced in Section 2.1. The way to segment the characteristic images generated by PCA is presented in Section 2.2.

2.1 PCA

Assume there are p thermal infrared images, and image sizes are mn. Let be the pixel be located at (i,j) positions of the p thermal image. Hence, the sample matrix X is given as follows:

$$X = [x_1, x_2, \dots, x_p]^T = \begin{bmatrix} a_{11}^1 & a_{11}^2 & \dots & a_{11}^p \\ a_{12}^1 & a_{12}^2 & \cdots & a_{12}^p \\ \vdots & \vdots & \cdots & \vdots \\ a_{m(n-1)}^1 & a_{m(n-1)}^2 & \cdots & a_{m(n-1)}^p \\ a_{mn}^1 & a_{mn}^2 & \cdots & a_{mn}^p \end{bmatrix}_{(mn)\times p} \quad (1)$$

The covariance matrix of columns can be formed as follows:

$$C = \frac{1}{mn-1}\sum_{k=1}^{mn}(x_k - m_x)(x_k - m_x)^T \quad (2)$$

where m_s is the average values of the given thermal images. Usually, the rows of matrix **A** are the eigenvectors of C, and the principal component transform can be given as follows:

$$Y = A(X - m_s) \quad (3)$$

Similarly, the X can be restored by taking the inverse transformation, and can be formed as follows:

$$X = A^T Y + m_s \quad (4)$$

2.2 IMAGE SEGMENTATION BASED ON KERNEL

Consider an image model, $I_0 = bT + n$, where $I_0$is the given thermal image, b is the environmental effects while the thermal images were taken, T presents the calibrated thermal image after removing envviromantal effects and n is noise effects . For a segmented regionR_i, a circular neighborhood with a radius r centered at each point $x \in R_i$is defined as $O_y = \{x: |x-y| \le r\}$. With introducing two level set functions, $M(\phi_1, \phi_2)$ is defined as the combinations of $H(\phi_1)$ and $H(\phi_2)$, for an example, $M_1(\phi_1, \phi_2) = \left(1 - H(\phi_1)\right)H(\phi_2)$. Hence, Li introduced the combinations of level set functions, regional constants c_i of the region R_i and non-local processing cencept patch *b(y)* to define the energy function [9]:

$$E(\phi, b, c) = \int (K(y-x)|I(x) - b(y)c_i|^2 M_i(\phi)dxdy) + v\int H(\phi)\,dx + \mu \int p(|\nabla\phi|)dx \quad (5)$$

where K is a weight function to give different weights according to the distances among the patch elements and *x*, the *p* is defined as $p(s) = 1/2(s-1)^2$ and v and μ are nonnegative constants. Li called K as a Kernel function and the function can be presented in a Gaussian form. By taking differential operation on the energy function defined by eq. (5) with respect to level set functions $(\phi_1, \phi_2, \cdots, \phi_n)$, *b* and *c*, respectively, a series of PDEs can be generated and the solutions of the PDEs can be obtained by applying the finite difference in an iteration scheme. Those PDEs are illustrated as follows

$$\begin{aligned} \frac{\partial \phi_1}{\partial t} &= -\sum_{i=1}^{N} \frac{\partial M_i}{\partial \phi_1} e_i + v\delta(\phi_1) div\left(\frac{\nabla \phi_1}{|\nabla \phi_1|}\right) + \mu div\left(d_p(\nabla\phi_1)(\nabla\phi_1)\right) \\ &\vdots \\ \frac{\partial \phi_N}{\partial t} &= -\sum_{i=1}^{N} \frac{\partial M_i}{\partial \phi_N} e_i + v\delta(\phi_N) div\left(\frac{\nabla \phi_N}{|\nabla \phi_N|}\right) + \mu div\left(d_p(\nabla\phi_N)(\nabla\phi_N)\right) \end{aligned} \quad (6)$$

where $e_i = \int K(y-x)|I(x) - b(y)c_i|^2\,dy$, $\delta(\phi_i)$is the differential form of Heaviside function$H(\phi_i)$, $\mathrm{div}(\cdot)$ is the divergence operator and the function d_p is approximated by $p'(s)/s$. Similarly, regional constant c_i and the shadow or environmental effects *b* are defined respectively as follows

$$c_i = \frac{\int (b * K) I_0 M_i(\phi(y))dy}{\int (b^2 * K) M_i(\phi(y))dy}, i = 1, \cdots, N \quad (7)$$

$$b = \frac{(I_0 \sum_{i=1}^{N} c_i M_i) * K}{(\sum_{i=1}^{N} c_i^2 M_i)} \quad (8)$$

where the symbol * is a convolution operator. Then, the optimal segmentation approximation can be obtained as follows:

$$U = c_1 M_1 + c_2 M_2 + \cdots + c_N M_N \quad (9)$$

The iteration scheme is employed to implement the whole processing steps such that the initial level set functions are changing till the convergences can be reached.

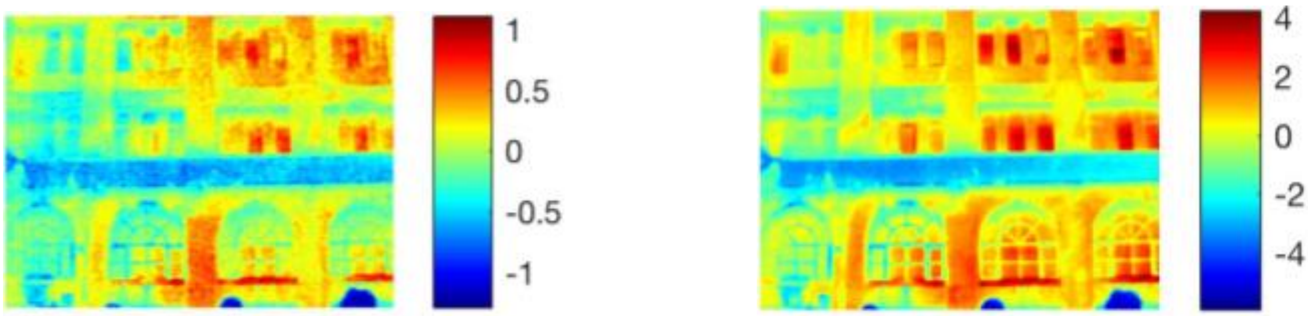
3. EXPERIMENTAL RESULTS

Thermal infrared camera Thermo Gear-G120 made by NEC was employed to record the surface temperature information, and it can simultaneously photo the same objects in a digital format. Each recorded thermography has 240 x 320 pixels, and it can measure the minimum temperature difference up to 0.08℃. A series of thermal images was taken from 14:54 to 15:02 PM on August 14, 2015; there were totally 10 thermal images taken. In this paper, PCA was applied on those thermal images, and the corresponding eigenvalues and mean surface temperatures are given in Table 1. The first and second images generated by applying Eq. (3) are illustrated in Fig.1.

Table 1 Eigenvalues and Mean Surface Temperatures

No.	1	2	3	4	5	6	7	8	9	10
Eigenvalue	12.024	0.1152	0.0395	0.0248	0.0113	0.0093	0.0069	0.057	0.0041	0.0037
Mean(°C)	31.36	31.60	31.55	31.52	32.05	32.55	32.40	32.44	32.29	33.01

http://dx.doi.org/10.21611/qirt.2017.018



(a) (b)

Fig. 1. Principal component images. (a) The first component image, (b) The second component image.

Image segmentation based on Section 2.2 was employed to segment the first and second component images; let the parameters be $\nu = 1$ and $\mu = 0.001 \times 255^2$, and the processed results are illustrated in Fig. 2.

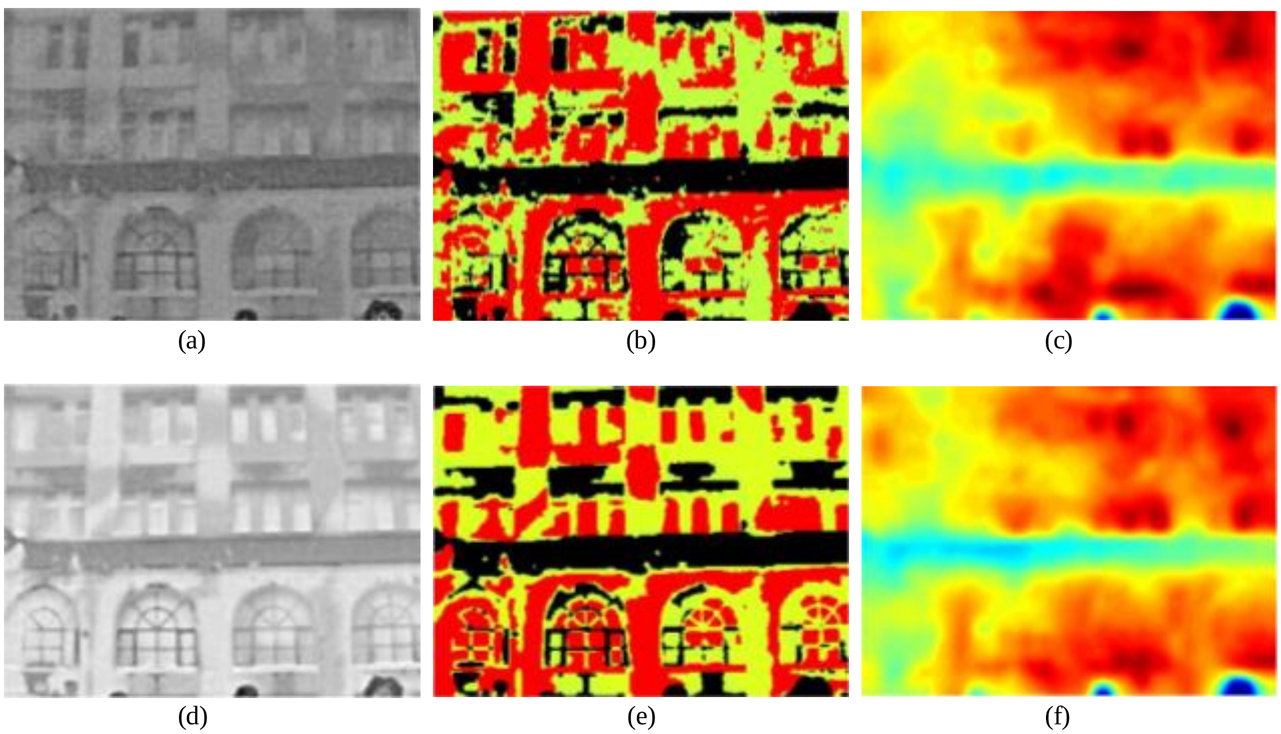


Fig. 2. The segmented results. (a) The calibrated image of the first component image after removing the environmental effects. (b) The segmented results of the first component image were illustrated. (c) The estimated environmental effects of the first component image. (d) The calibrated image of the second component image after removing the environmental effects. (e) The segmented results of the second component image. (f) The estimated environmental effects of the second component image were presented.

4. DISCUSSIONS

PCA can be used to extract principal components such that a series of thermal images can be restored from those components. In Fig. 2., the second component image can be used to present the characteristics of the given thermal images because it seeoms to present more details than the image restotred by the first component. Two thermal images were selected from the given thermal images: one was taken at 14:54 PM, and another was taken at 15:02 PM. Similarly, the parameters were set the same as those parameters were employed in segmenting the component images. The processed results were illustrated in Fig. 3. The segmented results of the first and last thermal images from the given thermal images can be clustered in three groups, and are colored as red, green and black, respectively. The average surface temperatures of the first thermal image were 31.85 °C, 31.29 °C, and 30.51 °C, respectively; similarily, the average surface temperatures of the last thermal image are 32.07 °C, 31.52 °C, and 30.73 °C, respectively.

http://dx.doi.org/10.21611/qirt.2017.018

With comparing the segmented results among the first thermal image, the last thermal image, and the second component image, the thermal flow patterns are similar. The second component image restored by applying PCA seems to provide more details than the given thermal images. The environmental effects affecting the given thermal images can be estimated by applying the thermal image model proposed by this research. The environmental effects of the given thermal images and the component image have the similar patterns; it means that the environmental effects do not have significant changes while monitoring the building by employing thermography.

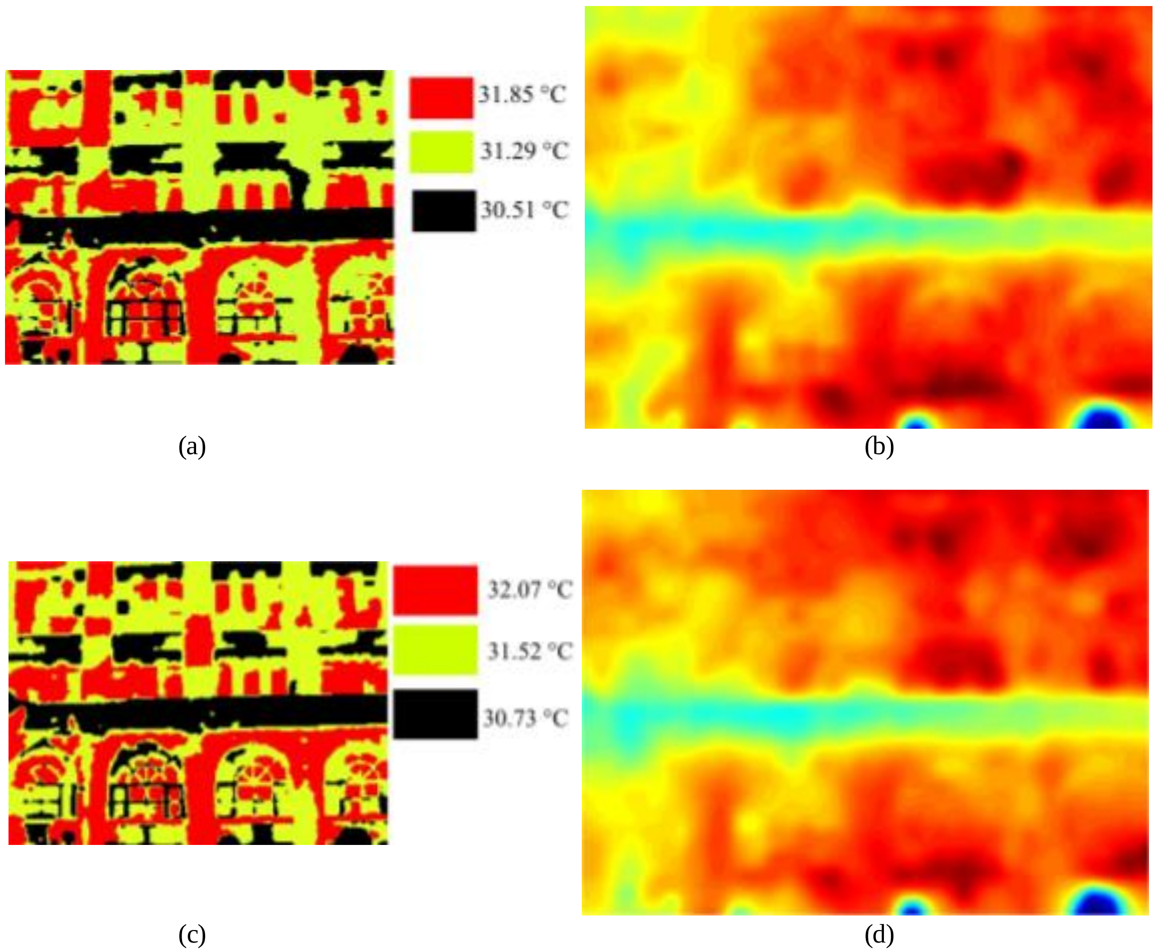


Fig. 3. The segmented results of the first and the last thermal images from the given thermography. (a) The segmented results of the first thermal image were divided into three groups, and the average surface temperatures of the segmented regions are 31.85 °C, 31.29 °C, and 30.51 °C, respectively. (b) The estimated environmental effects of the first thermal image were illustrated. (c) The segmented results of the last thermal image were divided into three groups, and the average surface temperatures of the segmented regions are 32.07 °C, 31.52 °C, and 30.73 °C, respectively. (b) The estimated environmental effects of the last thermal image were presented.

5. CONCLUSIONS

The paper proposes a schematic approach to identify the defects presented in the outside layers of a building. The regional boundaries of the surface temperature information can be determined by employing the image segmentation. From those extracted boundaries, the locations of defects can be determined by comparing the regional boundaries; defects usually occur at those places with higher surface temperatures than their neighbors. At last, the research results can be summarized as follows:

1. PCA does provide the significant characteristics for the time series of thermal images;
2. The second component image generated by PCA provides a complete information than other component images;
3. The proposed thermal image model does offer the quantitive descriptions of those environmental effects acting on the time series of thermal images;

4. The extracted boundaries of the surface temperature information can be used to identify those defects shown on the exterior layers of a building.The paper propose a schemantic approach to identify the defects presented on the outside layers of a building.

ACKNOWLEDGMENT

The authors like to show their acknowledgments to the financial supports from MOST 104-2632-E-324-001.

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