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Enhancement of thermographic images as tool for structural analysis in earthquake engineering

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ABSTRACT

In this paper, we present an application of a reconstruction method to thermographic images employed to analyze the response of a masonry structure under seismic actions.

At first the theory of linear multivariate sampling Kantorovich operators is presented. By means of the above operators, we are able to reconstruct images taken from thermographic survey of masonry walls, and enhance their quality. Digital image processing of reconstructed images allows us to identify the mutual arrangement of the blocks (made of stones and/or bricks) and mortar joints inside the wall portion analyzed, and therefore the texture of the masonry. Subsequently, the texture has been used to estimate the equivalent elastic properties of the masonry by means of homogenization techniques. Finally a real-world case-study is analyzed, taking into account the mechanical properties estimated from reconstructed thermographic images and evaluating the structural response in terms of modal analysis.

1. Introduction

In recent years, several researchers highlighted the advantages of using thermography in civil engineering applications [1–3]. Thermography is a remote sensing technique, performed by the image acquisition in the infrared, and therefore belongs to the family of non-destructive test for structures [4]. A survey of possible applications can be found in [5]. In particular, thermographic images can be used to make non-invasive investigations of structures, to analyze the story of the building wall, to make diagnosis and monitoring of buildings, and to make structural measurements.

The main use of thermography in civil engineering applications has been in the analysis of energetic performance of buildings, in particular to detect heat bridges and to assess the behavior at different seasons (see, for example, [6]); this is somehow similar to the heat transfer measurement in wind tunnel [7]. Subsequently, the possibility of using thermography as a non-destructive test has been acknowledged, with the further advantage of the possibility to analyze the building without contact and rapidly, with consequent advantages in terms of operativeness and costs. For instance, thermography can be used to measure the moisture contents on surface and to detect imperfections on the substrate [8], to reveal small defects on concrete elements [9], to assess actual conditions and internal compositions of bridges [10]. Applications to evaluate the conditions of masonry and historical structures are also available [11,12].

Unfortunately, the direct use of thermographic images can produce errors due to their low quality [13]. Therefore, several methods have been proposed in order to enhance the quality of thermographic images [14–16].

In the present paper, thermographic images are used both to assess effective dimensions of structural elements and for masonry texture, i.e. for the identification of the bricks and the mortar in masonries' images. The use of low quality images can induce errors when the image texture algorithm is used: in particular, an incorrect separation between the bricks and the mortar can occur. To enhance the quality of the thermographic images, reconstruction methods based on the theory of sampling Kantorovich operators are employed, and they have been proved to be very useful for the applications here considered. The reconstruction methods are used to estimate the mechanical characteristics of the masonry walls of a case-study. It is worth noting that the interest of the present paper is not in the actual evaluation of the structural response of the case study to earthquake loads but rather in the applicability of the proposed procedure and the advantages that can be achieved in comparison with more traditional approaches. Furthermore, the proposed approach allows us to estimate the mechanical characteristics of the masonries using non-destructive methods.

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The structure of the paper is the following: in Section 2 a brief introduction to thermography is given, with discussion of shortcomings when used for civil engineering applications; in Section 3 the application of the theory of sampling Kantorovich operators to reconstruct and to enhance the quality of thermographic images is presented: the reconstruction algorithm has been performed using MATLAB. In Section 4 the methods to estimate the mechanical characteristics of masonry wall using reconstructed thermographic images are described; in Section 5 an application to a case study is proposed; eventually, results are discussed in conclusions.

2. Thermography and its applications to civil engineering

Thermography is a technique which allows us to appreciate and measure the heat flux associated with infrared radiation emitted from every body without direct contact, therefore it supplies a non-invasive technique for investigating buildings. The thermography is therefore a remote sensing technique, which exploits the fact that all the objects at a temperature above absolute zero emit radiation in the infrared range (wave length of 700 nm – 1 mm, which corresponds to frequencies of 430 THz–300 GHz), which is located between the visible radiation (in particular the red component) and the microwave range.

The result of a thermographic survey is a bi-dimensional image, which is a thermic mapping of the heat flux of the body converted in temperature as will be detailed later. The measure of the surface temperature is indirect, since the thermographic cameras are only able to measure the input energy. Therefore, the quantity and quality of information which can be collected about the body examined strongly depends on the quality of the bi-dimensional image obtained from thermographic camera.

The radiation energy is measured by means of an infrared detector, which is able to absorb the incident energy and convert it in an electric signal. The main characteristic of the detector used in thermography is the reduced time elapsed from energy absorption to its conversion in electric signal, in the order of μs. The main parameters of the detector are its image resolution and intensity resolution [17]. The image resolution is the ability to accurately detect and measure the surface temperature of the bodies even if they have small size. The intensity resolution is the ability to appreciate small temperature differences in the body.

As stated in the introduction, the thermographic images are largely used to make diagnosis and monitoring of buildings. They can also be used for structural survey, for example in the location and quantification of the resisting elements.

In the present paper, thermographic images will be used in the latter sense cited above, and moreover to investigate the actual texture of the masonry wall, i.e. the mutual arrangement of blocks and mortar joints. Anyway, the image resolution is often too low to achieve consistent results, and therefore reconstruction techniques described in the following section will be used.

3. Image reconstruction by multivariate sampling Kantorovich operators

In this section, we recall the theory of multivariate sampling Kantorovich operators and we describe their applications to image processing. In particular, we will apply these operators to thermographic images, for which we will study the texture to perform structural analysis.

The sampling Kantorovich operators have been introduced in [18] in a univariate setting and in [19] in a multivariate setting and they are related to the generalized sampling operators (see e.g. [20–32]).

More in detail, the sampling Kantorovich operators (1), below defined, represent an averaged version of the generalized sampling operators introduced by Butzer and his school at Aachen, and they in turn furnish a rigorous theory of an approximate version of the classical Whittaker–Kotelnikov–Shannon sampling theorem, very useful for the applications, see e.g. [20,25,33–36]. In the Kantorovich case, instead of the evaluation of the signal f at the nodes $\underline{k}/w$, $\underline{k} \in \mathbb{Z}^n$, $w>0$ (or $t_{\underline{k}}/w$ in the case of a non-uniform sampling scheme, where $(t_{\underline{k}})_{\underline{k} \in \mathbb{Z}^n}$ is a suitable sequence), we have an average of f on a small multirectangle around $\underline{k}/w$. Practically, more information is usually known around a point than precisely at that point, and this procedure simultaneously reduces time-jitter errors. The algorithm deduced from the theory based on sampling Kantorovich operators, and discussed in Section 3.1, revealed to be very suitable for reconstruction processes, even in comparison with other approaches. Furthermore, the definition of the sampling Kantorovich operators is more suitable for the reconstruction of signals/images not necessarily continuous, and this fact plays an important role in image processing. This is an added value of these operators with respect to others, and in particular to the generalized sampling ones, since the latter depend on single function values $f(\underline{k}/w)$, and therefore not suitable in case of discontinuous functions.

Now, we recall the definition of the multivariate sampling Kantorovich operators. In what follows, we denote by $t_{\underline{k}} = (t_{k_1}, \dots, t_{k_n})$ a vector where each $(t_{k_i})_{k_i \in \mathbb{Z}}$, $i=1,\dots,n$, is a sequence of real numbers with $-\infty < t_{k_i} < t_{k_{i+1}} < +\infty$, $\lim_{k_i \to \pm\infty} t_{k_i} = \pm\infty$, for every $i = 1,\dots,n$, and such that there exists Δ, $\delta>0$ for which $\delta \le \Delta_{k_i} := t_{k_{i+1}} - t_{k_i} \le \Delta$, for every $i=1,\dots,n$.

A function $\chi : \mathbb{R}^n \to \mathbb{R}$ will be called a kernel if it satisfies the following properties:

(χ1) $\chi \in L^1(\mathbb{R}^n)$ and is bounded in a neighborhood of $\underline{0} \in \mathbb{R}^n$;
(χ2) For every $\underline{u} \in \mathbb{R}^n$, $\sum_{\underline{k} \in \mathbb{Z}^n} \chi(\underline{u} - t_{\underline{k}}) = 1$;
(χ3) For some $\beta > 0$,

$$m_{\beta,\Pi^n}(\chi) = \sup_{\underline{u} \in \mathbb{R}^n} \sum_{\underline{k} \in \mathbb{Z}^n} |\chi(\underline{u} - t_{\underline{k}})| \cdot \|\underline{u} - t_{\underline{k}}\|_2^{\beta} < +\infty,$$

where $\|\cdot\|_2$ denotes the usual Euclidean norm.

The linear multivariate sampling Kantorovich operators are defined by

$$(S_w f)(\underline{x}) := \sum_{\underline{k} \in \mathbb{Z}^n} \chi(w\underline{x} - t_{\underline{k}}) \left[\frac{w^n}{A_{\underline{k}}} \int_{R_{\underline{k}}^w} f(\underline{u})\, d\underline{u} \right], \quad (\underline{x} \in \mathbb{R}^n), \tag{1}$$

where $f : \mathbb{R}^n \to \mathbb{R}$ is a locally integrable function such that the above series is convergent for every $\underline{x} \in \mathbb{R}^n$,

$$R_{\underline{k}}^w := \left[\frac{t_{k_1}}{w}, \frac{t_{k_1+1}}{w}\right] \times \left[\frac{t_{k_2}}{w}, \frac{t_{k_2+1}}{w}\right] \times \cdots \times \left[\frac{t_{k_n}}{w}, \frac{t_{k_n+1}}{w}\right],$$

$w>0$ and $A_{\underline{k}} = \Delta_{k_1} \cdot \Delta_{k_2} \cdot \dots \cdot \Delta_{k_n}$, $\underline{k} \in \mathbb{Z}^n$. In [19], the following approximation theorem has been proved, which shows the pointwise and uniform reconstruction of a multivariate signal or image by means of the above operators (1). This result is fundamental for the following applications developed in this paper.

Theorem 3.1. *Let $f : \mathbb{R}^n \to \mathbb{R}$ be a continuous and bounded function. Then, for every $\underline{x} \in \mathbb{R}^n$,*

$$\lim_{w \to +\infty} (S_w f)(\underline{x}) = f(\underline{x}).$$

In particular, if $f : \mathbb{R}^n \to \mathbb{R}$ is uniformly continuous and bounded, then

$$\lim_{w \to +\infty} \|S_w f - f\|_\infty = 0,$$

where $\|\cdot\|_\infty$ denotes the sup-norm, i.e., $\|f\|_\infty := \sup_{\underline{x} \in \mathbb{R}^n} |f(\underline{x})|$.