



High-resolution thermal imaging methodology for non-destructive evaluation of historic structures



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ABSTRACT

This paper presents a methodology for automated, portable thermography, for the acquisition of high-resolution thermal image mosaics supporting the non-destructive evaluation of historic structures. The presented approach increases the spatial resolution of thermal surveys to a level of detail needed for building scale analysis. The integration of a robotic camera platform enables automated alignment of multiple images into a high-resolution thermal image mosaic giving a holistic view of the structure while maintaining a level of detail equaling or exceeding that of traditional spot surveys using existing cameras. Providing a digital workflow for automated data and metadata recording increases the consistency and accuracy of surveys regardless of the location or operator. An imaging workflow and instrumentation are shown for a case-study on buildings in Florence, Italy demonstrating the effectiveness of this methodology for structural diagnostics.

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1. Research aims

Thermography is a widely used technology in many disciplines, but there are still limitations in image resolution when it comes to diagnostic surveys on the scale of buildings. This paper presents a methodology that leverages a low-cost, automated portable thermography (APT) system, designed to increase the spatial resolution of thermal images by performing rapid acquisition of thermal image mosaics. The target application for the APT methodology is passive building-scale surveys at cultural heritage sites aiming to assist in monitoring energy losses, mapping areas of moisture, revealing structural features, and detecting damage such as delamination and cracking. Automating the process is a step towards a standardized methodology that provides consistency and accuracy in the acquired data and metadata independent of site or operator. The APT workflow aims to be repeatable, provide the necessary setup to ensure accuracy, as well as save time on acquisition and post-processing. The methodology, composed of the APT instrumentation, its sensors, workflow, and imaging results are presented as part of a case study conducted on buildings in Florence, Italy.

2. Introduction

Building-scale measurement and analysis are rapidly growing application domains, driven by the swift decay of our built-infrastructure. To address this growing need, instruments, techniques and methodologies for the surface and volumetric assessment of the geometric properties of a structure in combination with material characterization are necessary to create an accurate baseline for subsequent structural health assessments. Common techniques include photography and photogrammetry, light detection and ranging (LiDAR) for establishing geometry, sub-surface and volumetric imaging techniques such as thermography, ultrasound, ground-penetrating radar (GPR) and X-ray radiography. Thermography, which captures a combination of surface and sub-surface information, can measure spatio-temporal ambient signals, from a distance, accomplishing multiple non-destructive evaluation (NDE) objectives. Common application domains of this multi-purpose diagnostics tool include energy audits [1,2] which establish the thermal envelope of a structure, detection of pests, moisture, and mold [3], structural deficiency and integrity assessment focused on detecting cracks, delamination, as well as material characterization. The ability to characterize materials can aid in creating a baseline as-built record showing construction details and modifications of structures. This can be particularly useful when surveying historic structures because they often lack these construction records.

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Building-scale structural health assessment requires accurate and detailed measurements at the macro and micro scale, providing a holistic view of the structure, establishing the overall context, as well as the data needed to study small scale characteristics, deficiencies and damage patterns. Given the necessary resolution, instrumentation, time complexity and cost this is rarely done for thermographic surveys. The most advanced thermal cameras currently only achieve one megapixel resolution [4] and they come with a high price tag. When used in the field at building scale, different lenses may be used, a wide field of view lens providing context, but no detail, and a narrow field of view lens providing detail, but no context. With the available time budgets for site surveys, this often results in just a few spot surveys being performed.

In order to mitigate the issue of limited camera resolution, a methodology and optimized workflow are required to facilitate the rapid acquisition of building-scale thermal images. To fill a need for gigapixel imaging robotic camera platforms have emerged [5] to aid in acquisition and stitching of spatially accurate digital image panoramas. Now with the idea being well-established for digital photography, it seems reasonable that this approach should also extend to thermography to address its limitations in spatial resolution.

The purpose of this work is to highlight how high-resolution thermal data can be accurately acquired for large surface areas using the proposed methodological approach. The methods for interpretation of the data will not change, but the quality of the data will be much higher allowing for more precise analysis conducted by domain experts. The presented methodology is repeatable regardless of the user, and the workflow ensures accuracy and consistent post-processing of the images using recorded metadata.

3. Related work

Infrared thermography is an imaging technique that measures the radiation emitted by a surface in the long wave infrared range of the electromagnetic spectrum. Infrared waves have longer wavelengths than visible light, ranging from 0.78 to 1000 μm [6], but can be captured with infrared cameras and subsequently displayed in the visible spectrum. Infrared cameras that are sensitive to different wavelengths exist and wavelengths ranging from 7 to 14 μm are typically captured with thermographic camera sensors. These wavelengths shift with the temperature of the surface where the observed infrared wavelength decreases as temperature increases. When the emissive properties of the surface are known the camera can be calibrated to convert the observed wavelengths to emitted temperature. The set of recorded temperatures is then mapped to a range of colors in the visible spectrum in order to display the results against a scale that correlates each color to a temperature value.

Thermography is classified into two categories, passive thermography and active thermography. Passive thermography uses the ambient or natural heating and cooling of the specimen to measure differences in heat transfer. On the other hand, active thermography utilizes a controlled external heating or cooling source in order to record the heat flux, or rate of thermal energy transfer, across the target surface [6]. The main difference in the two methods is that passive thermography is a snapshot that gives a qualitative evaluation of the target structure while active thermography is a sequence of images that can also yield quantitative results because the external heat source is defined with a known time and strength [7]. For example, with a controlled heat source, the material and structural characteristics of the specimen can be calculated [8].

3.1. Thermography for structural evaluation

In structural engineering, passive thermography is the preferred technique to use in situ because it is not practical to have external sources that apply heat evenly to entire surfaces at building scale. In these areas of application, thermography can be used to monitor energy losses, map areas of moisture, and detect delamination and cracks. These inspection techniques are well documented [1,3,9–11] and extremely important, especially as structures age; it is crucial to monitor structures to detect damage and flaws early and take corrective actions before the damage has progressed or significant energy is wasted. Thermography presents a non-destructive approach for detecting warning signs and identifying issues that may not be visible to the human eye [11]. A fast thermal surveying methodology will be vital to efficiently monitor the natural aging and decay of the entire built infrastructure.

One of the most important applications for thermal imaging in NDE is detecting structural details and damage. Grinzato et al. [3,10], Hess et al. [12], and Imposa [13] explain how thermal image mosaics can be acquired and used towards determining what types of modifications have occurred over the history of the structure. Grinzato outlines the importance of knowing the history of structural modifications and any anomalies within the structure in general, highlighting that accurate structural evaluation and identification of construction details is vital for a proper conservation plan [3]. Thermal imaging is extremely useful in these situations because it is a non-intrusive technique that reveals information about features that are not visible without opening walls or damaging the existing structure in any way.

Balaras and Argiriou [1] explain how thermography can be used in the context of building diagnostics, specifically looking at building energy audits. This application uses thermography to detect areas where heating or cooling is escaping, insulation is missing, or areas where thermal bridges exist. All of these findings are then reported in order to develop a plan to address the issues that were found. The examples in [1] reveal some detail in the thermograms, but no context for the area. With the presented methodology, the whole context can be displayed while maintaining the same level of detail within the high resolution thermal image. The presented approach also allows for the creation of important baseline records for evaluating a building's thermal efficiency and pinpointing sources of heat flux losses and other undesirable environmental outcomes.

4. APT methodology

The APT methodology, consisting of the instrument and workflow, seeks to create a fast, high-resolution, low-cost approach that automatically acquires, corrects, and processes geo-located, temporally anchored, building-scale thermal surveys.

4.1. Proposed APT instrumentation requirements

The instrument consists of a robotic platform and remote imaging payload modules. The platform controls the imaging payload orientation with the ability to measure data such as position, heading, acceleration and vibration, humidity, and ambient temperature. The platform and the imaging payloads are responsible for the acquisition of the thermal images, while the additional sensor measurements from the platform enhance accurate post-processing, analysis, and metadata creation used to geospatially anchor the survey. For example, a GPS sensor can be utilized to geospatially locate the imaging data and a digital compass sensor used to provide the heading of the surface being imaged. Camera movement and vibrations can also be inferred from accelerometers

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