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Remote sensing of concrete bridge decks using unmanned aerial vehicle infrared thermography

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ABSTRACT

The present study explores the potential application of unmanned aerial vehicle (UAV) Infrared Thermography for detecting subsurface delaminations in concrete bridge decks, which requires neither traffic interruption nor physical contact with the deck being inspected. A UAV-borne thermal imaging system was utilized to survey two in-service concrete bridge decks. The inspection process involved the acquisition of thermal images via low altitude flights using a high resolution thermal camera. The images were then enhanced and stitched together using custom developed codes to create a mosaic thermal image for the entire bridge deck. Image analysis based on the k-means clustering technique was utilized to segment the mosaic and identify objective thresholds. Hence, a condition map delineating different categories of delamination severity was created. The results were validated using data generated by other non-destructive testing technologies on the same bridge decks, namely hammer sounding and half-cell potential testing. The findings reveal that UAV with high-resolution thermal infrared imagery offers an efficient tool for precisely detecting subsurface anomalies in bridge decks. The proposed methodology allows more frequent and less costly bridge deck inspection without traffic interruption. This should enable rapid bridge condition assessment at various service live stages, thus effectively allocating maintenance and repair funds.

1. Introduction

Bridges are a crucial component of transportation networks, requiring adequate maintenance to ensure safety and serviceability. The latest Canadian infrastructure report card (2016) indicated that 26% of bridges are in fair, poor or very poor condition. Among all reinforced concrete (RC) bridge components, bridge decks have been identified as the most problematic because they are susceptible to various forms of deterioration mechanisms. Indeed, RC bridge decks have been the leading contributor to most deficient bridges in the United States [1]. According to America's 2013 infrastructure report card, an annual investment of $20.5 billion is needed to eliminate the backlog of deficient USA bridges by year 2028. The largest portion of this expenditure is required for RC bridge decks [2].

Therefore, condition monitoring and timely implementation of maintenance procedures for RC bridge decks are paramount to reduce the costs related to bridge management. A major challenge associated with evaluating RC bridge decks is that defects are often concealed subsurface mechanisms which increase in severity until the damage becomes too severe for cost-effective repair. Application of non-destructive testing (NDT) technologies is one of the effective ways to both monitor and predict RC bridge deck deterioration. NDT tools enable the detection of deterioration processes at its early stages and hence, allow prioritizing repair efforts. Currently, the limited use of these techniques is in special inspection cases when severe defects and deficiencies are observed. Infrared thermography (IRT) is a NDT technology that is commonly applicable for detecting characteristic thermal signatures associated with RC bridge deck delaminations [1]. Such remote sensing technology allows for visualization of the data in the form of real-time thermal images and does not require direct access to the surface under inspection since the images can be captured from distance using appropriate optical lenses.

In accordance with the requirements of ASTM. D4788-03 [3], ground IRT testing in-situ on full-scale RC bridges should be conducted at low driving speeds of no greater than 16 km/h., which requires traffic control arrangements. To avoid such traffic interruption, aerial inspection by means of fixed wing aircrafts and satellites has been implemented for remote sensing of bridge infrastructure. The main limitation to perform a manned aircraft scanning is to maintain a fixed distance from the bridge structure, which can be mitigated using an unmanned aerial vehicle (UAV) equipped with a GPS system [4]. In addition, UAVs can be operated at lower altitudes than piloted aircrafts,

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resulting in a higher spatial resolution. Compared with satellite remote sensing and aerial photogrammetry, UAV has several merits, which makes it a reliable and cost-effective technology for data acquisition. It can be deployed frequently to satisfy the requirements of rapid assessment of bridge decks. UAVs can be equipped with imaging technologies including digital and thermal cameras that can record photo or video outputs for further processing. The present study investigates the application of a UAV-borne thermal imaging system for the condition assessment of RC bridge decks.

1.1. Research objectives

In-situ IRT testing of full-scale RC bridge decks aims at unveiling concealed defects. Extracting quantitative measures from IRT data relies on the user interpretation. Such a qualitative and subjective analysis is rapid, yet it does not warrant rigorous evaluation. Displaying IRT images in a geospatial format to produce GIS thermal maps usually requires manual editing, often resulting in undesired subjectivity. Moreover, the severity of delamination is commonly defined based on the pixels associated with temperatures higher than predefined threshold values that are arbitrarily selected, thus producing inconsistent results. Therefore, the present study has two main goals: (1) utilizing a UAV thermal imaging system for the detection of subsurface delaminations in RC bridge decks; and (2) developing a robust analysis procedure for the acquired data. The specific objectives of the study are: (i) establish the principles of aerial UAV remote sensing technology; (ii) develop a stitching algorithm to create a mosaicked thermogram of the entire bridge deck; (iii) identify objective thresholds; and (iv) produce a condition map indicating the severity levels of delaminations in bridge decks based on the results of UAV thermal imaging.

2. Background

2.1. Deterioration of RC bridge decks

The deterioration of RC bridge decks is primarily due to ageing, material defects, construction deficiencies, exposure to aggressive environments, lack of ductility and unforeseen excessive loads [5]. In general, such deterioration occurs through one or a combination of four major mechanisms: physical, chemical, mechanical, and biological processes. For instance, physically-induced deteriorations are those processes caused by factors such as freezing-thawing cycles, non-uniform volume changes, temperature gradients, creep, and abrasion. Chemically-induced deterioration can be induced by carbonation, chloride ions, sulfates and acid attack, or alkali-aggregate reactions. Mechanical-induced deterioration can be caused by static and/or dynamic loads, and construction faults such as those from premature loading during construction. Biological-induced deterioration can be induced by accumulation of organic matter, living organisms, fungi, and moss [6]. However, deterioration of RC bridge decks is commonly initiated by reinforcing steel corrosion where the passivity of the steel is compromised either by carbonation of concrete, chloride ions intrusion, or a combination thereof. As the steel corrodes, rust occupies increased volume, and cracking is initiated when the internal tensile stresses exceed the tensile strength of the concrete. Cracking accelerates the damage mechanisms by providing easy access for chloride ions, oxygen and moisture, resulting in subsurface fracture planes. As the deterioration progresses, a rupture between the delaminated region and the deck surface can occur, resulting in spalling of the concrete surfaces, which can cause catastrophic structural and functional failures in terms of human life and economic loss [7]. Therefore, subsurface delamination is a significant indication of deterioration and active corrosion. Locating and defining the extent of delaminations in its initial stages is critical to ensure bridge safety and optimize maintenance and repair needs.

2.2. Inspection techniques of RC bridge decks

The evaluation of RC bridge decks is complex due to the heterogeneous nature of concrete. Visual inspection has been the default bridge deck inspection methodology. However, it has several limitations, such as its inability to detect hidden defects and its operator sensitivity. Research results indicate that assessing bridge deck condition by visual inspection is unreliable and unable to correctly identify the repair priorities. For instance, Moore et al. [8] showed a significant discrepancy in results during routine visual inspections. A number of hand tools, including hammers, steel rods, and chains have been widely used to inspect concrete bridge decks. A delamination in concrete typically causes a dull sound when the deck surface is struck. While this is a low-cost method, the interpretation of the produced sound is subject to the operator's judgment and experience. Such techniques require hands-on access and can be labor-intensive and time-consuming. Traffic control must also be ensured so that inspectors can safely access the bridge deck. The inherent limitations of visual inspection and conventional sounding techniques have motivated the bridge community to seek advanced NDT technologies. There are currently several NDT methods capable of effective and reliable bridge condition assessment based on acoustic, seismic, electric, electromagnetic, thermal, and other physical phenomena. Generally, such techniques utilize an approach where the objective is to learn about the characteristics of the medium from its response to an applied excitation [2]. Further details about the principles, instrumentations, data analysis techniques, and some inherent limitations of these technologies are provided elsewhere in a report of the American Concrete Institute [9].

2.3. Infrared thermography (IRT)

Heat energy moves by conduction, convection and radiation. There are three ways by which the radiant energy striking an object can be dissipated: absorption, transmission and reflection [10]. Materials in which the transmissivity and the reflectivity are null are called blackbodies. Any object at a temperature above the absolute zero (− 273.15 °C or 0 K) emits infrared radiation (below red). Infrared radiation lies between the visible and microwave portion of the electromagnetic spectrum where the usable part is approximately defined from 0.8 to 14 μm. This range can be further subdivided into near-infrared (0.8–1.5 μm), short-wavelength infrared (1.5–2.5 μm), mid-wavelength infrared (2.5–8 μm), and long-wavelength infrared (8–14 μm). The intensity of the infrared radiation emitted by objects is a function of the temperature of the material and its emissivity. A material's emissivity is the ability of its surface to emit energy by radiation relative to a black body. For a perfect blackbody, emissivity is unity. For real surfaces, it is always less than unity. For concrete, this property is typically greater than 0.92 [10]. However, the surface roughness and moisture content of the concrete can influence its emissivity value. The presence of other materials on the surface of the concrete (e.g. staining, water, lane markings), which have different emissivity properties, can result in apparent temperature variations in the image, possibly masking the thermal anomalies created by delaminations [11].

There are two testing approaches for IR thermography based on the source of heat. The active approach uses an external thermal stimulus to induce the required heat flow condition on the concrete under testing. The passive approach uses natural heat sources, such as solar heating and ambient temperature changes [10]. The concept behind the application of passive IRT in concrete bridge evaluation is that the anomalies and subsurface delaminations interrupt heat transfer through the concrete and influence the amount of radiant energy emitted from the concrete surface and measured by the IR camera. During daytime, the sun heats the concrete directly by radiation and indirectly by raising the ambient temperature. Concrete absorbs heat and starts emitting radiant energy. The surface area above any subsurface delamination resists the heat transfer and warms up at a faster rate compared to the