Thermal Detection of Subsurface Delaminations in Reinforced Concrete Bridge Decks Using Unmanned Aerial Vehicle

Synopsis: Bridge deck condition assessment is commonly conducted through visual inspection by bridge inspectors. Considering the colossal backlog of aging bridge structures, there is a need to develop cost-effective and innovative solutions to evaluate bridge deck conditions on regular time intervals, without interrupting traffic. This makes remote sensing technologies viable options in the field of bridge inspection. This paper explores the potential for applying infrared thermography (IRT) using unmanned aerial vehicle (UAV) to detect and quantify subsurface delaminations in concrete bridge decks. The UAV-borne thermal sensing system focuses on acquiring thermal imagery using a UAV and extracting information from the image data. Two in-service concrete bridge decks were inspected using a high resolution thermal camera mounted on a UAV. The captured images were then enhanced and stitched together using a tailored procedure to produce a mosaic view of the entire bridge deck, indicating the size and geometry of the detected delaminated areas. The results were validated by conducting hammer sounding and half-cell potential testing on the same bridge decks. The findings reveal the capability of the technology to provide measurements comparable to those derived from traditional hands-on inspection methods. Thus, it can be an excellent aid in efficient bridge maintenance and repair decision-making.

Keywords: bridge deck, condition assessment, delamination, infrared, thermal image, unmanned aerial vehicle

INTRODUCTION

Concrete is the most used construction material in civil infrastructures. Its service life is considered synonymous to its mechanical strength, durability and serviceability. Durability of concrete can be defined as its ability to resist weathering action, chemical attack, abrasion, or any other processes of deterioration to retain its original shape, dimensions, quality and serviceability. However, concrete structures are vulnerable to a number of factors that can cause deterioration and result in loss of strength and unsafe or failure conditions. Existing concrete bridges represent strategic components of infrastructural networks. Bridge failures can be catastrophic, both in terms of human life and economic loss, rendering the task of managing this important infrastructure asset a complex endeavour that attracts growing attention. Among all reinforced concrete (RC) bridge components, bridge decks are rapidly deteriorating and have been the leading contributor to most deficient bridges in the United States (Maser *et al.*, 2012). A major challenge associated with inspecting 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. Therefore, condition assessment tools capable of detecting subsurface anomalies, such as voids, delaminations and cracks are required to ensure bridge safety and define maintenance and repair needs. Current bridge deck inspection practices rely on visual inspection, which heavily depend on the experience and engineering judgment of bridge inspectors. A number of hand tools, including hammers, steel rods and chains, have been widely used to detect subsurface delaminations and voids in RC bridge decks. Hammer sounding involves tapping the surface of a concrete member with a hammer at multiple locations, while chain dragging involves dragging a chain over the bridge deck surface. In both cases, the user listens to and interprets the distinctive sounds produced. A dull or hollow sound indicates delaminated concrete, and a distinct ringing sound designates non-delaminated concrete. The advantages of these methods include simplicity, portability and low operating cost. However, such techniques require hands-on access and can be labor-intensive and time-consuming for large areas of concrete, while being ineffective for detecting subsurface anomalies in decks having overlays. Traffic control must also be in place so that inspectors can safely access the concrete element. In addition, the interpretation of the sound produced is subject to the operator's judgment and experience, typically yielding primarily qualitative and subjective decisions.

These limitations have motivated the pursuit of advanced non-destructive testing (NDT) techniques for more effective and reliable bridge inspection. NDT methods used to assess subsurface defects in RC bridge decks vary in complexity and reliability and often applied only when severe defects and deficiencies are observed. Infrared thermography (IRT) is a NDT technology that has gradually gained wider acceptance as a condition evaluation tool to detect subsurface delaminations in RC bridge decks without physical contact. Such subsurface anomalies can be detected on the basis of variable concrete properties, such as density, thermal conductivity and specific heat capacity. Rapid data collection using remote sensing technology with thermal IR imagery can reduce traffic disruption and lane closures on and underneath bridge decks, thus, it is less costly than other NDT methods. Generally, IRT testing collects radiant temperature and visualizes the data in the form of real-time thermal infrared images. With the advent of newer generations of infrared cameras, IRT is evolving as an accurate, reliable and cost-effective technique that can yield both qualitative and quantitative indicators of a RC bridge deck condition. Conducting ground IRT testing in-situ on full-scale bridge decks requires mounting the IR camera on a vehicle. Collecting thermal IR images is highly dependent on the camera's field of view (FOV) and lens. The ideal option for data collection is to scan one traffic lane on each pass. However, obtaining such horizontal FOV is not always achievable in the field as it may require to mount the camera at a high level. Thus a number of survey passes should be adopted to cover the entire bridge deck area, which requires the arrangement of traffic control.

The generic definition of remote sensing technologies allows for a variety of deployment platforms including satellites, aerial inspection using fixed wing aircrafts, or vehicle mounted systems, making remote sensing potentially valuable in the field of inspection and monitoring (Harris *et al.*, 2016). In recent years, the unmanned aerial vehicle (UAV) technology has increasingly been used in various application areas, such as monitoring construction and operation of buildings and other types of civil engineering systems. For instance, UAVs can be equipped with different high definition cameras to offer several mapping applications in the field of photography, geology, geography, meteorology or in agriculture and forestry (Hallermann and Morgenthal, 2014). The improvements in navigation and sensor technology have made UAVs more reliable in terms of flight control. In addition, the advanced telecommunication technologies permit their flying at different altitudes over considerable distances (Chen *et al.*, 2011). Therefore, UAV equipped with high definition photo and video cameras can facilitate the inspection tasks of civil infrastructure, such as bridges as they are able to operate at low altitudes and acquire images with high resolutions. The limitations of applying ground IRT motivated the pursuit of this technology for bridge inspection. A UAV-borne imaging system with a high resolution thermal camera can provide a much safer and cost-efficient way for data acquisition. This study attracts the application of this system for evaluating the condition of full-scale deteriorated RC bridge decks.

RESEARCH SIGNIFICANCE

There is need for further research to develop more efficient bridge condition assessment for evaluating in-service bridges without interrupting traffic. Thus, remote controlled UAV equipped with a high resolution thermal imagery could be a good option to simplify the inspection tasks of RC bridge decks. This can provide rapid condition assessment and enable monitoring of deterioration progression through periodical surveys and thus, allow the surveys of hundreds of RC bridge decks to become feasible. Consequently, considerable reductions in costs associated with the inspection processes of bridge decks and in the frequency and duration of traffic interruptions can be achieved. In addition, the majority of IRT testing performed in previous research studies was based on testing specimens prepared in the laboratory environment with simulated defects, then exposing them to solar energy. Hence, several processing algorithms to extract information were developed based on the temperature of the pre-defined defects' locations and sizes with respect to the temperature of the surrounding sound concrete. However, when conducting IRT testing in-situ on full-scale RC bridge decks, the ability to extract quantitative information of unknown subsurface anomalies from images is still needed to fully realize its potential in detecting these defects.

RESEARCH OBJECTIVES AND METHODOLOGY

The main goal of the present study is to evaluate the reliability of using a UAV-borne thermal imaging system as an inspection tool for the condition assessment of RC bridge decks. The primary objectives of the study are: (i) studying the capability of UAV-borne thermal imaging system in detecting the delaminated areas in RC bridge decks; (ii) applying a rational procedure to analyze the thermal images captured by the system; (iii) creating a mosaicked thermogram of the entire bridge deck; (iv) producing a condition map indicating the geometry and sizes of delaminated areas. The methodology adopted for achieving these objectives consists of: (1) utilizing a UAV to conduct passive IRT testing in-situ on two deteriorated full-scale RC bridge decks using a thermal infrared camera; (2) enhancing the thermal contrast of the captured images using a commercial imaging software; (3) stitching the images to produce a thermal map for the entire bridge decks using especially developed Matlab codes; (4) identifying the defected areas based on the recorded thermal contrast values; (5) quantifying the delaminated areas within the bridge decks; and (6) validating the achieved results through data obtained using other technologies on the same bridge decks.

BACKGROUND

Deterioration of RC bridge decks

Deterioration of RC bridge decks is caused by multiple reasons and the distinction among their major causes is purely qualitative since such mechanisms can act in synergy. Different deterioration processes lead to different types of structural defects (e.g. delamination, spalling, cracking, rebar size reduction) or material alterations (e.g. reduced modulus, changed electrical and chemical properties). However, deterioration of RC bridge decks is commonly initiated by reinforcing steel corrosion often instilled 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 (delaminations). Such defects typically occur at or near the level of the top steel reinforcement layer. They also could occur below the bottom steel reinforcement layer as a result of chemical diffusion through construction joints. As corrosion damage advances, these delaminations can mechanically de-bond and separate from the concrete structure that can lead to structural and functional failures, which are catastrophic, both in terms of human life and economic loss (Gucunski and Nazarian, 2010). The spalling of the concrete further exposes the reinforcing steel to the ambient environment, resulting in accelerated deterioration rates. In addition, spalling in the soffit area of overpass concrete bridges can lead to falling debris, creating hazards to the traffic below. Therefore, the delamination-induced spalling of concrete represents the main challenge in RC bridge inspection and has been a concern for transportation agencies due to the related serviceability and safety considerations.

Detection of delaminations in RC bridge decks

Inspection of an existing bridge aims at determining whether the bridge will function safely over a specified residual service life. Guidelines for inspection of existing bridges have been developed in many countries. Visual Inspection is the predominant inspection technique used in bridge inspection manuals and serves as the baseline to which other techniques are often compared. Routine VI is often conducted within 24-month intervals depending on the condition of the bridge. While visual inspection can provide useful information on the condition of a bridge deck, the observed deterioration or damage is typically in its last stage of development. Moreover, visual inspection is effective in finding external defects such as surface cracks, scaling and spalls, yet it cannot detect subsurface flaws such as voids, internal cracks, delamination, or rebar corrosion. Application of NDT technologies has shown promise in detecting subsurface deterioration in RC bridges. Conventional acoustic methods, such as sounding with hammers, rods or chain dragging, are widely used to detect subsurface anomalies in RC bridge decks. However, initial or incipient delamination often produces oscillations outside the audible range and thus, cannot be detected by such basic techniques as they rely on the operator interpretations of the sound heard (Yehia *et al*., 2007). Due to such access requirements and inherent subjectivity of sounding techniques, a number of more advanced NDT techniques have been motivated. These NDT methods are capable of identifying different types of damage in RC bridges and can be applied alone to evaluate certain aspects, or can be combined to cover a wider range of testing capabilities in a complementary manner. The most commonly used NDT methods in onsite assessment and evaluation of RC bridge decks are: Impact Echo, Ultrasonic Pulse Echo, Half-cell Potential, Ground Penetrating Radar, and Infrared Thermography. Generally, such techniques learn about the characteristics of the medium from its response to an applied acoustic, seismic, electric, thermal, or electromagnetic excitation (Gucunski *et al.*, 2013). Further details about their theoretical bases, instrumentations, applications, and data analysis techniques are provided in a variety of sources such as the AASHTO manual for bridge evaluation (2011), and in a report of the American Concrete Institute (ACI 228.2R, 2013). Only the implemented IRT technology in this study is presented below.

Infrared thermography technology

Heat transfer takes place in three modes: conduction, convection and radiation. The internal properties of a material, such as the density, thermal conductivity and heat capacity play important roles in governing its temperature at equilibrium with its surroundings. For instance, heat capacity is defined as the amount of heat needed to raise the temperature of a unit mass of a material by one degree and describes its ability to store heat. Thermal conductivity is the rate at which heat flows through a material. Thermal diffusivity, on the other hand, is the rate at which temperature changes occur in a material. A high thermal diffusivity means that heat transfer through a material will be rapid and the amount of storage will be small. Conversely, low thermal diffusivity indicates a slower rate of heat transfer and a large amount of heat storage. Infrared thermography (IRT) is a technology to detect thermal radiation emitted from materials. It creates an image of surface temperatures based on the emitted radiation. Thermal IR radiant energy is emitted from all objects that have a temperature greater than absolute zero. The rate at which this energy is emitted 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 and has a value between 0 and 1. This value is typically greater than 0.92 for concrete (Robert, 1982). There are two testing approaches for IRT 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.

The concept behind the application of IRT in concrete bridge evaluation is that subsurface defects such as voids, cracks and delaminations disrupt heat transfer through the concrete. When the temperature of the concrete increases, such as during daytime when the sun and ambient environment are heating the concrete, the surface area above a subsurface delamination warms up at a faster rate than that of surface areas where the concrete is intact. Delaminations can be detected as "hot spots" on the surface of the material, relative to intact concrete. Conversely, during nighttime, the air temperatures usually decrease and the material cools. Thus, the surface area above the delaminations cool at a faster rate than the intact concrete and appear as "cold spots" relative to the intact concrete. ASTM D4788-03, (2013) describes the standard procedure and equipment necessary for conducting passive IR testing for detecting delaminations in bridge decks. Although radiated energy is the parameter that is measured by a thermal IR camera, the heat conductivity within the concrete and heat convection around the concrete can also influence this measurement. Therefore, areas such as bridge soffits, which typically are not exposed to direct sunshine, can be warmed over the course of the day through convective heating if the temperature increase is sufficient. Though the temperature contrasts are smaller than those for solar exposed surfaces, subsurface delaminations can be imaged. However, this application of IRT is much less common than for solar exposed surfaces (Washer *et al.,* 2013). It should be noted that detection of delaminations in the presence of an asphalt overlay is difficult because the overlay could dampen the thermal contrasts achieved due to the thermal mass above a potential delamination, and the thicker the overlay, the greater the damping effect. Therefore, a major concern for the reliability of IRT testing through asphalt overlay is the possible presence of a debonded area, which could mislead interpretation. The debonded area could appear as a flaw in the IR image, in addition to the actual delaminations in the concrete. To distinguish debonding for delamination, Roddis and Maser (1990) suggested that the delaminated areas appear as circular and uniform, while the debonded areas are present as large, non-circular, and non-uniform.

In addition, the environmental conditions, such as wind speed, solar energy, humidity and ambient temperature have an influence on the results from a thermal IR bridge inspection. The effects of these environmental factors can be difficult to characterize and vary over time, such that it can be difficult to determine whether environmental conditions at a given point in time are adequate to produce a high quality image. Favorable environmental conditions include sufficient solar loading or changes in ambient temperature to produce a thermal gradient in the concrete, where the concrete surface heats up at a much higher rate than the concrete core. For instance, when the ambient temperature is less than the temperature of the concrete, for example when radiant heating from the sun warms the concrete above the ambient temperature, increased wind speed in this case will result in increased energy transfer from the concrete to the surrounding environment. Accordingly, thermal gradients in the concrete decrease (Washer *et al.*, 2013). In other words, convective cooling for solar exposed surfaces may counteract the radiant heating of the sun and reduce the thermal gradient in the concrete. Conversely, if the ambient temperature is warmer than the concrete, for example when ambient temperatures are increasing but there is no heating from the sun, then the convective heating transfer is negative. In this case, increased wind speed will accelerate the heat transfer to the concrete, which increases the thermal gradients in the concrete, thereby increasing the detectability of a subsurface delamination.

Unmanned aerial vehicles technology

A general definition of remote sensing can be summarized as the collection and measurement of spatial information at a distance from the data source, without direct contact. Unmanned aerial vehicles (UAVs) are a remote sensing technology that have been referred to as drones, robot planes, pilotless aircraft, remotely pilot vehicles, remotely pilot aircrafts, and other terms which describe aircraft that fly under the control of an operator with no person aboard. For positioning, a UAV is commonly equipped with a GPS. Generally, a UAV remote sensing system consists of four main features: aircraft with sensor(s) for data acquisition; remote control for the entire craft; GPS for navigation; and inertial measurement unit (IMU) for attitude measurement (Hallermann and Morgenthal, 2014). All flight parameters (e.g. longitude, latitude, time, GPS altitude, position etc.) are usually stored in a log-file together with the aircraft status parameters (e.g. battery status, flight modus and GPS signal quality). Additionally, the camera parameters (position, image number, altitude relative to launching area etc.) are also stored in the log-file, and thus are available for processing the individual images (Vasterling and Meyer, 2013). During the UAV operations, the acquired images are stored on the SD card of the camera. Recently, ground station software releases on mobile device platforms have allowed operators to use tablets and smart phones to control aircrafts. Micro and mini UAVs are the smallest UAV technology, and a large variety of these commercial aircrafts have been recently developed. Their platforms can fly at low altitudes and are the most used for civil engineering applications. These UAVs are able to take off and land vertically, requiring less area to operate, and can hover over fixed areas. They have been applied in surveying construction sites, monitoring work-in-progress, creating documents for safety, and inspecting existing structures, especially inaccessible areas. The most critical factor in such applications is the movement of the camera directly caused by the movement of the flight system, which reacts to changes in wind conditions due to its low weight (Hallermann and Morgenthal, 2014).

Thermal imaging with a UAV has several advantages compared to satellite and ground-based measurements. It generates spatial data with good geometric resolution without the need to interpolate the data which might cause errors. Satellite imaging, in contrast, requires very high resolution data in order to obtain a high geometric accuracy. To successfully apply a UAV-borne thermal imaging, some important parameters should be considered (Vasterling and Meyer, 2013). For instance, the camera has to be sufficiently lightweight due to the limited payload of the UAV. It also has to be robust (e.g. insensitivity towards vibrations and dust). Thermal cameras for the (8–14) µm (1 µm = 3.94 x e^{-5} in.) bandwidth generally do not have a cooled sensor, resulting in a low signal to noise ratio. However, these camera systems are relatively lightweight, which is an essential advantage for use in UAV. It should also be noted that some lightweight infrared cameras do not have an autofocus. Thus, before mounting the camera onto the UVA the focus has to be adjusted manually by focusing at an object at the same distance as the planned flight altitude. Additionally, visual images or video recorded at the same time as the thermal image allow mapping thermal subsurface anomalies and differentiating the surface defects. The flight altitude is another parameter that has to be selected via a compromise between resolution and efficiency. If the data are not recorded continuously (video), then for satisfactory mosaicking a set of thermal images, the overlap of individual neighbouring images should be at least 50 %. Thus, only the central part of the images is used, which improves the quality of the composite image. Setting ground control points for further processing is another consideration. These points should preferably be visible in both the thermal and visual bandwidths. Therefore, a material with an emissivity as well as visual contrast to the survey area has to be chosen (e.g. aluminum foil). These marker points have to be positioned in the field accurately. The images can then be stitched to fit with the markers at the respective coordinates. The flight time of a UAV depends on its payload and is also strongly influenced by wind conditions (Vasterling and Meyer, 2013).

DATA COLLECTION

The UAV-borne thermal survey for this study was conducted onsite in a real-world application on two in-service RC bridge decks located in the city of London, Ontario. The bridges were scheduled, by the Ministry of Transportation Ontario (MTO) for rehabilitation because delaminations, the extent of corrosion and high chloride ions content in the bridges were recently identified by a condition survey. Thus, the bridges were considered as good candidates and selected for the UAV survey. The two bridges, (named herein bridge (1) and bridge (2)) were constructed in 1965 as single span cast-in-place RC frames passing over a creek. The frames are supported directly on the abutments, and paved with about 100 mm (4 in.) asphalt wearing surface, as indicated in the structural drawings. The bridge structures have a north-south orientation and their outer limits have concrete curbs and steel handrails. The critical deck characteristics include a total length of 15.24 m (50 ft.) with a transverse width of 12.18 m (40 ft.), which supports one lane of traffic with one side shoulder in each direction. The structural drawings of both bridges indicate a deck slab thickness varying from 0.91 m (3 ft.) at the abutments to 0.48 m (1.6 ft.) at the mid-span of the deck with a parabolic soffit. **Figure 1** illustrates the surveyed bridge (2) and a view of the condition of its deck. The utilized drone, thermal camera and the data collection methodology are briefly discussed below.

Figure 1-East elevation of the surveyed concrete bridge (2) and an overview of the deck condition.

The utilized aircraft in this study was Inspire 1 Pro, a quadcopter drone, which is equipped with a retractable arm system whereby the underside of each propeller motor has a foot to act as a landing pod when the arms are lowered. Thus, the propeller arms rest in a lowered position when the drone is on the ground and once in the air, they can be retracted to give the camera unobstructed views across 360-degrees. Using intelligent flight batteries allows up to 18-22 minutes of flight time and a maximum flight speed of 18 m/s (59 ft/s). The flight battery constantly supplies the flight computer with remaining voltage. Applying special algorithms, the computer supplies the operator with estimates of remaining flying distance and time to return. The drone relies on a GPS-based stabilization system that is able to hold a position even when experiencing wind interference and can automatically bring the aircraft to the home point in the event of signal loss. The system allows the drone to hold a position with ± 2.5 m (± 8.2 ft) horizontal and ± 0.5 m (± 1.64 ft.) vertical accuracy. **Tables 1** summarizes the specifications and features of the drone.

Table 1-Features and specifications of the utilized aircraft

Drone (Inspire 1 Pro)	
Characteristic	Specification
Aircraft Model	T600
Motor Model	DJI 3510H
Maximum Take-off Weight	3500 g (125 oz.)
Vertical Hovering Accuracy	0.5 m (1.64 ft.)
Horizontal Hovering Accuracy	2.5 m (8.2 ft.)
Maximum Aircraft Speed	18 m/s (59 ft/s)
Maximum Altitude	120 m (394 ft.)
Maximum Flight Time	18-22 Minutes
Maximum Wind S. Resistance	10 m/s (32.8 ft/s)
Operating Temperature Range	-10ºC to + 40ºC (14ºF to + 104ºF)
Propeller Model	DJI 1345 T
Maximum transmitting Distance	3.5 km (2.18 miles)

The FLIR Vue Pro thermal camera was utilized in this study. The camera weighs 113 grams (4 ounces), which makes it ideal for UAV applications. The camera is compatible with the utilized drone and can be mounted via an integrated 3-axis gimbal to maximize stability and weight efficiency while minimizing space. The gimbal uses brushless servo motors to keep the shot stable and the horizon level. The camera pans a full 360-degrees so that no matter which way the quadcopter turns; the camera can remain locked on the subject. Manual panning and tilting can be affected using controls on the transmitter (radio controller). Once the controller is ready to go, a tablet or smartphone can be attached, which allows the operator to see what the drone is viewing along with other statistics concerning its flight. The camera processes the temperatures by an automatic gain control (AGC) into a maximum of 256 shades of gray to display a thermal image. Since the imaging system is sensitive enough to distinguish many more than 256 different temperatures, each “shade of gray” represents a range of temperatures. The raw scene data could be stored as still images (TIFF, JPEG or in FLIR File Format (FFF)) for post processing using FLIR image processing software. It has an uncooled microbolometer detector and displays thermal images with a resolution of 640 x 512 pixels. **Table 2** summarizes the specifications and features of the camera.

Table 2- Features and specifications of the utilized thermal camera

Thermal Camera (FLIR Vue Pro)	
Characteristic	Specification
Size	62.7 mm x 44.5 mm (2.47 in. x 1.75 in.)
Weight	101 g to 122 g (3.61 oz. to 4.36 oz.)
Detector Type	Uncooled Microbolometer
Spectral Band	7.5µm – 13.5µm
Thermal Resolution	640 x 512 pixels
Full Frame Rate	30 Hz (15 fps)
Field of View	9 mm (0.35 in.) Lens (69º x 56º)
Input Supply Voltage	4-6 VDC
On-board Storage	MicroSD
Operating Temperature Range	-20ºC to +50ºC (-4ºF to +122ºF)
Operational Altitude	+ 12,192 m (40,000 ft.)
Polarity Control	Yes

The UAV-borne thermal imaging in this study was conducted by a consultant specializing in aerial photography, videography and thermography who has completed UAV training, IRT training, pilot licensing, and acquired special risk aviation insurance and gained a special flight operation certificate as per the requirements of the Canadian Aviation Regulations. The setup of both the drone and the thermal camera was firstly completed by the UAV operator. This includes the installation of the propellers and downloading the drone and camera operating software. The DGI Go app controls the flight and allows for a real-time view of a live video to line up the perfect shot where the data is automatically saved on the used mobile device. The FLIR Vue Pro app allows the setup of image format, orientation, shutter speed, camera focus adjustment, shooting mode, and color palette and communication options with the mobile device. All the batteries were recharged and the camera was mounted on the drone and oriented facing straight-down to be perpendicular to the concrete deck surface being investigated. It was not possible to measure the angle while flying. Hence, an estimation of the drone’s perpendicular position to the deck surface was made from the live stream video of the flight displayed in real-time on the monitor. **Figure 2** illustrates the utilized drone and thermal camera.

Figure 2-Aircraft (Inspire 1 Pro) and thermal camera (FLIR Vue Pro) utilized in this study.

Time of data collection is the most critical factor in a passive IR survey. In a study conducted by Washer *et al*. (2013) on concrete bridges, it was found that the effective time to perform a thermal IR test depends on the depth of the delamination. The most contrast appears on the thermal IR image approximately 4 hr after sunrise for a 50 mm (2 in.) deep delamination and 7 hr after sunrise for a 75 mm (3 in.) deep delamination. Therefore, the surveys were conducted on May 24th, 2016 at 1 PM, six hours after sunrise. During the survey, the ambient temperature was 26° C (79º F), relative humidity was 22%, and wind speed was 8 km/hr (5 mi/hr.). Bridge deck dryness was considered during data collection since surface moisture can reduce the thermal contrast on thermal IR images. Road traffic was not closed during data collection of the two bridges. While the total time taken to complete a bridge deck inspection from setup to tear-down was approximately 20 minutes, the total flight time was about three minutes for each bridge deck. A calibrated 9 mm (0.35 in.) focal lens (69º x 56º) was utilized, which allowed a FOV of 13.74 m (horizontally) x 10.62 m (vertically) (45 ft. x 34.8 ft.) for each image taken at a constant 10 m (32.8 ft.) altitude and resulted in 2.5 cm (1 in.) spatial resolution. Hence, a total of four thermal images, at spacing of 5 m (16.4 ft.), were collected with an overlap of 50% to cover the entire deck length. Each image covers the entire deck width and shoulders, in addition to the sidewalks at both sides. The still images were taken at the center of each bridge deck. **Figure 3** illustrates the UAV hovering process and a captured thermal image.

Figure 3-Setup of UAV-borne thermal system and a snapshot during flight over bridge (2).

DATA ANALYSIS

The captured IR images of the bridge decks were firstly pre-processed. Several functions in the *ImageJ* software were utilized to improve the images' quality. For instance, the Gaussian smoothing filter was used to reduce noise whereby the software selects the size of the filter automatically. The histogram equalization function was used to distribute the intensities on the histogram, which in turn enhanced the thermal contrast. The temperature data of each image was then saved in a separate Excel file. To create a mosaic thermogram of the entire bridge deck from the individual images, a selected window from each image was extracted and stitched together with the extracted window from the next image and so on. The height of each stitch window is the number of pixels that are equivalent to the images' spacing. Hence, this appending process produces continuous data for each survey pass. The dimension in pixels depends upon the pixel resolution in each direction. For the bridges under investigation, the dimension of the mosaic for each deck was 640 x 780 = 499,200 pixels. A Matlab code was written by the authors to extract and stitch the selected pixels from each image. For visualization and to simplify further processing, it was necessary to scale-down the data dimension of the mosaic. This was achieved by assuming the entire deck divided into small boxes of 10 cm x 10 cm (4 in. x 4 in.) in dimension in which the temperature does not change, then computing the average of pixels, which represents the resolution within the selected dimension. This resulted in a reduced file with 128 x 156 = 19,968 pixels. The mean function in Matlab was modified and a new code was written to calculate the mean for specified dimension of input data. The code at first operates and returns a raw vector containing the mean of each column element, and then provides a scalar value, which represents the mean of the elements in the raw vector. Another Matlab code was also written to identify the coordinates of each pixel in the temperature data file where the origin point (0, 0) was assigned to the corner of the bridge deck, then the coordinates of all other pixels in the file were computed. The final analysis output was an Excel file including pixel information (co-ordinates and temperature) arranged in a column order. The developed Matlab codes can customize the analysis process for any other IRT survey data. It should be noted that a more rigorous analysis could be achieved based on a photogrammetric 3D reconstruction and generation of orthophotos. There are several commercial software capable of producing accurate 3D stereomodels, orthophotos and orthomosaics from data collected by various sensor systems. These orthophotos and mosaics are geographically referenced and commonly created using automated tools for tie-point matching, orthorectification, relative orientation, and color-balancing. However, it should be noted that inaccuracies in input control values could cause problems in the photogrammetric modeling process, and thus it is preferable to employ the capture app belonging to the utilized software in the data acquisition process to ensure adequate quality imagery and accurate geospatial control.

Thresholding classification using the saved scaled temperature values was implemented in the present study to identify the defective areas in the concrete deck. Firstly, the thermal contrasts were calculated from the scaled temperature values of the mosaicked thermogram. It was then necessary to select a threshold value for the calculated thermal contrasts that could indicate where delamination was likely to be detectable. As per the ASTM D4788-03, 0.5°C (0.9° F) is the minimum contrast to distinguish between sound and defective concrete. Because the bridge decks are asphalt paved, the thermal contrast of 0.5°C (0.9° F) could be due to the effect of pavement thickness. In addition, spalling could be hidden under the asphalt layer, and thus a higher thermal contrast value of 1°C (1.8° F) was selected. It is about 20 times higher than the sensitivity of the utilized camera such that much smaller variations in surface temperature were easily detectable. The pixels with a higher thermal contrast than this threshold value were highlighted because delaminations appear as higher temperature features. Finally, the temperature values were grouped and a condition map was plotted using a commercial mapping software to construct a high contrast image, accurately delineating the geometry and location of subsurface delaminations. **Figure 4** illustrates the created maps of the two surveyed bridge decks where the delaminated areas are highlighted in red color and sound areas in blue color.

Quantitative analysis of UAV-borne thermal data enables an accurate determination of the temperature for a defective region. Thus, calculating the total delaminated areas from the produced mosaicked thermogram in **Fig. 4** provides a quantified basis for powerful decision making and hence, for prioritizing alternatives in bridge deck rehabilitation plans. For this purpose, the pixels with thermal contrast higher than the threshold were highlighted inside specific boundaries. The total percentage of delaminated areas in the bridge deck was then determined by computing the total percentage of pixels in higher temperature areas over the total bridge deck. To some extent, this could be a qualitative analysis since it is difficult for different analysts to have consistent judgment in selecting the threshold. The authors are currently developing a procedure to determine objective thresholds in order to categorize the detected delaminated areas in different classes based on the severity levels of the delamination.

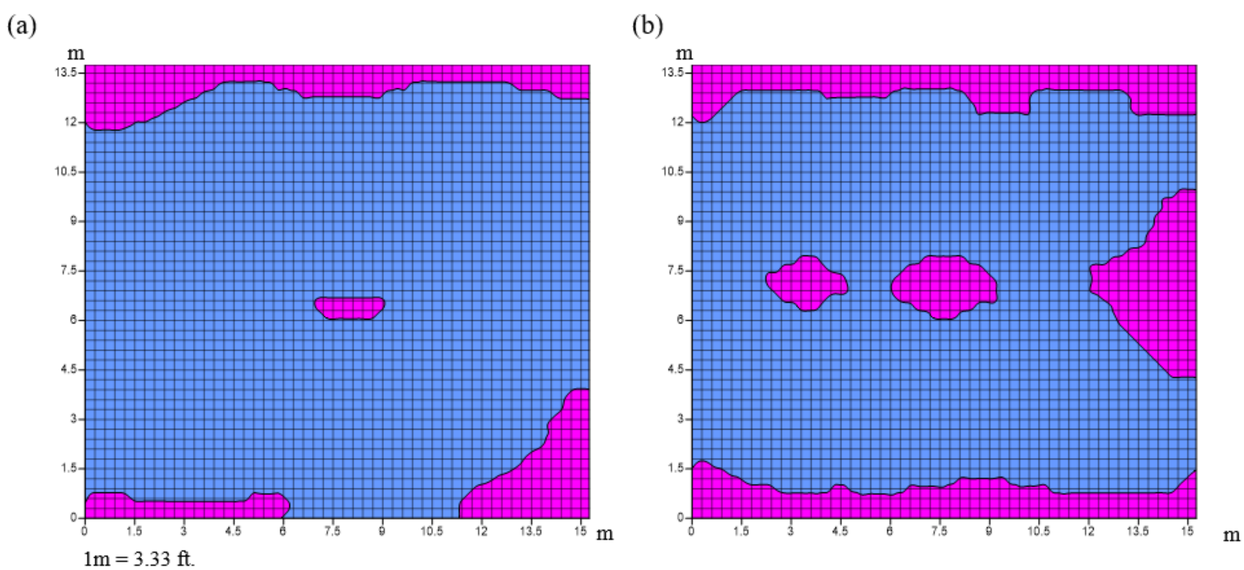

Figure 4- Delamination maps of: (a) top surface of bridge deck # 1; (b) top surface of bridge deck # 2 surveyed using UAV-borne thermal system.

VALIDATION USING RESULTS OF OTHER NDT

The achieved results were validated using the results of hammer sounding and half-cell potential corrosion tests conducted on the same bridge decks. The hammer sounding was conducted by a bridge inspector from the MTO, before the UAV-borne thermal imaging survey. The hammer sounding is a qualitative evaluation of concrete and was conducted by tapping the bridge deck with a hammer. When the hammer is struck on good concrete, a ringing sound is created. Conversely, on areas where delaminations or cracks occur, the striking of the hammer produces a drum-like sound. The delamination maps created by IRT for both bridge decks were compared with the hammer sounding results. It was found that the two methods provided considerably similar sizes and shapes of defects in the two decks. The quantified delaminated areas by both techniques are presented in **Table 2** below. For the first bridge, the hammer sounding results showed 17% total delaminated areas on the bridge deck, whereas the total delaminated area calculated from the thermal infrared imagery survey was 15.4% of the total bridge deck area (1.6% difference between the two methods). Similarly, the total delaminated areas on the second bridge deck identified by the hammer sounding and IRT were 32% and 29.3%, respectively (2.7% difference between the two methods). Thus, the UAV-borne thermal imagery system with the presented analysis procedure can define the location and extent of delaminations in bridge decks with considerably reasonable accuracy.

The two surveyed bridges were also investigated using the half-cell corrosion potential testing technique. Corrosion of reinforcing steel is an electro-chemical process and the behaviour of the steel can be characterised by measuring its half-cell potential to indicate the probability of active corrosion. The greater the potential the higher the risk that corrosion is taking place. An electrode forms one half of the cell and the reinforcing steel in the concrete the other. The preferred reference electrode for using in situ is silver/silver chloride in a potassium chloride solution although the copper/copper sulphate electrode is still widely used. However, the survey procedure was conducted as per the requirements of ASTM C876 and started firstly by locating the steel and determining the bar spacing using a covermeter. The cover concrete was removed locally over a suitable bar and an electrical connection made to the steel. It was necessary to check that the steel was electrically continuous by measuring the resistance between two widely separated points. The reinforcing bar was connected to the half-cell via a digital voltmeter. Readings of half-cell potential were taken over a grid of points to give a potential map of the area. The survey was conducted a few weeks before the UAV-borne thermal survey, by a consulting firm specializing in NDT of concrete structures, as part of a condition survey program with the MTO to evaluate the condition of 24 highway bridges. In addition, three drilled concrete core samples for visual inspection and chloride ion concentration analysis were retrieved from each bridge deck. The quantified results are presented in **Table 2.** The core samples indicated actual overlay thickness of about 50-60 mm (2-2.4 in.), while the delamination layers were observed at about 45-50 mm (1.8-2 in.) depth from the concrete surface.

Table 3- Percentage of defective areas in the surveyed decks

Bridge Deck	% Delaminated Areas (UAV-borne thermal)	% Delaminated Areas (Hammer Sounding)	% Potential Corrosion Areas (HCP)
(1)	15.4	17	14.1
(2)	29.3	32	27.4

For the first bridge, The HCP results showed probable active corrosion for 14.1% of the total deck area with corrosion potential values more negative than -0.350 V, whereas the total delaminated area calculated from the IRT results was 15.4% (about 9% difference in total defective area between the IRT and HCP surveys). Evidence of corrosion was not observed on the reinforcement encountered in the core extracted from the deck as the high corrosion potential areas were mostly found along the curb areas. The chloride content at the level of the reinforcing steel was below the chloride threshold level of 0.025%, by mass of concrete, in the three cores tested for this bridge deck. For bridge (2), the HCP results indicated probable active corrosion for 27.4% of the total deck area with corrosion potential values more negative than -0.350 V, whereas the total delaminated area calculated from the IRT results was 29.3% (about 7% difference in total defective area between the IRT and HCP surveys). The areas of potential active corrosion, as indicated by the HCP testing, have been validated by chloride ion concentration analysis of the three cores extracted from the deck and were found to be 0.033% by concrete mass. The core samples were extracted from areas prone to salt exposure, such as construction joints. In spite of the different mechanisms of the IRT and HCP techniques and their capabilities of indicating the potential of different deterioration types, it was noted that their condition maps were comparable to a high degree with respect to the location and shape of defects. It should also be noted that corrosion is among the primary reasons that could lead to delaminations in RC bridge decks, and thus could be the reason of obtaining potential corrosion areas smaller than the detected delaminated areas.

DISCUSSION AND FURTHER RESEARCH

Effective monitoring strategies are paramount in achieving the service life goals of bridge structures. Several remote sensing techniques have been used to assess conditions in different infrastructure applications. Incorporation of these techniques into the bridge monitoring and condition assessment scheme has the potential to not only enhance inspection practices, but also provide tentative assessments between inspection cycles, with minimal traffic disruptions. Vaghefi *et al.* (2012) argued that many aspects of bridge inspection could be aided by UAV remote sensing. For instance, a UAV-borne thermal imaging system deploys a UAV and utilizes an infrared thermal camera to provide spatially distributed information of the concrete surface temperature without the need to access the surface and hence, could play a major role in bridge condition assessment. The present study discusses a novel method of condition assessment for RC bridge decks based on airborne thermal photos taken by a UAV. The rationale of the analysis presented herein is that creating a plan view mosaic of the entire bridge deck facilitates the detection of defective areas. The thermal contrast developed from the concrete subsurface provided numerical values for the color contrasts that were used to process data more effectively than simply comparing multiple images. The specially written Matlab codes solved the question of how to create a mosaicked thermogram of the entire bridge deck from the individual thermal images.

The study demonstrated the applicability of this system in detecting subsurface delaminations in the surveyed RC decks. The developed methodology provided comparable condition measurements in a manner more efficient than standard practice. The achieved results comply with the results of previous studies. For example, Metni and Hamel (2007) successfully utilized UAV for different types of inspections including bridges. Similarly, Brooks *et al.* (2015) investigated several applications of UAV technology including bridge inspection. They used the UAV to capture imagery, both digital and thermal, of the bridge deck and applied some algorithms to detect surface defects on the deck. Khan *et al. (*2015) collected thermal images of a mock up bridge to demonstrate the types of data that can be collected with a UAV and were able to detect possible delaminations in the concrete bridge deck.

The UAV-borne thermal imaging system could be a valuable option to inspect inaccessible bridge components. For instance, subsurface delaminations within the bridge soffits can be imaged and detected. Thus, the system has the advantage of reducing the time required to conduct inspection and the costs associated with using special access vehicles. Such detection of delaminations and damage underneath the deck and within the bridge soffits is always a challenge for the bridge inspector due to the safety measures required for passing traffic under the bridge. In spite of the benefits of UAV systems, they have some limitations that require further research and development (Otero *et al.,* 2015). For instance, the limited payload allows only small battery packs, which cause a relatively short flight time. In addition, due to the small payload the flight system is very sensitive to changes in weather conditions, especially during high wind speeds, which can compromise image quality. Conducting cost estimation studies that consider cost parameters associated with operating UAVs during bridge inspection at the network level is also required. Furthermore, several effective image post-processing algorithms are required for accurate detection and classification of defects. The use of UAVs that could be equipped with multi-sensors along with inertial and spatial sensors to produce geo-registered 3D data for bridges should be investigated to enhance the bridge inventory management. It should also be noted that to utilize UAVs as an effective tool in bridge inspection, qualified bridge inspectors should be trained to operate the UAVs systems to provide high flight performance and objective inspection processes. Hiring private companies that offer UAV-based data collection services could also be another option.

CONCLUSIONS

The present study aims at advancing the UAV technology as a reliable and effective tool for bridge inspection, allowing improvements to the safety of highway bridges and better use of limited budgets of transportation agencies. Specifically, the application of UAV-borne thermal imaging systems for detecting delaminations in RC bridge decks was explored and a systematic data analysis of the captured images was developed. The results confirm previous findings and contribute additional evidence for the capability of the system to enhance bridge inspection methods, potentially achieving less-time consuming and more economical assessment that also creates a safer working environment. For efficient application of the system, the user should select the most compatible system of UAV and thermal camera, then plan and perform a successful field investigation, and finally derive a composite image mosaic of the concrete surface temperature patterns based on the acquired individual images. However, there are some challenges that require further research and are discussed in this study. While the attention herein has been mainly devoted to the condition evaluation of RC bridge decks, UAV-borne thermal imaging can be advantageously exploited for surveying other bridge components. Thus, by facilitating the early UAV-borne thermal imaging detection of deterioration in bridge components, transportation agencies should be able to apply proactive maintenance actions. The authors plan to explore the applicability of the deployed system to bridge soffit areas, in addition to studying the relation between the flight altitude and the accuracy of detecting subsurface anomalies in RC bridge decks. In conclusion, UAV-borne thermal imaging is a promising method to retrieve highly resolved spatial information on concrete surface temperature within a short amount of time. Once the UAV- born thermal images become available, the introduced procedure can analyze and determine whether a defect exists, and hence is useful in quantifying the delaminated areas present in a bridge deck. This system can be implemented in bridge inspection manuals to aid safer, more frequent, and potentially less costly bridge deck inspections and enable more informed decision-making.

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