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Bridge Pillar Inspection Using Thermography and Multispectral Images

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Abstract - Bridges play a vital role in the transportation sector, which is crucial to human life and the economy. To monitor the underlying deterioration of concrete bridges, this study investigates the potential use of unmanned aerial vehicles (UAVs) equipped with multispectral and infrared thermography sensors. The study area of this research was located at North-South Expressway Central Link (ELITE) Highway. A secondary multispectral and primary thermal images were used to inspect a bridge pillar's concrete surface fault. Using low-altitude planes, a high-resolution thermal camera was used to capture thermal images during the inspection process. A software program was used to improve the photos and stitch them together to create a mosaic thermal image of the entire bridge pillar. The mosaic thermal imaging image was segmented using K-means clustering, with the image analysis using the highest value thermal pixel in the image as the seed pixel. The results were then verified using multispectral photos taken using a high-resolution digital camera to evaluate the state of the surface. This study has successfully demonstrated the utility of a UAV outfitted with high-resolution thermal infrared imaging for accurately assessing subsurface faults on bridge supports. The suggested methodology encourages a safe working environment, allowing for more frequent and less expensive bridge pillar inspections. Quick bridge condition inspections during various service live phases should be possible, effectively allocating funds for upkeep and repairs.

Keywords - Thermography, Bridge pillar, Seed pixels, K-means Clustering

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1. Introduction

In the transportation sector, which is essential to both human life and the economy, bridges play a significant role. To offer the best possible service to the nations and people, the quick progress of bridge engineering has been closely tied to various advanced criteria, including materials, building methods, and modelling.

Parallel to the growth of technologies, the demand for a very effective work environment of inspection towards big structures has arisen as one of the significant issues involving bridges' structural health over the years. In recent years, structural failure and cracking plus natural disasters caused Pfeiffer Canyon Bridge in California and Milan Highway Bridge in Italy to collapse in 2017 and 2018, respectively. Besides, the local Public Account Committee of Malaysia has revealed that more than 70 million-ringgit Malaysia is required to repair the MRR2 flyover at Kepong (As of February 01, 2007, The Star listed on its website, www.thestar.com.my). It led to research and study to be carried out to seek advanced NDT (non-destructive testing) technologies for bridge inspection as an early stage of prevention of bridge collapse. NDT technique provides the knowledge and skills to swiftly and effectively evaluate and monitor ageing structures for engineers and owners. These techniques are employed for local structural health monitoring and damage detection (Rehman et al., 2016).

Furthermore, due to its suitability for locating cavities and honeycombs in concrete, infrared thermography has been used to inspect civil engineering projects for faults and anomalies (Zheng et al., 2022). Therefore, this study uses and examines the effectiveness of infrared thermography in identifying bridge structure defects. The bridge failure may be affected by several factors, including deficiencies in structure and design, corrosion, construction and supervision mistakes, accidental overload and impact, and lack of maintenance or inspection. It can be determined by using thermal imaging of the NDT technique for full-field detect imaging. For this study, three bridge piers or pillars identified as 34A, 34B, and 35B, respectively, were selected to be inspected for any defect occurrence.

2. Literature Review

The issue of structural failure has widely been discussed, especially in the inspection aspect, where such traditional methods through visual and climbing employment become unrealistic due to the risk posed by them. For the case of pillar concrete, implementation of a suitable technique and method in structural condition assessment is important to allow "full-cover" inspection, including the subsurface deficiencies mechanism.

Deterioration of Concrete Bridge

Cracking and spalling is the most common defect of concrete in Malaysia (King & Mahamud, 2009). They occur through one or a combination of three significant subsurface deficiencies mechanisms in concrete: physical, chemical, and mechanical. For instance, temperature gradients, abrasion, non-uniform volume fluctuations, and freezing-thawing cycles are the factors that may induce physical deterioration. Steel reinforcement of concrete mass could chemically reduce the alkalinity of concrete. The penetration of aggravating agent chloride ions from rain or water into the concrete, mixed with hydrogen ions on the steel surface, may create acids. The continuous process of mixing the ions produces enough acids to neutralise the alkalinity of concrete; thus, cracking is the result (Edwards, 2012). Besides that, during the operation, concrete deteriorates with cracks and delamination due to various variables, including repeated loads, the environment’s climate, wind velocity, and water movement. There are indeed air holes and delamination in concrete during construction (Huh et al., 2016).

Infrared Thermography

Conduction, convection, and radiation are the three methods of moving heat (Omar. and Nehdi, 2016). There are three ways an object being hit dissipates radiant energy: absorption, transmission, and reflection. If the transmissivity and reflectivity are zero, the material being hit is called blackbodies. Objects produce infrared radiation at temperatures higher than absolute zero (273.15 °C or 0 K). The useful range of infrared radiation, described as being between 0.8 and 14 m in the electromagnetic spectrum, is located between the visible and microwave portions. The near-infrared region (0.8-1.5 m), short-wavelength infrared region (1.5-2.5 m), mid-wavelength infrared region (2.5-8 m), and long-wavelength infrared region (8-14 m) can all be further broken down into their categories.

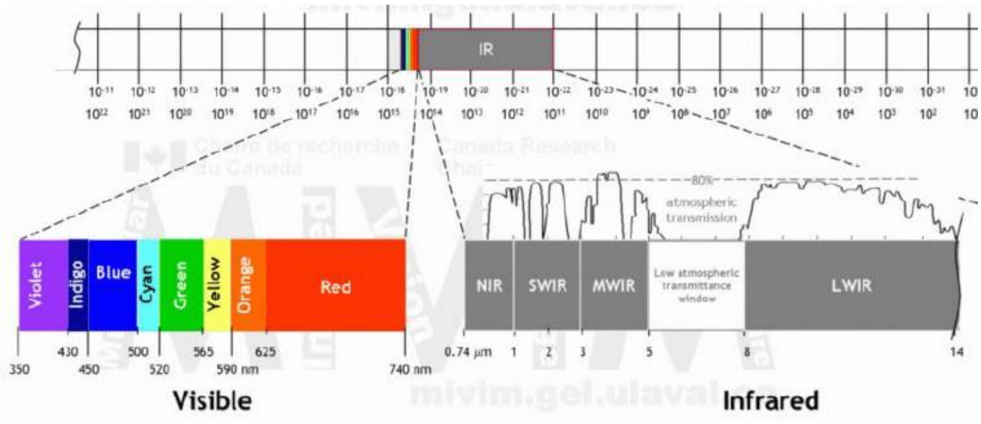


Figure 1. The electromagnetic spectrum (Akhloufi & Bendada, 2013)

The temperature of a substance and its emissivity determine how much-infrared radiation an object emits. This can be referred to as the Stefan-Boltzmann Law; it describes the total maximum radiation energy that a surface can release:

$$E = \mathcal{E}\, \sigma\, T^4 \ldots\ldots\ldots\ldots\ldots (1)$$

Where E is the radiation energy (W.m−2), σ is the Stefan-Boltzmann constant, T is the temperature (K), and Ɛ is the object's emissivity.

The capacity of a surface to radiate energy in relation to a dark body is known as emissivity. The emissivity of a perfect blackbody is unity; on actual surfaces, it is never more than unity. Concrete typically has an emissivity higher than 0.92 (Omar and Nehdi, 2017). However, the value is influenced by the surface roughness and moisture content of the concrete. Other substances on the concrete surface, such as stains, water, and lane markings, might cause visible changes in the image temperature, potentially hiding the thermal anomalies caused by delamination due to the different emissivity characteristics.

Infrared thermography is used to assess concrete bridges because underlying delamination obstructs heat transfers through the concrete and alters how much an infrared camera can detect radiant energy from the concrete surface. Basically, it observes electromagnetic wave surface radiations connected to changes in temperature in the infrared spectrum to find subsurface flaws (Watase et al., 2015). During the day, the light, directly and indirectly, warms the concrete by increasing the surrounding temperature. Heat is absorbed by concrete, which then begins to radiate energy. The area above subsurface delamination inhibits heat conduction and warms up faster than the surrounding area or unaffected concrete. This can be seen on infrared imagery as a "hot spot" on the concrete surface that has a higher temperature. The sound concrete region loses heat slower than delaminated sections at night when the ambient temperature typically drops. Thus, "cold spots" on the concrete surface with lower temperatures indicate underlying delamination on thermal infrared pictures.

Unmanned Aerial Vehicle

UAVs are aircraft that don't have human pilots on board. It can be piloted remotely by a ground navigator, autonomously under computer control, or partially autonomously. To provide a variety of mapping applications in many fields, including photography, geology, geography, engineering, agriculture, and forestry, UAVs can be fitted with various cameras or sensors. An inertial measuring unit (IMU) for altitude measurement, GPS for navigation, remote control for the entire craft, and aircraft with sensors for data collecting make up a UAV system. The availability of ground station software that works with mobile device platforms has made it possible for operators to fly using tablets and smartphones. Flight licenses are frequently needed to ensure civil and security authorities' rules are respected. Using unmanned aerial vehicles (UAVs) in construction engineering spans many tasks, including surveying job sites, keeping an eye on construction activity, and examining existing buildings, particularly in difficult-to-reach places. One of the primary applications for UAVs in construction is the planning and monitoring of construction activities, where their performance and speed can be significantly enhanced. In reality, practically every functional area of the building sector can benefit from such technologies. For instance, UAVs may be utilised during several phases of a building project, such as pre-planning, thorough job site mapping, monitoring the construction process, post-build checks, and sales and marketing (Anwar et al., 2018).

The most important component in these applications is the camera's movement, which is directly influenced by the motion of the flight control system and reacts to changes in wind flow conditions due to its lightweight. UAVs have a capacity for pre-planned flight paths and data collection at low altitudes. Additionally, they may land and take off vertically, requiring a smaller operating area. Operators can watch the camera's live feed on a screen monitor while the UAV is in flight. To create 3D models of structures, the collected data can be georeferenced. The inspection results can be matched to specific points on the bridge for a clear visual of the damage found. Therefore, UAVs have the potential to significantly alter how to bridge infrastructures are evaluated and how their upkeep is prioritised. Without entering the ground, a UAV-borne thermal imaging system uses a thermal infrared camera to deliver geographically dispersed data on the ground surface temperature. As a result, it might be pretty important to determine the state of a bridge.

For instance, UAV technology has numerous uses, such as bridge inspection. They captured digital and infrared photographs of the bridge pier using the UAV and then used specific algorithms to find surface flaws on the deck. However, several important factors must be considered to successfully use a UAV-borne thermal imaging system for bridge inspection (Vasterling and Meyer, 2013). For instance, given the UAV's limited payload, the camera must be sufficiently lightweight. It must also be strong, for example, insensitivity towards vibrations and dust. Another parameter that needs to be chosen to strike a balance between resolution and effectiveness is the flight height. Finally, more work must be done to successfully mosaic a collection of thermal images. Therefore, if the data are not continually collected, each image's overlap should be at least 50%. (video). Ground control points in thermal bandwidth must also be correctly set up and positioned in the field to facilitate later processing.

Previous Study

Based on previous studies, most of the passive thermal imaging technique applications for bridge inspection were used for bridge decks due to their total exposure to solar energy. For example, Mac et al. (2019) have produced a comprehensive system for inspecting bridges that uses passive infrared thermography (IRT) to find concrete bridge deck delamination. This study establishes the boundaries and usefulness of passive IRT in spotting delamination in concrete bridge decks with various width-to-depth ratios (WTDRs, the ratios between the size and depth of delaminations), which suggests that the impact of the delamination's size and depth are not taken into account separately.

Furthermore, data collection and interpretation become easier and faster because of a greater thermal gradient of the object under test and can also capture large area images from a distance. However, the passive thermal imaging technique is limited to locating the defects of non-solar exposure on the bridge, such as at the intersection of bridge soffit and abutments. This research aims to examine how well the thermal imaging technology performs for spotting bridge defects at the pier or pillar, one of the components of the bridge with low solar exposure.

3. Methodology

A research methodology is proposed to complete the research work systematically within the time frame. It is divided into three phases, as shown in Figure 2.

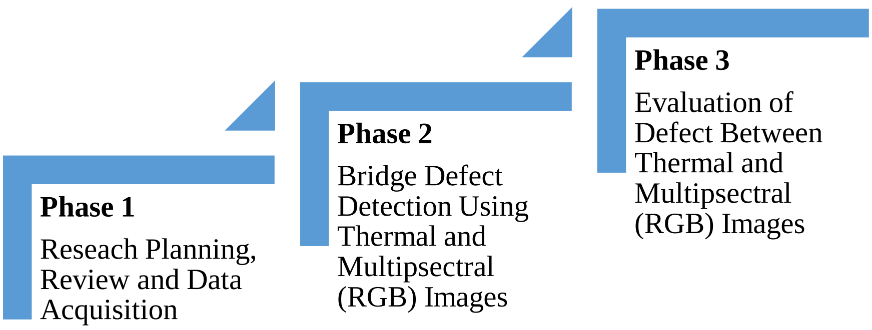


Figure 2. The framework of the research methodology

__Phase 1: Research Planning, Review and Data Acquisition__

The study was conducted in response to the demand for an effective working environment for inspecting bridges in the transportation sector. The relevant information was studied from several resources on a related topic for a clear understanding. The related studies conducted by other researchers were described in the literature review. The scope of the study, such as area, instrument, and time duration, was defined. The data acquisition process was carried out to capture images of bridge structures in thermal, infrared, and RGB environments. These images were arranged accordingly to ease the processing work.

Establishment of Control Target

A set of targets was placed on top of the pillar surface to aid the photogrammetric processing. The target coordinate was measured using the tachometry technique from two stations. All the coordinates will be computed based on the assumed coordinate of the control station.

Figure 3. Example of targets

UAV Data Collection

During aerial data collection, UAV was flown facing the pillar to obtain the images of the vertical pillar. The thermal images were captured by using a thermal camera Zenmuse XT. Selection of camera specification is important to ensure the data quality can achieve the study's objective. Moreover, some parameters of an infrared camera system specification, and the digital camera's resolution, can affect the quality of the thermal image captured and point cloud, respectively.

Figure 4. Thermal camera Flir Zenmuse XT

Table 1. Specifications of the utilised thermal camera (FLIR Zenmuse XT)

General	
Dimensions (size)	103mm × 74mm × 102mm
Weight	270g
Gimbal	
Mount	Detachable
Controllable Range	Tilt: +30° to -90°; Pan: ±320°; Roll: ±15°
Maximum Controllable Speed	120°/s
Camera	
Thermal Imager	Uncooled VOx Microbolometer
Spectral band	7.5 – 13.5 μm
Digital Video Display Formats	640 × 512
Analog Video Display Format	720 × 480 (NSTC); 720 × 576 (PAL)
Pixel Pitch	17 μm
Full frame rate	30 Hz (NTSC); 25 Hz (PAL)
Exportable Frame Rates	7.5 Hz (NSTC); 8.3 Hz (PAL)
Sensitivity	< 50mK at f/1.0
File Storage	Micro, SD Card
Photo Format	JPEG, R-JPEG
Video Format	MP4
Image Processing and Display Control	
Image Optimisation	Yes
Digital Detail Enhancement	Yes
Polarity Control	Yes
Colour and Monochrome Palettes	Yes
Digital Zoom	2×, 4×, 8×

For the entire airborne data collecting procedure to gather photographs of bridge pillars, the DJI Inspire 1 model is utilised as the UAV platform. A photographic platform that is ready to fly straight out of the box is the DJI Inspire 1. It has an on-board camera with a lens, stabilised gimbal, and retractable landing gear that can be pulled out of the way to provide the camera with an unhindered 360-degree view of the landscape below. The capabilities and safety of this type of UAV model were other factors in its selection, and the rotors' symmetrical placements help to maintain the UAV's planar angle.

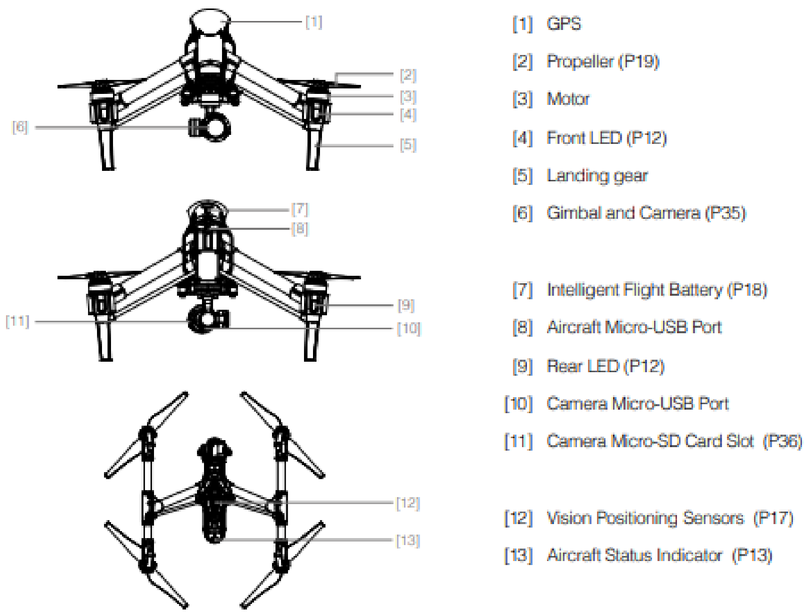


Figure 5. Aircraft component of DJI Inspire 1

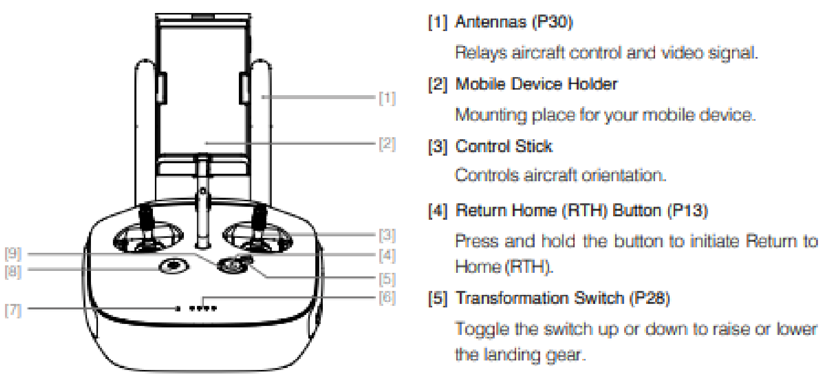


Figure 6. Remote controller component of DJI Inspire 1

One unit of UAV DJI Inspire 1 is deployed near the required bridge pillar to carry out thermal imaging. After the control targets are placed on the interest pillar surface, the flight is taken off. The flight planning is done by using DJI Go Application installed on the smartphone. The details of flight planning are shown as follows:

Table 2. Flight planning

Planning	**Description**
UAV operation	Manual
Flight period	15 minutes
Total number of photos taken	53 units
Camera model	DJI Inspire 1
No of light line	3 horizontal lines
Focal length of the camera, f	13mm
Flying height (Distance of UAV to bridge)	1.5 m

Phase 2: Bridge Defect Detection Using Thermal and Multispectral (RGB) Images

Data Processing

Image stitching is done to produce image mosaic, including thermal and RGB images. Pix4D Mapper and Flir Tools + were used as the platform to produce it. For Pix4D Mapper, both RGB and thermal datasets were processed separately due to photographs' different geometric and radiometric features. Based on SfM algorithms, Pix4d Mapper provides an automated processing method. SfM involves looking for and matching similar points (key points) by examining the imagery with various descriptors (Ivelja et al., 2020). The RGB contained the geometric information; however, the thermal records the scene in terms of temperature, thus complicating the process of image matching on a low-spatial resolution thermal image. Moreover, since the flight mission cannot log the GPS signal, no information on camera orientation can be used for automatic processing on Pix4D Mapper, especially for thermal images. Thus, the control target was used to control the processing in terms of orientation and scaling.

The image stitching processed by FLIR Tools+ is straightforward, commenced by importing the images into the FLIR Tools+ workspace. By using panorama mode, FLIR Tool+ stitched together several smaller images into a larger one by analysing each image to detect pixel patterns that match pixel patterns in other images. The successes mosaic is then saved as a new file in *.jpg format for downstream analysis.

Furthermore, Matlab programming software was used to process infrared images. The processing through Matlab Image Processing Toolbox was applied with the assistance of the Matlab help centre, involving image enhancement processing until the segmentation procedure. The purpose is to improve the quality of the image and partition the image into parts or segments, respectively. Gaussian smoothing filter and histogram equalisation were used to enhance image quality. The strategy used to segment the image is the determination of seed pixel and type of segmentation algorithm.

The segmentation process divides the image into regions of individual objects based on the ideas of point-based segmentation (e.g., value-based technique), object-based segmentation (e.g. region growing technique), or edge-based segmentation (e.g. edge detection technique). The most common choice for statistical data analysis is K-means clustering, often known as the unsupervised segmentation method, due to its simplicity, effectiveness, and empirical grouping. The clustering algorithm may quantify the degree of similarity, pinpoint critical characteristics in the data to be categorised, and arrange the information using cluster prototypes. To establish objective thresholds, the K-means clustering algorithm in Matlab was used in this work.

Phase 3: Comparison Between Thermal Image and RGB

In this stage, possible crack detection by the thermal environment is compared with RGB images in terms of the “true” existence. The crack detection using RGB images will evaluate the performance of thermal images for detecting bridge cracks. The analysis was conducted based on the difference thermal defect detection and RGB defect detection.

4. Result and Discussion

Mosaic

Due to the difference in geometric and radiometric features of photographs, both thermal and RGB datasets were processed separately in Pix4D software. The same procedure of photo alignment is implemented on both image datasets to generate a tie point; however, for thermal photographs, the need to neatly connect to the control point target on the image to orientate the photographs due to low spatial resolution. Both images will be combined into a new processing project in Pix4D Mapper, one successfully oriented. The tie point and photo orientation information were maintained. The photo orientation information is used to generate a dense point cloud based on RGB photographs, while the texture of the 3D model is generated based on thermal images. The vertical feature of the pillar was set up to extract the thermal mosaic. Figures 7, 8 and 9 show the output of processing from thermal and multispectral sensors for bridge pillars.

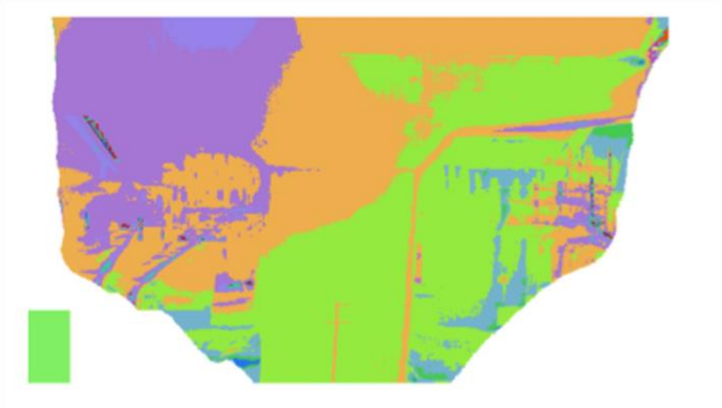


Figure 7. Thermal Mosaic by Pix4D Mapper software

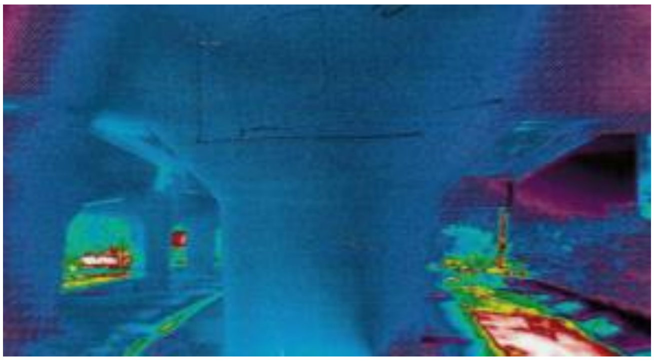


Figure 8. Thermal Mosaic by Flir Tools + software

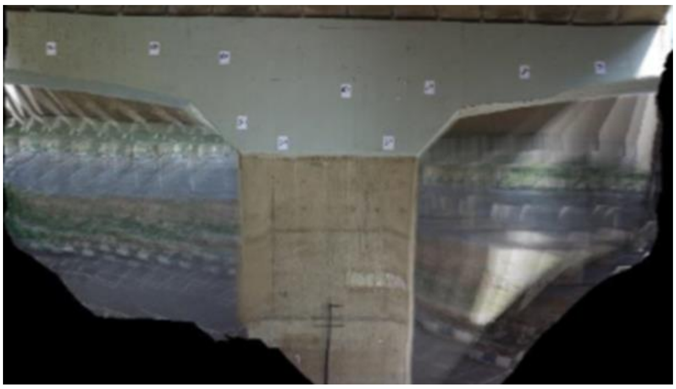


Figure 9. Mosaic RGB images of the bridge pillar

Figure 10. Bridge 34B for the testing

A pillar of the bridge named 34B was the subject of the testing. A spot was recognised visually as a potential crack, namely spot 1. The spot was captured with Zenmuse XT thermal camera. Figure 11 shows spot 1 of the possible crack on pillar 34B. Figure 12(a) is the raw thermal image in jpeg format directly from the thermal camera, while 12(b) is the respective thermal image in a different colour palette (Rainbow). One can see the temperature distribution in the image with a colour palette. The higher temperature is at the upper part (pier cap), and the low temperature is towards the bottom (pier column).

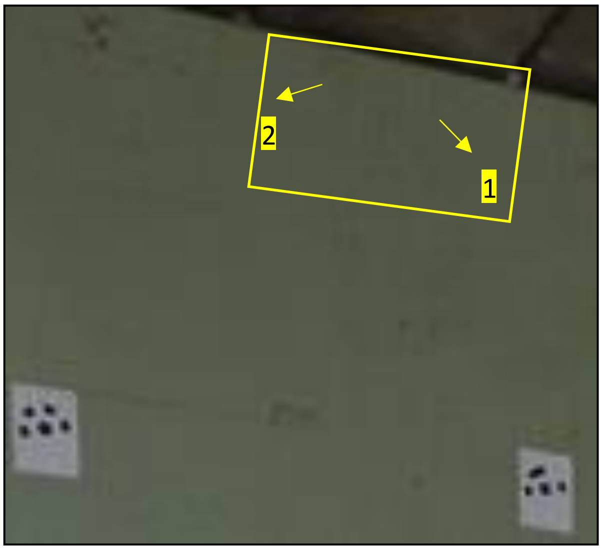
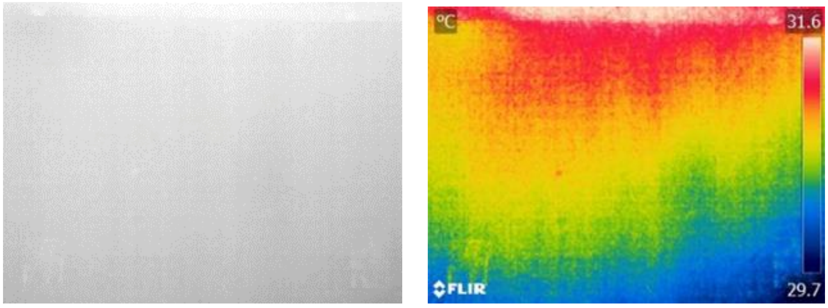


Figure 11. The potential crack of spot 1

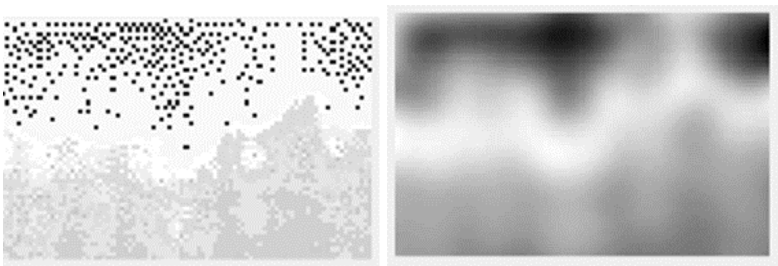


(a) (b)

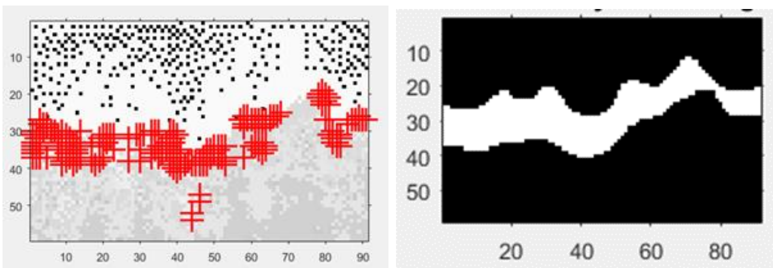
Figure 12. Thermal results of a spot (a) raw thermal image and (b) rainbow palette of the thermal image

Thermal Image Segmentation

The term "image segmentation" refers to dividing an image into several meaningful, non-overlapping regions that share the same qualities. Digital image processing relies heavily on image segmentation, and the efficiency of the subsequent tasks is strongly influenced by the segmentation process' accuracy (Zheng et al., 2018). The K-means algorithm comprises two distinct phases in which the k centroid is calculated in the first phase, and then in the second phase, each point is taken to the cluster with the centroid closest to it (Dhanachandra et al., 2015). The K-means clustering algorithm with five predefined clusters was implemented on the spot. The original, filtered image, distribution of hot pixel, and segmented image are shown in the figure below.



(a) (b)



(c) (d)

Figure 13. Segmentation result of spot 1 pillar 34B

Figure 13(a) is the original grayscale image from the conversion of the pseudocolour image in Figure 13(b). Figure 13(b) is the pre-processed image after applying a filter to remove noise, the resulting image exhibit better contrast. Figure 13(c) marks the pixel with the hottest spot as a cross to indicate the potential occurrence of a crack on the bridge pillar. Figure 13(d) is the K-means clustering image with five predefined clusters.

Multispectral Image (RGB)

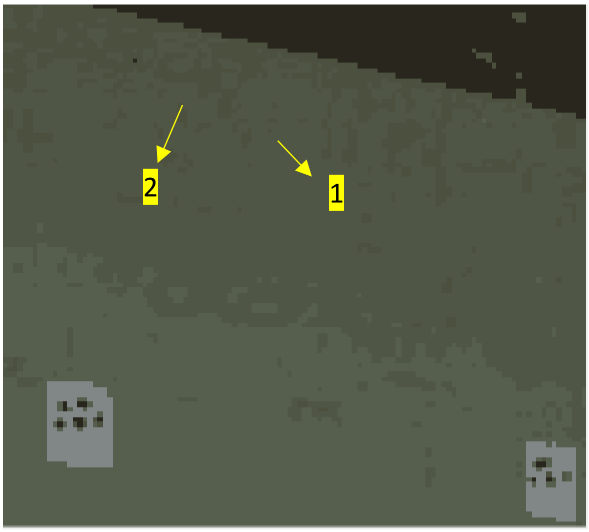


Figure 14: Segmentation RGB image of pillar 34B

Figure 14 shows the implementation of K-means clustering to the potential crack area on bridge 34B with the same clusters as thermal image segmentation. In detecting cracks on bridge piers, by implementing the same number cluster of K-means clustering, RGB gives better results than thermal images specifically for defect detection of the concrete bridge. This evaluates that the thermal image depends on the excellent heat source for analysis. For RGB image, it provides a true colour image which a real-life image can be replicated, which is determined by a combination of red, green, and blue intensities stored in each colour plane at the pixel's location. In another aspect, the thermal image contrasts potential defects and non-defect on the concrete bridge surface.

This relates to the concept that subsurface deficiencies in concrete structures heat up faster during daytime compared to non-defect areas. Considering suitable environmental conditions that support infrared or thermal radiation from the bridge surface and the strategy to segment the thermal image can improve the quality of defect detection on the concrete structure by the thermal imaging technique.

5. Conclusion

In short, it can be concluded defect detection using the thermal image on the concrete bridge is better than RGB remote sensing. However, it depends on the environmental condition and strategy of segmentation. Segmentation chosen is necessary to partition the image into parts of interest to suit the application.

This study applied a new technology method to monitoring the geotechnical structure. The presence of a crack can be identified using the thermal camera by the temperature difference on the bridge pier or pillar. The result of the thermal image shows that the crack behaves at the highest temperature while the surrounding surface of the wall represents a lower temperature. The validity of this approach is compared with RGB images. The methods of capturing are pretty challenging due to the loss of signal and the need to operate the UAV manually. The raw data can be seen on site by observing the display connecting to the camera. However, this thermal camera also has some limits. It needs enough heat sources such as sun and ambient temperature, and because the bridge deck obstructs the pillar, it seems to be less infrared radiation from concrete. This show that this thermal camera is a sensitive device.

This paper investigates an image segmentation technique to analyse the crack existing in the bridge pillar. As the subjective selection of threshold values remains a limitation in interpreting the IRT (Infrared Thermography) analysed data to identify the boundaries of different levels of deterioration severity, the K-means clustering algorithm is implemented in this study to segment the void area from the sound area on the pillar surface. The algorithm results in a proper segmentation and is suitable for thermal detection of deteriorations.

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