A Feasibility Study to Monitor Crack Width Displacement Using Images Taken with Pan-Tilt-Zoom Cameras

Afia BONEY[1*], **Satoshi NISHIYAMA**[1], **Osamu MURAKAMI**[2], and **Shosuke AKITA**[1]

[1] *Okayama University, Okayama City, Japan, (pyws76e8@s.okayama-u.ac.jp; nishiyama.satoshi@okayama-u.ac.jp; pnos832z@s.okayama-u.ac.jp)*

[2] *Tsukuba Software Engineering Co., Tokyo, Japan, (murakami@tse.co.jp)*

[*] *corresponding author*

Abstract

Ageing civil engineering structures such as bridges, tunnels and retaining walls are increasingly prone to failure. These structures must be monitored to ascertain their safety. Cracks and flakes are common visual indicators of weakening structures, which inspectors utilise for crack width monitoring over time. However, this traditional method, which uses crack gauge or scale, is time consuming and subjective to the inspector. Hence, over the last decade, myriads of research has been conducted using Digital Image Processing techniques to combat these issues and have proven to be effective as a form of non-contact monitoring. In this research, low-cost Pan-Tilt-Zoom (PTZ) cameras are explored as suitable instruments for image acquisition to monitor crack width of single cracks in bridges. There is little research on the use of PTZ cameras for civil engineering applications, and with their massive advancement over the years, PTZ cameras show potential for automatic image acquisition. Through laboratory tests, the influence of the distance, and zoom level of the lens are observed. By applying perspective projection, the displacement of the cracks can be measured. The results are evaluated by assessing the Root Mean Square Error and precision of the measurement system. The experimental results demonstrate the effectiveness of these cameras for crack width monitoring, validated by the case study in Okayama Japan.

Keywords: *PTZ cameras, crack width monitoring, Digital Image Processing, bridge inspection*

Received: 8th December 2024. Revised: 21st February 2025. Accepted: 5th March 2025.

1 Introduction

Transportation is the backbone of any country, essential for the movement of goods and people. A well-functioning transportation system is crucial not only for daily mobility but also for economic stability. When transportation networks are compromised, the entire economy can feel the impact. This is especially concerning as many civil engineering structures, such as bridges, tunnels, and retaining walls, are ageing and becoming more susceptible to damage or even collapse. The deterioration of these critical infrastructures can have far-reaching consequences, directly affecting both economic and social life. Most bridges were designed to last for fifty (50) years (American Society of Civil Engineers, 2021). In Japan, based on the period of economic growth in the 1970s, many bridges are approaching this age (Fujiu et al., 2022; Humpe, 2020). If these structures are not properly maintained, they will not only deteriorate further but will be costly to replace (Humpe, 2020). To extend the life of bridges in Japan, the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), from 2014, required all bridges greater than two metres in length to be visually inspected every five years (MLIT, 2018). These inspections rely on experienced inspectors who use visual and manual methods, often with handheld instruments, to assess the structure's health and durability. Cracks are the main visual component used to evaluate the condition of the bridge. The number, length, width, and types of cracks are recorded, analysed, and monitored over time. However, these methods are expensive, time consuming, subjective to the inspector and can be physically challenging. Additionally, roadways may be inoperable while inspections are underway. To address these challenges, extensive research over the past few decades has been carried out on different non-contact techniques for crack monitoring. One promising approach is Digital Image Processing (DIP) which emerged as a viable alternative or complement to visual inspection. DIP techniques use computer algorithms to analyse and extract essential information from images. Some image-based methods commonly applied in crack monitoring include image binarization (Sohn et al., 2005), edge detection (Abdel-Qader et al., 2003), and more recently, advanced techniques such as machine learning algorithms (Okazaki et al., 2020) and Deep Convolutional Neural Networks (DCNNs) (Kim et al., 2018). These methods have proven to be efficient, accurate and more objective, helping to address the aforementioned limitations of the conventional methods. In recent years, various optical devices such as Digital Single-Lens Reflex (DSLR) cameras (Belloni et al., 2023), smartphones (Nyathi et al., 2023), Unmanned Aerial Vehicles (UAVs) (Murao et al., 2019), and Pan-Tilt-Zoom (PTZ) cameras (Shao et al., 2021) have been utilised for data acquisition in crack inspections. While each of these technologies offers distinct advantages, they also have limitations. For example, UAVs present challenges such as the need for operating licenses, flight restrictions, managing the distance between the UAV and the object being inspected, and dealing with weather conditions. Additionally, continuous monitoring over time is difficult to achieve.

To reduce workload, cost, and time while increasing inspection frequency, automation is essential. Chun et al. (2020) proposed that remote testing could eliminate the need for physical presence at the inspection site, streamlining the process. Internet Protocol (IP) cameras could play a pivotal role in this approach. An IP camera, also known as a network camera, is a digital video camera that can receive and send data over a network (Local Area Network) or the Internet (Sheta and Mokhtar, 2022). Unlike the grainy, low-resolution analog security cameras of the past, IP cameras offer superior image quality. There are various types of IP cameras designed for different applications, including PTZ cameras. The acronym PTZ stands for pan (rotates on the vertical axis), tilt (rotates on the horizontal axis) and zoom (adjustment of the focal length). Although these cameras were initially designed for surveillance and security purposes, their use has expanded into other fields such as robotics and civil engineering in recent years. PTZ cameras offer several advantages: they are easy to install, weatherproof, can be controlled from a remote location, and can be programmed to preset positions. They are also capable of producing high resolution video and image outputs (Olagoke et al. 2020). Furthermore, PTZ cameras offer a wide field of view (FOV) providing high mobility, comprehensive information, and detailed imagery, especially when the optical zoom is utilised (Olagoke et al., 2020; Jiang et al., 2022). Lastly, these cameras can capture other bridge maintenance issues, such as concrete spalling, scaling, delamination, corrosion, and weathering (Humpe, 2020).

Jeong et al. (2017) proposed a PTZ camera system to measure displacement on buildings. They recommended using an IP camera with PTZ functionality as video data could be sent directly from the camera to the computer, either wirelessly or via Ethernet. The proposed method demonstrated the ability to measure over nine planes with high accuracy having a Root Mean Square (RMS) of 0.05–0.26 mm. More recently, Arif and Khan (2021) installed an IP camera to monitor the progress of building construction, which is critical for Building Information Modelling (BIM). The IP camera enabled real-time data capture and live video streaming, which was necessary for implementing a framework in MATrix LABoratory (MATLAB), a programming and numeric computing platform to analyse data, and create models. They also highlighted the camera’s ability to rotate both horizontally and vertically. Advancements in PTZ cameras have resulted in high-end models capable of capturing detailed images for a variety of applications. For example, Shao et al. (2021) utilised a PTZ-camera-based traffic monitoring system on China’s expressway to automatically estimate crack sizes on the roads, varying the camera distances. By calculating pixel size based on camera parameters, the system was able to accurately assess crack length and thickness, achieving a minimum estimation accuracy of 0.1616 mm. The method demonstrated the potential for real-time monitoring, which is advantageous for efficient highway maintenance. Later Sheta and Mokhtar (2022) developed an Autonomous Robot System (ARS) to detect cracks in pavements, using a CNN model. The ARS was equipped with a mobile device and an IP camera. The research found that the model was able to classify the cracks in the pavement with over 97% accuracy. Jeong et al (2023) mounted a 3D LiDAR, PTZ camera and microcomputers onto a ground vehicle robot for the detection of cracks and the estimation of propagation rates in tunnels. They used a multiscale multi-level mask deep con-volutional neural network (MSML Mask DCNN) in combination with a pixel-based clustering method to accurately identify cracks in the area of interest within images. The method demonstrated high robustness, with quantitative results showing low error margins and reliable propagation rate estimations, including rates of 198.1% and 141.8% for different tunnel images in the Republic of Korea.

In 2015, Nishiyama et al. proposed a crack width monitoring system using reflective targets placed on either side of a crack in a concrete tunnel to measure its expansion over time using a DSLR camera. The principle of the crack measurement is based on perspective projection, which adheres to the collinearity condition. The current study builds on their work, aiming to further explore crack width measurement using PTZ cameras, eliminating the need for human intervention and enabling continuous, remote monitoring.

The proposed system is designed for long-term monitoring of cracks in bridges. It is easy to install and requires no maintenance once the targets are in place. Since PTZ cameras can be monitored remotely, images can be captured 24hr/day, allowing for constant observation. The environmental effects can also be considered. This study evaluates whether the images captured by PTZ cameras are reliable for crack width monitoring and explores a workflow for remote monitoring, including the required hardware and software. Initial tests are conducted in a laboratory setting, followed by a validation of the remote monitoring setup on a bridge in Okayama, Japan.

2 System Design

2.1 System Requirements

The system developed in this research represents the first phase of a multi-phase project aimed at crack width monitoring on bridges. It is designed to be compact, durable, and cost-effective. Several critical factors are considered. Since it will be placed outdoors, it is built to operate efficiently under various weather conditions, including extreme temperatures. To minimise costs, off-the-shelf cameras were selected. Image analysis plays a crucial role in the system's functionality, so key considerations included camera resolution (Forcael et al., 2024), the distance to the targets (Guo et al., 2022), and optical zoom capabilities (Jiang et al., 2022). Additionally, the system is designed for minimal maintenance and remote monitoring, incorporating internet access, power supply, and security features to ensure reliable and continuous operation.

2.2 System Components

The system consists of several key components, including a power supply, a minicomputer, a Power over Ethernet (PoE) hub, and a Wi-Fi unit, all housed in a 25 x 14 x 30 cm IP66-rated metal enclosure that is both waterproof and dust proof (Figure 1). For the laboratory test, the main electrical supply is a portable power station with a high-capacity 60,000mAh (222Wh) battery, chosen for its ease of use, compact size, durability, and efficient charging time. In contrast, for the on-site test, the electrical supply is sourced directly from an outlet.

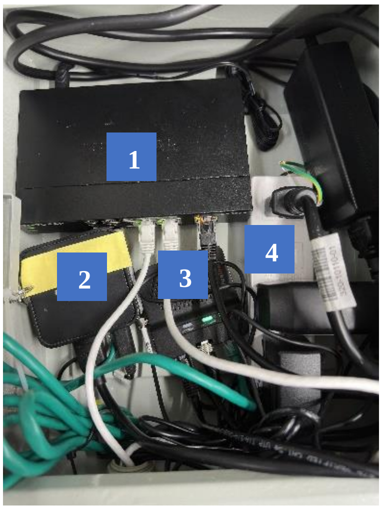

Figure 1. IP66 housing with components: 1) PoE switching hub 2) Mini computer 3) WiFi router 4) Power strip

The minicomputer (NUC) selected for this research is the MousePro-C100P (now discontinued), chosen for its availability in the laboratory. Serving as the central hub for network communication at the remote location, it runs Windows 10 IoT Enterprise (CBB) 64-bit and features a compact design that is both space-saving and practical. Despite its small size, it offers powerful processing capabilities that meet the demands of the research. It is equipped with an HDMI port, USB 3.0 ports, a microSD card reader, wireless LAN, and RJ-45 Ethernet port. The minicomputer provides secure Virtual Private Network (VPN) access to the workstation at the University, enabling remote monitoring of the cameras while ensuring confidentiality, integrity, and authenticity. A VPN creates a secure tunnel by encrypting data during transmission, protecting it from unauthorized access and ensuring the privacy of sensitive information. For this purpose, SoftEther VPN® (SoftEther VPN Project, n.d), developed by Daiyuu Nobori at the University of Tsukuba (Japan) was utilised due to its robustness, multi-protocol support, open-source nature, and strong encryption. Released in 2014, it has been continuously refined since then. A 5-port PoE hub connects to the minicomputer through its Network Interface Card (NIC), providing a dedicated network connection. This powers and connects the Pan-Tilt-Zoom (PTZ) cameras at the remote location via Ethernet cables. Additionally, a mobile Wi-Fi unit is directly connected to the minicomputer via the RJ-45 port for Internet access. An antenna is attached for enhanced signal. The workstation at the University establishes connection to the minicomputer at the remote location via the VPN. Through this secure connection, the operator at the workstation can control the PTZ cameras, thus monitoring the condition of the cracks at the bridge. This system set up is shown in Figure 2.

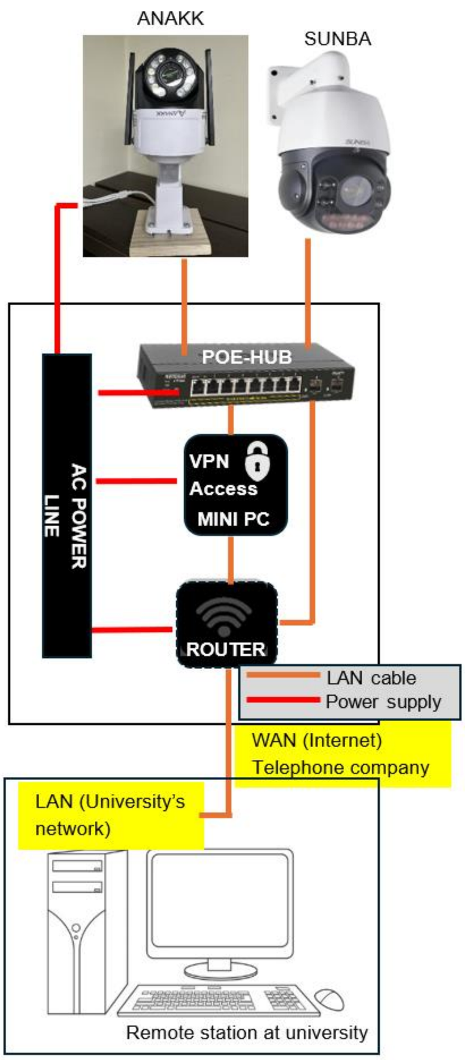

Figure 2. Remote crack monitoring system set up

2.3 Camera Specifications

The selection of cameras for crack width monitoring was influenced by several key factors, including distance from the surface, lighting conditions, resolution, and cost. To meet these requirements, the authors purchased two off-the-shelf, low-cost PTZ cameras for evaluation. These cameras have the ability to pan, tilt, and zoom, providing flexibility in tracking and focusing on the cracks and targets. The models selected were the ANAKK-FD1-HXQJ-20X (herein called ANAKK), and SUNBA-405-D20X-5MP (herein called SUNBA), chosen for their affordability and optical zoom capabilities. Both cameras are housed in IP66-rated casing, ensuring they are weather-resistant and suitable for outdoor monitoring. Despite having a resolution of only 5MP, both cameras produced high-quality images that met the needs of the research. Table 1 shows the specifications of each camera. Additionally, both cameras feature programmable preset positions for quick recall of camera views and are equipped with night vision, which was also tested in the experiment (not included in this research).

Table 1. Specifications of the two PTZ cameras

		
Model name	ANAKK-FD1-HXQJ-20X	SUNBA-405-D20X
Resolution	5MP	5MP
Optical zoom	20X	20X
Rotation	355° horizontal and 90° vertical	360° rotation and 90°tilt
Image Sensor	1/2.8" CMOS	1/2.8" CMOS
Lens	2.8-30 mm	4.7~94mm

3 Methodology

3.1 Basic principle of target coordinate measurement

In this research, the cracks are measured by capturing a digital image of two targets. The targets serve as a reference scale for performing the projective transformation, as the four white circles are precisely positioned (Figure 3). This transformation maps the camera coordinates to the object space coordinate system.

Using image processing techniques, the centres of the circles on the targets are determined. Through binarization, the white areas are categorized using a threshold intensity. The coordinates of the centroids of the circles are calculated by determining the centre of gravity of the white areas in the binary image. This process is based on the equations shown below, which are adapted from Nishiyama et al. (2015).

$$x = x_0 + a_x \left(\frac{\sum_{i=1}^{n} \sum_{j=1}^{m} (q(i,j) \times x_{ij})}{\sum_{i=1}^{n} \sum_{j=1}^{m} q(i,j)} \right)$$

$$y = y_0 + a_y \left(\frac{\sum_{i=1}^{n} \sum_{j=1}^{m} (q(i,j) \times y_{ij})}{\sum_{i=1}^{n} \sum_{j=1}^{m} q(i,j)} \right) \quad (1)$$

Where $\boldsymbol{x_0}, \boldsymbol{y_0}$ represent the origin of the image coordinate system in the x-, y-directions, $\boldsymbol{a_x}, \boldsymbol{a_y}$ are the pixel sizes in the x-, y-directions, $\boldsymbol{q(i,j)}$ is the intensity value of pixel $\boldsymbol{(i,j)}, \boldsymbol{x_{ij}}, \boldsymbol{y_{ij}}$ are the coordinates of the pixel at $\boldsymbol{(i,j)}$ and n, m are the dimensions of the image in pixels.
The coordinates of the four circles on one of the targets are used to perform the perspective projection, which is based on the collinearity condition. The equation for calculating the perspective projection is as follows:

$$x' = \frac{x'_1}{x'_3} = \frac{h_{11}x + h_{12}y + h_{13}}{h_{31}x + h_{32}y + 1}$$

$$y = \frac{x'_2}{x'_3} = \frac{h_{21}x + h_{22}y + h_{23}}{h_{31}x + h_{32}y + 1} \quad (2)$$

Where $\boldsymbol{h_{11}}, \boldsymbol{h_{12}} \dots \boldsymbol{h_{32}}$ are the conversion coefficients. These coefficients are obtained using the least-squares method.

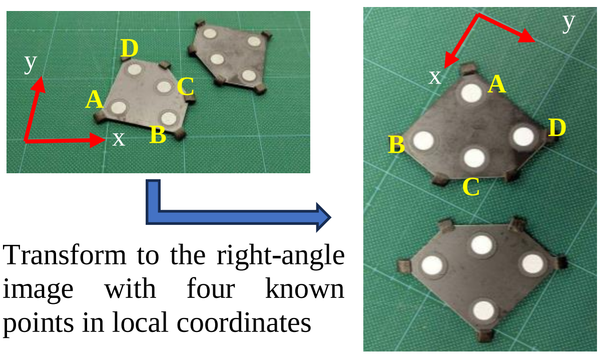

Figure 3. Transformation of targets for measuring the deformation

3.2 Laboratory Test

The laboratory test had two main objectives. First, it aimed to determine the maximum distance at which the camera could be positioned without compromising image quality. Second, it sought to assess the measurement accuracy of the PTZ cameras. A micrometre was used to simulate displacement during the test. The setup, as shown in Figure 4, involved affixing one target to the micrometre while the other was securely attached to the surface. The cameras were mounted on a tripod, and five images were captured at distances of 1m, 3m, 5m, and 7m at an angle of 0° (perpendicular to the micrometre). Preliminary tests showed that the standard error of mean remained consistent whether five or ten photos were taken. However, a reduction in the number of images resulted in a slight increase in the standard error. As a result, the authors chose to capture five photos to ensure reliable data. The micrometre displacement is in 0.2mm increments from 0.2 to 0.6. Optical zoom was used to adjust the framing of the targets, ensuring that they remained centred in the image for each shot, as the zoom was applied. Additionally, a DSLR camera equipped with an 18-250mm focal length lens (Table 2) was used for comparison as a high-end option, commonly employed for crack width monitoring (Belloni et al., 2023). The DSLR offers high image resolution and delivers consistently stable images, making it an ideal reference for evaluating the performance of the PTZ systems.

Figure 4. Laboratory set up of ANAKK at 1m from the micrometre (inset).

Table 2. Specifications of the DSLR camera

Camera Model	**Canon EOS Kiss X7**
Sensor	18MP
Focal Length (mm)	(SIGMA) 18-250
Sensor size (mm)	22.3 x 14.9

3.3 Evaluation of Accuracy

Two types of accuracy, as defined by Nishiyama et al. (2015), are used to evaluate the effectiveness of the research: Root Mean Square Error and Precision.

$$\text{RMSE} = \sqrt{\frac{\sum(D_i - D_0)^2}{n}} \qquad \text{Precision} = \sqrt{\frac{\sum_{i=1}^{n}(D_i - \overline{D})^2}{n`}}$$

Where D_i is measured displacement, D_0 is the distance of the micrometre movement, $\overline{D}$ is the mean of the displacements, n is the number of displacements and n` is the number of measurements. Both result values should be small, which would suggest a higher precision of the measurement. Table 3 shows the influence of the shooting distance on the precision and RMSE for all three cameras. Table 4 shows the camera parameters used for each distance.

Table 3. Relationship of the accuracy/precision and the shooting distance.

Distance from target	1m	3m	5m	7m
CANON Kiss X7				
RMSE (mm)	0.24	0.05	0.04	0.01
Precision (mm)	0.15	0.03	0.03	0.01
ANAKK				
RMSE (mm)	0.13	0.10	0.06	0.09
Precision (mm)	0.03	0.07	0.04	0.07
SUNBA				
RMSE (mm)	0.23	0.15	0.03	0.01
Precision (mm)	0.12	0.11	0.02	0.004

Table 4. Camera parameters for each distance in the experiment.

Distance from target	Focal length (mm)/ PTZ Optical Zoom (x)		
	Canon Kiss X7	**ANAKK**	**SUNBA**
1m	18mm	No zoom	No zoom
3m	50mm	9x	7x
5m	250mm	17x	9x
7m	250mm	20x	11x

3.4 On-site Test

After analysing the results of this test, it was determined that the PTZ cameras provided comparable performance to the DSLR camera. Based on these findings, the authors visited the bridge site to conduct a similar experiment, testing the procedure under varying lighting conditions and assessing potential challenges for the remote monitoring system. At the bridge site, four targets were placed on various girders between P5 and P4. For this field test, two types of targets were used: reflective black-and-white targets and standard white-and-black targets (Figure 5), both measuring 110 x 110 mm. According to Nishiyama et al. (2015), the diameter of the circles on the targets influences the accuracy and precision of measurements. Smaller target size, similar to those used in the laboratory test, result in a larger dispersion of the centre of gravity in the white areas of the circles. This increased dispersion can cause greater variability in the calculated center of gravity due to the reduced resolution and smaller target size. To mitigate this, larger targets were used in this field test to improve the accuracy and precision of measurements, particularly under reduced lighting conditions. The PTZ cameras were used to pan and tilt toward each target and zoom in to ensure the target remained centred within the frame (Figure 5). The camera parameters, including optical zoom, varied depending on the target's location and the desired view, and were adjusted remotely via the cameras' interface. The authors will evaluate in future work the effectiveness of the white-and-black targets, as they are more cost-effective than the reflective targets and could serve as a suitable replacement. The small-scale test revealed that the system was able to establish a remote connection, with the laptop viewing and capturing images through the cameras' interface.

Figure 5. Targets placed on the bridge girder, captured using the SUNBA PTZ camera.

4 Discussion

The two PTZ cameras used in the final evaluation utilized optical zoom. DSLR cameras, such as the Canon Kiss X7, achieve zooming by switching lenses to match the desired focal length. On the other hand, PTZ cameras utilize optical zoom (as opposed to digital zoom) which adjusts the focal length of the lens to enlarge the image (Blahnik & Schindelbeck, 2021). This process allows more light to enter the lens, which helps maintain the original image resolution and quality, rather than losing clarity as with digital zoom. This distinction contributes to the favourable accuracy and precision results observed for both the ANAKK and SUNBA cameras. It is important to note, however, that zoom function was not employed at the 1m distance for either the PTZ cameras or the DSLR camera (focal length was 18mm). The DSLR performed worse than the two PTZ cameras at this distance, primarily due to poor image quality caused by hand instability. In the study by Nishiyama et al. (2015), accuracy and precision were found to be proportional to distance, as the authors used a fixed focal length (50mm) for all distances. To achieve equivalent results, the same focal length would need to be employed, but this approach is not recommended for longer distances. Hence Nishiyama et al. (2015) increased the focal length to 300mm for greater distances to maintain the accuracy. Nonetheless, in this study, the displacement was measured with an accuracy and precision of less than 0.23mm. The maximum measured distance was set at 7 meters, based on the distance between the placement of the targets and the cameras on the bridge, which was approximately seven meters. However, the authors intend to explore the performance of these PTZ cameras over longer distances in future experiments. As shown in Table 3, the SUNBA outperformed the ANAKK in terms of both accuracy and precision at longer distances. The authors attribute this improvement to the SUNBA's longer focal length range, which provides greater magnification at longer distances. Unlike DSLR cameras, where the focal length is clearly specified, PTZ cameras do not provide a direct focal length value, making it difficult to compare results between PTZ and DSLR cameras. The inability to determine a specific focal length presents a foreseeable challenge.

Regarding remote monitoring, the authors successfully tested the connection from the bridge site. Moving forward, images will be collected daily at various times to assess the quality of the images for crack width monitoring. One benefit that became even more evident during the experiment was the quantity and speed of image acquisition, which will allow for more frequent monitoring of crack progression over time. It must be noted that there are many types of PTZ cameras available on the market and in this case, only two made the final analysis. These cameras were low-cost models with 5MP resolution and 20x optical zoom. However, there are other PTZ cameras on the market with higher resolutions and more advanced features, which could be tested in future analyses.

5 Conclusion

Crack width monitoring is essential for bridge maintenance and management. PTZ cameras were used to evaluate their accuracy and efficiency in this task. The authors developed a remote monitoring system to assess the cameras' performance, and the results demonstrated that these cameras are effective for remote monitoring. They are easy to set up, cost-effective, and enable 24-hour monitoring. Remote monitoring reduces the need for on-site visits, cutting costs, workload, and time. This approach also allows for more frequent inspections, addressing a current challenge for bridge managers. The system can be further developed into an early warning system for rapidly developing cracks, helping to prioritize safety and timely interventions.

6 Future Work

This research demonstrated the feasibility of using images from PTZ cameras for monitoring crack width. In this phase of the study, the targets were positioned in an orthogonal direction. However, future work will evaluate the impact of different angles using PTZ cameras. Additionally, the authors plan to further automate the process by uploading the images to a File Transfer Protocol (FTP) server, creating a script and incorporating environmental conditions to analyse any potential influence on the captured images. By refining the system developed, the authors aim to minimize human intervention, while improving the accuracy and efficiency of crack monitoring, leading to more timely inspections.

Acknowledgements

The authors would like to acknowledge the use of ChatGPT for proofreading and grammar checking.

References

Abdel-Qader, I., Abudayyeh, O., Asce, M., & Kelly, M. E. (2003). Analysis of Edge-Detection Techniques for Crack Identification in Bridges. *Journal of Computing in Civil Engineering*, 17 (4).

American Society of Civil Engineers (2021). *2021 report card for America's infrastructure.* https://infrastructurereportcard.org/wp-content/uploads/2020/12/National_IRC_2021-report.pdf

Arif, F., & Khan, W. A. (2021). Smart Progress Monitoring Framework for Building Construction

Elements Using Videography– MATLAB–BIM Integration. *International Journal of Civil Engineering*, 19(6), 717–732.

Belloni, V., Sjölander, A., Ravanelli, R., Crespi, M., & Nascetti, A. (2023). Crack Monitoring from Motion (CMfM): Crack detection and measurement using cameras with non-fixed positions. *Automation in Construction*, 156.

Blahnik, V., & Schindelbeck, O. (2021). Smartphone imaging technology and its applications. *Advanced Optical Technologies*, 10(3), 145–232. https://doi.org/10.1515/aot-2021-0023

Chun, P. J., Dang, J., Hamasaki, S., Yajima, R., Kameda, T., Wada, H., Yamane, T., Izumi, S., & Nagatani, K. (2020). Utilization of unmanned aerial vehicle, artificial intelligence, and remote measurement technology for bridge inspections. *Journal of Robotics and Mechatronics*, 32(6), 1244–1258.

Forcael, E., Román, O., Stuardo, H., Herrera, R.F., Soto-Muñoz, J. (2024). Evaluation of Fissures and Cracks in Bridges by Applying Digital Image Capture Techniques Using an Unmanned Aerial Vehicle. Drones 2024, 8, 8.

Fujiu, M., Minami, T., & Takayama, J. (2022). Environmental Influences on Bridge Deterioration Based on Periodic Inspection Data from Ishikawa Prefecture, Japan. *Infrastructures*, 7 (10).

Guo, Y., Wang, Z., Shen, X., Barati, K., & Linke, J. (2022). Automatic Detection and Dimensional Measurement of Minor Concrete Cracks with Convolutional Neural Network. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 10(4/W3-2022), 57–64

Humpe, A. (2020). Bridge inspection with an off-the-shelf 360° camera drone. *Drones*, 4 (4), 1–23.

Jeong, S., Kim, M. G., Kim, S. T., & Oh, K. Y. (2023). Crack inspection in tunnel structures by fusing information from a 3D light detection and ranging and pan-tilt-zoom camera system. *Structures*, 58.

Jeong, Y., Park, D., & Park, K. H. (2017). PTZ camera-based displacement sensor system with perspective distortion correction unit for early detection of building destruction. *Sensors (Switzerland)*, 17(3).

Jiang, M., Zhang, Z., Shimasaki, K., Hu, S., & Ishii, I. (2022). Multi-Thread AI Cameras Using High-Speed Active Vision System. *Journal of Robotics and Mechatronics*, 34(5), 1053–1062.

Kim, I., Jeon, H., Baek, S., Hong, W. and Jung, H. (2018). Application of crack identification techniques for an aging concrete bridge inspection using an unmanned aerial vehicle. *Sensors (Switzerland)*, 18(6).

Ministry of Land, Infrastructure, Transport and Tourism (2018). *Roads in Japan*. https://www.mlit.go.jp/road/road_e/pdf/ROAD2018web.pdf

Murao, S., Nomura, Y., Furuta, H., & Kim, C. W. (2019). Concrete crack detection using UAV and deep learning. *In Proc. 13th Int. Conf. Appl. Stat. Probab. Civil Eng. (ICASP)*. Vol. 2019, pp. 1-8.

Nishiyama, S., Minakata, N., Kikuchi, T., & Yano, T. (2015). Improved digital photogrammetry technique for crack monitoring. *Advanced Engineering Informatics*, 29(4), 851–858.

Nyathi, M. A., Bai, J., & Wilson, I. D. (2023). Concrete Crack Width Measurement Using a Laser Beam and Image Processing Algorithms. *Applied Sciences (Switzerland)*, 13 (8).

Okazaki, Y., Okazaki, S., Asamoto, S., & Chun, P. jo. (2020). Applicability of machine learning to a crack model in concrete bridges. *Computer-Aided Civil and Infrastructure Engineering*, *35*(8), 775–792.

Olagoke, A. S., Ibrahim, H. and Teoh, S. S. (2020). Literature Survey on Multi-Camera System and Its Application. *IEEE Access*, Vol. 8, pp. 172892-172922.

Shao, C., Zhang, L., & Pan, W. (2021). PTZ Camera-Based Image Processing for Automatic Crack Size Measurement in Expressways. *IEEE Sensors Journal*, *21*(20), 23352–23361.

Sheta, A., & Mokhtar, S. A. (2022). Autonomous Robot System for Pavement Crack Inspection Based CNN Model. *Journal of Theoretical and Applied Information Technology*, 31 (16).

SoftEther VPN Project. (n.d.). SoftEther VPN: Free cross-platform multi-protocol VPN software. SoftEther. https://www.softether.org/

Sohn, H. G., Lim, Y. M., Yun, K. H., & Kim, G. H. (2005). Monitoring crack changes in concrete structures. *Computer-Aided Civil and Infrastructure Engineering*, 20 (1), 52–61.