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Non-contact intelligent detection technology for railway arch bridge performance degradation based on UAV Image recognition

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Original research paper

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Non-contact intelligent detection technology for railway arch bridge performance degradation based on UAV Image recognition

Bridges are crucial components of high-speed railway projects, and their structural integrity significantly impacts the operational safety of high-speed railways. This paper introduces a non-contact intelligent detection technology for assessing the deterioration of high-speed railway bridges using unmanned aerial vehicle (UAV) image recognition. The methodology involves collecting image data using a UAV and digital camera and processing them technically to generate consistent point-cloud data. Subsequently, these data are integrated into a unified point-cloud model through point-cloud alignment. Finally, a refined three-dimensional (3D) model of a high-speed railway bridge was developed by fusing heterogeneous data through live 3D reconstruction. The method has the advantages of high detection speed and fewer personnel requirements; this technology can be used for daily monitoring of the technical basis and can arrange a small number of personnel to complete the daily inspection. The empirical results demonstrate that this inspection method is not constrained by skylight points and provides a real-time and highly efficient reflection of the conditions of the bridge. The recognition accuracy and image acquisition range satisfy the inspection requirements for the operation and maintenance of high-speed railway bridges.

Key words:
high-speed railway bridge, bridge faults, non-contact measurement, UAV

Izvorni znanstveni rad

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Beskontaktna inteligentna tehnologija detekcije degradacije performansi željezničkoga lučnog mosta temeljena na UAV prepoznavanju slike

Mostovi su ključne komponente projekata brzih željeznica, a njihov konstrukcijski integritet znatno utječe na operativnu sigurnost brzih željeznica. U ovome radu predstavljena je tehnologija beskontaktne inteligentne detekcije za procjenu propadanja željezničkih mostova za velike brzine pomoću prepoznavanja slike bespilotnih letjelica (UAV). Metodologija uključuje prikupljanje slikovnih podataka pomoću UAV-a i digitalne kamere te njihovu tehničku obradu za generiranje dosljednih podataka oblaka točaka. Naknadno se ti podaci integriraju u jedinstveni model oblaka točaka poravnanjem oblaka točaka. Konačno, rafinirani trodimenzionalni (3D) model željezničkog mosta za velike brzine razvijen je spajanjem heterogenih podataka kroz 3D rekonstrukciju uživo. Metoda ima prednosti poput velike brzine otkrivanja i manje zahtjeva za osobljem. Ta se tehnologija može primjenjivati za dnevno praćenje tehničke osnove i za obavljanje dnevne inspekcije uz manji broj radnika. Empirijski rezultati pokazuju da ta metoda inspekcije nije ograničena točkama svjetlarnika i da pruža vrlo učinkovit odraz stanja mosta u stvarnome vremenu. Točnost prepoznavanja i raspon snimanja slike zadovoljavaju zahtjeve inspekcije za rad i održavanje željezničkih mostova za velike brzine.

Ključne riječi:
željeznički most za velike brzine, oštećenja na mostu, beskontaktno mjerenje, bespilotna letjelica

1. Introduction

High-speed railway bridges, especially those in mountainous regions, are vital to ensure secure operation of high-speed railway networks. The challenges include potential damage from perilous rockfalls on steep slopes, which can lead to mountain collapse. Moreover, bridges in densely populated river areas are susceptible to minor damage owing to water current scouring. The design life of high-speed railway bridges typically spans hundreds of years [1]. Throughout their service lives, various defects, ailments, and natural infringements are inevitable, potentially resulting in structural damage or even collapse in severe cases. Potential damage or collapse significantly affects the regular use of high-speed railway bridges and substantially increases the maintenance costs of these critical infrastructures. Currently, the prevalent inspection methods for high-speed railway bridges primarily encompass three approaches (mainly applied in Europe, Southeast Asia, and China).

1. Manual inspection, universal inspection numbering, essential inspection treatment, and inspection methods in rainy mountains. Subsequently, relevant personnel conduct unified modelling and archiving. However, this method exhibits drawbacks, including low security, inefficiency, substantial workload, extensive stored information, and inadequate traceability.
2. Manual inspection, video inspection, and reinforcement. While this method is capable of accommodating day and night inspections, it faces challenges, such as extensive video storage, difficulty in adverse weather detection, and high costs.
3. An infrared laser-based monitoring system for dangerous rocks and stones. Although this system meets the requirements for night-time and adverse weather operations, it exhibits limitations in detecting smaller lesions.

In modern industrialised production, three-dimensional measurements of targets are frequently required. Non-contact inspection of targets has been extensively investigated in numerous engineering research fields [2, 3]. The mechanical damage-energy evolution characteristics of coal rock were explored using digital image measurement technology (DIMT) [4]. The results revealed that DIMT offers a non-contact and non-interference approach compared to traditional measurement methods (for example, strain gauge and extensometer measurements). This technology effectively circumvents errors arising from the limitations of traditional methods for measuring coal deformation and damage.

Consequently, it enables high-precision and real-time monitoring of coal body deformation and strain changes. A hybrid surface-topography measurement instrument for engineering surface-topography measurements was introduced [5]. This instrument is capable of contact and non-contact measurements and is suitable for various applications. The vertical measurement range and resolution are 1 mm and 10 nm for contact measurements and 500 μm and 3 nm for non-contact measurements, respectively. The presentation of various application scenarios confirms the extensive applicability of non-contact measurements. The progress and applications of optical measurement systems for the surface inspection of standard components in the analytical industry have been summarised [6]. An automated deformation analysis method was proposed based on a topographic laser scanner [7]. The rigid analysis method utilises a landslide physical simulation approach with point-cloud processing to quantitatively obtain three-dimensional (3D) deformation field information. The results indicate that organised and spatially correlated point-cloud segmentation of spherical targets allows the fitting of the segmented point cloud to determine the location and positional variations of all predefined targets. These studies affirm the applicability and reliability of non-contact measurements across various scenarios.

The traditional segmented measurement method, which relies on years of experience, is characterised by a complex and time-consuming measurement process, making it challenging to meet the requirements of modern monitoring and mapping. In recent years, the application of digital cameras has gained popularity, and the advantages of employing digital cameras for three-dimensional measurement have been highlighted [8, 9]. A charge-coupled device camera can serve as an image sensor, and by integrating image-processing and precision measurement techniques, non-contact 3D coordinate measurements can be achieved. Image-based 3D measurements involve capturing two-dimensional images of an object from multiple angles using a digital camera to obtain 3D information. Subsequently, the correspondence between the image features is established to determine the spatial coordinates of the object being measured. A new method for the construction deformation measurement of ship hull segments was proposed based on 3D image reconstruction technology [10]. This method can reconstruct the 3D model of the entire hull segments using only photographs. This process includes camera calibration, image pre-processing, feature point matching, dense point-cloud generation, mesh delineation, and texture mapping for 3D reconstruction. In the feature point-matching step, the scale-invariant feature transform algorithm is employed and optimised by introducing global vectors to reduce mismatches, thereby enhancing the reconstruction accuracy. The study results indicate that this method can measure hull segments faster and with higher accuracy than other methods. An optical obliquity method for reconstructing 3D terrain was introduced using surface-scattered light to recover fine terrain details from monocular images [11].

With the rapid advancement of computer and photographic technologies, the resolution of aerial images has significantly improved compared with previous remote-sensing images, and costs have decreased substantially. This progress has made it feasible to apply aerial photography and computer vision technologies in shipping management. A geomorphological measurement system integrating light detection and ranging with an unmanned aerial vehicle (UAV) was proposed using a multi-rotor vehicle [12]. This system is designed to predict, monitor, and forensically analyse landslides and maintain debris flow barriers. UAV RGB images were used to predict the grassland above-ground biomass (AGB) using a random forest (RF) machine-learning technique [13]. This technique enables the rapid estimation of regional-scale grassland AGB within the sampling range in a significant and non-destructive manner. In a study focused on accurate plant trait prediction (phenotyping), a UAV (DJI Mixire 1 Raw) equipped with an RGB camera (DJI Zenmuse x5) was employed to standardise canopy cover (CC) probing of an annual endemic crop [14]. The technology of using UAV with tilt camera equipment for aerial surveying, capturing 3D topographic information, and structural measurement data over extensive areas, has widespread applications across various industries. Compared to traditional measurement methods, this approach allows for the rapid acquisition of more data, eliminating manual measurement errors and achieving sub-centimetre measurement accuracy. These advantages present promising prospects in engineering surveying.

Research findings indicate that noncontact intelligent detection technology based on drone-acquired images has been extensively applied in various fields. However, the practical applications and research on the deterioration of high-speed railway bridges are limited. They are considering the characteristics of deterioration prevention and control in high-speed railway bridges, such as high probing difficulty, a wide range, and a large amount of investigation work, aligning with the advantages of non-contact intelligent detection technology. Therefore, this paper focuses on detecting bridge foundation deterioration in high-speed railway bridges. It considers the engineering context and combines offline drones, 3D laser scanning, and 3D digital camera measurements for air and land image acquisition. Intelligent fusion with an online point-cloud multi-source database and the application of digital twin technology are adopted. This study proposes a non-contact intelligent detection technology based on drone image recognition for deteriorating high-speed railway bridges. This technology is utilised to inspect conditions, such as bridge cracks, corrosion, deformation, and other issues in arch bridges.

2. Engineering background, testing, and calculation instruments

2.1. Engineering background

This paper focuses on the Bali Street Cross-Highway Tie Arch Bridge on the Guiguang High-Speed Railway in Guilin City, Guangxi Province, as the engineering background. The bridge features a reinforced concrete tie arch structure with a span arrangement of 65m+65m. It was constructed in 2013 and spans a Y-shaped urban road in the Bali Street area. With nearly 10 years of operation, the bridge has exhibited various types and degrees of deterioration, including cracked concrete, exposed reinforcement, and rusted components. In this study, a UAV-video non-contact-surveying technique was employed to create a 3D bridge model and identify and characterise the location, type, and severity of deterioration.

2.2. Detection and calculation instruments

In this study, the instrumentation primarily comprised two components. The first part was dedicated to conducting on-site image acquisition with an inspection instrument designed for fine aerial photography using a drone. The drone was a DJI Elf 4P equipped with forward-looking, rear-view obstacle avoidance, left and right infrared obstacle avoidance, five-direction obstacle sensing, and a remote-control operating frequency of 2.4 GHz/5.8 GHz. It features a three-axis self-stabilizing gimbal, and its camera is a 1-inch CMOS with 20 million effective pixels, as depicted in Figure 1. The use of 12 V lithium batteries on the UAV battery forcible cooling can be about 5 min to the battery temperature cooling to the charging temperature to ensure that the UAV battery charges within a short period in the field operating environment. The use of the strong-wind-cooling fan and semiconductor-forced cooler is as shown in Figures 2 and 3, respectively. At the same time, the low-voltage-charging equipment (Figure 4), powered by 12 V lithium batteries, can be converted to 17.8 V by boosting and filling four batteries simultaneously in approximately 70 min, ensuring that the UAV can operate continuously for 10 h.

Figure 1. Aerial photography drone

Another part of the instruments used in this study are the graphics-processing workstations for graphics processing and high-precision 3D model modelling, in which the fixed graphics processing workstations are HPZ-840 professional graphics workstations with six cluster computing. The processor was an Intel Xeon E5-2690 with 192 GB memory and a professional Nvidia Quadro M5000 graphics card (8 GB). A mobile professional graphics workstation using a Del Professional Graphics Workstation with an Intel Core i7-4810MQ processor,

Figure 2. Strong-air-cooling fan

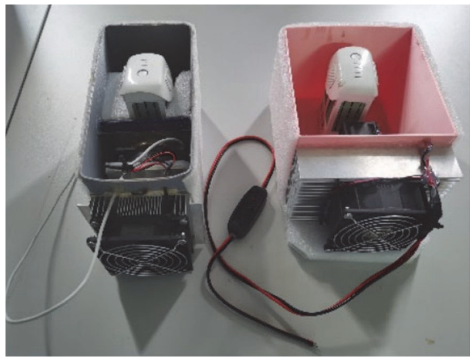

Figure 3. Semiconductor forced cooler

Figure 4. Low-voltage chargers

16 GB RAM, and a professional discrete graphics card (Nvidia QuadroK2 100M [2GB]).

3. Non-contact intelligent detection technology method for bridge deterioration

3.1. UAV flight electronic image acquisition and optimization

UAV flight electronic image acquisition mainly involves UAV flight electronic fence + AI warning technology before the flight, based on the site environment and GPS information, preliminary determination of the flight boundaries, and accurate adjustment of flight control parameters, including heading and side overlap, camera angle, and flight altitude. The process diagram is shown in Figure 5. For the UAV automatic aerial photography line planning, according to the aerial photography area conditions, aerial photography routes generally has two options. One is to use a straight-line multitask aerial photography (camera overhead, camera at a 45° angle left and right, front and back flights, a total of five times), as shown in Figure 6. The other is a single-task ring (camera lens toward the centre of the ring) flight aerial photography, as shown in Figure 7. The planning principle is to ensure that the photos have appropriate overlap, ISO, exposure, and clarity. The difference in aerial height is ≤200 mm, and the difference in latitude and longitude is ≤300 mm. After planning the aerial line and uploading it to the UAV, the UAV flies automatically and takes photos according to the set parameters of the photo to ensure that the photos are taken with equal spacing and parameters.

It is also necessary to carry out UAV hand-controlled supplemental photography to ensure the resolution and clarity of the 3D model, in which the actual case is mainly on the berm and tunnel mouth, and other parts of the increase are in the close-range manual control of UAV supplemental photography. Supplementary photography requires the operator to have specific experience to ensure the overlap of each photo (usually

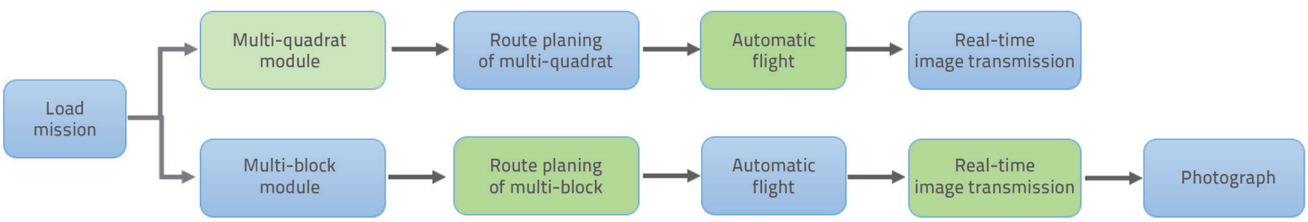

Figure 5. Multi-mission linear aerial photography

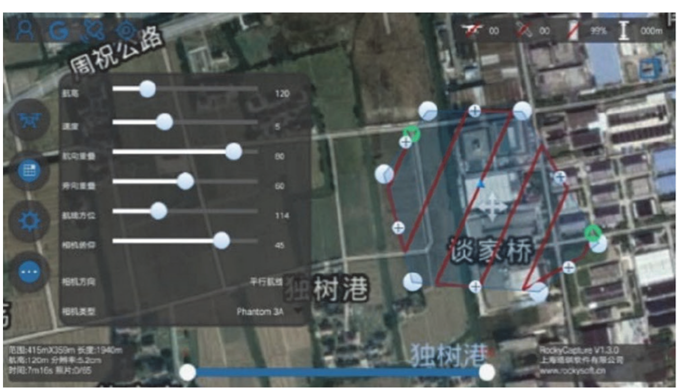

Figure 6. Multi-mission linear aerial photography

Figure 7. Single-mission loop aerial photo

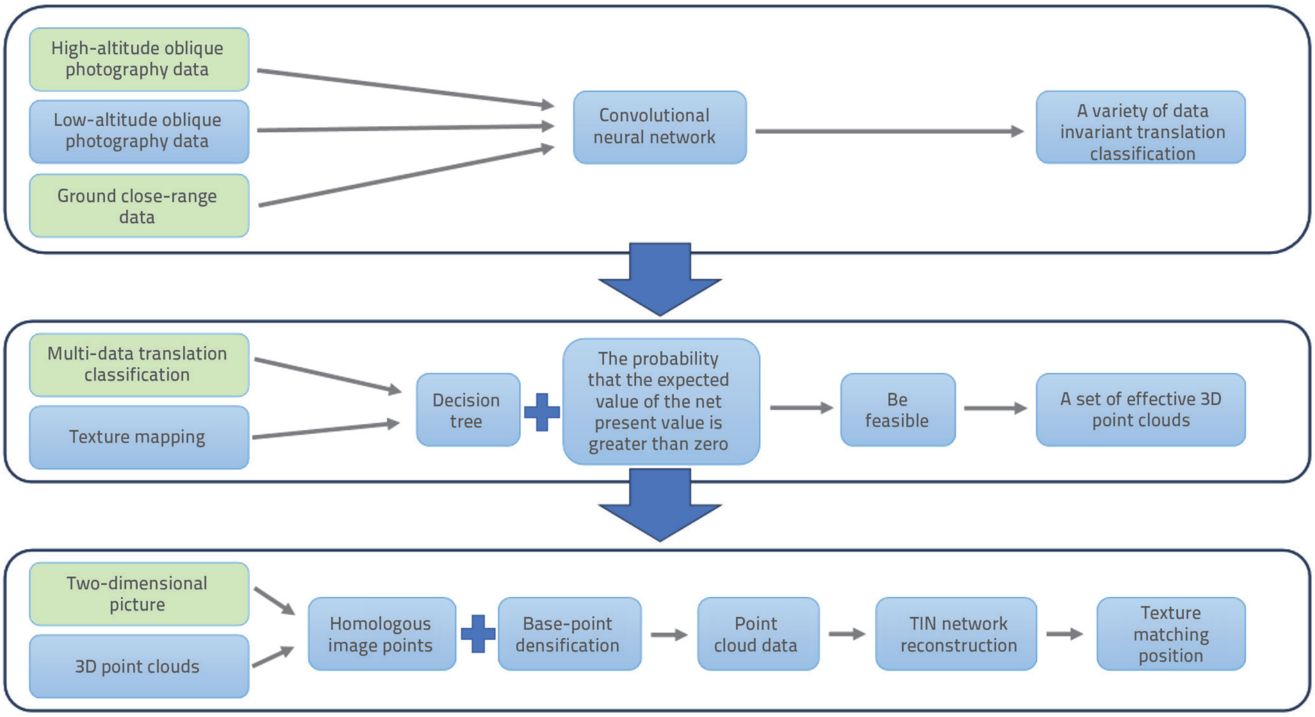

Figure 8. Flowchart of multi-source data fusion

50%–85%), exposure, and clarity, and at the same time, to ensure that the distance between the drone and the object to be photographed are the same (to ensure that the photo object and visual image size are the same). The large-arch bridge external aerial photography was completed using combined automatic flight and artificial aerial photography, and the ratio of the drone automatic flight aerial photography time and artificial aerial photography time was approximately 1:4.

Figure 9. Multi-area terrain stitching map with direct aerial photography

An effective method is to de-noise and baseline-align the original photos and achieve the organic fusion of multisource data using a convolutional neural network, base and image element matching, and decision tree techniques, which can optimise the graphics captured by the UAV. The specific processing flow is shown in Figure 8, using the series of optimisation methods to complete the splicing of the UAV and big data of thousands of photos through seamless splicing of nearly 10,000 photos to generate a high-definition topographic map of the target area. As shown in Figure 9, the area of a high-definition topographic map (nearly 110 square kilometres) was compared to the clarity of the multi-area topographic splicing map (red boxed area in Figure 9) and direct aerial photography (black boxed area in Figure 9). In this study, the image clarity was evaluated using the maximum local variation algorithm [15]. This algorithm evaluates the sharpness of an image by calculating the difference between an image pixel point and its eight neighbouring pixel points. The clarity of the picture obtained through the multi-area topographic splicing and optimisation algorithms adopted in this study is 100 times that of ordinary aerial photographs.

3.2. Multi-environment refined structural modelling

For the multi-environmental refined structural 3D modelling, the image data collected by the UAV and digital camera are mainly fused into the same type of point-cloud data through technical processing and then fused into the integrated point-cloud model through point cloud alignment. Finally, the refined 3D model of the HSR bridge with heterogeneous data fusion is realised through real-life 3D reconstruction. The high-precision establishment of the 3D structure model mainly involves processing the spatial stereo inverse structure and air-three optimisation, the calculations of which are shown in Figures 10 and 11, respectively.

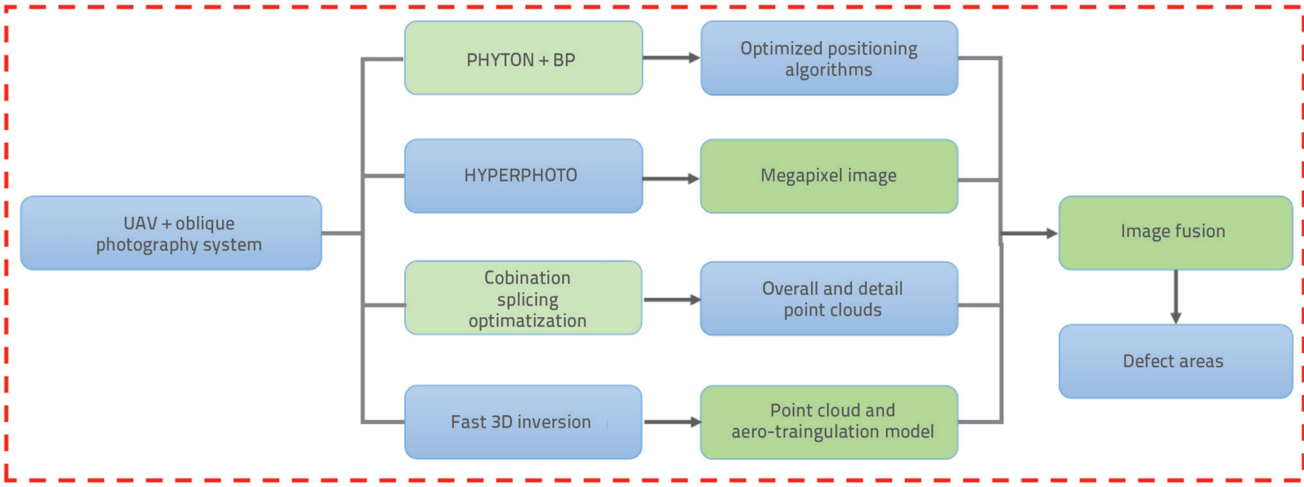

Figure 10. Flowchart of aero-triangulation calculation

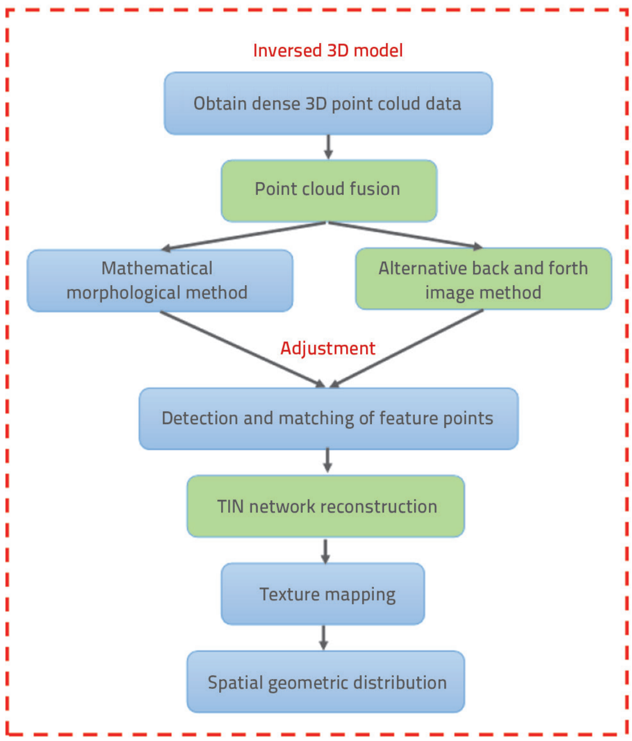

Figure 11. Spatial cubic inversed structure

Point-cloud data processing is divided into two aspects: point cloud splicing between different sites and point cloud alignment between the image dense matching point cloud and the multi-site splicing. Because the coordinate system of each site in 3D laser scanning and the geographic coordinate system of UAV aerial photography are not the same, it is necessary to unify the point-cloud coordinates through coordinate translation and rotation transformation to achieve coarse alignment. After the coordinates are unified, the ICP algorithm performs least-squares iterative optimisation on the point cloud, and the optimal rigid transformation completes the accurate matching of the two groups of point clouds to fuse the UAV images and point cloud data. The accurately aligned point cloud is then imported into Context Capture to produce a realistic 3D model and obtain the final high-precision results.

At the same time, based on the 3D model, through a series of optimisation algorithms (specifically, as shown in Figure 12), 3D model optimisation is carried out to improve the accuracy of the model. In this study, the planimetric, elevation, and 3D errors of each model were calculated using Equations (1), (2), and (3), respectively, based on the RTK measured coordinate values of the checkpoints and the measured coordinate values of the corresponding positions in the model. Thus, the recognition accuracy of 3D modelling adopted in this study was evaluated. Among them, the error limits were set to ≤1 cm in plane error and ≤2 cm in elevation error when the coordinates of the points were measured via real measurements. When the data reaches a fixed solution determined as the real coordinate value, the testing results show that the accuracy is much higher than the model accuracy of general photographic 3D modelling.

$$M_{xy} = \sqrt{\frac{\sum_{i=1}^{n}\left[\left(X_{R_i} - X_{M_i}\right)^2 + \left(Y_{R_i} - Y_{M_i}\right)^2\right]}{n}} \tag{1}$$

$$M_z = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{R_i} - X_{M_i}\right)^2}{n}} \tag{2}$$

$$M = \sqrt{M_{xy}^2 + M_z^2} \tag{3}$$

The relative orientation accuracy of the photo stitching and the inverse projection error of the connecting points after the optimisation process were better than 1 pixel, and the maximum residual difference was 3 pixels. A 20-megapixel camera was used to take the photos, and the size of each pixel was 3.3 μm.

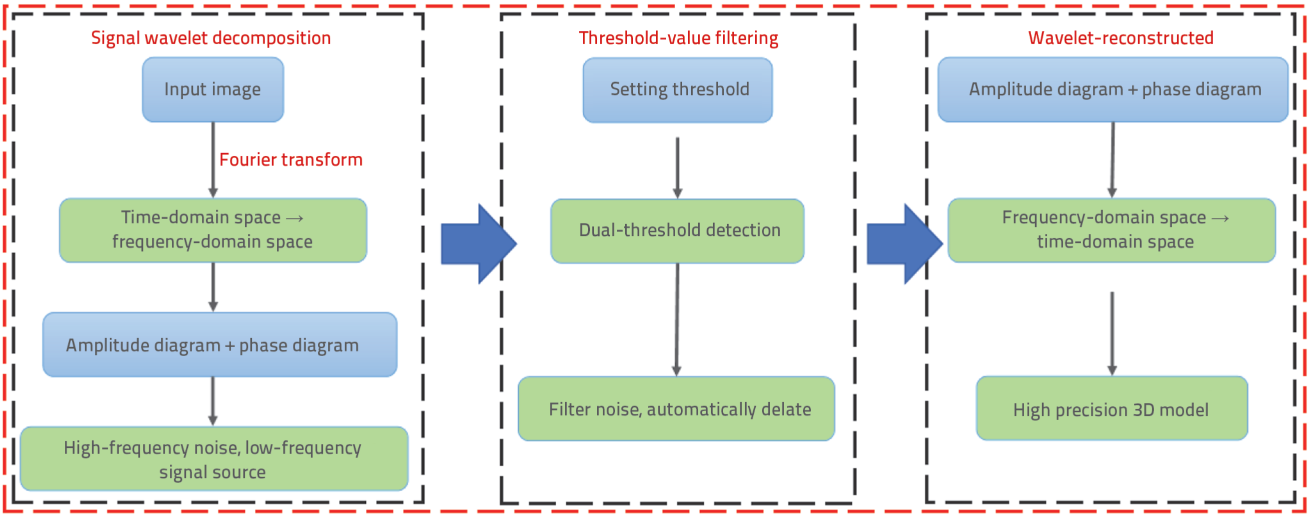

Figure 12. 3D model high-precision optimization process

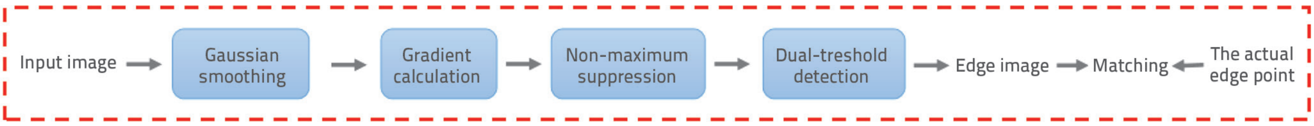

Figure 13. Flowchart of the edge estimation method

By creating 'actual edge points' (Figure 13) and 'hypothetical edge points' (Figure 14), the problem of difficulty in quantifying the edge loss due to the limitation of the resolution of the 3D inverse structure is solved, and accurate estimation of the edge of an arbitrary angle is realized, which significantly improves the accuracy of the object size.

The development of spatial stereo-matching techniques (Figure 15), the effective integration of image modelling and 3D scanning, and other non-contact mapping techniques through the convolutional neural network result in significant data analysis aggregation to form the required data source. 3D surface model splicing, fusion, editing, and other spatial stereo matching technology are used to obtain the traditional ancient architecture 3D point-cloud data, and a complete, high precision based on the 3D spatial coordinates of the 3D digital model of the bridge components.

The final result can be obtained by completing the actual 3D model, which is subjected to three-level processing of general repair, fine repair, and ultra-fine repair, removing scattered fragments, data edges, and other aesthetic finishing. The 3D model obtained using the detection and processing method proposed in this study has the characteristics of high resolution (ground resolution ≤ 3 mm), high definition (model accuracy ≤ 0.5 mm), and belongs to the highest precision 3D model. It is worth mentioning that this detection accuracy is sufficient to spot the cracks in a reinforced concrete (RC) bridge because cracks that reach the level of deterioration in RC bridges are usually more than 0.5 mm in width and more than 5 mm in length. The model texture is natural, the overall hue of the data is the same, and the colour reproduction contrast error is ≤ 5%. There are no suspended debris and no 100 mm × 100 mm holes in the effective area of the bridge, which fully satisfy the accuracy and other requirements for bridge deterioration detection.

4. Evaluation of field test results

This study considers a high-speed railway arch bridge as the engineering background. It adopts the non-contact intelligent detection technology method proposed in a previous study to investigate the virus situation of the bridge. The first step is to establish a high-precision solid 3D model of an arch bridge. The upper part of the arch bridge was generated from UAV aerial photography through image pre-processing, image feature-point matching, sparse point-cloud reconstruction based on the

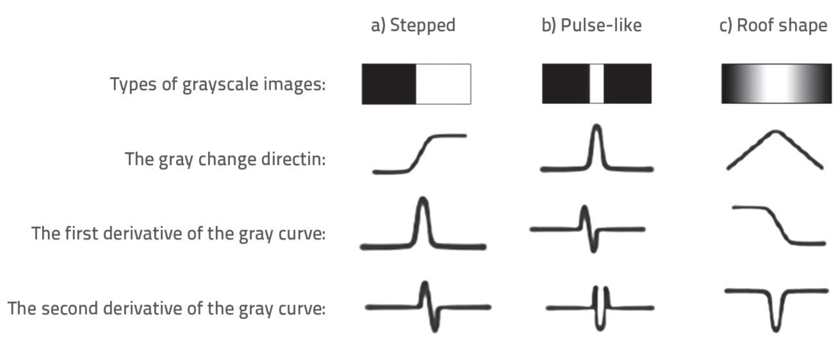

Figure 14. Illustration of the optimization process of the hypothetical edge points

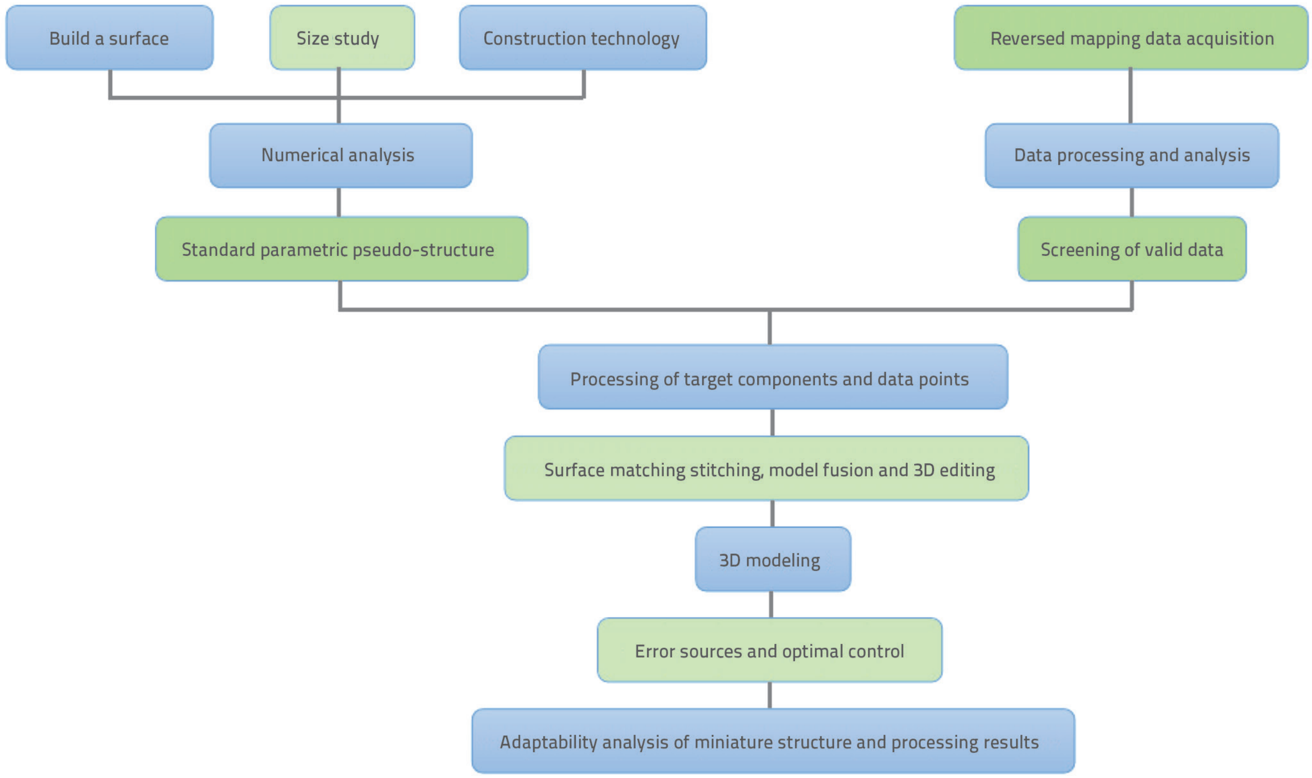

Figure 15. Spatial 3D-matching technique

motion recovery structure, and dense point-cloud reconstruction based on the CMVS–PMVS method. Subsequently, the 3D laser scanner multi-site point cloud data were imported into the SCENE software for splicing and colour assignment, and the spliced point cloud of the lower part of the bridge and the point cloud generated by the UAV aerial photography were accurately aligned to form the complete point cloud data of the arch bridge. Finally, the point-cloud data were imported into the Context Capture through the addition of control points and check points, construction of an irregular triangular mesh, and automatic texture mapping to generate the final high-precision realistic 3D model. The arch bridge model is shown in Figure 16.

Figure 16. Solid 3D model

The results show that the established model can effectively represent the overall situation of the bridge and the environment and can be used to continue to examine the arch bridge details of the deterioration investigation and research.

This probe adopts the secondary aerial triangulation solution and proposes to use the transition image as a medium to unite the aerial images of different aerial heights. This eliminates the effect of the exposure point approaching the baseline too quickly and effectively solves the phenomena of the point-cloud mislayer, image loss, and spherical surface that will occur in the current aerial modelling to ensure the effect of the overall modelling.

The local area model shows that the arch bridge is mainly in the arch ribs in many places; the deterioration can be divided into two categories. The first is the occurrence of arch cracking (Figure 17). The investigation results show that this type of damage accounts for the most significant proportion, from the foot of the arch to the quarter and the top of the arch. Many penetrating cracks are observed, indicating that the bridge arch is unsafe.

For quantifiable deterioration, such as cracks and local brokenness, image enhancement processing and edge detection effectively improve detection accuracy. Taking the existing damage features as a reference, image processing separates the damage area and concrete surface, eliminating the influencing factors of the unattended area. Through enhancement processing, edge detection, and feature extraction, it accurately extracts the area, length, width, and

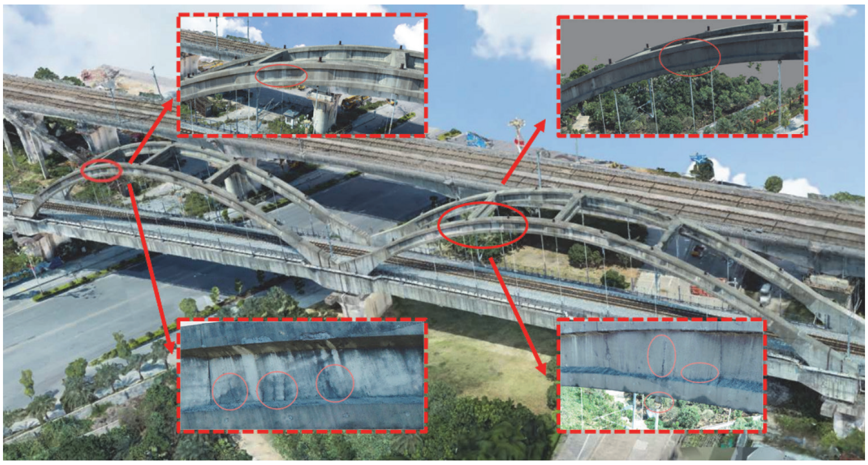

Figure 17. Arch structure cracking

Figure 18. Blooming of the arch surface

other characteristic dimensional information of the key lesions. It overcomes the difficulty of accurate quantification of key areas owing to the loss of damaged edges caused by resolution limitations of traditional inspection images and significantly improves the inspection accuracy.

The other primary type of deterioration is the presence of blooming in many places at the bridge arches, as shown in Figure 18. This is presumed to be caused by the infiltration of moisture from the surface of the material to the interior of the material, and then seeping out from the interior of the member. Long-term development may affect the structural strength and aesthetic appearance of buildings and may cause deterioration in the performance of steel reinforcement. The degree of damage caused by cracks is not as high as that caused by direct cracks. However, if long-term neglect is not dealt with, it will potentially cause irreversible damage to the strength of the steel reinforcement. Considering the presence of blooming in the bridge part is significant, the problem of this deterioration also needs to be considered. The details of the upper part of the bridge from bottom to top are shown in Figure 19, which, combined with the previously measured pictures, shows that this non-contact intelligent detection technology can have a good collection effect on the bridge as a whole.

Based on the deterioration detection results mentioned above, it is evident that most of the deterioration is concentrated in the arch of the bridge. In addition, many deterioration locations fall within conventional artificial observation dead zones, which makes timely detection challenging using traditional inspection methods. This method underscores the advantages of the proposed non-contact intelligent detection technology for high-speed rail bridge deterioration. The on-site results demonstrate that the technology offers several key advantages:

- High security: The detection personnel can operate remotely from the ground, eliminating the risk of climbing or working at heights.
- High efficiency: A team of four individuals can complete fieldwork for two arch bridges in a day.
- True 3D data: The 3D model provides a full 720° dead-angle view at any time, enhancing data traceability.
- Convenient and intuitive work reporting: Using the 3D model for reporting allows viewing site conditions at any reporting location, providing clarity and intuitiveness.
- Convenient for meetings or remote analysis: Experts in design, civil engineering, testing, and other relevant fields can be consulted based on the initial identification of deterioration foci, eliminating the need to be physically present at the site.
- Permanent data preservation: The 3D model records the site environment in real-time, ensuring permanent preservation for viewing, analysis, diagnosis, and determining the development and trends of deterioration processes.
- Easy to operate: Operators can quickly get started and, with simple training, collect on-site data efficiently.
- Promotes the transformation and upgrading of daily inspection work: Leveraging on modern equipment and advanced technology, this approach replaces manual inspection work, reducing labour intensity, enhancing efficiency, and improving inspector safety.

Compared with traditional manual inspections and semi-automated techniques, the proposed non-contact intelligent inspection technology for high-speed rail bridge deterioration is not restricted by skylight points and high flight speeds. By using high-precision 3D modelling technology and real-time dynamic high-precision positioning technology, the actual condition of

Figure19. Details of bridge superstructure from below

the bridge can be reflected comprehensively and realistically, and it is possible to scan the key components in an all-round and 720° multi-point scanning at any time. The bridge can be scanned at any time by any component of the bridge, and the key components can be scanned in all-round, 720° multi-point scanning. It can solve the limitations of the current stage of the high-speed-railway 6C inspection perspective blind area, inspection cycle, and inspection time. It is an effective supplement to the 6C system, which plays an important role in reducing the burden of manual inspection work, improving the inspection and maintenance efficiency and inspection precision, and dynamically and real-time grasping of the external environment of the line, which is especially suitable for railway operation and maintenance. It forms a data ecological chain of "producing data with information, assisting analysis with data and supplementing data with analysis results" for high-speed railway inspection work.

This study suggests that adopting this technology will fundamentally transform the monitoring methodology for railway bridges. It incorporates contemporary technologies, such as image recognition, photoelectric conversion, machine vision, and AI extensive data analysis into the traditional railway maintenance industry. This innovative approach seeks to replace manual inspection with extensive detection data. The benefits of this approach are harnessed to perform theoretical unstructured data mining for the high-speed railway infrastructure, evaluate the health status of the infrastructure, and establish a new framework for the safe operation and maintenance of railway facilities. This transformation signifies a paradigm shift in railway maintenance, heralding a more advanced and efficient era for ensuring the safety and operational integrity of railway structures. However, several studies have also indicated that an advanced structural inspection technique should also consider stability and accuracy under various harsh conditions, such as poor GPS connection signals, poor visibility, and areas with large elevation span [16-20]. Further in-depth research should be conducted in this direction.

5. Conclusion

In this paper, we propose a noncontact intelligent detection technology based on UAV image recognition for detecting the deterioration of high-speed railway bridges. Image data were collected separately using a UAV and digital camera (without GPS information and POS data). These data were fused into the same type of point cloud through technical processing. Subsequently, they are integrated into a unified point-cloud model through point-cloud alignment. Finally, a refined 3D model of a high-speed railway bridge was developed through heterogeneous data fusion using live 3D reconstruction. This refined 3D model facilitated the identification and daily monitoring of bridge deterioration. It is worth mentioning that the daily monitoring here is not real-time monitoring, but a type of periodic detection based on the advantages of the proposed detection method, such as high detection speed and fewer personnel required, which is realised by adjusting the staffing within a specified period. The effectiveness and efficiency of this technology were validated by detecting the deterioration of a high-speed railway main arch bridge. This study demonstrates that this detection method is not constrained by the skylight point and provides a comprehensive and realistic reflection of the actual bridge condition. It can be applied at any time for any bridge component, conducting all-around, 720° multi-point scanning of critical components. The proposed technology addresses the limitations of the current high-speed railway 6C inspection, including viewpoint blindness, inspection cycle, and inspection time. It effectively supplements the 6C system, significantly reducing the burden of manual inspection operations, enhancing inspection and maintenance efficiency, improving detection accuracy, and dynamically capturing real-time external environmental conditions along railway lines. This technology is particularly suitable for railroad operation and maintenance.

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REFERENCES

[1] EN 1992-1-1: Design of concrete structures (Part 1) General rules and rules for buildings Report No. BD 49/01, Eurocode Committee for Standardization, EU, n.d. 2004.

[2] Pearson, E., Smith, M.W., Klaar, M.J., Brown, L.E.: Can high resolution 3D topographic surveys provide reliable grain size estimates in gravel bed rivers, Geomorphology, 293 (2017), pp. 143-155. https://doi.org/10.1016/j.geomorph.2017.05.015

[3] Zhang, B.Y., Li, M.Y., Huan, Y.K., Khan, U., Wang, L.F., Wang, F.Y.: Bedrock mapping based on terrain weighted directed graph convolutional network using stream sediment geochemical samplings, Network using stream sediment geochemical samplings, Transactions of Nonferrous Metals Society of China (English Edition), 33 (2023), pp. 2299-2814. https://doi.org/10.1016/S1003-6326(23)66299-5

[4] Wang, X., Qi, X., Gao, W., Ma, H., Dong, J.: Research on mechanical damage-energy evolution characteristics of coal based on digital image measurement technology, Measurement (Lond), 220 (2023), https://doi.org/10.1016/j.measurement.2023.113394

[5] Lu, S., Gao, Y., Xie, T., Xie, F., Jiang, X.Q., Li, Z., Wang, F.: A novel contact/non-contact hybrid measurement system for surface topography characterization, International Journal of Machine Tools & Manufacture, (2001)

[6] Walczak, D., Krolczyk, J.B., Chudy, R., Gupta, M.K., Pruncu, C., Krolczyk, G.M.: Role of optical measurement systems in analysing the surface topography of an industry standard component, Optik (Stuttg), 283 (2023), https://doi.org/10.1016/j.ijleo.2023.170919

[7] Cáceres-Criado, I., Triviño-Tarradas, P., Valderrama-Zafra, J.M., García-Molina, D.F.: Proposition for the graphic representation, interpretation and evaluation of the degree of terrain resolution in virtual reconstructions, Interpretation and evaluation of the degree of terrain resolution in virtual reconstructions, J Cult Herit, 63 (2023), pp. 42-51. https://doi.org/ 10.1016/j.culher.2023.07.009

[8] Ramos, T., Furtado, A., Eslami, S., Alves, S., Rodrigues, H., Arêde, A., Tavares, P.J., Moreira, P.M.G.P.: 2D and 3D Digital Image Correlation in Civil Engineering - Measurements in a Masonry Wall, in: Procedia Engineering, Elsevier Ltd, (2015), pp. 215-222. https://doi.org/10.1016/j. proeng.2015.08.061

[9] Shao, Y., Li, L., Li, J., Li, Q., An, S., Hao, H.: Monocular vision based 3D vibration displacement measurement for civil engineering structures. Eng Struct, 293 (2023), https://doi.org/10.1016/j.engstruct.2023.116661

[10] Wei, Y., Ding, Z., Huang, H., Yan, C., Huang, J., Leng, J.: A non-contact measurement method of ship block using image-based 3D reconstruction technology, Ocean Engineering, 178 (2019), pp. 463-475. https://doi.org/10.1016/j.oceaneng.2019.03.015

[11] Liu, W.C., Wu, B.: Atmosphere-aware photoclinometry for pixel-wise 3D topographic mapping of Mars, ISPRS Journal of Photogrammetry and Remote Sensing, 204 (2023), pp. 237-256. https://doi.org/10.1016/j.isprsjprs.2023.09.017

[12] Choi, S.K., Ramirez, R.A., Kwon, T.H.: Acquisition of high-resolution topographic information in forest environments using integrated UAS- LiDAR system: system development and field demonstration, Heliyon, e20225 (2023). https://doi.org/10.1016/j.heliyon.2023.e20225

[13] Zhang, H., Tang, Z., Wang, B., Meng, B., Qin, Y., Sun, Y., Lv, Y., Zhang, J., Yi, S.: A non-destructive method for rapid acquisition of grassland aboveground biomass for satellite ground verification using UAS RGB images. Glob Ecol Conserv, 33 (2022), https://doi.org/10.1016/j.gecco.2022.e01999

[14] Priyanka, G., Choudhary, S., Anbazhagan, K., Naresh, D., Baddam, R., Jarolimek, J., Parnandi, Y., Rajalakshmi, P., Kholova, J.: A step towards inter-operable Unmanned Aerial Vehicles (UAV) based phenotyping; A case study demonstrating a rapid, quantitative approach to standardize image acquisition and check quality of acquired images, ISPRS Open Journal of Photogrammetry and Remote Sensing, 9 (2023), 100042, https://doi.org/10.1016/j.ophoto.2023.100042

[15] Bahrami, K., Kot, A.C.: A fast approach for no-reference image sharpness assessment based on maximum local variation. IEEE Signal Processing Letters, 21 (2014) 6, pp. 751-755

[16] Milić, I., Bleiziffer, J.: Rating systems for the sustainability assessment of infrastructure, GRAĐEVINAR, 76 (2024) 4, pp. 335-345, https://doi.org/10.14256/JCE.3858.2023

[17] Ereiz, S., Bartolac, M., Goričanec, J., Orsag, M.: Application of UAVs for assessment of bridge infrastructure, GRAĐEVINAR, 73 (2021) 11, pp. 1095-1106, https://doi.org/10.14256/JCE.3254.2021

[18] Zambon, I., Vidovic, A., Strauss, A., Matos, J.: Use of chloride ingress model for condition assessment in bridge management, GRAĐEVINAR, 71 (2019) 5, pp. 359-373, https://doi.org/10.14256/JCE.2411.2018

[19] Ristic, J., Ristic, D., Hristovski, V.: Upgrading of isolated bridges with uniform gapped HS devices: Seismic tests, GRAĐEVINAR, 74 (2022) 12, pp. 1047-1058, https://doi.org/10.14256/JCE.3580.2022

[20] Wang, C.: Overview of integrated health monitoring system installed on cable-stayed bridge and preliminary analysis of results, GRAĐEVINAR, 73 (2021) 6, pp. 591-604, https://doi.org/10.14256/JCE.2940.2020