Development and Application of Tunnel Apparent Distress Monitoring System Based on Video Image Analysis

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Abstract. With a lack of complete system and hardware equipment for long-term monitoring of distresses in an operating tunnel to address theoretical and technical issues, it is necessary to develop an IoT-based integrated system for long-term monitoring of lining crack, water leakage and spalling in an operating tunnel using video image processing technology and technique in conjunction with computer programming languages. Use of video image processing methods of this monitoring system allows rapid, accurate identification of distresses and the extent thereof. It is concluded that linear array CCD is the best option for engineering surveillance cameras since such CCD is able to accurately capture both static and dynamic targets; the use of higher-definition cameras provides for tiny target identification under remote monitoring conditions and the addition of temporary storage module for field data.

1. Introduction

With fast development of expressways in southwestern China and implementation of the Belt and Road Initiative, there remains enormous room for expressway development and operation in China. Existing monitoring technologies mostly based on point and contact monitoring cannot produce good results. The long-term monitoring theory for tunnels is based on device vision. Zhu Liqiang et al. improved tunnel image quality using Mask dodging and other pre-processing algorithms and increased the accuracy of crack image identification through in-depth analyses of components of tunnel surface crack images using template, Hough transformation, SVM and other methods [1]. Based on water leakage image characteristics and improved CTA algorithm He Guohua et al. explored how to identify and locate water leakage in the tunnel structure using morphological processing method [2]. Wang Yaodong, Cheng Yanzhi, Tan Zhijian et al. modeled distress treatment by analyzing tunnel crack based on image processing [3]-[6]. The use of remote networked image processing technology will avoid many problems. The information source of the monitoring system is cameras. Using intelligent cameras will significantly expand monitoring field of view. A PTZ camera can be mounted at fixed intervals in the tunnel to scan a large area by moving its lens left to right (PAN) and up and down (TILT) or movable cameras in prescribed track for real-time monitoring. Such a camera expands coverage areas through its ability to monitor multiple areas and points. In addition to its ability to monitor normal field of view such a camera has a monitoring accuracy from 0.01mm to infinity and better practicality. Its simplicity and ease of installation makes it less susceptible to external
interference. The entire monitoring system reduces labor consumption via automated transmission of electronic information which also aids in remote control, information visualization and remote early warning.

2. Apparent Distress Image Capture and Processing Algorithm

A CCD camera is usually used for image capture. An industrial camera made of CCD image sensors is used to capture information from structure surface for efficient and accurate crack detection. The CCD camera comes in two types: area array CCD camera suitable for static and slow target capture and linear array CCD camera for dynamic and accurate target capture. In view of the accuracy requirement and time limitation on image capture, linear array CCD is generally selected for design of a vehicle-mounted system. For a static detection system linear array CCD can also be selected.

Traditional image processing methods including gray processing, noise reduction, object identification and segmentation against static and dynamic backgrounds and feature extraction have many drawbacks. Despite improvements and applications already made in various respects the application in video image monitoring remains to be improved. The proposed monitoring system is optimized on the basis of numerous improved methods.

Currently most color images are in RBG color model. In processing images a lot of computational effort is required to process each of the three additive primary colors. Additionally this model cannot represent morphological characteristics of an image since it only mixes colors optically. The variable truly representing image features is black-and-white brightness while all others are representations of colors.

Existing video image object detection algorithm can generally be grouped into 6 categories: frame-to-frame difference method, background differencing method, image segmentation method, motion compensation method, optical flow method and clustering method. Liu Xuezeng et al. developed an entire set of digital image processing algorithms including denoising, sharpening, segmentation and modification. Successive steps of pre-processing, grey level transformation, threshold segmentation and form correction enable distress target to be identified. Among these moving target detection methods frame-to-frame difference method and background differencing method for detecting moving target against static background are widely used. There are relatively more static cameras in traffic monitoring and management unit service. These two algorithms are simple and can yield satisfactory results in general conditions. They are suitable for tunnel spalling monitoring. However, image segmentation method is used more frequently in static target or micro-motion target monitoring, e.g. tunnel lining crack and water leakage. This method facilitates target feature extraction and calculation. Dou Haitao, Liu Shanjun, Zhao Weimin and Cheng Yubao laid the groundwork for developing a dynamic detection software system for tunnels by studying infrared image features and using programs to extract water seepage area information from thermal images [7]-[10]. Because this monitoring system is designed with PTZ holder the identification of targets against dynamic background shall also be addressed. For detection of moving targets against dynamic background other algorithms such as motion compensation method and optical flow method can be used. Discussions are therefore carried out in respect of static and dynamic backgrounds hereunder. Crack identification is mainly based on the error after fitting Polyfit to determine whether the crack is mesh or linear. If the error exceeds a certain range of values, the crack type is considered to be mesh-shaped, otherwise it is considered linear. For the determination of linear cracks, the projection method is chosen. It is also a relatively common method to determine whether the linear crack is transverse or longitudinal by the gray distribution on the x-axis and y-axis. Linear and nonlinear multi-curve fitting, the so-called curve fitting is that given a set of discrete data sets, it is required to construct an analytic function so that the graphical curve of the analytic function in the coordinates is as close as possible to the given discrete point. data. The Polyfit function in Matlab can be used to fit the curve.
3. Monitoring System Design and Implementation

3.1. System composition design

The macro work process of the entire tunnel distress monitoring and warning system: the image capture equipment installed at monitoring points in the tunnel sends captured real-time images via wireless communication network to the system's remote server where image analysis and processing and comparison with threshold values occur to determine whether to send corresponding disaster warning information to client. To the outside world it fulfills two functions: 1) dynamic real-time monitoring of tunnel facilities; 2) accurate identification and timely forecast of disaster. Consequently, the entire system is composed of image capture terminal, network transmission component, server and client. The main procedure is as follows: captured data from the port are processed and promptly transmitted to the monitoring server for analysis, processing and storage. The client mainly serves monitoring personnel by enabling remote control and warning and allowing the control center to receive information.

The system components are shown in Figure 1.

Figure 1. System composition

The module involving data management is, simply put, a B/S mode based information management system as shown in Figure 2 below. The advantage of the B/S model is that access to relevant services requires no specialized software installed at the client as long as the client can connect to network. Its cost is low and its system scalable. Users with appropriate authority can gain access to the management platform by connecting to the server via IoT and import data into the system according to respective authority. This system allows tunnel monitoring data to be displayed, added, deleted, modified and checked. It also allows establishment of time dependent trends by comparing historical information in the database, and warning based on preset threshold. In addition, the system offers different privileges to the administrator, monitoring personnel and user. The user can only view data while monitoring personnel can view data and submit maintenance reports. In addition to the above authority the administrator can add/delete data, review monitoring reports, submit treatment comments, etc.
3.2. System server

As the core of the entire monitoring system the server is where almost all functions and implementation details of the system are fulfilled. Figure 3 displays its components including video image receiving subsystem, system database, image processing subsystem, digital information management subsystem and message concurrence subsystem.
3.3. Field operation

Figure 4. Camera installation

Figure 5. Camera adjustment

Perform temporary test on site by connecting a computer (a laptop for instance) of ordinary digital monitoring system to monitoring mode. First of all, investigate the environment of monitoring site, select an optimum mounting location and then lay a network cable from the mounting location to the nearest network access point using RJ45 interface. IP address of network camera and other parameters can be visited by typing default IP into a web browser in computer connection mode and setting parameters (camera IP can be modified via CMS monitoring client and recorder but the method varies due to different protocols of equipment from different manufacturers. The camera has built-in controls and all its functions can be fulfilled through web browser loading). Type IP to log into the equipment, click equipment parameter setting and change network parameters to complete LAN monitoring setting.

Figure 6. Communication connection

In this study the tunnel lining crack and water leakage are monitored; through on-site data connection test and comparison different pixel widths, different crack width thresholds corresponding to different distances and corresponding water seepage area thresholds are obtained. Once the thresholds are obtained, the system only needs real-time monitoring of crack width and seepage area developments to give warnings and alarms.
3.4. Test results

In this study the tunnel lining crack and water leakage are monitored; through on-site data connection test and comparison different pixel widths, different crack width thresholds corresponding to different distances and corresponding water seepage area thresholds are obtained. Once the thresholds are obtained, the system only needs real-time monitoring of crack width and seepage area developments to give warnings and alarms.

Table 1. Test data

| Camera parameters (3 million pixels; focal length 104mm) | Unit: mm |
|---------------------------------------------|-----------|
| Camera parameters | Corresponding pixel width | Object distance | Focal length | Corresponding crack width threshold | Corresponding area threshold |
| L1 | D1 | D2 | L2 | S1 |
|---------------------|----------|-----|------|------|-------|
| 0.00223214 | 1000 | 104 | 0.0215 | 0.0005 |
| 0.00223214 | 5000 | 104 | 0.1073 | 0.0115 |
| 0.00223214 | 10000 | 104 | 0.2146 | 0.0461 |
| 0.00223214 | 15000 | 104 | 0.3219 | 0.1036 |
| 0.00223214 | 20000 | 104 | 0.4293 | 0.1843 |
| 0.00223214 | 25000 | 104 | 0.5366 | 0.2879 |
| 0.00223214 | 30000 | 104 | 0.6439 | 0.4146 |
| 0.00223214 | 35000 | 104 | 0.7512 | 0.5643 |
| 0.00223214 | 40000 | 104 | 0.8585 | 0.7371 |
| 0.00223214 | 45000 | 104 | 0.9658 | 0.9328 |
| 0.00223214 | 50000 | 104 | 1.0731 | 1.1516 |
| 0.00223214 | 55000 | 104 | 1.1805 | 1.3935 |
| 0.00223214 | 60000 | 104 | 1.2878 | 1.6584 |
| 0.00223214 | 65000 | 104 | 1.3951 | 1.9463 |
| 0.00223214 | 70000 | 104 | 1.5024 | 2.2572 |
| 0.00223214 | 75000 | 104 | 1.6097 | 2.5912 |
| 0.00223214 | 80000 | 104 | 1.7170 | 2.9482 |
| 0.00223214 | 85000 | 104 | 1.8243 | 3.3282 |
| 0.00223214 | 90000 | 104 | 1.9317 | 3.7313 |
| 0.00223214 | 95000 | 104 | 2.0390 | 4.1574 |
| 0.00223214 | 100000 | 104 | 2.1463 | 4.6066 |

Check "PTZ holder adjustment" and click the corresponding text box to enter input status. When the cursor stops, according to the data type requirement enter the inspection time length for preset location, corresponding pixel width for instance 0.00223214mm and alarm threshold width 2.1463mm. Complete the setting by clicking "save setting parameter".

As shown the crack width has exceeded preset threshold thereby reaching alarm condition. This suggests the serious condition of Changchong Tunnel operating with cracks and prompt maintenance is required to ensure its safe operation.

To verify feasibility of the monitoring system we arranged four monitoring points in a selected tunnel area on site for comparison of manual measurements and system monitoring results, as shown in the table 2 below.
Table 2. Comparison between crack widths from Yunsui system and actual measurements

| Method          | Monitoring point 1 (mm) | Monitoring point 2 (mm) | Monitoring point 3 (mm) | Monitoring point 4 (mm) |
|-----------------|-------------------------|-------------------------|-------------------------|-------------------------|
| Yunsui test     | 0.55                    | 0.11                    | 0.81                    | 0.32                    |
| Actual measurement | 0.60                  | -                       | 0.78                    | 0.27                    |

Note: "-" denotes no measurement result.

Comparison of the test results shows the Yunsui monitoring system has an accurate detection capability relative to actual measurements.

4. Conclusions

This paper has proposed a complete set of system and hardware equipment to address theoretical and technical issues of long-term monitoring of various distresses in operating tunnels. From study of video image principles, systematic methods, system monitoring algorithms, crack feature algorithm and implementation of the proposed monitoring system, the following conclusions are drawn:

Comparison of different charge coupled devices (CCD) suggests linear array CCD is the best option for engineering surveillance cameras since such CCD is able to accurately capture both static and dynamic targets.

To create an intelligent monitoring system that can transmit information in different environments, the proposed monitoring system is designed with a dual-line information transmission capability that works with or without communication network. To reduce computation space the proposed system is designed with tunnel distress image and distress-free image analysis modules at remote end. To ease users’ use and operation and facilitate system maintenance and expansion, a "big server, small client" design mode is adopted. To enable the "big server" to function normally (i.e. all functions and details) it is composed of interconnected and mutually independent subsystems to achieve intellectualization.

Building on video image processing technologies to process dynamic remote monitoring images from a PTZ camera this paper has discussed how to identify spalling distress using background subtraction and frame-to-frame difference methods for dynamic target identification against static background, how to identify crack water leakage using edge monitoring and gray-level segmentation methods for static target identification against static background and how to monitor large areas by a PTZ camera using compensation method and optical flow method for target identification against dynamic background.

In this paper we have investigated tunnel lining cracks separately by classifying cracks using a combination of Polyfit fitting method and projection method, connecting cracks using connected domain method and selecting the optimum segmentation threshold using ROC curve. We have implemented the proposed system using remote monitoring and video image processing technologies and developed two vital modules (emergency repair alarm and distress forecast alarm) to fulfill long-term monitoring function. The early warning function allows threshold setting. We have studied the implementation of early warning using ratio of similitude and camera pixel indicators to map actual dimensions (mm) and by reference to specified threshold. The software is developed on Microsoft Visual C++ 6 platform. The tested and adjusted equipment can satisfy precision requirements.

We have improved existing on-site products by using higher-definition camera to identify tiny targets under remote monitoring conditions and adding a data storage module on site to address far base station and poor signals in the event of wireless transmission.

We have upgraded the monitoring system to increase data management capability and add expert diagnosis database. This proposed system allows dynamic preparation of maintenance program, i.e. "dynamic" development of appropriate maintenance plans and strategies based on industry standard method and maintenance information organization, comparison and analysis.

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References

[1] Zhu L.Q., Bai B., Wang Y.D., et al. (2015) Crack Identification Algorithm for Subway Tunnel Based on Feature Analysis[J]. Journal of the China Railway Society, 37(5): 64-70.

[2] He G.H, Liu X.G., Chen Y.Y., et al. (2019) Research on Recognition Method of Tunnel Apparent Disease Based on Digital Image[J]. Journal of Chongqing Jiaotong University, 38(03): 25-30.

[3] Wang Y.D., Yu Z.J., Bai B., et al. (2014) Research on crack identification algorithm of subway tunnel based on image processing[J]. Journal of Scientific Instrument, 35(7): 1489-1496.

[4] Wang Y.D., Zhu L.Q., Shi H.M., et al. (2018) Tunnel crack visual inspection based on local image texture calculation[J]. Journal of the China Railway Society.

[5] Cheng Y.Z. (2015) Design and research of tunnel lining crack detection system based on image processing [D]. Taiyuan University of Technology.

[6] Tan Z.J. (2011) Development of Digital Image Processing Software for Tunnel Deformation Monitoring [D]. Huazhong University of Science and Technology.

[7] Dou H.T., Huang H.W., Xue Y.D. (2011) Model test and image processing of infrared radiation characteristics of tunnel leakage water[J]. Chinese Journal of Rock Mechanics and Engineering, (S2): 3386-3391.

[8] Liu S.J, Zhang Y.B, Wu L.X, et al. (2009) Infrared radiation characteristics of concrete rupture and water seepage process[J]. Chinese Journal of Rock Mechanics and Engineering, 28(01): 53-0053.

[9] Zhao W.M, Zhao H, Zhao M. (2004) Application of Infrared Thermal Imaging Technology in Detecting Building Leakage[J]. Residential Science & Technology, (5): 38-40.

[10] Cheng Y.B, Xu H.P. (2008) Infrared image enhancement based on wavelet reconstruction and gray segmentation[J]. Infrared Technology, 30(10): 567-570.