Feasibility Study on the Application of Visual Measurement Technology in Deformation Measurement of Irregular Arch Bridge

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Abstract. The irregular arch bridge is increasingly favored by designers for its aesthetic appeal. However, traditional displacement measurement methods fail to meet the high-precision, high-frequency requirements for health monitoring of such Irregular arch bridge structures. Therefore, based on the Echeng Bridge in Huizhou City, a study proposes a close-range photogrammetry system using ellipse fitting and inverse perspective transformation principles. This system effectively eliminates displacement errors caused by shooting angles and improves measurement accuracy. Experimental results demonstrate that compared to traditional total station measurement methods, both methods yield highly consistent results with measurement accuracy reaching millimeter-level requirements. The study analyzes the feasibility and measurement accuracy of applying this visual measurement system to the EchengBridge, providing a theoretical basis for similar irregular arch bridges.

Keywords: Displacement; visual measurement; irregular arch bridges; digital image processing.

1 Introduction

Irregular arch bridges, while meeting basic transportation needs, are also favored by designers for their aesthetic appeal and structural diversity[1-2]. During the construction and usage of these bridges, various adverse loads act on them, causing structural displacement and deformation. Given the limitations of traditional measurement methods and the requirements for deformation monitoring of Irregular arch bridges, DIC have started to be widely used in the structural health monitoring of such bridges due to their high accuracy, real-time monitoring capabilities, and moderate equipment costs. Based on the Echeng Bridge, a study proposes a close-range visual measurement system. This system effectively reduces the impact of image noise caused by changes in the visual measurement system and shooting environment, achieving millimeter-level measurement accuracy. Extensive

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experimental verification shows that the results of this close-range visual measurement system are highly consistent with those of total station measurements, with positioning accuracy below 2.3mm and repeatability control within 1.6mm. Additionally, the study analyzes the feasibility of applying this visual measurement system to the Echeng Bridge, providing a theoretical basis for its application in similar Irregular arch bridge structural health monitoring.

2 Principle of displacement measurement

The health monitoring technology based on visual measurement is widely used in the civil engineering industry due to its ease of installation, moderate cost, and high measurement accuracy[3]. The process of tracking the displacement of target measurement points through image processing techniques is illustrated in Fig. 1, and consists of four main parts: (1) Image acquisition of the target scene, combined with image preprocessing techniques to improve the quality of captured images; (2) Identification of feature points of the target measurement points using artificial markers or features, and track the motion trajectory of the measurement points; (3) Determine the scale factor between pixel coordinates and real coordinates; (4) Calculation of the real-world displacement of the measurement points.

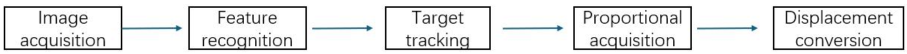

Fig. 1. Displacement monitoring process based on visual measurement

2.1 Image acquisition and preprocessing

Before performing image processing, use Shi-Tomasi corner detection to automatically extract pixel edge points, as shown in Fig. 2, and fit the extracted corners into regions of interest (ROI).

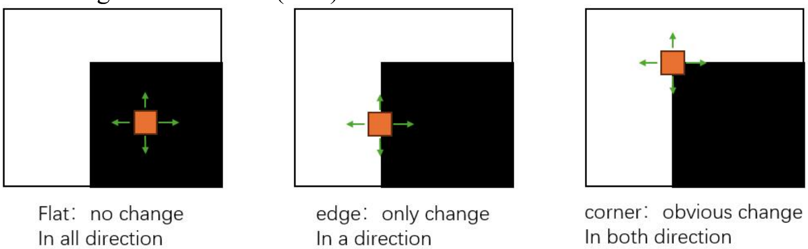

Fig. 2. Shi-Tomasi corner detection for edge pixels

Image noise refers to unnecessary interference information in digital images, which significantly affects image quality[4,5]. Considering spatial and grayscale information of the image, the study employs a filtering and denoising method combining median filtering and Gaussian filtering.

To further enhance useful information in the images, Laplacian transformation (Equation 1) is applied to strengthen local or overall features of the target area, increasing the contrast between the target and the background.

$$\nabla^2 f(x,\ y) = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} \#(1)$$

2.2 Detection point feature recognition

The study employs an edge-following method to identify arc segments and initially fit ellipses. Combining the principles of Hough transform, the fitted ellipses (arc groups) are grouped based on their 5D parameters, followed by secondary fitting to ensure the accuracy and robustness of detection and localization.

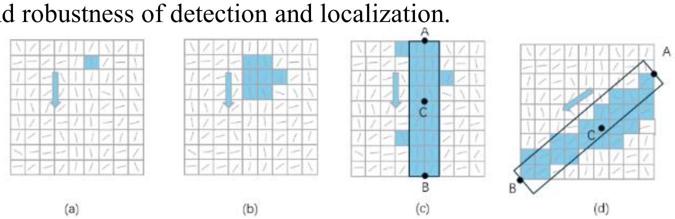

Fig. 3. (a)~(c)The growth region algorithm generates line segments(d)Arc segments

Fig.3（a）~（c）depicts the generation of line segments using edge pixel recognition and region growing algorithm. Only line segments with an angle difference greater than Ta are recognized as arc segmentsas shown in Fig.2(d).An ellipse may consist of multiple arc segments. The identified arc segments can be connected following principles of continuity and convexity to form an initial ellipse segment group. According to the 5D parameters of ellipses, the initial ellipses are grouped $E_c = \{(x, y)_c, \varphi_c, (a, b)_c\}$. To further ensure the quality of detected ellipses, a completeness score is assigned to each ellipse, computed according to the following formula:

$$Goodness(E) = \sqrt{\frac{\sum_{i=1}^{n} P_i}{B} \cdot \frac{C}{360°}} \#(2)$$

Where $\sum_{i=1}^{n} P_i$ represents the length of the initial elliptical arc segment, B represents the circumference of the ellipse, and C represents the initial angle of the ellipse.
The ellipses with high completeness are selected for secondary fitting, satisfying the criteria that the length of the arc support segment is greater than$T_r \mathcal{B}$ and the coverage angle is at least T_{ac}.

2.3 Subpixel algorithm

After obtaining the image through ellipse feature recognition algorithms, appropriate sub-pixel algorithms are employed to partition the pixels of the image, thereby enhancing the precision of visual measurement monitoring[6]. The study utilizes bilinear sub-pixel interpolation to extract the positions of edge pixels, effectively improving the accuracy of edge pixel localization while reducing computational time. The calculation formula is as follows.

$$f(x_g,\ y_g) = \frac{(x_2 - x_g)(y_2 - y_g)}{(x_2 - x_1)(y_2 - y_1)} f(x_1,\ y_1) + \frac{(x_g - x_1)(y_2 - y_g)}{(x_2 - x_1)(y_2 - y_1)} f(x_2,\ y_1) \qquad (3)$$

$$+\frac{(x_2-x_g)(y_g-y_1)}{(x_2-x_1)(y_2-y_1)}f(x_1, y_2)+\frac{(x_g-x_1)(y_g-y_1)}{(x_2-x_1)(y_2-y_1)}f(x_2, y_2)$$

After sub-pixel localization calculation for each edge pixel, non-maximum suppression is applied to prevent duplicate calculations of the corner points.

3 Visual measurement accuracy analysis

3.1 Theoretical accuracy

The theoretical accuracy (pixel accuracy) of visual measurement is related to parameters such as the lens magnification partial $\partial(1)$, the physical distance D between the target measurement point and the camera, the camera focal length$f(120mm)$, pixel size $p(1.67\mu m)$, and sub-pixel subdivision factor $k(4)$. The calculation formula is as follows.

$$S=\partial\frac{D}{kf}\cdot p\#(4)$$

By substituting the preset measurement distance D and the parameters, the pixel accuracy under ideal conditions can be obtained as shown in Table 1.

Table 1. Theoretical pixel accuracy.

Argument	Value			
Measuring distance (m)	20	50	100	125
Theoretical accuracy (mm)	0.07	0.17	0.35	0.43

3.2 Measured accuracy

In practical engineering measurements, visual measurement systems are affected by environmental changes, human interference, and internal system errors, resulting in measurement errors that exhibit statistical randomness.[8] Actual measurement accuracy in engineering is primarily categorized into positional accuracy and repeatability.[9]Positional accuracy (σ_p)refers to the error between the actual position of the measurement target in the real world and its position as measured by the visual measurement system. Repeatability (σ_r) is the error generated from multiple measurements of the same stationary target. The calculation formula is as follows.

$$\begin{cases}\sigma_o=\frac{1}{M}\sum_{k=1}^{M}\left(X_k-\bar{x}_k\right)\\ \sigma_r=\sqrt{\frac{\sum_{i=1}^{N}\left(x_{k,\ i}-\bar{x}_k\right)^2}{N-1}}\end{cases}\#(5)$$

Where $X_k$represents the actual displacement of the target point in the k-th movement; $\bar{x}_k$ represents the average of N repeated measurements for the k-thmovement; and C represents the i-th repeated measurement result for the k-th movement. Through extensive measurement experiments, the result is determined as shown in Table 2.

Table 2. Actual accuracy of visual measurement system.

Argument	Value			
Measuring distance (m)	20	50	100	125
Positioning accuracy (mm)	0.63	1.07	1.82	2.27
Repeatability (mm)	0.35	0.63	0.91	1.59

4 Feasibility study of engineering applications

4.1 Project Overview

The Echeng Bridge is a four-span continuous irregular inclined cable-stayed arch bridge with a span of 460 meters. The arch structure is made of steel, and the arches are fixed, with piers and beams separated as shown in Fig.4.

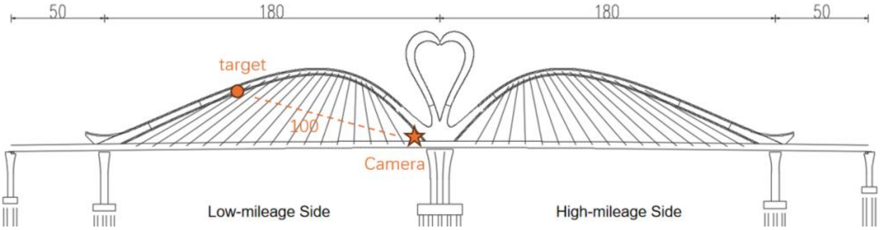

Fig. 4. Overall Elevation Plan of the Main Bridge（m）

4.2 Analysis of bridge deck deformation effects

The displacement（Δ）at the equipment installation point（θ） due to torsion causes the offset of the camera's center point, and the offset formula is as follows:

$$\sigma = \Delta + D \cdot tan\,\theta \#(6)$$

Based on the design data of Echeng Bridge, a finite element model is established as shown in Fig. 5. During construction, the maximum translation deformation is Δz = 1.87 mm, other deformations are close to 0. Therefore, the displacement of the bridge causes the camera's center point to move downward by 1.87 mm.

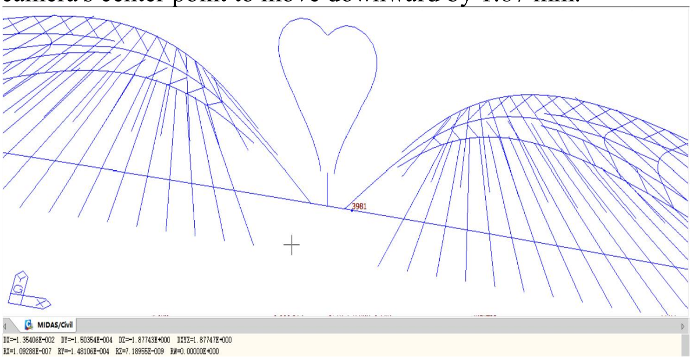

Fig. 5. Maximumdeformation (mm) at the installation point

4.3 Engineering accuracy analysis

The camera equipment installation point and the farthest target installation point are selected as shown in Fig.4, with a distance $D = 100m$ between them. And research design for image acquisition and transmission system as shown in Fig.6, the camera with a focal length of 120 mm and pixel size of 1.67 mm. According to Equation 4, the theoretical accuracy of the visual measurement system is calculated as S = 0.35 mm/pixel. Comparing this with the angle measurement accuracy of 1" from a total station, the visual measurement system's accuracy is less than the total station's measurement accuracy of 0.49 mm.

Fig. 6. Image acquisition and transmission system

Considering the Echeng Bridge midas model, the maximum displacement of arch measurement points during cable-stayed phase is 137.4 mm as shown in Fig.7. Therefore, the theoretical relative displacement between the camera and the measurement points is 133.5 mm. The theoretical accuracy of the visual measurement (0.35 mm) is less than 5% of the relative displacement (6.68 mm).Therefore, the system meets the monitoring requirements.

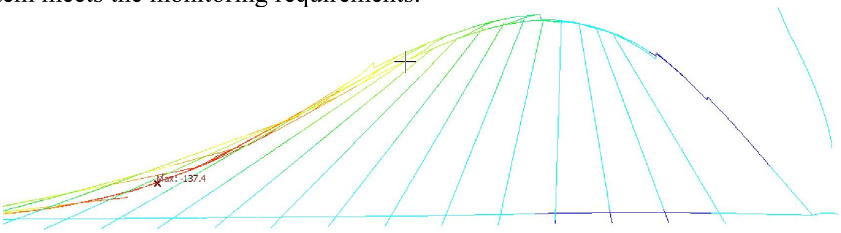

Fig. 7. Maximum deformation (mm) of the arch during the cable-stayed phase

5 Conclusion

This paper investigates a structural displacement measurement system based on image processing, focusing on the Echeng Bridge project in Huizhou City. The main conclusions are as follows:

(1) Proposed a close-range visual measurement system based on ellipse feature recognition and perspective transformation principles, which eliminates displacement errors caused by shooting angles when monitoring the deformation of irregular arch bridges, enabling high-precision real-time monitoring of displacement points.

(2) Comparative accuracy experiments between the close-range visual measurement system and traditional leveling methods showed consistent displacement results at the millimeter level, effectively verifying the accuracy of the visual measurement system.

(3) Based on the proposed accuracy calculation formula in the study and analysis using design data from Echeng Bridge to establish a structural finite element model, it was determined that the theoretical accuracy of the visual measurement system exceeds that of a total station. Moreover, it meets the accuracy requirements for arch displacement monitoring.

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