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Research on real-time monitoring methods for intelligent tower base health based on machine vision systems

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Abstract. This article introduces an innovative real-time health monitoring method for the tower foundation— a system based on machine vision technology. This system is committed to overcoming the issues associated with traditional manual inspection methods and the high cost and technical challenges faced by sensor-based online monitoring systems during implementation. We delve into the principles of stereo imaging technology, employing a tilt monitoring algorithm to accurately measure the relative tilt angle, and perform an evaluation of the tower foundation's health status based on this tilt angle range. We believe this technology has the potential to revolutionize the field of real-time tower foundation health monitoring, offering a more flexible, accurate, and cost-effective solution.

Keywords: Machine vision, Tower base health, The inclinometer algorithm

1. Introduction

Infrastructure is a crucial support for the economic and social development. The maintenance and monitoring of tower foundations are vitally important, especially in critical infrastructure such as communication towers, power transmission towers, and wind power towers. The stable operation of these facilities directly impacts important areas such as communication, power, renewable energy, and even national security in our country.

Currently, the market is still dominated by the traditional manual inspection method, which incurs extremely high labor costs, especially for the extensive and complex inspection requirements. Moreover, as the implementation mainly relies on human intervention, it is difficult to completely cover all details and hidden areas, leading to the possibility of omissions or missed issues. Prolonged or frequent visual inspections and patrols are prone to cause eye fatigue, affecting work efficiency and accuracy. Furthermore, visual inspections heavily rely on subjective judgments, resulting in individual differences and subjective biases, leading to inconsistent results.

In response to these issues, the industry has begun to focus on the development of real-time online monitoring systems for tower bases, with the mainstream direction being the use of sensors to collect structural vibrations, strains, temperatures, and other parameters. Data collectors receive and record data from sensors and then send it to data processing units for analysis, utilizing data mining, machine learning, and other technologies to identify anomalies or potential structural issues. However, this sensor-based real-time online monitoring system for tower bases requires a large amount of funding and

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technical support, particularly for already constructed tower bases, making it difficult to promote and implement. In light of these challenges, the advantages of machine vision systems are highlighted.

2. Design of an intelligent tower base health real-time monitoring system based on machine vision system

2.1. Overall system framework design

This system is based on machine vision technology for image acquisition, and through professional image analysis and data calculation, it evaluates the health status of the tower base. It achieves real-time sharing of tower base detection information, visual image analysis, data acquisition and storage, as well as health status warning and other functions, empowering real-time monitoring, management and maintenance of the tower base health.

2.1.1. Explanation of Logical structure. The system logical structure can be divided into four levels: visual perception, image capture, data transmission, and state analysis and early warning, as shown in Figure 1.

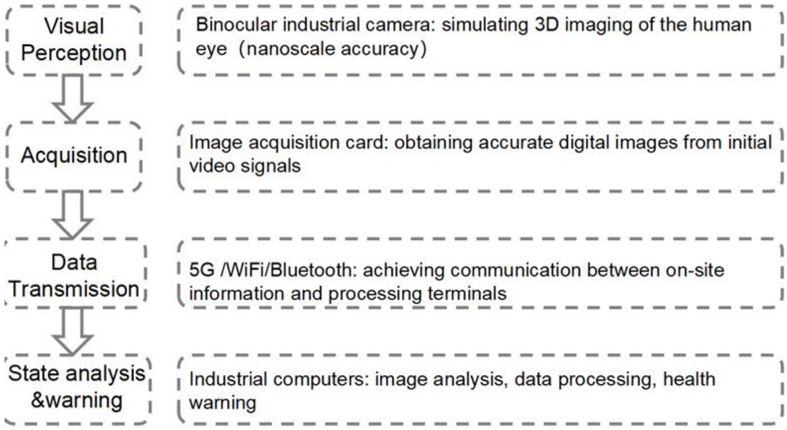

Figure 1. Logical Structure.

2.1.2. Explanation of Physical Structure

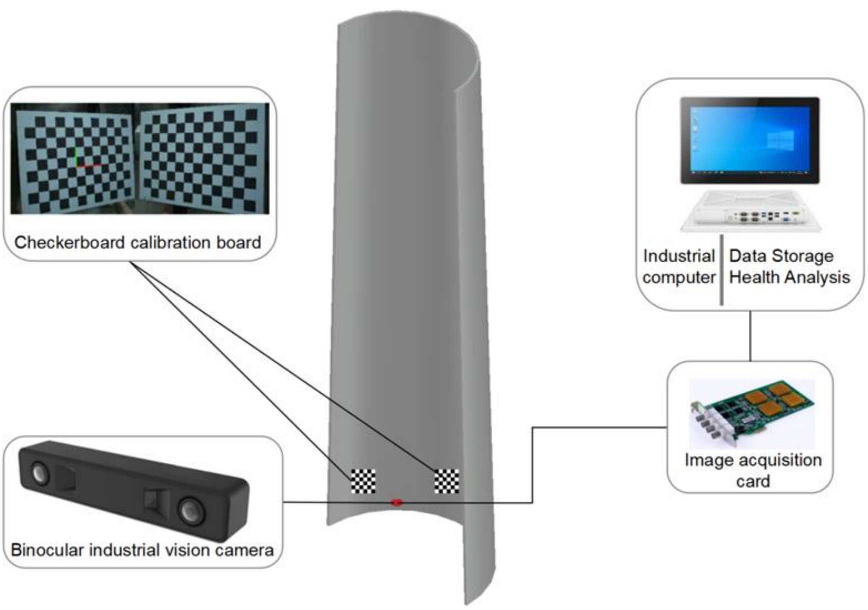

Figure 2. Physical Structure.

The binocular industrial vision camera needs to be placed inside the tower at a distance of 0.5-1 meter from the ground. The calibration board needs to be fixed within the testing range of the camera on the tower wall, approximately 1.5-2 meters away from the camera in a straight line. This system can measure the relative tilt angle, foundation and tower displacement (in the horizontal and vertical directions), tower vibration, and frequency with high precision.

2.2. Binocular industrial camera imaging technology

The “binocular stereopsis” refers to the use of two CCD cameras with similar performance and fixed positions to obtain two images of the same scene. By using the two-dimensional images captured by the two cameras, the three-dimensional information of the scene can be calculated. In principle, this is similar to human binocular vision. Building a complete binocular stereoscopic vision system generally requires processes such as camera calibration, image matching, and depth calculation.

The two camera optical axes are parallel, the line connecting the cameras is perpendicular to the optical axes, and the X-axes of the two cameras are taken on the line of the camera connection. The world coordinate system is taken at the midpoint of the camera connection, with the same orientation as the camera orientation, as shown in Figure 3.

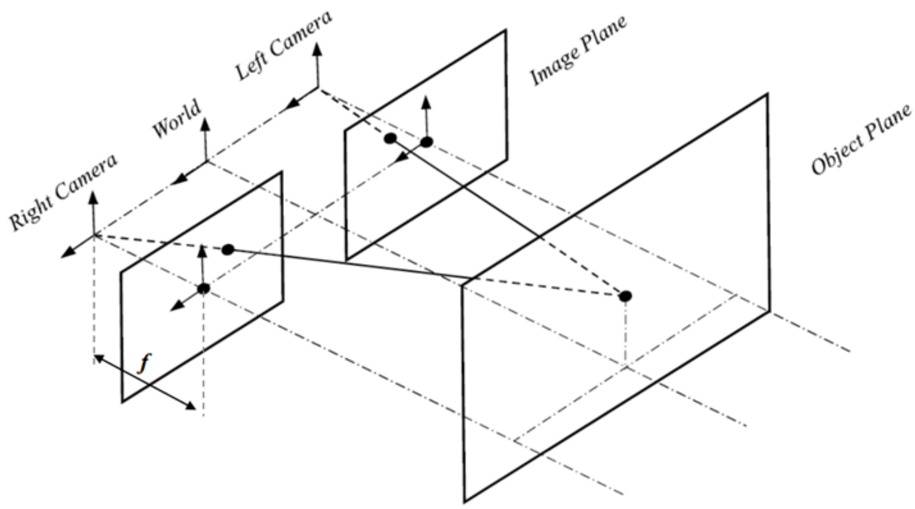

Figure 3. Schematic of binocular imaging principle.

In the world coordinate system, the coordinates of the object are (X_W, Y_W, Z_W). In the left camera coordinate system, the coordinates are (X_L, Y_L, Z_L), and in the right camera, the coordinates are (XR, Y_R, Z_R). On the image plane of the left camera, the imaging position of the object is (X_l, Y_l), and on the image plane of the right camera, the imaging position is (X_r, Y_r).

According to the principle of monocular imaging, there are:

$$\frac{X_l}{X_L} = \frac{f}{Z_L}, \frac{X_r}{X_R} = \frac{f}{Z_R}$$

According to the physical structural positions of the left and right cameras:

$$Z_L = Z_R$$

The distance between the two cameras is defined as D:

$$D = X_L - X_R$$

Then

$$\frac{X_l \cdot Z_L}{f} - \frac{X_r \cdot Z_R}{f} = D = \frac{d \cdot Z_L}{f} (Z_L = Z_R)$$

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Therefore

$$\mathrm{Z_W} = \mathrm{Z_L} = \mathrm{Z_R} = \frac{D \cdot f}{d}$$

The transformation formula for mapping points from image plane to camera coordinate system yields the object's position relative to the left camera as:

$$\mathrm{X_L} = \frac{X_l \cdot \mathrm{Z_L}}{f} = \frac{D \cdot X_l}{d}$$

$$\mathrm{Y_L} = \frac{Y_l \cdot \mathrm{Z_L}}{f} = \frac{D \cdot Y_l}{d}$$

Converted to world coordinate system:

$$\mathrm{X_W} = \frac{D \cdot X_l}{d} - \frac{D}{2}$$

$$\mathrm{Y_W} = \frac{D \cdot Y_l}{d}$$

$$\mathrm{Z_W} = \frac{D \cdot f}{d}$$

3. Relative inclination monitoring algorithm

Using a Binocular industrial camera to capture images of calibration boards A and B, with a duration of 2 seconds, capturing five sets of images per second. Through image analysis and data computation, the first set of vector values can be obtained:

$$\vec{a} = (\mathrm{X_A}, \mathrm{Y_A}, \mathrm{Z_A})$$

$$\vec{b} = (\mathrm{X_B}, \mathrm{Y_B}, \mathrm{Z_B})$$

The normal to the plane measured at this instant can be obtained from this:

$$\mathrm{L}\vec{e} = \vec{a} \times \vec{b} \text{(L is the length of the normal vector.)}$$

After a period of time, following the same method, conducting the second round of image acquisition, analysis and data calculation, the second set of vector values can be obtained:

$$\overrightarrow{a'} = \left(\mathrm{X_A}', \mathrm{Y_A}', \mathrm{Z_A}'\right)$$

$$\overrightarrow{b'} = \left(\mathrm{X_B}', \mathrm{Y_B}', \mathrm{Z_B}'\right)$$

The normal to the plane measured at this instant can be obtained from this:

$$\mathrm{L}'\overrightarrow{e'} = \overrightarrow{a'} \times \overrightarrow{b'} \text{(L}' \text{ is the length of the normal vector.)}$$

This would lead to the calculation of the relative dip angle θ.

$$\theta = \left|\arccos\left(\vec{e} \cdot \overrightarrow{e'}\right)\right|$$

The assessment of the tower base health status is conducted based on the calculated relative tilt angle results, as shown in Table 1.

Table 1. Tower Base Health Assessment

Tilt Angle Range	Health Assessment
$\leq 0.86°$	Healthy
$0.86{\sim}1.72°$	Warning
$\geq 1.72°$	Danger

4. Conclusion

Based on the monitoring results of the relative inclination angle, when the inclination angle is within the healthy state, the tower base is in a healthy condition; within the warning state; or within the dangerous state. When the tower base is in the latter two states, further precise quality analysis can be conducted by utilizing the self-owned tower foundation data model, theoretical and experimental data models, in combination with the actual detection and monitoring results of the tower base.

The intelligent real-time monitoring method for tower base health based on machine vision system is characterized by convenient installation, low operating cost, especially in covering a wide range of tower base health detection applications. It exhibits significant cost-effectiveness advantages, greatly overcoming the pain points of high labor costs in traditional manual inspection methods and high construction costs and deployment difficulties in real-time online monitoring methods using sensors. By using binocular industrial cameras, higher precision monitoring and more comprehensive coverage can be achieved, with image recording and playback capabilities, providing more comprehensive and tangible data for post-analysis and fault diagnosis. When combined with artificial intelligence technology, it can achieve intelligent diagnosis and prediction of tower base health, which is difficult to achieve with other monitoring methods.

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