Research Article

Pantograph Catenary Performance Detection of Energy High-Speed Train Based on Machine Vision

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With the rapid development of high-speed rail in China, addressing the issue of safety assurance during the operation of the train is very important. A very important part of a train’s power supply system is the pantograph and catenary system, which consists of a pantograph and a catenary. Failure of the pantograph-catenary system can cause significant damage to the normal operation of the train. The dynamic performance of the pantograph-catheter system must be detected in real time during the operation of the train. This paper is based on the study and analysis of pantograph-catheter dynamic performance parameters and developed a system for real-time detection of pantograph-catheter dynamic performance parameters based on a car visual system. The results are as follows: based on this detection method, the visual error is low and the accuracy is high. The machine-based directional height detection module developed in this paper has a good detection effect and high test accuracy; the arcing detection module designed in this paper can effectively detect the arcing and store the arcing pictures and can display the duration of single arcing and the arcing rate of the section in real-time. The practical application effect is good. The results show that the focal length of the camera lens is 16 mm, and the error of the machine vision system is low. The system designed in this paper may make a great contribution to the operation condition monitoring and fault diagnosis of the pantograph-catenary system of a high-speed train in the future.

1. Introduction

Railways have long been an important part of China’s transportation system, which is important for the development of the region’s economy and people’s livelihoods. The rapid development of railways is critical to China’s current sustainable development strategy [1]. The high-speed locomotive power supply system consists of a locomotive substation and a catenary system. The catenary system consists mainly of pantographs and catheters. The high-speed train receives electricity through a pantograph on the roof and the locomotive runs [2, 3]. During the train operation, the upper surface of the pantograph sliding plate directly contacts the catenary conductor. Under the action of internal lifting force, the pantograph will change the height of the sliding plate according to the change of the catenary conductor height, so as to ensure good pantograph catenary contact [4]. At the same time, in order to ensure that the catenary conductor will not be separated from the pantograph sliding plate and increase the service life of the pantograph sliding plate, it is required that there is a certain distance between the contact line and the center of the train pantograph carbon sliding plate, which is called the “zigzag” value in the straight line section and the pull-out value in the curve section. The height of the catenary conductor also needs to be set according to certain standards. If the height of the wire is too high, the pantograph and catenary will break instantly, resulting in a pantograph and catenary arc, interrupting the current flow, and greatly affecting the quality of the pantograph and catenary current reception. The height of the wire is too low, which increases the wear of the catenary wire and reduces its service life [5]. Whether the
pantograph and catenary can work normally determines the current collection quality of the train, the normal service life of the equipment, and the operation safety of the train. Therefore, it is of practical importance to continuously improve the ability to test the dynamics of high-speed rail pantograph-catenary, to improve the safety and reliability of high-speed railway power supply systems, and to meet the operational and management needs of high-speed rail for the intensive development of high-speed railways and high-speed railways [6].

2. Literature Review

In the 1970s, the Academy of Sciences of the Ministry of Railways developed the first catenary detection vehicle, which can only detect the parameters of catenary conductor height and off-line phenomenon of signal network [7]. In the 1980s, China developed testing equipment for operating lines with a speed of 80 km/h. The equipment can detect parameters such as pull-out value, conduction height, and off-line spark [8]. In the 1990s, Zhengzhou Railway Bureau installed an angular displacement sensor to detect the height of the conductor. In this method, the angular displacement sensor is installed to obtain the angular displacement data on the pantograph main shaft to detect the height of catenary conductor. This method is a kind of contact detection, which can effectively detect the height of catenary conductor, and the measuring point is relatively single [9]. In the late 1990s, Southwest Jiaotong University successfully developed JJC-1 catenary inspection car field. The parameters that can be detected by the detection vehicle include pull-out value, catenary conductor height, pantograph catenary contact force, and hard points. It is suitable for operation lines with a speed of 160 km/h, which greatly improves the detection level for pantograph catenary relationship. At the beginning of the 21st century, the staff of the Shanghai Railway Bureau proposed using CCD camera to detect the dynamic performance parameters of pantograph and catenary. The system uses two cameras to obtain the pantograph catenary image and uses the image processing method to detect the relevant parameters. Lu et al. proposed a method based on image processing, using the high-definition camera installed on the roof to obtain the pantograph catenary image and calculate the relevant parameters. This method only uses one camera, and the detection structure is relatively simple, but the accuracy needs to be improved. Based on the principle of laser ranging, Shandong Laser Research Institute has developed catenary detection equipment, which is fixed on the rail and has high measurement accuracy. However, the changes of relevant parameters cannot be measured in real time [10]. Tang et al. proposed an image processing method to detect arcing. This method detects arcing through the processing of offline video. The detection effect is good, but it cannot achieve the effect of real-time detection [11]. Aiming at the problems of arc detection, Li et al. designed an image real-time processing system based on DM642. The system uses image processing technology to analyze and recognize the arc of pantograph and catenary [12]. Alrabahia et al. developed a portable catenary detection equipment, which can detect the pull-out value and conductivity parameters. It is temporarily in the trial stage and has not been widely promoted [13]. The pantograph system, which consists of catenary-related devices and pantographs, is an important part of the high-speed train traction system. The quality of the traction current received by a high-speed train depends on whether the receiving signal is able to collect the current from the catenary wire evenly and steadily. Therefore, it is important to study the dynamic performance parameters of the pantograph and catenary systems. The pantograph is installed on a high-speed train and collects current through contact with catenary. It is the main component of a high-speed train to obtain energy. In the process of sliding, the clue along the pantograph is called catenary conductor, which transmits current through sliding contact. The contact line not only provides the sliding path of the pantograph, and then the electric number is transmitted to the traction power equipment [14]. The position relationship between the train pantograph and catenary conductor is shown in Figure 1.

The dynamic performance parameters of pantograph catenary of high-speed train mainly include conductor height, pull-out value, and arcing. Conductor height refers to the height of catenary conductor, which refers to the vertical distance of catenary conductor relative to the plane connection of steel rail. If the contact wire height is too high, the pantograph skateboard will deviate from contact with the contact line, due to the presence of instantaneous high pressure, produce combustion arc, and damage the contact line and the pantograph skateboard. If the height of the contact wire is too low, it will endanger the safety of the train. In addition, arcs formed when large changes in the height of the contact wire over short distances can directly endanger the current reception quality of the pantograph and catenary system, affecting the normal operation of the train and causing significant damage to the pantograph sliding plates and contact wires. If the pull-out value is set too small, the pantograph sliding plate will be abnormally worn in some areas and deep grooves will appear. If the pull-out value is adjusted too much, it will aggravate the generation of arcing, and in serious cases, there will be accidents such as scraping and threading [15]. Arcing phenomenon refers to the discharge phenomenon caused by poor contact between the pantograph sliding plate of the train and the conductor of the catenary. During the operation of the train, the pantograph sliding plate makes sliding friction with respect to the catenary conductor. The operation speed of the high-speed train has been greatly improved, which intensifies the vibration. The contact between the pantograph sliding plate and the catenary conductor is becoming more and more unstable, and the occurrence frequency of the arcing phenomenon increases immediately [16, 17]. There are many reasons for arcing phenomenon, such as too small pantograph catenary contact pressure, too large amplitude of vertical vibration of pantograph sliding plate, and poor smoothness and hard points of catenary line. Machine vision is also known as computer vision or image-based analysis and processing. The main means for human beings to perceive the world and obtain information are vision, hearing, smell, and touch. Among them, most of the information is obtained through vision. In essence, machine
vision is to use machines to replace human eyes, simulate human visual system, measure, understand, and judge, so as to obtain relevant information [18]. The car’s visual system mainly consists of modules such as a visual sensor, a high-speed imaging system, and a special image processing system. A block diagram of the car’s visual system is shown in Figure 2.

Based on the principle of machine vision, two industrial cameras need to be installed on the train roof to measure the guide height and pull-out value. The field of view covers the entire pantograph and catenary system, and the contact points of the pantograph and catenary wires can be found in the video images taken by the left and right cameras. Taking the contact point as the research object, the coordinates of the point can be obtained through image processing technology, and then the values of guide height and pull-out value can be calculated [19]. The measurement principle is shown in Figure 3.

As can be seen from Figure 3, the connecting line between the centers of the cameras on both sides is their common axis. The line connecting the centers of the two sides of the camera is their common axis, the axis is perpendicular to the surface of the paper, and the axis is parallel.

The origin of the coordinates is their center, the focal length, and the distance between the center points of the two sides of the camera. If a global coordinate system is chosen, the origin of the coordinate system is the midpoint of the line connecting the center points of the two sides of the camera.

When the cameras on both sides are placed as shown in Figure 3, the relationship [20] between the coordinates \((X_0, Y_0, Z_0)\) of a point in the space and its coordinates \((x_1, y_1)\) and \((x_2, y_2)\) in the imaging plane of the left and right cameras is shown in formulae (1)–(3).

\[
\begin{align*}
\frac{x_1}{f} &= \frac{x_0 + L/2}{Z_0} \\
\frac{x_2}{f} &= \frac{x_0 - L/2}{Z_0} \\
\frac{y_2}{f} &= \frac{y_2 - Y_0}{Z_0}
\end{align*}
\]

From (1), we have

\[
Z_0 = \frac{L}{x_1-x_2}
\]

Equations (3) and (4) can be obtained from equations (1) and (2):

\[
\begin{align*}
X_0 &= \frac{L(x_1 + x_2)}{2(x_1 - x_2)} \\
Y_0 &= \frac{L(y_1 + y_2)}{2(x_1 - x_2)}
\end{align*}
\]

It can be seen from the above formula that the test result of this point coordinate is only related to the installation position and focal length of the camera, which is less disturbed by the outside world and has high test accuracy.

3. Research Methods

3.1. Camera Selection. The industrial camera mentioned in the pull-out value and guide height detection subsystem is the digital camera [21, 22]. Compared with civilian cameras, industrial cameras have high image stability, better image quality, strong anti-interference, and data transmission ability. Therefore, in this paper, in order to meet the test requirements, industrial camera is selected.

At present, the sensors used by industrial cameras are mainly divided into two categories: CMOS (additional metal oxide semiconductor) and CCD (combined charging device). CMOS sensor adopts photodiode as photoreceiver, and CCD sensor adopts photodiode or grating transistor. Compared with the two, the CCD transmitter is more sensitive to light, the signal-to-noise ratio of image is higher, and it is used more in low contrast occasions. CMOS sensor has a higher transmission speed to obtain images, so it is widely used in occasions requiring high-speed acquisition. In this paper, two CCD industrial cameras with the same model parameters are selected for the detection of pull-out value and guide height. According to the detection characteristics and requirements of guide height and pull-out value, this paper adopts the high-performance industrial camera el-2800c of Jai Company [23]. The relevant parameters are shown in Table 1. The spectral curve is shown in Figure 4.

3.2. Pantograph-Catenary Dynamic Performance Test Device. To test the effectiveness of the high-speed train pantograph-catenary performance detection system, the system effectiveness shall be tested on a high-speed train pantograph-catheter performance test bench in the state key laboratory of the train. The test bench is mainly composed of two parts: one is pantograph device and the other is reciprocating device. The reciprocating motion device of the test-bed can move laterally on the pantograph sliding plate, during which dynamic contact force can be applied. The movement of the device can be regarded as the movement of the catenary conductor during operation. The reciprocating device contacts the sliding plate of the pantograph through two fixed components, so the pull-out value during
under the action of the lifting force inside the pantograph, so the change of the conductor height can also be detected [24].

4. Result Analysis

4.1. Analysis of Pull-Out Value Test Results. During this test, the frame rate of the camera is 50 fps; that is, 50 images are collected per second. In the test, the total length of the carbon sliding plate of the pantograph is 1060 MM, the distance between the center of the sliding plate and both sides of the sliding plate is 530 mm, and the transverse movement range of the reciprocating device is ±500 mm. During the test, the transverse motion range of the reciprocating device is concentrated near the center of the carbon sliding plate [25]. In order to better compare the test results with other methods, select the test results of a certain test under the condition of static debugging, use the monocular CCD camera [26–29] to detect the pull-out value, and analyze the accuracy of the machine vision system [30–33] by comparing the relative errors between them. The comparison results are shown in Table 2.

It can be seen from Table 2 that the detection method based on machine vision has small error and high precision.

4.2. Analysis of Test Results of Catenary Conductor Height. In this experiment, the detection of guide height is also based on machine vision technology. The reciprocating motion device of the test bench used in this test can not only move laterally but also exert a certain force in the vertical direction, so the pantograph sliding plate will also move up and down in the vertical direction. The reciprocating motion device of the test-bed simulates the catenary conductor, which is fixed. However, due to the contact force of the pantograph and the catenary, the pantograph slide plate will change in height in the vertical direction. Therefore, this test uses machine vision technology to detect the height change of pantograph sliding plate to detect the height change of catenary conductor. In the static state, the maximum pantograph lifting height of the pantograph of the test-bed is 1400 mm, and the minimum height from the installation base is 550 mm. In order to calculate the accuracy of the conductor height test results, the pantograph of the test bench is slowly reduced from the maximum pantograph lifting height of 1400 mm to 1200 mm, the height of each reduction is 50 mm, and it stays for 1-2 s after each reduction. The test height of the pantograph sliding plate is calculated by the system and then compared with the actual height. The results of the method based on machine vision and other methods described in

| Name                      | High-resolution industrial camera |
|---------------------------|-----------------------------------|
| Imaging device            | CCD                               |
| Exposure time range       | 10 µs to 8s                       |
| Resolving power           | 1920 × 1440                       |
| Frame rate                | 50 fps                            |
| Data interface            | Camera link                       |

Figure 2: Composition block diagram of the machine vision system.

Figure 3: Schematic diagram of machine vision measurement.

Figure 4: Spectrum curve of the industrial camera.
this paper were selected to compare and contrast the skate height data obtained by the laser displacement distance meter for analysis and comparison. For better explanation, the error comparison between the two results is shown in Table 3.

Through experimental analysis, the machine vision-based directional height detection module developed in this document has a good detection effect and high test accuracy. In addition, the hardware visual measurement method based on hardware is not very expensive, but it has better test effect than ordinary laser displacement rangefinder and will be used on a large scale in engineering practice.

4.3. Analysis of Arcing Test Results. Pantograph-catenary arcing detection is based on the photosensitive characteristics of arcing. An ultraviolet camera is installed on a subway line to detect the arcing phenomenon during operation. During the test, in order to improve the detection accuracy, set the frame rate of the UV camera to 500fps to detect the arc burning phenomenon within the time range of 2 ms and above.

In order to verify the arc detection module designed in this paper, we open the original arc video stored in the test process for manual retrieval. The comparison between the manual retrieval results and the system test results is shown in Table 4.

It can be seen from the Table 4 that there is a certain difference between the arcing detection module designed in this paper and the manual detection results. There are two reasons for the difference: (1) the UV camera sets a high frame rate, so there are many arc burning pictures detected. In addition, since the quantum efficiency of the UV camera in the UV band is not 100%, there will be misjudgment under the interference of light; (2) the identification degree of manual detection is relatively low, and the retrieved arc burning pictures will have deviation. In addition, the manual determination of the maximum duration of a single arc burning is not accurate. Through this test, it is proved that the arc detection module designed in this paper can effectively detect the arc and store the arc picture and can display the duration of single arc and the arc rate of the section in real time. The practical application effect is good.

4.4. Error Analysis of Machine Vision System. The car’s visual system uses two cameras to mimic human eye function. The car’s visual system uses the coordinates of the point to depict the perspective of the space point in the plane of the image of the two cameras to obtain the three-dimensional coordinates of the space point. The left and right cameras are placed in a horizontal position, and the coordinate source of the visual system is the center of projection of one of the cameras. The focal length of the camera is set as \( f_1 \) and \( f_2 \), respectively, the included angle between the optical axis and the axis as \( \alpha_1 \) and \( \alpha_2 \), respectively, and the projection angle as \( \omega_1 \) and \( \omega_2 \), respectively. The error analysis model of machine vision system is established, as shown in Figure 5.

As shown in Figure 5, the coordinates of any point in space are shown in the following equation:

\[
\begin{align*}
    x &= \frac{B \cot(\omega_1 + \alpha_1)}{\cot(\omega_1 + \alpha_1) + \cot(\omega_2 + \alpha_2)} \\
    y &= Y_1 \frac{z \cdot \sin \omega_1}{f_1 \sin(\omega_1 + \alpha_1)} = Y_2 \frac{z \cdot \sin \omega_2}{f_2 \sin(\omega_2 + \alpha_2)} \quad (5) \\
    z &= \frac{B}{\cot(\omega_1 + \alpha_1) + \cot(\omega_2 + \alpha_2)}
\end{align*}
\]
Assuming that the errors of the two cameras in the \( X \) direction are \( \delta X_1 \) and \( \delta X_2 \), respectively, and the errors in the \( Y \) direction are \( \delta Y_1 \) and \( \delta Y_2 \), respectively, the errors of the \( P \) point in the \( x \)-axis direction in the space are shown in the following equation:

\[
\Delta x = \sqrt{\left( \frac{\partial x}{\partial X_1} \delta X_1 \right)^2 + \left( \frac{\partial x}{\partial X_2} \delta X_2 \right)^2}.
\]

(6)

The error of point \( P \) in the \( y \)-axis direction is shown in the following equation:

\[
\Delta y = \sqrt{\left( \frac{\partial y}{\partial Y_1} \delta Y_1 \right)^2 + \left( \frac{\partial y}{\partial Y_2} \delta Y_2 \right)^2 + \left( \frac{\partial y}{\partial Y_2} \delta Y_2 \right)^2}.
\]

(7)

The overall measurement error of point \( P \) is shown in the following equation:

\[
\Delta xyz = \sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2}.
\]

(8)

Analysis known from equation (9), once the camera installation angle is determined, the larger the focal length and of the two cameras selected, the lower the comprehensive error of the system. The focal length of the camera lens selected in this paper is 16 mm. After the test, the error of the machine vision system is low.

5. Conclusion

With the rapid development of China’s high-speed rail and the need to detect the dynamic performance of the pantograph-catenary in order to ensure the security of power supply. Based on current technology research and analysis, this paper proposes a method for detecting pantograph and catenary dynamic performance parameters based on machine vision and implements real-time online testing, which has a certain engineering application. This paper designs a detection system for pantograph-catenary dynamic performance parameters. Including the complete overall detection scheme, the hardware equipment is selected according to the detection characteristics of different parameters, and the relevant programs are written. The expected results are achieved through the test. The pantograph-catenary dynamic performance parameter detection system based on machine vision proposed in this paper has the following characteristics:

(1) Based on the principle of machine vision, two high-resolution industrial cameras are selected to detect the pull-out value and guide height, which not only realizes the noncontact detection but also improves the detection accuracy.

(2) According to the photosensitive characteristics of arc burning, the ultraviolet camera equipped with ultraviolet bandpass lens is used for arc burning detection, which improves the accuracy of arc burning detection and avoids the interference of visible light to a great extent.

(3) The real-time online test is realized, and the test results of relevant parameters can be clearly obtained in the program user operation interface, which is helpful to the monitoring and fault diagnosis of pantograph catenary state during train operation.

(4) The combination of video image processing and kilometer marker detection is conducive to the location and fault analysis of fault points or over standard points.

Data Availability

The dataset can be accessed upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
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