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Vision-Based Railway Wheel Profile Defect Detection System

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Abstract

Railway transport plays a vital role in the transportation of passengers and cargo; its safe operation depends greatly on the condition of railway wheels. Such wheel problems as sharp flange, thin flange, deep flange, hollow tyre, flat tyre, thin tyre, and reduced radius at the root of the flange result from prolonged wheel operation under high load conditions. These defects can cause vibration, increase in repair expenses, and derailment, therefore, regular inspection of railway wheel geometry is required. The purpose of this paper is to propose an automated visual detection system for railway wheel profile defects based on laser projection and image acquisition by a camera. This system works through laser line projection on the wheel surface and recording the deformation of the laser line through a USB camera. Using computer vision methods implemented in Python, a geometric profile is calculated and transformed into a waveform that is further compared with the standard one. Notable advancements in the technology include adaptive HSV brightness gating to achieve laser isolation, intensity-based centroid detection, frame averaging using 30 frames to reduce noise, and a rule-based multi-class classifier capable of detecting eight types of defects within a speed range of 15 to 18 frames per second. The system serves as an affordable and contactless solution for the identification of flaws on wheels.

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1. Introduction

One of the key factors in the development of today's infrastructure is the transport system, which allows for the efficient transportation of people and cargo over long distances. In this regard, the safety and functionality of railways require proper working of the mechanical elements of the train such as rails, suspension system, axles, and wheels. Of particular importance in this context is the railway wheel, which suffers from constant mechanical stress due to its direct interaction with the track. As a result of its operation, it undergoes wear and mechanical damage due to friction, loads, braking, and other reasons [1], [2].

Defects in railway wheels can be represented by flanges, cracks, spalling, and flat spots, which are often caused by mechanical damage and sharp braking. In addition, they can lead to vibration and uneven loading due to damage to the contact between the wheel and rail. In extreme cases, the presence of wheel defects leads to train instability and even a derailment. It is for this reason that regular examination of wheels should be considered one of the mandatory aspects of railway maintenance [4].

The traditional approach towards wheel inspection requires performing physical measurements with mechanical devices and visual inspections carried out by maintenance staff. While manual inspection is able to detect visible defects, it is rather time-consuming and relies entirely on people's skill level. In large railway systems when several thousand wheels need regular inspection, manual inspection proves itself to be slow and ineffective [5].

In order to solve these issues, advanced maintenance systems have started implementing automated inspection procedures. Specialized industrial laser scanners and sensors are used to accurately measure the wheels' profile. Yet, such systems imply costly equipment installations and high costs for maintenance purposes. This fact gives rise to increased interest in building small-scale inspection units capable of providing accurate data.

New developments in camera technologies and image processing algorithms have made it possible to develop vision-based inspection systems that can detect surface geometry by optical means. Such inspection systems employ cameras and light sources to acquire images of surface geometry and analyze them by employing computational algorithms. There are some benefits associated with vision-based inspection including lack of contact, reduced hardware requirements, and flexible data analysis capabilities.

In the research, we propose a vision-based system for detecting defects in railway wheels. The proposed system will use laser line projection and camera imaging to analyze the geometry of the wheel surface in motion. The detected laser line will be processed by the use of image processing algorithms and will be used for forming waveforms of wheel surfaces. By comparing this waveform with reference waveform derived from a healthy wheel, any defect in the wheel profile will be revealed.

2. Related Work

Some researchers have attempted to automate wheel examination processes on railways through optical detection and image processing techniques. The early attempts were made based on laser scanning systems which could determine the 3D geometry of the railway wheels. Though such methods produce high-precision results, they are expensive and involve complex calibration mechanisms [6].

According to the research conducted by Soleimani et al., image processing is an effective approach to examine the wear-related parameters of railway wheels through camera images. The study proved that with proper calibration techniques, computer vision-based methods are able to produce fairly accurate results [7].

Laser triangulation sensors have been tested to measure wheel geometry. In these devices, laser rays are projected to the wheel surface while their deformations are detected by optical sensors. Thus, the changes in laser beams help reveal the cross-section shape of the wheel. Although these sensors offer highly precise results, they are often intended to be used in an industrial setting [8].

New technologies related to computer vision and embedded systems have provided an opportunity to develop small inspection devices using inexpensive cameras along with the latest image processing techniques. These devices can recognize surface characteristics and identify any geometry abnormalities without the use of costly industrial machinery [9].

The designed device introduced in this study takes advantage of the existing concept by integrating the use of laser stripe projection and image acquisition via camera into one prototype that will be able to identify defects on the surface of railway wheels.

3. Proposed Methodology

The design of the vision-based railway wheel inspection system consists of the use of optical techniques to determine the geometry of a rotating wheel. This system consists of three main modules including the laser line projection system, the image capture system using a camera and the processing system, which includes profiling and defect detection. Overall, the design of the system architecture is intended to be compact for prototyping.

The Figure 1 below depicts the overall architecture of the proposed vision-based railway wheel inspection system.

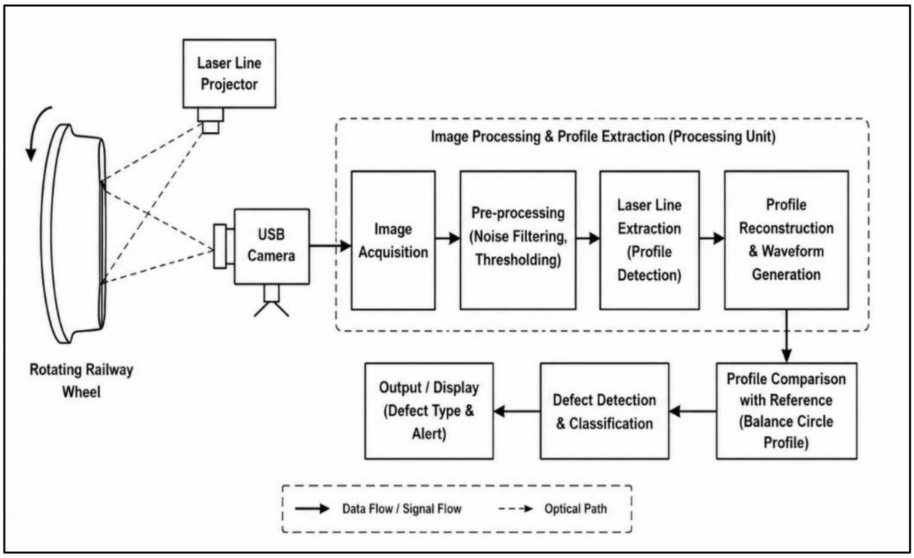

Figure 1. System Architecture of the Vision-Based Railway Wheel Inspection System

The working principle of the mechanism involves the use of laser line projection. In this case, a laser device creates a beam of light that is directed towards the surface of the rotating wheel. If there are no deformations in the surface of the wheel (e.g., scratches, dents, or uneven surfaces), the beam of light will be projected in a continuous manner. On the other hand, when the surface of the wheel is not even, the beam will be distorted due to surface irregularities. The distorted light gives insight into the geometry of the wheel surface.

To observe how the laser line is projected, a USB camera is mounted at a certain angle opposite the laser projector and captures the distortion in the projected laser line. The images are then transferred to a computer system where image processing algorithms are used to obtain the laser profile. Laser profile extraction will be translated into wave form. This wave form acts as the simplified version of the shape of the wheel within the scanning area. The wave form of the existing wheel is compared to the wave form of the normal wheel. In case any discrepancy arises in between these two wave forms, it means that there is a problem with the wheel surface.

4. Implementation

The hardware layout for the suggested setup comprises multiple units (Fig. 2) used to enable the rotation of the wheel, laser projection, capturing of images, and the overall control of the system. The hardware design is aimed at being simple and effective while preserving basic functional properties that are necessary for wheel profiling. The wheel rotation system involves the employment of a DC motor that is controlled by the L298N motor controller module. The controller receives signals from the ESP32 microcontroller and sets up the necessary speed of wheel rotation. It is important to ensure the consistency of speed due to the need to conduct accurate scans of the wheel surface.

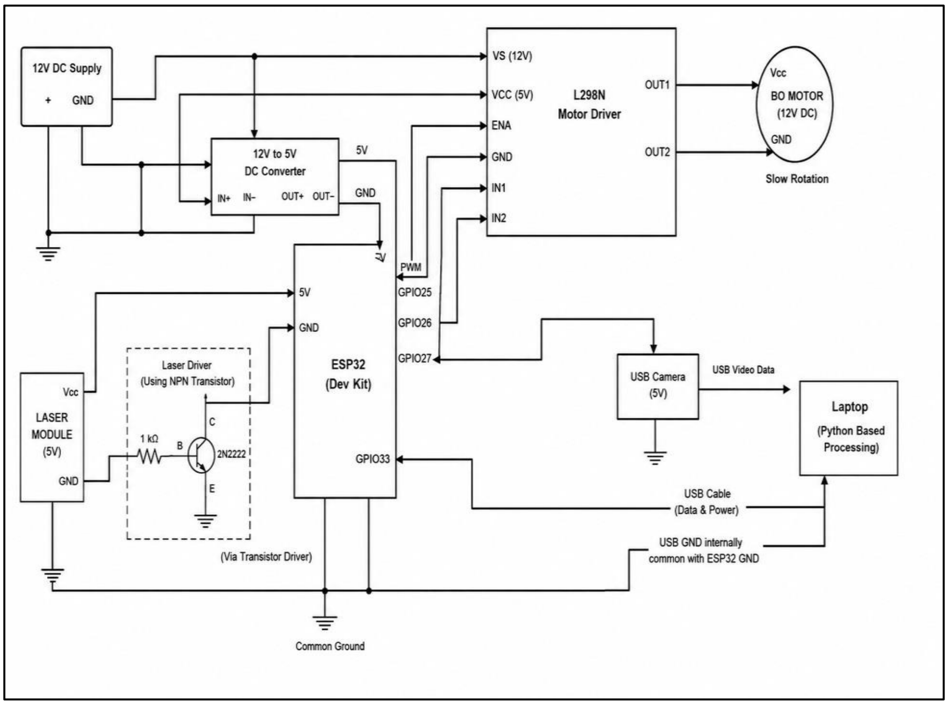

Figure 2. Circuit Diagram

The laser module is employed to produce an illuminated line on the wheel surface. The laser is operated at low power and directed in a manner such that the beam produced by the laser creates a clear line on the surface of the wheel. While the wheel is rotating, the illuminated line by the laser scans various sections of the wheel surface to detect the profiles of the wheel. Image acquisition is performed using a USB camera plugged into the computer. This camera records video images of the rotating wheel and processes them to generate an image that will be used to determine the profile of the wheel's surface. These image acquisitions are accomplished by performing image processing tasks using the computer vision module.

The control module is provided by the ESP32 microcontroller board. This board can effectively manage the rotation of the wheel and switching of the laser module on and off. Moreover, communication can be established between the microcontroller board and the computer through software programming. The ESP32 microcontroller provides a means for regulating motor speed using PWM signals.

Table 1 summarizes the main hardware components used in the prototype system.

Table 1. Hardware Components Used in the Prototype System

Component	Description
ESP32 Microcontroller	Control unit for motor and laser module
L298N Motor Driver	Drives the DC motor used for wheel rotation
DC Motor	Rotates the wheel for continuous scanning
Line Laser Module	Projects laser line on the wheel surface
USB Camera	Captures images of the laser deformation
Computer System (Processor - Intel Core i5, RAM - 8 GB, OS- Windows 11)	Performs image processing and analysis

Hardware parts have been placed in an experimental prototype set up, where the wheel has been mounted properly on the motor shaft. The positioning of the laser module and camera has been done with certain angle settings to facilitate the proper projection of the laser line.

Figure 3 below depicts the experimental prototype set up that was used to design the system.

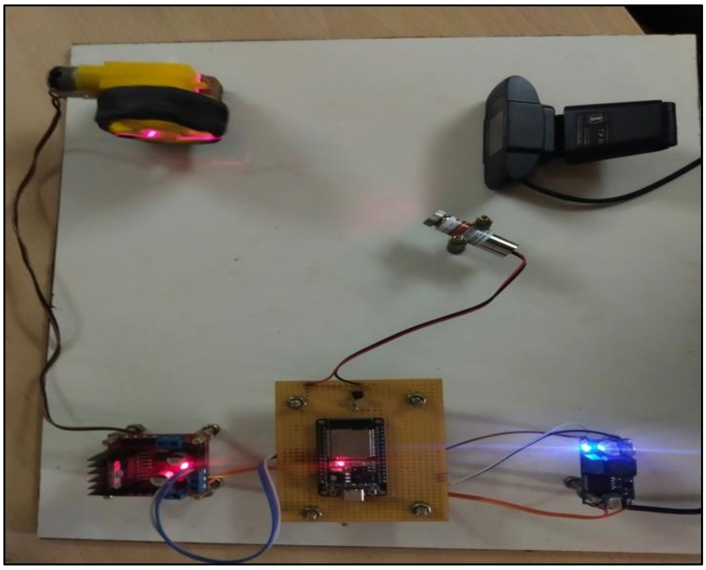

Figure 3. Experimental Hardware Setup Used for Wheel Profile Inspection

Computer vision methods have been suggested in order to detect the deformation of the laser line projected on the surface of the wheel. The main purpose of the image processing phase will be to detect the geometry of the wheel, and generate a waveform signal which will be useful for identifying any abnormalities. A USB camera will capture images from the wheel as it rotates, where the laser line is projected on the surface of the wheel. As the laser line contains the geometry of the wheel's surface, it is imperative to extract it in order to identify any defects within it. An image processing technique includes a number of steps which include acquiring images, laser line extraction, filtering, profile extraction, and waveform generation.

4.1 Image Acquisition

The first step in the system consists of recording the video frames by the USB camera. The camera is placed in an angle that ensures clear reception of the reflected laser line by the camera. The frames recorded are analyzed in real time through programming in languages such as Python with OpenCV and NumPy. In the frame captured, color information is contained in the form of RGB. The laser line projection normally takes red color. This implies that the red part of the color information gives high contrast information on the laser line profile.

4.2 Laser Line Extraction

The extraction of the laser line from the captured picture is performed using color filtering approach. The pixels, whose red component is high enough, will be considered as part of the laser line. All other pixels will be eliminated from further processing. Following the initial filtering, morphological procedures are utilized to eliminate possible noise and any artifacts. This will ensure the acquisition of clean laser line picture. Once the laser line has been acquired, morphological filtering is used to eliminate any noise and possible artifacts due to lighting variations. After that, the acquired pixels of the laser line are analyzed one column at a time to detect their location on the wheel surface vertically. The result of this step gives us the geometric representation of the wheel surface, which will be transformed into waveform.

Figure 4. Image Processing Pipeline for Extracting the Wheel Profile

Figure 4 shows the entire process of the image processing pipeline employed by the algorithm. This image processing pipeline comprises several steps involved in converting the captured image into a usable wheel profile. In the first step, the captured RGB image is broken down into separate color components, with the red component processed as the projected laser line exhibits high red intensity values. Thresholding operations are then performed on the image in order to filter out the laser pixels.

4.3 Profile Extraction

After isolating the laser line from the background noise, the second task consists of obtaining the vertical position of the laser line for each image column. The vertical position of the laser line corresponds to the height of the wheel at that particular point. In each image column, the pixel intensity corresponding to the laser line's position either at median value or at maximum value can be determined. This set of pixels makes up the profile of the wheel. To stabilize the obtained profile data, various filters such as moving average or Savitzky-Golay filters can be used to smooth the data. This helps in getting rid of small deviations caused due to noise while retaining important geometric features.

4.4 Waveform Generation

This extracted profile is then transformed into a waveform pattern. The waveform serves as a visual presentation of the geometry of the wheel surface that has been scanned.

Assume that this profile can be expressed in terms of values such that:

$$P = \{p_1, p_2, p_3, \ldots, p_n\} \quad (1)$$

where p_i represents the vertical coordinate of the laser line at column i of the image.

A reference profile generated from a normal wheel is stored as follows:

$$R = \{r_1, r_2, r_3, \ldots, r_n\} \quad (2)$$

The difference between the present profile and the reference profile can be determined by calculating the Root Mean Square (RMS) error:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (p_i - r_i)^2} \quad (3)$$

A large RMS deviation indicates a potential irregularity in the wheel surface.

4.5 Waveform Visualization

The generated waveform could be displayed using graphing tools like Matplotlib. Waveform plots include the reference waveform and the present wheel waveform for comparative purposes. Any differences observed in the waveforms can help in detecting any defects that could be present in the wheel surface.

The example illustration of wheel profile waveform generation by the proposed system can be seen in Figure 5 below.

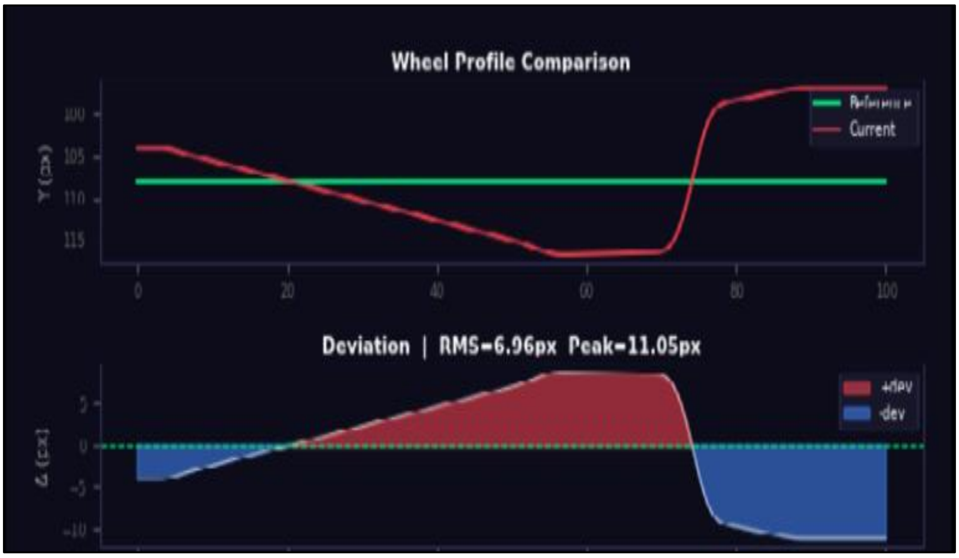

Figure 5. Example Waveform Representation of the Extracted Wheel Profile

Once the wheel profile waveform has been generated from the image, the next step involves determining the deviations present between the reference waveform and the measured waveform. Some minor differences may be detected due to noise or errors in measurements; therefore, a threshold-based process is used to differentiate between normal and defect surfaces. In the event that the RMS deviation is above the threshold value, the wheel will be flagged as possibly being defective. In other cases, where the RMS deviation is lower than the threshold value, then the surface of the wheel is regarded as normal.

5. Experimental Evaluation

The performance of the proposed vision-based railway wheel profile inspection system was tested on a small-scale prototype. The testing mainly involved determining whether the system can correctly identify surface defects through analysis of the distortion of the projected laser line. At first, the testing was carried out on the surface of the wheel without any surface defect to determine the reference waveform for the wheel. This involved rotation of the wheel by the motor arrangement while projecting the laser line on the outer surface of the wheel. The deformation of the laser line on the outer surface of the wheel during rotation was recorded by the USB camera and converted into waveforms using the implemented computer vision algorithm.

After setting the reference waveform, experiments were performed for all eight defined wheel defect cases, which included thin flange, deep flange, sharp flange, hollow tyre, flat tyre, thin tyre, less radius at root, and normal wheel. For each defect case, experiments were done for a period of at least 60 seconds and their classification and deviation results were recorded. Defect conditions were induced through experiments on different wheel models with surfaces modified to create different types of defects.

During scanning of the wheels, the generated waveform demonstrated deviations from the reference waveform depending on the defect present. Deviation between the present waveform and the reference waveform was calculated numerically using Root Mean Square (RMS) method. Experimental data indicated that wheels having surface defects showed more deviation in waveforms than those with smoother surfaces. The healthy wheel gave RMS results of 0.8-1.2 pixels while the classification threshold was 6.0 pixels. All other defective conditions gave RMS greater than 2.5 pixels and thus were distinctly different from the healthy one. An average classification accuracy of 96.9% for all the eight defects was obtained at a rate of 15-18 frames per second.

Table 2. Summary Of Experimental Observations

Wheel Condition	RMS Deviation (px)	Peak Deviation (px)	Classification Result
Healthy Wheel	0.8 – 1.2	2.0 – 4.0	HEALTHY WHEEL
Flat Tyre	4.5 – 6.2	18.0 – 24.0	FLAT TYRE
Hollow Tyre	3.2 – 4.1	12.0 – 18.0	HOLLOW TYRE
Thin Flange	2.8 – 3.6	10.0 – 15.0	THIN FLANGE
Deep Flange	4.2 – 5.3	16.0 – 22.0	DEEP FLANGE
Sharp Flange	3.8 – 4.9	20.0 – 28.0	SHARP FLANGE
Less Radius at Root	3.1 – 4.0	11.0 – 16.0	LESS RADIUS AT ROOT
Thin Tyre	2.5 – 3.2	8.0 – 12.0	THIN TYRE

From the experiment conducted, it can be seen that the system proposed here is able to detect any irregularity on the surface of the wheel profile through the use of the optical method. The system successfully uses laser line projection to convert surface variations into waveform measurements. One of the strengths of the system proposed is the ease of installation and relatively low installation costs compared to other industrial railway inspection systems.

While industrial railway inspection systems depend on precision lasers and sophisticated sensing equipment, this prototype makes use of inexpensive items like USB cameras and laser modules. Another strength is the non-contact nature of the method used. Since it utilizes optical inspection, it does not require contact between the equipment and wheel, making the whole process easier and more efficient.

Another advantage of the system modular structure is its capability to interface well with more sophisticated image processing technologies. The first innovative feature of the technology developed is the adaptability of the HSV brightness gate that defines the laser detection threshold at 75% of the maximum brightness of red pixels in each frame. It helps to isolate the lasers efficiently from any changing indoor lighting, making any external settings unnecessary. Another improvement made in order to avoid any defects is using the blob-width rejection process that removes those motor-body and surface reflection laser blobs which were larger than 18 pixels. The 30-frame majority-vote labeling provides no classification fluctuations. It makes this defect labeling approach appropriate for demonstrations in real time.

6. Conclusion

In this paper, a vision-based railway wheel profile defect detector utilizing laser line projection technology was introduced. The proposed technique involves capturing the deformation of a laser line projected onto the wheel surface and then determining the wheel profile through image analysis. The profile is further transformed into a waveform and then compared with the reference waveform of a normal wheel. Any deviations are detected based on numeric methods such as RMS errors. It has been shown experimentally that the prototype developed here is capable of detecting any irregularity on the wheel profile. The developed system offers a low-cost and compact solution as compared to the existing wheel inspection technologies used by railways. The developed vision-based system serves as a proof-of-concept of an optical wheel profiling system using computer vision. Future directions include the development of techniques for geometric calibration for millimeter-level measurement precision, band-pass filtering for outdoor usage, rotary encoders for circumferential defect location, light-weight CNN classifier to be trained with the help of profiles acquired using the system, and ESP32 wi-fi to transmit wireless data to railway management systems.

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