The Researches on Vehicle-borne Speed and Direction Detection Method Based on Binocular Image Matching

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Abstract. In order to realize accurate perception of vehicle speed and direction, a method for perceiving vehicle speed and direction accurately is proposed, which is based on road surface information images captured by two parallel vehicle-borne imaging devices. The interval time between two imaging devices is controlled accurately, so the overlapping road surface information images can be obtained. The relative motion distance and direction is calculated by image matching. The vehicle speed and direction can be calculated based on the calibration parameters and interval time. The experimental results show that the proposed method has high reliability and accuracy.

1. Introduction
The important premise of realizing unmanned ground vehicle (UGV) and cooperative vehicle infrastructure system (CVIS) is to detect vehicle speed accurately. At present, the main methods of vehicle speed detection are wheel speed measurement and GPS detection. The wheel speed is detected by measuring the driving wheel speed and the wheel radius. When the wheel is rolling on the ground, the wheel speed can be regarded as the actual speed [1]. However, due to the changes in wheel and the slip between wheel and ground, the calculated vehicle speed is not often the real speed. The accuracy of GPS detection, due to the weather conditions of ionospheric and tropospheric, is low [2].

In order to perceive vehicle speed and direction accurately, some scholars use road surface texture. They use vehicle-borne imaging devices to collect road surface texture image sequence firstly. Then they use image matching technology to detect the changes of the image sequence. At last, they continuously measure of the vehicle speed and direction by the sequence [3-5]. This method has some limitations, for example the frame rate of single imaging device is low, when the vehicle is fast there are not overlapping part for image matching, so that the speed and direction cannot be calculated by image matching. In order to solve this problem, this paper proposes a vehicle-borne speed and direction detection method based on binocular image matching. This method can obtain road surface texture image sequence by controlling the interval between two parallel imaging devices. And then use image matching technology to detect the changes of two parallel imaging devices. At last, the vehicle speed and direction can be calculated by two parallel imaging devices combining with the calibration parameters and interval time.
2. Principle of vehicle speed measuring system

The vehicle speed measurement system is shown in Figure 1. Imaging device has independent clock signal source. When the frequencies of two imaging devices are different, the frame signals of two imaging devices are different. So it needs to connect two imaging devices to the same clock signal source to make sure the acquisition times of two imaging devices are synchronous.

In order to control and stabilize the interval of two imaging devices, one of the imaging devices need to be connected with a delay circuit module in the power to make sure on of the imaging devices is delay. For this reason, once two imaging devices start, there is an interval between two imaging devices. Use these two imaging devices to capture images and use image matching technology to calculate the relation between the imaging devices, the distance can be detected. The time interval can be detected by detecting the frame signals of two imaging devices. Use the distance and the time interval, the vehicle speed and direction can be calculated.

The parallel imaging devices in vehicle speed measuring system are installed outside the vehicle and make the optical axis of the imaging devices perpendicular to the ground, make sure the devices can observe the road surface texture. As shown in figure 2, suppose that the coordinate system of image devices coincides with the coordinate system of vehicle. The road images collected by imaging devices are image A and image B, and the coincidence region is image C. At the moment $t_1$, a feature point in image A is also in image C, assume its coordinate is $C_1(x_1, y_1)$ in image C. At the moment $t_2$, this feature point in image B is also in image C, assume its coordinate is $C_2(x_2, y_2)$ in image C. It means that the road surface moves from $C_1(x_1, y_1)$ to $C_2(x_2, y_2)$. Relatively the imaging devices (and the vehicle) moves from $C_2(x_2, y_2)$ to $C_1(x_1, y_1)$.

The relation between image coordinate system and ground coordinate system is the result of image transformation between imaging device and the ground. In the process of image capture, the feature point on the ground need to be transformed by linear imaging model and nonlinear imaging model. The linear imaging model is a pinhole imaging model [6]. The nonlinear imaging model is the distortion error of the imaging device, including decentering distortion, thin prism distortion and radial distortion.
[7]. Suppose that a feature point in image coordinate system \( C(x, y) \) corresponds to the point \( (X, Y) \) in ground coordinate system:

\[
(X, Y) = f(x, y)
\]  

(1)

In the formula, \( f(x, y) \) is the transform function of the imaging system. It can be obtained by the internal parameters and external parameters [7-8]. Therefore, the actual distance of the imaging devices (and the vehicle) is:

\[
d = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2}
\]  

(2)

The angle between vehicle moving direction and the headstock is:

\[
\theta = \arctan \frac{X_1 - X_2}{Y_1 - Y_2}
\]  

(3)

The interval time of the imaging devices is \( \Delta t = t_2 - t_1 \). The actual speed of the vehicle is:

\[
v = \frac{d}{\Delta t} = \frac{\sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2}}{t_2 - t_1}
\]  

(4)

The vehicle speed measurement system overcomes the problems in traditional methods. For example, the speed of vehicle is too fast but the frame rate of the imaging device is too low. The vehicle speed measurement system in this paper improve the accuracy of speed and direction detection effectively.

3. Image matching technology

According to the principle of image matching algorithm, the image matching methods can be divided into 4 kinds, which are gray level matching, template matching, transform domain matching and feature matching [8].

Feature matching is one of the most common image matching algorithms. Feature matching extracts the point, line and outline information set and matches these features. Feature matching not only reduces the computational complexity and improves the efficiency, but also has a certain robustness to the change of gray level in the image [9]. However, feature matching requires high accuracy in feature extraction and feature matching because it uses only a small part of feature information in the image. The vehicle moves fast to causes the degradation of the road surface image. The error rate based on the feature matching method increases dramatically. Template matching is simple and direct, and the template range is large so more image information is used. Therefore, it is robust to the degradation of the road surface image. But template matching needs to extract a template in the road surface image in advance, then uses sliding matching to match template in another image. The extraction and matching are repeated, so the calculation is larger. In order to make full use of the advantages of feature matching and template matching, vehicle speed measurement system uses the coordination of them. Use the feature matching to provide the bases for template matching, improve the matching speed and use the template matching to improve the accuracy.

3.1 SURF matching

Speeded up robust feature (SURF) matching was first proposed by Herbert Bay [10] et al in 2006. The SURF matching algorithm is improved by the scale invariant feature transform (SIFT) matching algorithm, which greatly improves the calculation speed of the program while ensuring robustness.

The Hessian matrix is the core of SURF matching, the discriminate can be used to determine whether a certain point is the value extremum point of the image. Suppose a pint in the image is \( P(x, y) \) and its gray value is \( I(P) \), then the Hessian matrix of \( P(x, y) \) is:

\[
\mathbf{H}(P, \sigma) = \begin{bmatrix}
L_{xx}(P, \sigma) & L_{xy}(P, \sigma) \\
L_{yy}(P, \sigma) & L_{xy}(P, \sigma)
\end{bmatrix}
\]  

(5)

In the formula, the \( L_{xx}(P, \sigma) \) is convolution of the gray value of the point \( I(P) \) and the two order partial derivative of the standard Gauss function \( g(x, y, \sigma) \) under specific scale \( \sigma \):
In the formula, * is the convolution operator. In this time, the discriminant of the Hessian matrix of the point is:

\[ \Delta = L_{xx}L_{yy} - L_{xy}L_{yx} \]  

This method can use the gray value of each pixel in the image to calculate the Hessian matrix and its discriminate formula, and determine whether the pixel is the extreme value of the image [11].

In order to locate the best feature points in different scale images, the extreme point should be selected. When value of the detected point is less than a preset value, it should be discarded. So the number of the detected feature points is reduced, the remaining feature points are strong feature points [12].

Make the feature point as the center, take 8 pixels × 8 pixels image area and divide it into 4 × 4 blocks. Calculate the Haar wavelet response values of each pixel and its neighborhood in x direction and y direction, which are denoted by \( dx \) and \( dy \) [10].

Haar wavelet response values of these blocks are counted, which are denoted by \( \sum dx \), \( |\sum dx| \), \( \sum dy \), \( |\sum dy| \), \( \sum|dx| \), \( \sum|dy| \), \( \sum dx \), \( \sum dy \), \( \sum|dx| \), \( \sum|dy| \). \( \sum dx \), \( \sum|dx| \), \( \sum dy \), \( \sum|dy| \) is composed as a four-dimensional vector, the process of the extraction is shown in Figure 3.

![Figure 3 Extraction of the feature vector](image)

In summary, each feature point and its selected image region can be described by a \( 4 \times (4 \times 4) = 64 \) dimension vector [13]. The Euclidean distance between feature vectors is used as similarity measure.

### 3.2 Template matching

After feature extraction and feature description by SURF matching, there may still be errors. Especially when the vehicle is moving at higher speed, the probability of error will increases. Therefore, it is necessary to take the feature points which is better matching as the key points of template matching. Because the key point is the extreme value of the image, so the key point must be obvious in the image. Obtain a range of image around the key point as the template. If another image is the image to be matched, the obtained template is matched with another image [14], and then the template matching result can be obtained.

Template matching can be divided into 3 kinds by matching algorithms: squared difference (SQDIFF) matching, correlation (CCORR) matching and correlation coefficient (CCOEFF) matching [15]. Suppose \( I(x, y) \) is the image to be matched, \( T(x', y') \) is the template image, and \( R(x, y) \) is the result of the point \((x, y)\), then:

Squared difference (SQDIFF) matching:
\[ R_1(x, y) = \sum_{x', y'} (T(x', y') - I(x + x', y + y'))^2 \]  

Correlation (CCORR) matching:
\[ R_2(x, y) = \sum_{x', y'} (T(x', y') \cdot I(x + x', y + y')) \]  

Correlation coefficient (CCOEFF) matching:
\[ R_3(x, y) = \sum_{x', y'} (T'(x', y') \cdot I'(x + x', y + y')) \]  

In this formula, \( T' \) and \( I' \) is the difference between the mean value of \( T \) and \( I \) respectively.
\[ T'(x', y') = T(x', y') - \frac{1}{(w \cdot h) \sum_{x', y'}} T(x'', y'') \]  
\[ I'(x + x', y + y') = I(x + x', y + y') - \frac{1}{(w \cdot h) \sum_{x', y'}} I(x + x'', y + y'') \]

Usually, the accuracy of the matching results is improved gradually from the squared difference matching to the correlation coefficient matching, the computation is gradually increasing. So it needs to choose the optimum matching scheme. The vehicle speed measurement system firstly selects the key points by SURF matching, so the effect of the template matching is small. Therefore, choose the correlation coefficient matching method can effectively improve the image matching accuracy of the vehicle speed measurement system.

3.3 Matching reliability analysis
In order to ensure the matching reliability and improve the matching accuracy, this paper adds the false matching point elimination algorithm in the existing image matching algorithm and adds a false value detection algorithm to the speed detection.

In the image matching, most of the matching results in the image are consistent, only a small number of matches are mismatched because of the difference of brightness between the images. Therefore, after matching, the average and standard deviations of the matching result are calculated, and the difference between the matching result and the average is analyzed. When the difference exceeds 2 times of the standard deviation, the matching result is considered wrong and the point is eliminated.

In the speed detection, the speed and direction of the vehicle will not be mutated, so the detected speed is analyzed statistically, and the speed curve is fitted. The misjudgment of the detected speed is eliminated, the remaining speed is reliable detected speed. The experimental results show that the false rate of detection is less than 3%, and can be eliminated by statistical analysis.

4. Experiment and result analysis
4.1 Static experiment
In order to test the performance of vehicle speed measurement system without external factors, static test is designed to analyze. The vehicle speed measurement system is installed on the test platform on the lane above, strictly control the test platform to move precisely along the \( x \) direction and \( y \) direction of image coordinates, record the distance and capture the road surface image. The test platform can only generate displacement in \( x \) direction and \( y \) direction, so the distance and angle of the other direction is hard to control. Therefore, the distance and angle of the other direction need to be used of the \( x \) direction and \( y \) direction to calculate.

The static distance test results are shown in table 1, and the static angle test results are shown in table 2.
Table 1 Static Distance Test Results

| Detected distance(mm) | Actual distance(mm) | Absolute error(mm) |
|-----------------------|---------------------|--------------------|
| 2.61                  | 2.60                | 0.01               |
| 5.17                  | 5.20                | -0.03              |
| 7.71                  | 7.80                | -0.09              |
| 10.31                 | 10.40               | -0.09              |
| 12.93                 | 13.00               | -0.07              |
| 13.13                 | 13.26               | -0.13              |
| 13.84                 | 14.00               | -0.16              |
| 15.28                 | 15.16               | 0.12               |
| 16.76                 | 16.45               | 0.31               |
| 18.46                 | 18.38               | 0.08               |

Table 2 Static Angle Test Results

| Detected angle(°) | Actual angle(°) | Absolute error(°) |
|-------------------|-----------------|-------------------|
| 0.54              | 0               | 0.54              |
| 0.09              | 0               | 0.09              |
| -0.15             | 0               | -0.15             |
| -0.20             | 0               | -0.20             |
| -0.43             | 0               | -0.43             |
| 11.02             | 11.31           | -0.29             |
| 21.55             | 21.80           | -0.25             |
| 31.43             | 30.96           | 0.47              |
| 38.99             | 38.66           | 0.33              |
| 45.21             | 45.00           | 0.21              |

From the above results, it can be seen that in the millimeter range of motion, the distance detection error is not more than 0.5 mm and the angle detection error is not more than 0.6° in the vehicle speed measurement system. It shows that the vehicle speed measurement system has high precision without movement.

4.2 Vehicle experiment
In order to test the detection accuracy, validity and reliability of vehicle speed measurement system when driving, a vehicle test is designed. The photoelectric speed sensor is installed on the wheel of the model vehicle to collect the rotation rate of the wheel, and the vehicle speed is calculated according rotation rate and the diameter of the wheel. Make the model vehicle run straight to eliminate the influence of the vehicle roll, eliminate the influence of the wheel deformation during calculation. The photoelectric speed sensor can be used to provide the reference speed. The vehicle speed measurement system is installed on the model vehicle, the performance of vehicle speed measurement system is tested, both in speed detection and direction detection. The speed test results of the model vehicle are shown in Figure 4.
The test results show that the detected speed and the reference speed are in good agreement with each other.

Combine the external and internal parameters of the imaging device to calculate that the reference angle of the vehicle speed and the body of the vehicle is 47°, so the detected angle between the vehicle speed and the body of the vehicle is shown in Figure 5.

As can be seen from Figure 5, the angle detection value of the vehicle proposed in this paper is in good agreement with the actual value, and the relative error is less than 5%, and it has higher accuracy.

In summary, the proposed vehicle speed measurement system and method have higher accuracy, validity, and reliability.

4.3 System error and applicable range
Because of the discrete characteristics of digital images, there is a general system error when converting the distance of the images. Assuming that there is a point in the image, the pixel has a certain size, this point may fall at any place in the pixel. When convert the image distance to the detected distance, the error between the image distance and the detected distance is caused by the position of the point.

Assuming that the detected distance is $L_{\text{det}}$, the interval between imaging devices is $\Delta t$, the detected speed is $v_{\text{det}}$:

$$ v_{\text{det}} = \frac{L_{\text{det}}}{\Delta t} = \frac{L + \epsilon}{\Delta t} $$

In the formula, $L$ is the actual distance, $\epsilon$ is the actual distance of each pixel.
From the above analysis, it can be seen that under the same field of camera and installation condition of the imaging devices, the system error can be reduced by increasing the resolution of the camera.

The actual distance of image diagonal is $L_{\text{max}}$, then the range of image distance which can be detected is $\varepsilon \sim L_{\text{max}}$. It means that the minimum value is 1 pixel, the maximum value is the image diagonal. Therefore, the range of speed is $\varepsilon/\Delta t \sim L_{\text{max}}/\Delta t$. The relative error of the vehicle speed is:

$$\delta = \frac{\varepsilon}{v_{\text{real}} \Delta t}$$

In the formula, $v_{\text{real}} = L/\Delta t$ is the actual speed.

The interval time of the vehicle speed measuring system is shorter than single imaging device (1 ~ 5 ms), so it can ensure that when the vehicle speed is high, the road surface images still have sufficient area for image matching. However, it also lead to inaccurate measurement of vehicle speed and direction when vehicle speed is low. In this time, the frame rate of a single imaging device is low and the image interval is usually 40 ms, which can improve the accuracy. The relation between relative error and vehicle speed is as shown in Figure 6. The binocular image detection system can detect a large speed range and has high precision, but the precision fell sharply when the vehicle speed is low. The monocular image detection can provide high precision at low speed, but the range is smaller than the binocular image detection.

![Figure 6 Relation between relative error and vehicle speed](image)

5. Conclusion

The method presented in this paper is simple and fast, it overcomes the shortcomings of the single imaging device and the single image matching method. This method reduces the cost of the equipment and improve the accuracy of speed detection, which can effectively detect the speed and direction at the same time. This method has certain research and application value in all kinds of embedded vehicle applications. As the system needs to use two imaging devices, the requirement of imaging devices are relatively high. So how to eliminate the difference between the imaging devices needs to be further studied.

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