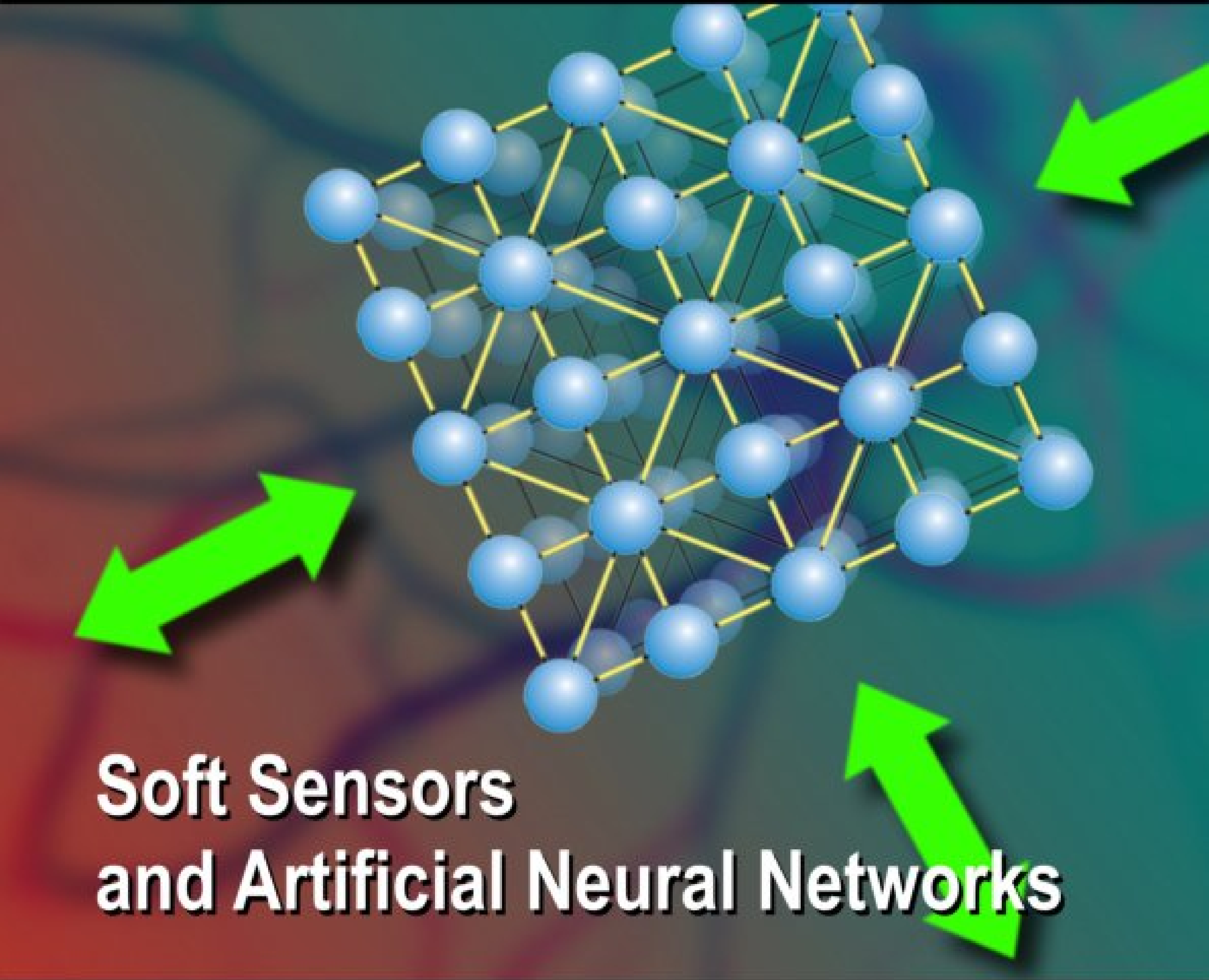
ISSN 1726-5479

SENSORS & TRANSDUCERS

10/12 vol. 145



Soft Sensors and Artificial Neural Networks

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 145, Issue 10
October 2012

www.sensorsportal.com

ISSN 1726-5479

Sensors & Transducers Journal

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Volume 145
Issue 10
October 2012

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal, Vol. 145, Issue 10, October 2012, pp. 138-148

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

High-Speed Fastener Detection System Based on Machine Vision

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Received: 11 July 2012 /Accepted: 22 October 2012 /Published: 31 October 2012

Abstract: For high-speed railway, rail maintenance is a very important task. Rapid railway transportation needs a stable rail state, including rail surface roughness, rail profile and gauge, etc. As an important rail attachment, rail fastener is to prevent track horizontal and vertical movement, its defect and missing may cause changing of track spacing and destruction of rail joints. So the regular detection of fastener is necessary. This paper introduced fastener detection method using machine vision technique. According to fastener's fixed structure, feature of Direction Field (DF) was proposed for recognition. DF feature is simple and robust for fastener detection in the field under environmental circumstances. Combining the HPC (High Performance Computing) of GPU, it can complete fastener detection task in 400km/h. A significant consideration is the need to obtain continuous video of the target sections of fastener. By processing the image sequence, two algorithm was presented for pre-position of follow fasteners, and then it can complete targeted acquisition of the fastener location. Pre-position can increase the stability of recognition, and control cost. Through mathematical simulation, verified the feasible of this pre-position method. *Copyright © 2012 IFSA.*

Keywords: DF (Direction Field), Fastener, Pre-Position, High-railway.

1. Instruction

Now, most railway maintenance is performed by trained personnel, walks along the railway and checks the rail condition, included fastener. It is slow, laborious and lacks the ability to easily record. Sometimes negligence will occur, and leads to the hidden trouble. With the great development of rail transport, the railway network is too huge, and enhances the demand for transportation security, so massive maintenance work needs the help of automatic equipment for regular detection. Track inspection vehicle appeared, and use the modern technology to complete comprehensive detection of rail anomalies [1-5], such as gauge measurement, track profile and wear measurement, ballast measurement, rail defect diagnosis, and concrete rail seat abrasion, etc. It requests a variety of high-speed detection equipment and mean.

This paper focuses on the fastener detection [3], mainly aims at German VOSSLOH style，The present literature provides a few methods for fastener detection on the basis of image, and most is in the research stage. Practical application is rarely, such as Stella, Mazzeo et al. [6] and Marino, et al. [7], use Wavelet analysis and Multilayer Perceptron Neural classifiers to detect hexagonal-headed bolts (a kind of fastener), revealing the presence/absence of the fastener bolts with high detection and classification rate. However, the result is not applicable to our situation for the complex shape and environment of VOSSLOH fastener, Taiwan Hsieh, Chen et al. [8] Applied morphological approach to get the outline of the fastener, which can inspect fastener on concrete or ballasted track to determine if it is broken and has a 77 % recognition rate for broken clips. Hsieh's method is based on fastener's body (clips) extraction, using complex image processing. But, for environment circumstances and high-speed image acquisition, fastener body is hard to extract in image, so it is not suitable for VOSSLOH fastener detection.

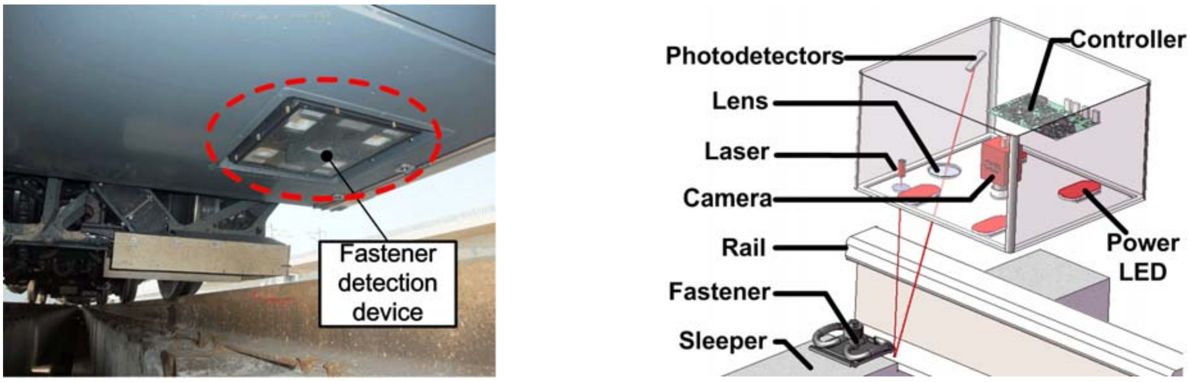
This paper presents a practical high-speed fastener detection system for complex environments (natural erosion, foreign objects), high-speed and curve shape of the fastener, use pre-position to complete targeted image acquisition, and then complete recognition. This system is suitable for track inspection vehicle in high-speed, and preliminary test is completed with track inspection vehicle in 400 km/h. After manually obtain the fastener template, this system can complete fastener detection automatically.

Taking into account the camera cost and transmission limit of image data, the image sequence cannot cover the whole course along the rail with panoramic images. Using seamless image mosaic method to detect fastener is impossible. It requests targeted sampling according fastener location, which is helpful for stable recognition and reducing costs. It needs the information of vehicle speed and fastener position, which can be evaluated by image sequence according to appropriate algorithm. This paper presents appropriate algorithms for pre-position of fastener by previous image sequence, and provide synchronization trigger signal for camera and light.

The detection system is briefly introduced in the next section. The recognition algorithm is presented in 3rd section, it about the detail for fastener feature and recognition. Next, two methods for pre-position of fastener are discussed in section 4. Finally, in section 5, simulation is shown using mathematical methods based on Matlab, which proved the feasibility of the method.

2. System Overview

This system acquires images of fastener by high-speed camera (AVT GE680 [9]), which having 640×480 pixels. GE680 can perform at maximum rate of 205 frame/s by 640×480 pixels, and 380 frame/s by 320×240 pixels. This camera transmit image through network, so the speed limited by the quality of cable and transmission distance. In 640×480 pixels resolution, it is difficult to obtain image with suitable brightness for processing, so we adopted a resolution of 320×240 pixels, and the camera can work stable with acceptable image quality in 300 frame/s. This system used a Power LED to enhance the image brightness，power rating is 4×30 W, color temperature is 5000-5500 K, luminous flux is 2400-2600 lm. Using camera trigger signal as synchronization stroboflash pulse, the LED ensure that the system will not overheat during operation, and get image with better brightness. The device and system block diagram shown in Fig. 1.



(a) The actual fastener detection device. (b) Structure diagram of system.

Fig. 1. The structure of detection device.

The detection of fastener is performed by two part, Pre-position Module (PM) and Fastener Detection Module (FDM). At beginning, we need the position of fastener to determine image sampling location, to ensure that fastener is in the view field of follow-up image sequence that makes recognition stable and the sampling interval is corresponding to fastener's actual interval along the rail. In FDM, PM is also called when location of fastener has large offset in image, caused by cumulative sampling location shift, effect of turnout or fastener interval change. Judgment for need of PM is:

a) Fastener loss rate in recognition is bigger than a certain threshold in image sequence.

b) The fasteners average location has too large off-center in image of sequence.

3. Fastener Recognition

This paper aimed at VOSSLOH Fastener, which is common in modern railway, and is the main fastener type in china high-speed rail project. It is shown in Fig. 2.

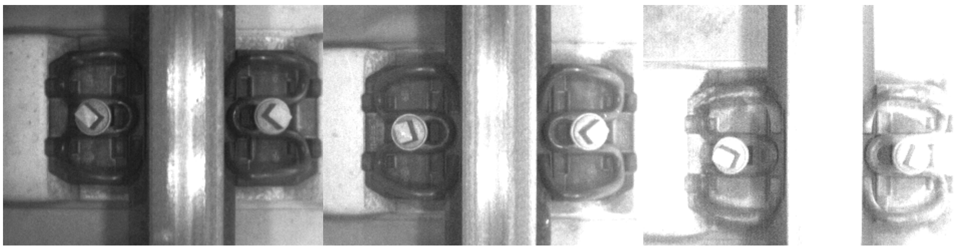


Fig. 2. Actual high-speed rail fastener samples in china.

VOSSLOH Fastener is deferent from that mentioned by Stella, Mazzeo [6-7], and it has a more complex shape. Meanwhile, we should complete images acquisition in very high speed and nature environment, the ambient and motion noise is more severe, as shown in Fig. 2 and Fig. 3, which increase the difficulty of feature extraction and recognition.

Our system and algorithms do some test in actual high-speed rail detection vehicle, and it worked well for fastener recognition. Even when a half fastener appears at the edge of image, we can complete recognition and find the location.

Fig. 3. Fastener Image Samples of natural corrosion and environmental interference.

The matching process of the fastener can refer to already published papers [10]. After much experiment, we find the stable "texture" feature of fastener, like fingerprint identification method [11-12]. Based on Rao's [13] algorithm, we extraction the Direction Field (DF) feature for fastener, and complete recognition. It works well due to follow reason. First, the fastener is artificial standard accessories, has fixed and special shape. On the other hand, we used Power LED, which make fastener edge to produce "shadow texture". DF descriptor is valid and stable for simple texture, can well represent the characteristics of fastener clips shape sand its subsidiary structure. For fastener's DF feature, major is about shape of clips. Clip is the main component of the fastener, so it represents the present/absent of fastener. In the process of fastener recognition, there is two parts:

1) First, we get Fastener DF template through manual selection and window split. At beginning, we get fastener image sequence by high-speed acquisition, and then look for the fastener in images, split some good fasteners with window of same size. Then we get a number of fastener templates, and extract its' DF feature. Every DF feature has some noise, so we use the arithmetic mean method, and synthesize multiple fastener DF features to be a standard DF template feature. This stage can be called Template Acquisition Model (TAM), and we get typical and stable characteristics of feature for recognition. As shown in following Fig. 4.

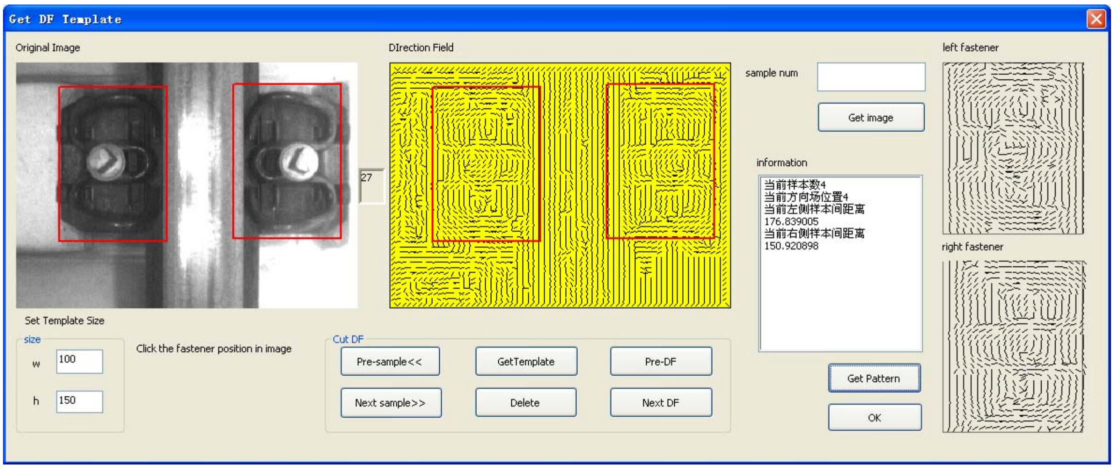


Fig. 4. Template Acquisition Interface.

2) Complete Fastener Recognition in image sequence that we get through high-speed acquisition. In detection process, get image sequence through high-speed camera mounted on detection vehicle, and then Host(CPU) call GPU to complete parallel computing for DF computing and recognition. Marching processing is a sliding window distance computing between fastener DF pattern and image sample DF. If the match distance is bellow than a certain threshold, fastener is present in that image, and minimum distance point is the position of fastener according to the correlation criterion.

In matching process, the accuracy of fastener location is relevant to DF sampling interval. In order to reduce computing cost, we use Block DF method, not the Point DF which has accuracy of a pixel. It combines N×N pixels to Blocks, and every Block has an optimum Direction based on intensity gradient, which represent the texture trend. The sets of Block Direction form image DF feature, and feature location accuracy is proportional to N. In practical application, we using 5×5 sampling interval and it can reach 5-pxiel precision for fastener location in theory. However, due to projective transformation, fastener imaging will be of the deformed when it is off-center of image, result in reduced positioning accuracy. So the actual fastener positioning accuracy is reduced to about 10 pixels. Fig. 5 shows the difference of fastener position that calculated by our algorithm and manually confirmed in image. There are 15 image samples selected randomly from High-Speed acquisition by fastener detection device.

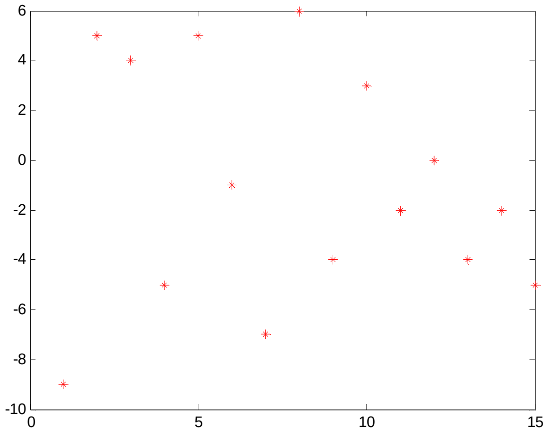


Fig. 5. Precision of Fastener Positioning.

The abscissa is the image number and the ordinate is the deviation of the fastener positioning by pixels. As an experiment, our method can be achieved 99.9 % of the fastener recognition in the test of High-Speed Railway Xuzhou section of china.

4. Fastener Pre-Position

Our fastener detection speed up to 400 km/h, and will be 500 km/h in the future, so the image data is too huge, that we cannot use high-resolution image. Limited by the image transfer rate and exposure brightness, 320×240 pixels is appropriate. For CCD camera, view field is inversely proportional to object resolution, so we can adopt lens with large Field of View. Now, for plane of rail basement, camera's Field of View is about 370 mm along the rail, and assume that fastener spacing is 550 mm, if want to obtain panorama along the rail, sampling frequency should be $400\times10^6/3600/370=300$ frame/s. However, in order to achieve good image stitching, it is important that there is certain overlap region, assume that the overlap region is 1/3, and then frame rate should up to 400 frame/s, it is beyond affordable range of this camera. To make the camera work in a stable state while completing fastener recognition very well, fastener should appear near the center of the images, thus minimizing the effect of lens distortion and projective deformation. In other words, for processing, fastener should at least appear in image. Therefore, camera trigger signal for sampling should correspond with the fastener location. This work is called fastener pre-position.

Reference [10] present a pre-position method based on high-speed laser triangulation sensor. This paper introduces another two methods for information of fastener pre-position rely on image sequence processing. Depending on whether using vehicle encoder pulse signal, two methods is:

1) Take use of the encoder signal, combining the fastener location information in image sequence, we can get a property Pre-Triggering Strategy. In detection, this system processing image sequence (about 20-100 images) periodically, and we can correct trigger signal every second sequence based on analysis result. Encoder signal corresponds to displacement of vehicle, and fastener location in image shows the deviation of trigger position. So we get correction for next trigger signal based on appropriate method. This method is stable.

2) Without encoder signal, just dependent on analysis of the previous image sequence, then get correction strategy for every second image sequence trigger signal. This method has strong independence. However, it requires steady speed of the vehicle.

4.1. Fastener Pre-Position based on Image Sequence and Vehicle Encoder Signal

The encoder signal of vehicle is corresponding to displacement, so this pre-position method is independent of speed. Encoder signal is a direct reflection of some location information, combining the fastener location in image sequence, we can get the trigger signal's correction for pre-position of fastener, and following introduce the correction process.

Assume that fastener spacing is equal to P encoder pluses, but actual camera trigger cycle is equal to $P1$, that is to say, camera completes a sampling after $P1$ encoder pluses periodically. Error is $dP = P1 - P$. For sequence with enough number of images, the fastener location changing loop cycle is P/dP in image. For example, if the sampling pulse count error P/dP is 10 %, then fastener location in image will repeat every 10 images.

If the pulse interval of camera trigger and fastener spacing has less difference by encoder signal, there will be some continuous images with fastener in image sequence(if most images has no fastener, prove that there is overall offset of trigger by encoder pulse, and it need offset adjustment by delay the pulse count). Find the largest consecutive sub-sequence with fastener, marked as *Ic*, the length is *n*. Assume that the fastener position is *V1* in first image *Ic(1),* and *Vn* in the end *Ic(n)* of sub-sequence. Then the correction formula is:

$$\Delta P = \frac{(Vn - V1) \cdot k}{n-1} \tag{1}$$

k is the corresponding number of encoder pulse of a pixel corresponding to field of view. Because the camera installation position is inaccuracy relative to the fastener plane, so we can get the actual size of scope for object (fastener) plane. While encoder pulse is corresponding to actual displacement, so just get an evaluation proportion between pixel and encoder pulse count. Meanwhile, there is error for fastener location algorithm itself in image. Take account of above problem, we need multiple iterations to obtain a better bias correction.

Use fastener average position change ΔP in sub-sequence as correction, this parameters show that we should shorten or increase the encoder pulse count cycle. *k* is an estimate value, so we need a conservative value to avoid divergence of correction. Suppose that camera's Field of View is F>300 mm along the rail, one encoder pulse is corresponding to certain displacement d<0.6 mm, the camera resolution along the rail is 240 pixels, so *k*>300/0.6/240=2.08. In this case, we can set *k*=2.0.
And the error $dP(m)$ after *m*-1 times correction is:

$$dP(m)=dP(m-1)-(V_{nm}-V_{1m})k/(n_m-1) \tag{2}$$

Because $\left|(V_{nm} - V_{1m})k/(n_m - 1)\right| < \left|dP(m-1)\right|$, and correction make $dP(m)$ tend to reduced, that is to say $\left|dP(m-1)\right| > \left|dP(m)\right|$, $dP(m)$ will tend to zero, this method is convergent.

A special state, there is no fastener in most image for a sequence, or all fasteners are off-center in images, then we confirm that sampling signal is advance or delay and make the following correction:

$$JP = \begin{cases} 120 \cdot k & \text{if there is no fastener} \\ mean(Vn\text{-}120) \cdot k & \text{if most of fasteners are appear} \end{cases} \tag{3}$$

This correction make fastener position close to center in image, it will be convergent through iterative. The while pre-position processing is following chart (Fig. 6):

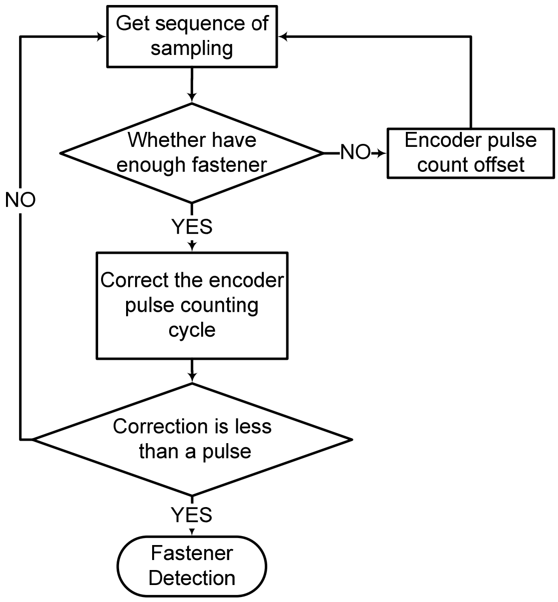


Fig. 6. Chart for Fastener Pre-position Based on Image Processing and Encoder Pulse Count.

4.2. Fastener Pre-Position only Rely on Image Sequence Processing

If there is no encoder signal, we can only complete pre-position rely on time base count and image sequence processing. In this case, the system is independent to external signals, such as speed, displacement. In theory, both time based trigger signal and fastener appearing state are periodic. The sampling image sequence is a synthetic signal of them, and if the cycle of them has less difference, according to signal synthesis theory, result shown in Fig. 7.

In Fig. 7 High-frequency component represents the sampling signal, amplitude descripts the distance of sampling location and nearest fastener along the rail. Because the Field of View is less than fastener spacing, so fastener will appear in image only when amplitude is in certain extent. According to this phenomenon, we can calculate the fastener appearing cycle and position along rail. However, there are periodic solutions for periodic problem, so we set the initial sampling rate higher than which need in max vehicle speed, to avoid the possibility of periodic multi-solution. According to Sampling Theory, there is a unique mapping between fastener location in image and sampling rate based on above condition, if the image sequence is large enough.

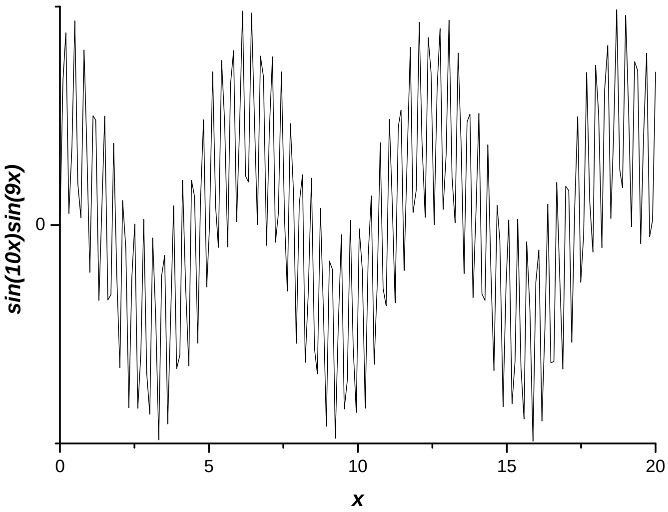


Fig. 7. Indication for Mixed Cycle of Fastener Sampling Location along Rail and Appearing Position in Field of View.

Assume that the initial sampling trigger cycle is t_0, and fastener appearing time cycle is t_1, then mixed cycle is equation (4), which indicates the fastener position change cycle in image sequence:

$$T = \frac{1}{1/t_0 - 1/t_1} = \frac{t_0 t_1}{t_0 - t_1} \tag{4}$$

According to the possible situations, here are 4 type of correction for pre-position signal:

1) If number of fastener in the images sequence is less than 1/3, we can confirm that is caused by overall delay of trigger time, so adjust delay for follow-up trigger signal.

2) If it is the first correction for sampling cycle time, there are fasteners in image sub-sequence continuously, the length of that sub-sequence is bigger than 3, and fastener position in image move to the opposite direction of vehicle speed. Then we can judge that the actual fastener sampling cycle is much smaller than it's appearing cycle and the position change of the fastener in the adjacent image is the product of sampling period and vehicle speed. In this case, we should find the max image sub-sequence with fastener continuously, and use the arithmetic average to get the fastener displacement dP between images. Assume that the camera field of view is F along the rail, and fastener spacing is L， then corresponding distance per pixel is F/240， and correction equation is equation (5):

$$t' = -t_1 \cdot dP \cdot F / (240 \cdot L) \tag{5}$$

F and L is estimate value according to actual situation, and conservative estimate will work well.

3) Exclusion case 2, there are fasteners in image sub-sequence continuously, the length of that sub-sequence is bigger than 3, then we know that the actual fastener sampling cycle is close to its appearing cycle. In this case, fastener position in image sequence has Periodic offset like Fig. 6. Therefore, we should find the max image sub-sequence with fastener continuously, and use the arithmetic average to get the fastener position changing dP between images. Using dP and previous sampling cycle t_{m-1}, correct pre-position trigger signal cycle by equation (6). t_m is corrected sampling cycle.

$$t_m = \frac{t_{m-1}}{(1 - dP \cdot F/(240 \cdot L))} \tag{6}$$

Guarantee that $F/(240 \cdot L)$ is smaller than actual, t_m will converge to ideal sampling period $\lim t_m = t_0$, which is equal to fastener actual appearing cycle.

(4). There are no continuous fasteners appearing in image sub-sequence, or the length of that continuous sub-sequence is smaller than 3, it prove that the actual fastener sampling cycle has significant difference with its appearing cycle, and difference is bigger than $t/3$. In this case, we make substantial adjustment for sampling cycle to close the ideal cycle. The equation is (7):

$$t_m = t_{m-1} \cdot 6/5 \tag{7}$$

By the iteration of the above four processes, if speed is stable and error of estimate value of $F/(240 \cdot L)$ is smaller than 1/3, it can ensure that the iterative process is convergent. By the way, $F/(240 \cdot L)$ higher precision, the correction value is more accurate, it will converge faster.

5. Simulation of Fastener Pre-Position

This section only introduce the pre-position simulation depending on the image sequence solely, because the method combining encoder pulse and image sequence is very stable that it can rapidly converge to the ideal trigger signal obviously.

Here, we do some assumptions. First, the vehicle velocity is uniform, or the change is very little. Second, fastener positioning accuracy is ± 20 pixels in image for our DF algorithm (this accuracy at least twice the actual result). Third, the estimate error of $dP \cdot F/240L$ is not more than $1/3$. The proportion of camera Field of View and the fastener spacing is $1/2$. Forth, we process 50 images in every image sequence. Meanwhile, the correction value can only be passed to controller every second sequence time, which means two consecutive sampling sequence parameters is same.

Based on the above assumptions and considering the actual situation, we use Matlab to make a position sequence due to the fastener appear cycle, and then sample by the sampling cycle that is corrected iteratively in processing. We can get fastener position in image is

$$pos(n) = K \cdot \mathrm{mod}(rand(1) \cdot t0 + n \cdot t1(m-1) + rand(n), t0) \tag{8}$$

$K \cdot rand(1) \cdot t0$ is initial position , and it's a random value, $t0$ is the ideal sample cycle, $t1$ is the sample cycle set initially, and it should be corrected to $t0$ during the sample process, $rand(n)$ is the error of fastener position in our DF algorithm in image processing, K is the corresponding coefficients of speed. We use Section 4.2 method to correct the pre-positioning signal. Fig. 8 shows the initial fastener sampling position in image, abscissa represents the image number in that sequence, and the ordinate represents the location of the fastener in the image.

Fig. 9 shows the fastener sampling positions after 6 times correction. Result shows this method can pre-position the fastener by the image sequence processing in detection process, that is to say, can pre-trigger the image acquisition very well.

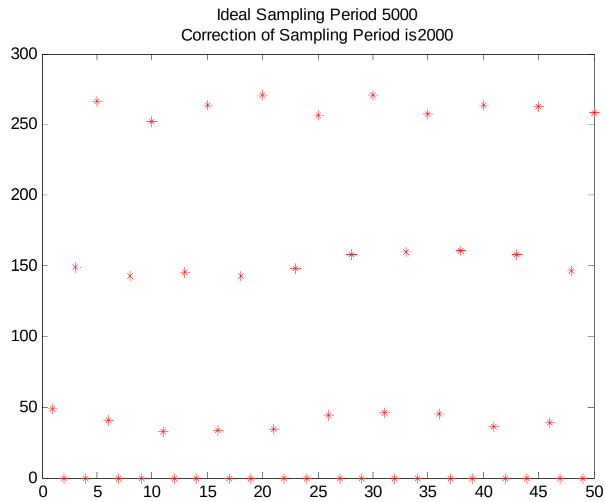


Fig. 8. The initial fastener position in sampling sequence.

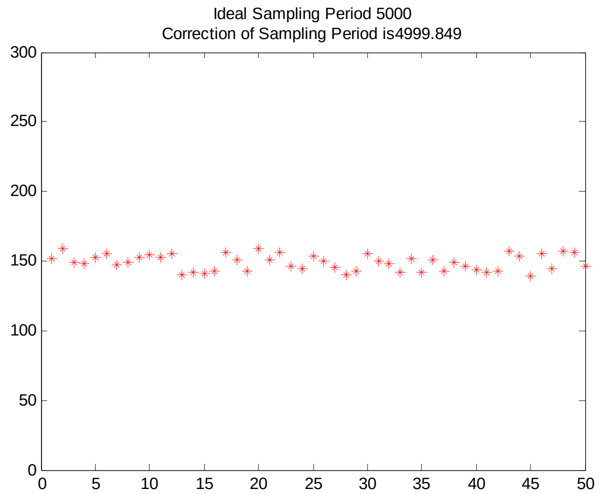


Fig. 9. The fastener position in image after 6 times correction.

6. Conclusion

This paper has proposed a new high-railway fastener detection system based on machine vision, which can complete 99.9 % fastener recognition with is visible in image sequence. It can detect the fasteners present/absent in high precision, and offer data support for rail maintenance.

This paper proposed two pre-positioning method for fastener detection system, one is based on the encoder signal and image sequence processing, and another only rely on image processing which simplify the composition of the system, enhance the intelligence degree of detection system. This system can complete recognition in 500 km/h with high precision, benefit from CPU+GPU.

Acknowledgements

The authors appreciate the financial support by National High-Tech R&D Program of China (863 Program) (grant 2009AA110301).

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

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Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

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